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A Decision Support Model for Maintenance of a High Speed Railway System

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Abstract
This paper reports on a Maintenance Decision Model which has been developed to provide a structured approach to decision-making early in the design phase for the maintenance of a high speed railway system. The model functions as a decision support tool and focuses on the analysis of risks, and life cycle costs (LCC) of the maintenance phase.
A literature study on aspects related to life cycle costing and decision analysis concerning high speed railway systems was carried out and a maintenance risk regime of the Dutch part of the trans-European high speed railway system 'HSL South' was analysed.
Based on the above studies and knowledge acquired from experts a maintenance model was developed that acts as a decision support tool. The starting point of the developed model is a base case scenario, which reflects basic values of maintenance costs and risks of the system to be analysed. The model allows 'What-If' analysis to be carried out in order to determine the effects of possible design choices and risks on the costs of maintenance of the system in relation to the base case scenario. The developed system uses Monte Carlo simulation for analysing the influences of various scenarios on the maintenance costs.
Experiments using the proposed system have shown that the model produces useful analysis that supports effective decisions with regards to the maintenance of the high-speed railway system.

Keywords
Risk Management, Life Cycle Costing, Decision Analysis, High Speed Railway System Maintenance.

1. Introduction

From the year 2006 a high speed railway track will run from Hoofddorp, the Netherlands, to the Belgian border, linking the port of Schiphol in Amsterdam and the Harbor of Rotterdam to the Trans-European High Speed Railway Network, connecting them with other European main ports including Paris, London, and Antwerp. The project called 'infraprovider for the Dutch part of HSL-South' is the largest project the Dutch government ever contracted to a private corporation, with a value of €3.0 billion. The project is undertaken as a Design, Build, Finance, and Maintain (DBFM) contract. The private finance and the maintenance aspects of this contract are unique in the Netherlands. The availability of the railway is based on a 25-year maintenance contract during which a fee is to be received, based on the availability percentage of the railway. The project incorporates a PPP (Public Private Partnership) contract. This entails that project risks lie with the party which has the possibility to influence them. This has led to a contract between the Dutch government and a consortium named Infraspeed B.V. with a clear assignment of responsibilities for various risks to each party. Infraspeed's consortium partners are Fluor Infrastructure BV, Royal BAM Group, and Siemens.

The research deals with life cycle costing and risk analysis of the maintenance phase of a high speed railway project. In current practice for life cycle cost analysis of maintenance only best estimates are used. Such analysis does not incorporate the effect of uncertainties into the system and hence does not provide a realistic basis for decision making vis-à-vis maintenance. Because of the size and importance of the project, the cost of maintenance is considerable. A system was required to structure this task at early stages in order to be able to optimize its costs under various scenarios and under conditions of uncertainties. A maintenance system, which functions as a decision model, is believed to provide the answer to this problem. The cost estimates for the maintenance phase of the HSL-South is usually based on information provided by experts from various companies and institutes such as BAM NBM Rail B.V., a subsidiary company of BAM NBM Infra (a leading company in the Dutch railway maintenance industry), IFB (German railway techniques institute), NMBS (Belgian railway authorities) and DB (German railway authorities). The estimates used are most likely values and the uncertainties within this estimate are worded, but not quantified. If a maintenance risk model could be established during the design phase, influences on the maintenance phase could be accounted for in this model. The model could act as an additional decision support tool during the design of the infrastructure of HSL-South.

This paper describes the development of a Maintenance Decision Model for the Dutch HSL South System. This model provides a structured approach to maintenance for the Infraspeed HSL South project. The model is intended to be used to analyze and predict the maintenance costs of the project for various design options and under conditions of uncertainties. As such the model will help to anticipate maintenance risks related to design choices and taking measures to mitigate them.

The paper also describes how the model works and its use in the project.

2. Basic Concepts

2.1 Risks and Risk Management

A literature review has revealed that there are many definitions of risk management, just as there are of risk, see for example, Al-Bahar and Crandall (1991), Bannister and Bawcutt (1981) and Flanagan and Norman (1993). The review has also shown that there is no consistency in the definition of risk, this is compounded in the definitions of risk management.

There is also disagreement on the matter of what should be the focus of risk management within construction. Many of the definitions define it in terms of construction projects whilst for others risk is viewed purely from a business perspective, as in Bannister and Bawcutt, 1981. Indeed, Perry and Hayes (1985), identify the benefit of understanding the cumulative effect of project risks, but concede that this is not undertaken.

Many authors, rather than providing a definition of risk management, describe the process and, in doing so, definitions can be inferred. Risk management is described by many as a three stage process (Perry and Hayes, 1985, Clark, Pledger and Needler (1990), Bannister and Bawcutt (1981), and Toakley and Ling (1991) entailing identification, analysis, and response.

As defined by the Project Management Institute (PMBOK, 2000), a *Project Risk* is an uncertain event or condition with a probability of occurring, which if it occurs, has a positive or a negative consequence on the project objectives. Risk has a cause and, if that cause occurs, a consequence. Therefore, the definition of risk consists of a probability component and a consequence component and is defined as the product of multiplying the probability of occurrence with the outcome of the occurrence. This definition gives a basis for comparing the expected values of various risks. A general extension of this definition is the one where risks are redefined as a function of probability and effects.

In this work a model is developed at the project level, which considers the sources of uncertainty in the project and which can be extended for use at the company level.

2.2 Life Cycle Costing

The determination of costs is an integral part of the asset management process and is a common element of many of the asset manager's tools particularly Economic Appraisal, Value management and Risk management.

In the past, comparisons of asset alternatives, whether at the concept or detailed design level, have been based mainly on initial capital costs.

Growing pressure to achieve better outcomes from assets means that ongoing operating and maintenance costs must be considered as they consume more resources over the asset's service life. Both capital and the ongoing operating and maintenance costs must be considered wherever asset management decisions involving costs are made. This is the Life Cycle Cost approach.

Life Cycle Costing is a process to determine the sum of all the costs associated with an asset or part thereof, including acquisition, installation, operating, maintenance, refurbishment and disposal costs. It is therefore pivotal to the asset management process as an input to evaluation of alternatives via Economic appraisal, Value management and Risk management.

2.3 Decision Analysis

The process described in the previous section produces the costs figures for an asset, which are usually variable and which are influenced by a set of, mostly uncertain, conditions. The nature of variability and uncertainty involved in the costs requires the use of scenarios analysis of possible future conditions and risks in order to forecast their effects on costs. In this way the process behaves as support tool to assist in the decision-making (Zoeteman, 2001). The life cycle cost analysis under uncertainties is about the process of decision making. To investigate the impact of a risk or a factor on the life cycle project cost, a system is required whereby the relationships between the project elements that make up the final cost are determined. The project under consideration is hence decomposed into a framework of smaller parts that can easily be analyzed and understood (Clemen 1996).

3. The Maintenance Decision Model

3.1 Characteristics and Aim of the Model

The Maintenance Decision Model functions as a decision analysis tool for Infraspeed. The aim of the model is to provide an easy-to-use tool that is capable of providing maintenance cost estimates under the influence of various decisions and scenarios. The main function of the developed maintenance decision model is hence to provide a structured approach to decision making concerning maintenance costs under uncertainties. Additional objectives of the model are:

- To provide the relations and influences of the components of the project
- To provide a visual structure for the interrelationships between components affecting maintenance
- To be flexible to include all value ranges and uncertainties in the analysis
- To be used for analysis of costs on the basis of what-if scenarios,

In general, the model is designed to be used for analysis of possible cost and risk consequences of choices made during the design phase on the maintenance phase of the project. This is essential as decisions made in the engineering phase of the HSL project will affect the projects' life cycle costing from that point on. With the availability of such a model, valid predictions can be made about the risk and impact of decisions made on the project as a whole and on the maintenance in particular.

3.2 Build Up and Working of the Model

The basis of the developed maintenance model and how it works can be represented as in Figure 1. This figure shows that the model consists of a number of steps. The first step in the decision making process used by the model is to determine a *Base Case Scenario* which functions as a starting-point for decision making. The base case scenario produces a most likely value (accompanied by a probability distribution) for total maintenance costs, or total maintenance costs of a maintenance element, in its most basic form. Adding up all mean values of the lowest level costs will produce a similar value. Modifications in the base case scenario will provide information on increase or decrease of risks and costs as a result of those modifications.

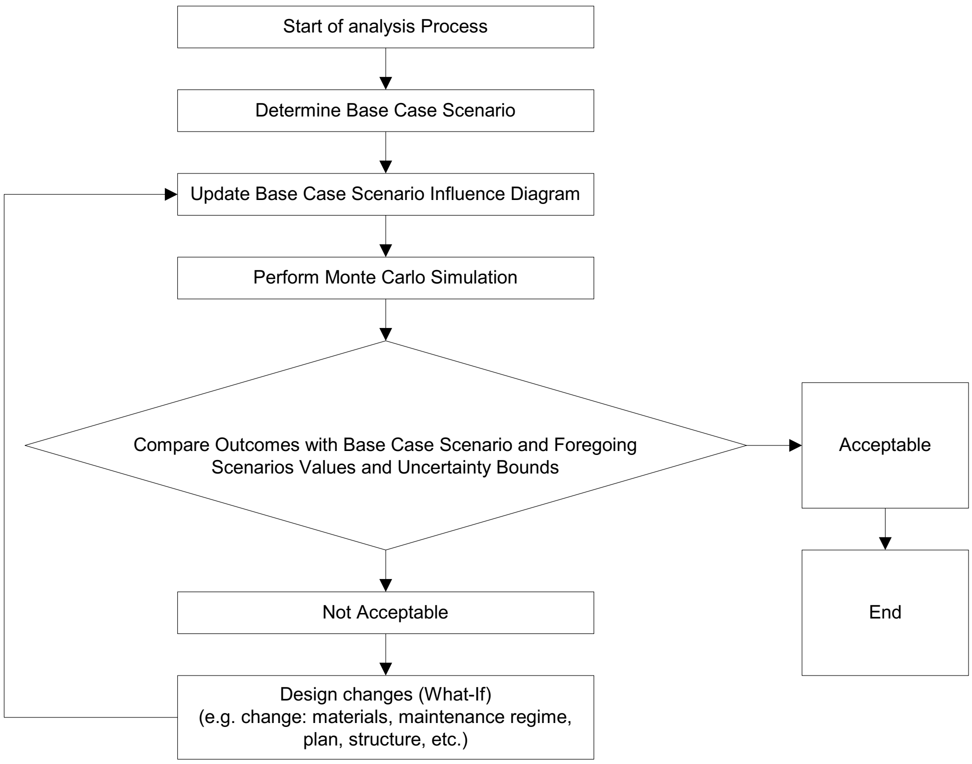

Figure 1: Flowchart for the developed model

The Base Case can be graphically presented with the help of an *Influence diagram*. Influence diagrams are useful tools for the graphical representation and hence the visualization of the relationships between components of a system or an object (Vatn, 2001). This is a complicated process that requires considerable knowledge of the project and experience. To complete the influence diagram for a project using the developed model requires the decomposition of the project into its structural maintenance elements. At a certain point, the decomposition will stop and the influence diagram will reach its lowest level. The lowest level of an influence diagram always consists of a number of influence variables that most likely are uncertainty bound. These influence variables form the basis for calculations of the maintenance costs of the whole project.

The influence diagram, with the input values for the variables, serves as the input for a Monte Carlo Simulation (Vose, 1996). The output of the simulation is a probability distribution for the total maintenance costs from all the identified influence variables. To test if the outcomes from the Monte Carlo scenario are correct, the Monte Carlo simulation output base value has to be checked to correspond with the sum of all elements mean values. If this is not the case, the influence diagram should then be checked for errors. These can be the results of inaccuracies in the construction of the influence diagram or the input values.

Figure 1 shows the process used by the model after the base case scenario is determined. The model helps in reaching decisions that influence the total maintenance costs of a large infrastructure system or an element of that system. Through the use of the influence diagram and on the basis of using what-if scenarios, it is possible to determine what elements in the total system influence the final total maintenance costs under uncertainties. When this is determined, certain possible measures can be taken, if required, to reduce the effects of such uncertainties on the total costs. These measures can then be implemented in the influence diagram and their effectiveness in reducing the costs can be investigated by performing a Monte Carlo simulation. Comparing the outcomes from such simulation with the ones produced from the base case will show the impact on the total maintenance costs.

The developed model can be used to run various scenarios such as the impact of general risks, effects of organizational changes and the effects of using different construction materials during the design phase. Using the model, the decision-making process starts by determining a base case scenario that will function as point of departure for the 'What-If' scenarios. 'What-if' scenarios are carried out to determine the influences, in cost, of specific factors on the final outcome. The decision maker makes up a scenario that, in his perception, possibly has an influence on the final value of the maintenance cost. Such scenario has then to be implemented into the base case scenario. By comparing the outcomes of the Monte Carlo simulation of the new scenario with the outcomes of the base case scenario, a conclusion can be drawn on the impact on maintenance costs or risks of the examined system. If the outcomes do not have the desired effects, more scenarios can be investigated.
The model is also useful to determine which variable or subsystem has large or small influence on the total maintenance costs of the examined system. When the variable or subsystem with the greatest influence is determined, cost or risk reducing measures can be then determined.

An example of some of the results produced by the system is shown in Figure 2. The figure shows two distributions of costs. The left histogram represents the output of a Base Case Scenario for the total maintenance cost distribution of Civil Structures in the HSL South railway system. Simulating a What-if Scenario, in this case by assigning a general risk with the potential to influence maintenance costs and a cost- and uncertainty-influencing graffiti scenario (graffiti on civil structures results in extra maintenance), leads to a scenario output as presented by the right histogram in Figure 2. In Figure 2 the x-axes of the graphs represent Euro's and the y-axes represent the percentiles. Note that the scales in the graphs differ.

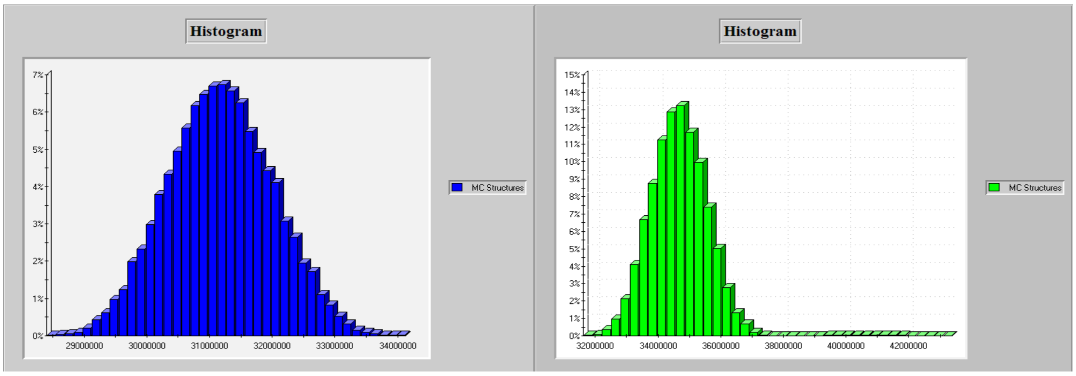

Figure 2: Example of a Base Case output for total maintenance costs (left) and an output of a Scenario Case influenced by a general risk and a graffiti scenario (right) (Numbers in these figures are for illustrative use only).

4. Conclusion

The developed model has provided a structured approach to analysis of maintenance costs at early stages of the project. It has provided an easy to use tool for testing alternatives in order to optimize the maintenance costs over the life cycle of the high-speed railway system.
Testing of the model has shown that the developed system produce very useful results that can assist in the decision making process. The forecasts produced of the maintenance cost under various uncertainties through 'what-if' scenarios can also provide assistance for developing management strategies to reduce cost of maintenance of the project.

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