Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Operationalizing risk-based decision support to improve the management of transport infrastructure networks

Clemente Fuggini [a]*, Ivan Tesfai [a], Paolo Basso [a], Claudia Pani [b], Romina Colciago [b], Andrea Zuanetti [b], Mark Gaddes [c], Federico Di Gennaro [d]

[a]*Rina Conuslting S.p.A. Via Gran S. Bernardo,- 20089 Rozzano (MI), Italy; Via Liri 19, Genova, Italy*
[b]*AoN: Via Andrea Ponti, 8/10 – 20143, Milan, Italy*
[c]*Network Rail: The Quadrant, Elder Gate, Milton Keynes, MK9 1EN, UK*
[d]*Aiscat Servizi S.r.l:. Via G. Donizetti 10 – 00198 Rome, Italy*

Abstract

Activities performed through the life-cycle of a transport infrastructure may be negatively affected by a substantial number of different risks. These risks may dramatically increase costs and cause significant delays while negatively affecting the quality of services provided and overall efficiency. This paper introduces risk-based approaches and solutions to enable, from an operational point of view, decision support in various aspects and topics during the whole life-cycle of an infrastructure project, from design to operation and maintenance stages. The main objective of this work is to provide a specific Operational Risk Strategy (ORS), to be implemented in a specific risk-based tool, able to optimize how the Infrastructure Managers (IMs) and Operators (IOs) manage the network and to guarantee them the adequate knowledge and resources to timely and effectively react to potential risks that might arise. Implementing the proposed ORS will definitely result in a better management of the available resources, towards a safer, more resilient and more productive Transport Infrastructure (TI) network.

Keywords: transport infrastructure project;. operational risk strategy; risk management

* Corresponding author. Tel.: +39 02 52876730; Mobile: +39 344 0179979
E-mail address: clemente.fuggini@rina.org

1. Introduction

This paper is part of a broader work under development in the RAGTIME Research and Innovation project (GA n° 690660, http://cordis.europa.eu/project/rcn/204766_en.html) co-funded by the European Commission under the H2020 framework programme. The main objectives of RAGTIME are to develop, demonstrate and validate an innovative management approach and to layout a whole system planning software platform able to facilitate the management throughout the entire lifecycle of a transport infrastructure.
Life-cycle management of infrastructure projects is, in fact, a very complex process from both the managerial and economic point of view and ever growing infrastructure systems increase the likelihood of potential issues within the decision making process. Maintenance phase of life-cycle management of transport infrastructure projects are not exception. Infrastructure maintenance process becomes an even more complex and demanding task in case of long-term planning. The reasons for complexity are: numerosity of actors involved, multi-disciplinarity, huge quantity of information, limited budget, conflict goals and criteria. These facts indicate that decision making processes in urban infrastructure management undoubtedly belong to ill-defined problems. In order to cope with such complexity and to help project managers during decision making processes, multi-criteria methods are needed.

In the framework of the RAGTIME project, a specific focus has been identified in deploying risk-based approaches and solutions to enable, from an operational point of view, decision supports during the life-cycle of an infrastructure project. Decision Support is intended from design to operation and maintenance, in order to optimize how the Infrastructure Managers (IMs) and Operators (IOs) manage the network and to provide them the adequate knowledge and resources to react to potential risks that might occur. To achieve this objective, RAGTIME will implement an Operational Risk Strategy (ORS) that considers the “risk-related” aspects in all phases of the process from planning and design, to the delivery, deployment and management of the infrastructure. This strategy will raise the awareness of the operational, technical, governance and financial risks of the infrastructure by providing suitable instruments for addressing and managing risk. A more effective analysis of the risk processes will potentially result in savings on the operational losses, while better approaches to mitigate risk will be identified. This will give an:

- improvement in the overall process efficiency;
- optimization in the number of actions required by the IMs and the IOs;
- identification of means/actions/alternatives in terms of capacity transfer among transport modes in critical situations (e.g. in emergency) to ensure business continuity and usage of the networks for users/citizens.

The implemented ORS will lead to a Decision Support tool mainly constituted of the following modules: a risk assessment and risk-transfer module; predictive models for operations and maintenance within a life-cycle approach; a module for prioritization of strategies and interventions gathering as inputs the risk strategies previously defined.

Following the aforementioned aspects, the paper is structured as follows: Section 2 presents the ORS paradigm of RAGTIME, Section 3 introduces the risk assessment and risk transfer approach, Section 4 highlights the methods for likelihood and impact estimation focusing on both performance-based probabilistic methods and predictive methods; Section 5 introduces methods and modules for prioritization of strategies and interventions taking into account the risks that may affect the infrastructure as well as the potential (counter)measures to be adopted, Section 6 draws conclusions and discusses future developments.

2. Operational Risk Strategy – proposed paradigm

Decision support logic will enable the process by focusing on different but strongly interconnected modules:

- **Risk assessment and risk-transfer module**.
  A three-step methodological approach is presented and it is composed by three main steps:
  - Risk mapping – designed to provide a complete overview of the main risks;
  - Risk evaluation – aimed at providing suitable and more effective instruments for estimating risks;
  - Risk strategy – designed to identify a set of mitigation actions able to mitigate the impact of risks.

- **Predictive maintenance methods** using logic and procedures to **forecast damage/degradation and identify potential countermeasures** and intervention strategies.
- Methods and modules for **prioritization of strategies and interventions** taking into account the risk the infrastructure is exposed to as well as the potential (counter)measures to be adopted.

Integration of the models will happen within a broader Operational Decision Support System (ODSS) that will provide an important support tool for stakeholders for addressing and managing risks.
In a very simplified view, the ODSS can then be represented as follows:

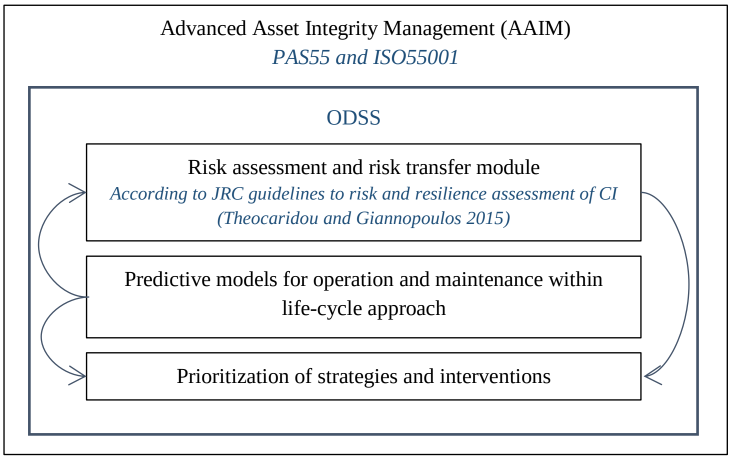


Fig. 1: ORS paradigm.

The result is a tool to be part of an Advanced Asset Integrity Management (AAIM) solution of RAGTIME. A Service Oriented Database Architecture (SODA) will be used to allow the collection and integration of inputs from multiple heterogeneous sources.

3. Risk assessment and risk transfer approach

Activities performed through the life-cycle of a transport infrastructure may be negatively affected by a number of different operational risks that often manifest themselves in considerable cost overruns (Miller and Szimba, 2013; Flyvbjerg et al., 2004). The scientific literature showed the lack in the transport infrastructure sector of a multimodal standardized and comprehensive risk assessment approach able to consider operational risks which may occur during the life-cycle of a generic transport infrastructure project. The majority of the studies and researches highlighted that, in the transport field, risk assessment is sector specific: several approaches have been proposed from different authors in order to better manage risks with reference to a specific transport mode and during the single stages of evaluation (e.g. Ye and Tiong 2000; Salling 2008; Salling and Banister 2009), appraisal (e.g. Miller 2013) construction (e.g. Ashley et al. 2006) and operation & maintenance (e.g. Alfen et al. 2011).

Moreover, discussions with stakeholders highlighted the need to develop a systemic and multimodal approach able to support cohesion among the different stages of a transport infrastructure project by means of the representation of risks in a standardized format taking advantages of Failure Modes and Effects Analysis (FMEA) approaches (Spreafico et al., 2017).

One of the main objective of this work is to propose a comprehensive approach in the transport sector aimed at defining a standardized three-step methodology for the risk assessment of infrastructure projects . Every different step (risk mapping, risk evaluation and risk strategy) represent a separate tool section. The risk assessment will be conducted directly from the end-user who will be guided through the completion of each section by suggestions and examples. The proposed risk analysis will consider:

- Variables related to the infrastructure features:
  - *Transport mode*: road, rail, air and maritime

    - *Infrastructure life-cycle phase*: five main stages in the life-cycle of a transport infrastructure will be considered (Planning, Procurement, design, construction, operation&maintenance). Each of this phase will be evaluated both as possible phase of risk origin or as possible phase affected by the risk (or both/none);
- Variables related to the risk characteristics:
    - *Risk Driver*: every operational risk identified during the analysis will be described and clustered depending on the risk driver (Process, Systems, People, External Events);
    - *Event type*: every risk will be assigned to one of the possible event type, depending on its cause and nature;
    - *Stakeholder*: for every risk, all the stakeholders involved in the risk consequences/management will be identified;
- Variables related to the consequences (risk severity):
    - *Loss Type*: the nature of the resulting damage will be identified. For every risk, an estimate of the damage extent will be provided for every kind of damage it can provoke (extra – costs, asset damage, reimbursement, sanctions, missing gain, penalties).
    - *Probability & Severity*: Estimate of risk probability and severity, see section 2.2 Risk Evaluation for further details.

The main steps of the proposed methodology are summarized below.

3.1. Risk Mapping

In the first step, users will be required to identify risks. A pre-determined set of operational, technical, governance and financial risks will be provided to the user thanks to previous desk analysis, interviews to the stakeholders (different functions of transport operators), available claim historical records. The user is required to determine the applicability of every risk to its specific case. Risks will be also assigned to a Risk Driver (Either “Processes”, “Systems”, “People” or “External events”) and will be clustered by Event Type (i.e. “Natural Event”, “Cyber Risk”,…). For every risk, a set of causes will be identified. As an example a “Major Incident” risk may have several causes, such as *Poor Maintenance*, *Poor Traffic Management* or *Natural Event*. In addition, user will have to indicate in which phase(s) the risk can originate from, and which phase(s) may be affected by the risk. Finally, involved stakeholders will be identified.

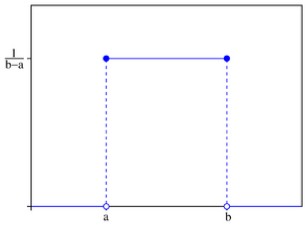
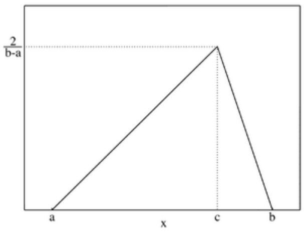
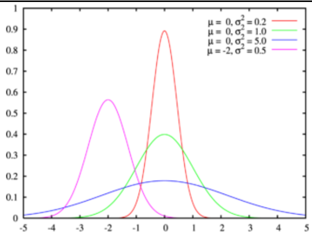
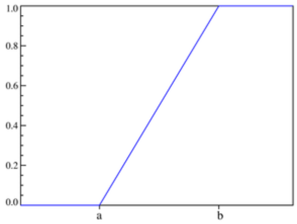
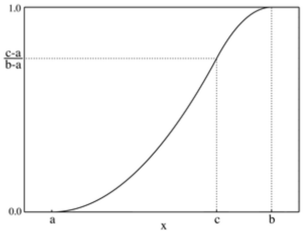
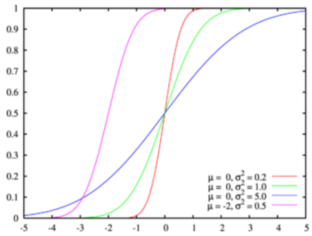
3.2. Risk Evaluation

In this delicate step, users will have to assign to each source of risk an estimate of the probability of occurrence and risk severity. Given the complexity of this task, user will be required different inputs, depending on the user experience and familiarity with the Risk Assessment activity. More novice users will be using a quali/quantitative approach, defining a range of probability and severity among those suggested by the system, while users with some experience/knowledge of the Risk Management activity will be granted the possibility of defining exact values of Probability and Severity. Finally, expert Risk Managers will be provided with a comprehensive tool capable of modelling several probability distribution allowing for a precise quantification of risk relevance. In this latter case, Risk Managers will be allowed to introduce positive risks (opportunities).

Dens. Lin. $\frac{1}{a-b}$ $\quad \frac{1}{a-b}$ Cumul. Lin. $\frac{x-a}{b-a}$

Dens.Tri $\begin{cases} \frac{2}{b-a}\frac{x-a}{c-a} & for\ a \leq x < c \\ \frac{2}{b-a} & for\ x = c \\ \frac{2}{b-a}\frac{b-x}{b-c} & for\ c < x \leq b \end{cases}$ Cumul Tri $\begin{cases} \frac{1}{b-a}\frac{(x-a)^2}{c-a} & for\ a \leq x < c \\ \frac{c-a}{b-a} & for\ x = c \\ 1-\frac{1}{b-a}\frac{b-x^2}{b-c} & for\ c < x \leq b \end{cases}$

Dens. Norm. $\frac{1}{\sqrt{2\pi\sigma^2}} exp\left\{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right\}$ Funz. Norm $\frac{1}{2}\left(1+erf\,\frac{x-\mu}{\sigma\sqrt{2}}\right)$

	Linear Distribution	Triangular Distribution	Normal Distribution
Probability density function			
Cumulative distribution			
Parameters requested to user	P = Probability of occurrence a = min. impact b = max. impact	P = Probability of occurrence a = min. impact b = max. impact c = most likely impact	P = Probability of occurrence μ = most likely impact μ±1,96σ = value within 95% of occurrences will fall

The qualitative evaluation is oriented to understand the residual risk of each transport infrastructure cluster, considering current measures of mitigation. Based on Manager's risk perception both Intrinsic risk of the process (RPN index) and Existing mitigation elements (RMI index) will be calculated. Furthermore, from a quantitative point of view, all users will be able to conduct Montecarlo simulations that will draw the Project Risk Profile, providing a comprehensive picture of the project risk exposure. At the end of this phase the most meaningful risks will be identified and highlighted in red.

3.3. Risk Strategy

In the last step, the tool will provide samples and suggestions about most common mitigations for pre-defined risks of interest. This will include operational, contractual and insurance mitigations.
The main outcome will be a set of strategies and proper action plans, including risk transfer approaches in order to mitigate and reduce the impact of risk events that may occur and to consider a sustainable retention of the risk.
During the Risk Strategy it will be presented a complete framework and guidelines regarding:

- Operational Mitigation (e.g. evidence of the necessity of conducting a review of process/procedures,…);
- Contractual Mitigation (e.g. indication about clauses review with reference to responsibility, subcontractors, insurance guarantees, …);
- Insurance Mitigation (e.g. suggestions about required reviews in terms of guarantees, payments limits and/or indications about new insurance solutions).

Users will have the possibility to determine mitigation cost and impact on risks either by defining a reduction in risk likelihood or severity (e.g. risk probability reduced by 20%), or by defining a new likelihood or severity (e.g. new risk probability is 15%). In line with the objective of providing a comprehensive tool of Risk-Based decision support, users will not be constrained in the mitigation definition and will be allowed to insert "negative mitigations", that will introduce savings by increasing risk exposure in accordance with the user's risk appetite.
Mitigation can be either Cause-based, if it affects the risk only if generated by a specific cause, or Risk-based, if it affects the Risk, regardless of its cause.

3.4. Main outcomes

The main objective of the first module is to provide a standardized user-centered three-step methodology for evaluating and implementing risk assessment and appropriated strategies for risk mitigation with the main aim of minimizing the impact that risks may have on the business. Specific business requirements will be provided through a panel of recommended Risk Mitigation actions empowering decision makers to set up a structured and effective risk assessment process. Fig. 1 shows the proposed methodology workflow.

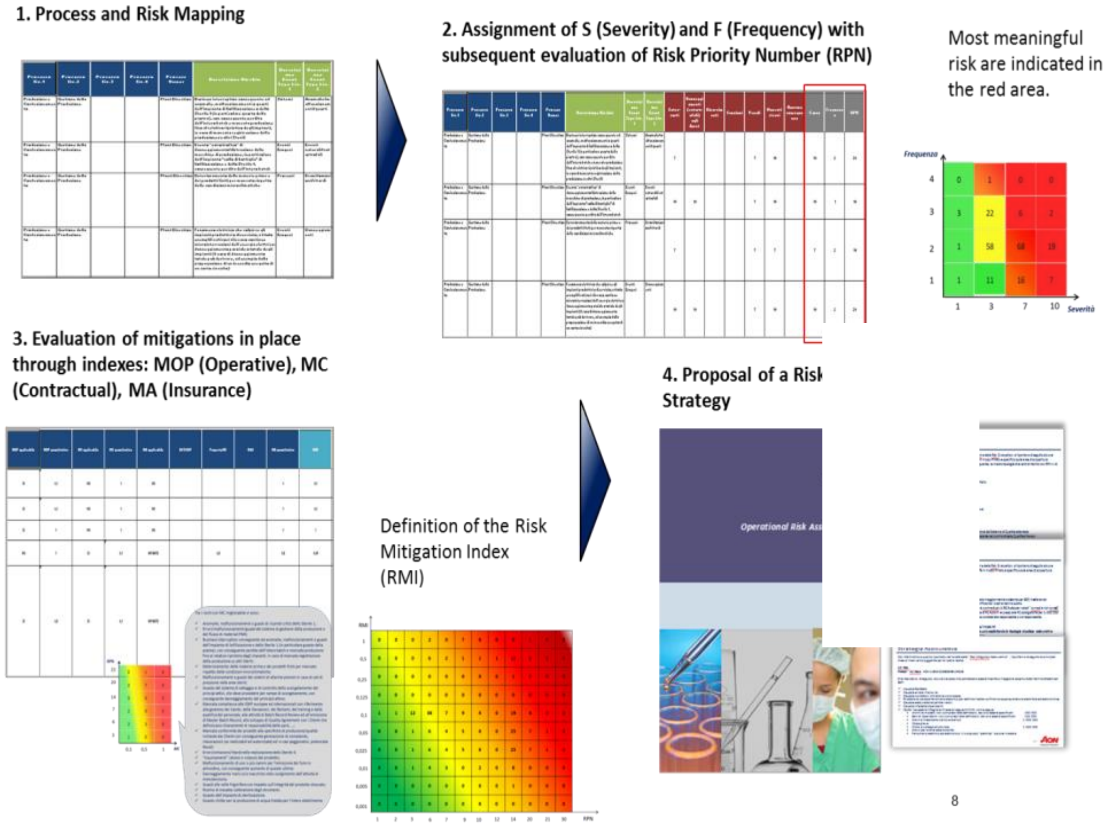


Fig. 2: Methodology workflow

4. Predictive maintenance - methods for likelihood and impact estimation

In order to predict maintenance, two main approaches are adopted in RAGTIME:

- Statistical approach – statistical and analytical techniques (e.g. robust regression analysis) are applicable to identify patterns usable to develop models that predict the likelihood of future events or asset behaviours.
- Updated Performance-Based Probabilistic Models – Performance-based probabilistic models of infrastructure strategic assets (e.g. bridges) that are real-time informed of the behaviour of their components through a monitoring system.

To the first approach, a preliminary data harmonization phase is necessary. The main requirement for an effective predictive modelling process is a noticeable amount of reliable data, preferably using several data sources. Although recent data is usually weighed more heavily for trending purposes, the deeper the history of the asset the better. Missing, incomplete, or erroneous data have a negative impact on the accuracy of the predictive model, so for such reason is necessary to ensure clean and accurate data by firstly defining a framework and the specifications of the architecture to collect and homogenise statistical and historical data. Following a data harmonization phase, the implementation of performance-based probabilistic and predictive methods is possible and achievable by using a Predictive Model Mark-up Language (PMML).

To the second approach, a simplified Displacement-Based Assessment procedure based on the work done by Sullivan et al. [2012] for development of fragility curves of existing bridges has been considered. A comprehensive direct displacement-based algorithm with the objective of including piers, abutments, bearings and shear keys exposing all parameters as random variables.

However, bridges with similar geometrical and material properties could have different age and/or could deteriorate at a different rate. Fragility curves are then calculated not only based on the geometry and material properties but also on vibration data. The data are recorded by a structural health monitoring system and are used to track changes of the structural parameters of a bridge throughout its service life.

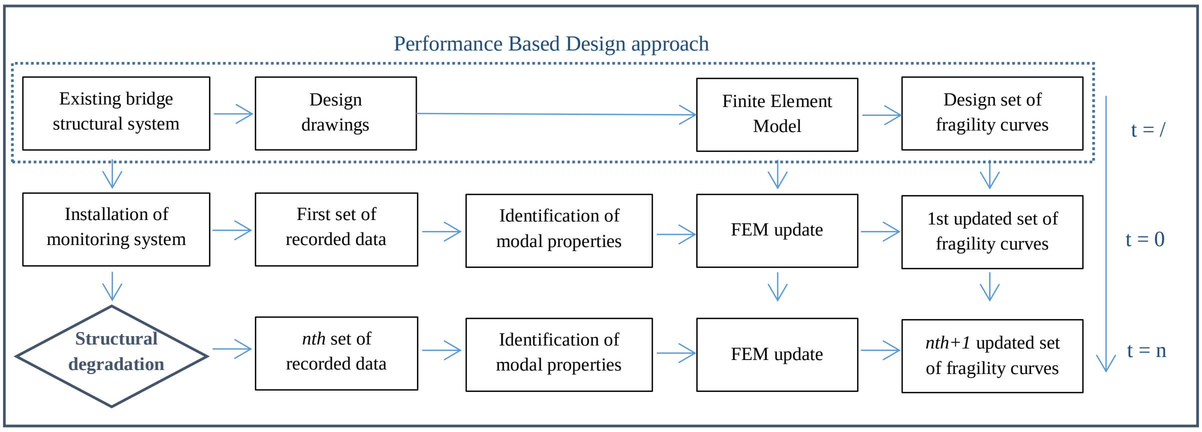


Fig. 3: Fragility curves updating process (adapted from Torbol et al. 2013)

Potential outcomes are the availability of models (algorithms/tools) for predictive maintenance of transport infrastructures based on risk analysis and real performance assessments: future state indicators (expected values of the variables of interest), risks indicators and the probabilistic representation of the residual lifetime of the infrastructure to provide support to decision mechanism.

5. Methods for prioritization of strategies and interventions

The operationalization of prioritization strategies and intervention is the comparison of the cost of loss (statistically deducted or computed through one of the developed models) with the cost of maintenance.
This comparison is, in turn, the result of the application of two main contributions: a cash-flow approach and a socio-environmental benefits assessment.
Considering the cash-flow approach, in order to evaluate the feasibility of an investment, a necessary step of assessment is performed to evaluate the relationship between benefits (rates and residual value) and costs (investment and maintenance, exploitation and replacement). This balance has to be updated to the reference year by using a discount rate. In this way, the difference between benefits and costs for a given year is obtained through the following formula:

$$\frac{(b_t - c_t)}{(1+i)^t}$$

Where:

b_t = annual benefits in the year “t”
c_t = annual costs in the year “t”
t = number of years taking as origin the year of reference

This formula has been determined to be the most suitable one in order to assess the effective profitability of the project owing to its high social-environmental value, something that would make no sense on the economic assessment because it would not consider such kind of benefits since it focuses exclusively monetary values. The results of the cost-benefit analysis will be expressed through two economic parameters: Net Present Value (NPV) and Internal Rate of Return (IRR).
Following the guidelines of the Regional Directorate for Regional Policy of the European Commission, the amortization costs that enable the replacement of the work at the end of its design life shall not be considered. This is due to the fact that because of not being considered an actual amount of the cash spent or received by the project. On the other hand, for the design life of the project, the social and environmental benefits will be also estimated. Both values arise with the implementation of the sanitation process and the residual value of the initial investment at the end of the design life of the infrastructure. Through this procedure, it is possible to obtain the minimum internal profitability that can be expected from a given investment. Along the costs-benefits analysis,

the most significant parameters have been taken into consideration in terms of their economic quantification. Therefore, for every single year, the difference between the positive flow (socio-environmental benefits) and the negative flow (investment and exploitation costs) is calculated.
As already mentioned, the second main contribution is the socio-environmental benefits assessment, which is defined as the whole of characteristics such as the increment in a service satisfaction (warrantee, availability and quality supply), improvement in the quality of life, etc. The lack of historical data of similar construction works which is studied in this analysis makes harder for the completion of a risk assessment to rely on similar projects in the area of study.
Regarding to the quantification of the socio-environmental benefits there are several factors with an important economic incidence on the project, either due to how they can affect its costs or have a great influence on the earned benefits. The risk analysis is included along the whole life cycle from a technical aspect to different financial issues to develop new investment strategies based on feasibility studies for large infrastructure projects.

6. Conclusions

The presented study is part of a broader research project funded under the European programme H2020 (RAGTIME - Risk based approaches for Asset inteGrity multimodal Transport Infrastructure ManagEment) aimed at establishing a common framework for governance, management and finance of transport infrastructure projects. This paper introduces a specific Operational Risk Strategy (ORS) that allows considering the “risk-related” aspects in all phases of the process from the planning and design, to the delivery, deployment and management of the transport infrastructure. To this end the main objectives of this work are:

- To implement a multi-step risk management and risk transfer methodology from both a technical and economical point of view;
- To implement performance-based probabilistic and predictive models;
- To support cohesion among the different stages of a transport infrastructure project by means of the representation of risks in a standardized format;
- To support Operational decisions by means of a software oriented architecture gathering as inputs the risk analysis and the probabilistic and predictive models.

All the aforementioned methods and models will be implemented in a specific Decision Support Tool, composed by different but strongly interconnected modules, designed to assist infrastructure managers and operators in the management of the transport network and to give decision makers adequate instruments to efficiently react to potential risks that might arise during the whole infrastructure life-cycle. This will allow:

- Raising the awareness on the operational risks of transport infrastructures by providing suitable instruments for addressing and managing them;
- Increase savings on the operational losses through the implementation of a more effective analysis of the risky processes;
- Identifying a strategy to mitigate risk through the underlying of ad hoc solutions.

The adoption of an Operational Risk Strategy (ORS) can improve overall process efficiency ensuring a better governance of the transport infrastructure throughout entire lifecycle. This will improve the efficiency of the process and will allow delivery in time regarding to the asset main objective and its capacity planning.
In the coming months, a testing phase is planned in order to evaluate the performance of the tool thanks to the help of two main case studies: Network Rail, in the railway sector, and AiSCAT, in the transport road sector.

Acknowledgements

The RAGTIME Consortium would like to acknowledge the financial support of the European Commission under the H2020 programme, Grant Agreement (GA) n° 690660

7. References

Ashley, D. B., Diekmann, J. E., Molenaar, K. R., 2006. Guide to Risk Assessment and Allocation for Highway Construction Management. U.S. Department of Transportation Federal Highway Administration (Ed.).

Flyvbjerg, B., Skamris Holm, M. K., Buhl, S. L., 2004. What causes cost overrun in transport infrastructure projects?. Transport reviews, 24, 3-18.

ISO 550001: 2014. International Standard for Asset management — Management systems — Requirements.

Jajac, N., Knezić, S., Mladineo, N. , 2008. DSS for Urban Infrastructure management, Parking Garages Case Study, Book of proceedings, 8th International Conference on Organization, Technology and Management in Construction, Umag, Croatia

Jajac, N., Knezic S., Marovic I., Decision support system to urban infrastructure maintenance management, International Conference on Organization, Technology and Management in Construction, 1(2)2009, 72-79

Miller, M., Szimba, E., 2013. How to Reflect the Issue of Risk in Transport Infrastructure Appraisal: Synthesis of Methods and Best Practice. Selected Proceedings of the 13th World Conference on Transport Research, Rio de Janeiro.

PAS 55-1: 2004. Asset management – Part 1 – Specification for the asset management of physical infrastructure assets. The Institute of Asset management (IAM).

Salling, K. B., 2008. Assessment of transport projects: risk analysis and decision support. Doctoral dissertation, Ph. D. thesis, Department of Transport, Technical University of Denmark.

Salling, K. B., Banister, D., 2009. Assessment of large transport infrastructure projects: The CBA-DK model. Transportation Research Part A: Policy and Practice 43, 800-813.

Spreafico, C., Russo, D., Rizzi, C., 2017. A state-of-the-art review of FMEA/FMECA including patents. Computer Science Review 25, 19–28.

Sullivan. T.J. Priestley, M.J.N., Calvi G.M. Editors, 2012. "A model code for the Displacement-Based Seismic Design of Structures, DBD12" IUSS Press, ISBN 978-88-6198-072-3, 105.

Theocaridou M. and Giannopoulos G., 2015. Risk assessment methodologies for critical infrastructure protection. Part II: A new approach. JRC Science and Policy Report.

Torbol, M. & Gomez, H. & Feng, M., 2013. Fragility Analysis of Highway Bridges Based on Long-Term Monitoring Data. Computer-Aided Civil and Infrastructure Engineering. 28. . 10.1111/j.1467-8667.2012.00805.x.

Ye, S., Tiong, R. L. K, 2000. NPV-at-Risk Method in Infrastructure Project Investment Evaluation. Journal Construction Engineering and Management 126, 227-233.