RAMS and LCC in the design process of infrastructural construction projects: an implementation case

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Abstract

The implementation of RAMS (acronym for Reliability, Availability, Maintainability and Safety) and Life Cycle Costing (LCC) in construction industry is in its infancy compared to other industrial sectors. These two concepts can be used within the design of infrastructural construction projects to make a trade-off between performance and costs. RAMS and LCC are methods used to quantify performance and different cost categories such as initial costs, maintenance costs and operational costs. This paper investigates existing models for the implementation of RAMS and LCC in design processes that have been proposed by other researchers. Out of these existing models a suitable model is adopted to test implementation in construction industry to identify problems that are associated with implementation of such a model. The results of the implementation are discussed and conclusions are drawn.

Introduction

There is increasing demand in the Dutch construction industry for the implementation of life cycle aspects like reliability, availability, maintainability and safety, often referred to as RAMS, in design of infrastructural projects. This is particularly true in the context of the new integrated contracts such as D&C (Design & Construct) and DBFM (Design, Build, Finance and Maintain), where maintenance has become the responsibility of the contractor.

RAMS is defined according to CENELEC (1999) as "a qualitative and quantitative indicator of the degree that the system, or the subsystems and components comprising that system, can be relied upon to function as specified and to be both available and safe".

In recent cases of mainly road and rail projects, clients have specifically demanded from the parties responsible for the design to provide evidence of the application of the RAMS concept in their designs as part of the tender evaluation process. In all of these cases clients have provided very little specifications of the required components of the project to allow contractors who are undertaking the design process the freedom to innovate and choose the appropriate design to satisfy the RAMS requirements. However, these cases are not standard because a recent study related to the application of RAMS in the construction industry has shown that the knowledge and application of

RAMS and its techniques in infrastructural designs are in their infancy compared with other industrial sectors and that many designers in construction do not have the knowledge and experience in how to apply it (Ogink & Al-Jibouri, 2008).

Whilst RAMS is new to construction, it is widely used in for example the chemical and nuclear industries. An important reason for its wide application in other industries but scarce use in the construction industry is related to its association with Systems Engineering. Systems Engineering has been a standard method in the design processes in other industries and RAMS has been part of Systems Engineering for providing evidence of the performance of the designed systems. Systems Engineering has been introduced relatively recently in the construction industry, hence the application of RAMS within its design practices remains slow and limited.

RAMS elements have not always been developed as a unified discipline but as separate engineering practices, such as reliability or safety engineering. The integration of all these elements was an attempt to balance benefits against risks and to select the design compromise which balances value enhancement of the whole system against the cost of failure reduction (Smith, 2005). The balance between costs and benefits explains the strong link between the application of RAMS and the use of Life Cycle Management, specifically Life Cycle Costing (LCC) that is commonly associated with the method. This is often the case with integrated contracts that involve maintenance obligations for which the method is used to investigate different design alternatives to find the best balance between cost, performance and the maintenance strategy over the life cycle period of the designed system.

One of the very few examples of the application of RAMS and LCC in infrastructural projects in the Netherlands is shown in figure 1. This is based on a study of a major high speed link railway project named ‘HSL-Zuid’ which is procured on the basis of a DBFM contract. The obligation of the contracting party which is a consortium of a number of companies was to design, build and finance a 100 kilometer long rail track and to maintain the track for a period of 25 years. During the 25-year maintenance period, the contractor has to ensure availability of the rail track for at least 99% of the operational hours (Infraspeed, 2004). The contract stipulates that failure to do so will result in reduced payments. Figure 1 shows how various alternative designs of the rail track are presented on the basis of LCC concept and how for example an alternative with a higher construction cost can be more economical in the long run in terms of its total life cost.

This paper describes the concept of RAMS in general and the way it could be used in the construction industry in the Netherlands. It describes and discusses some conceptual models for the implementation of RAMS in the design process which have been proposed by other researchers. The paper also investigates how one of these models can be implemented in design using a case example. The case is used to examine the method of implementation of this model in the design process and the possible problems that can arise from such implementation.

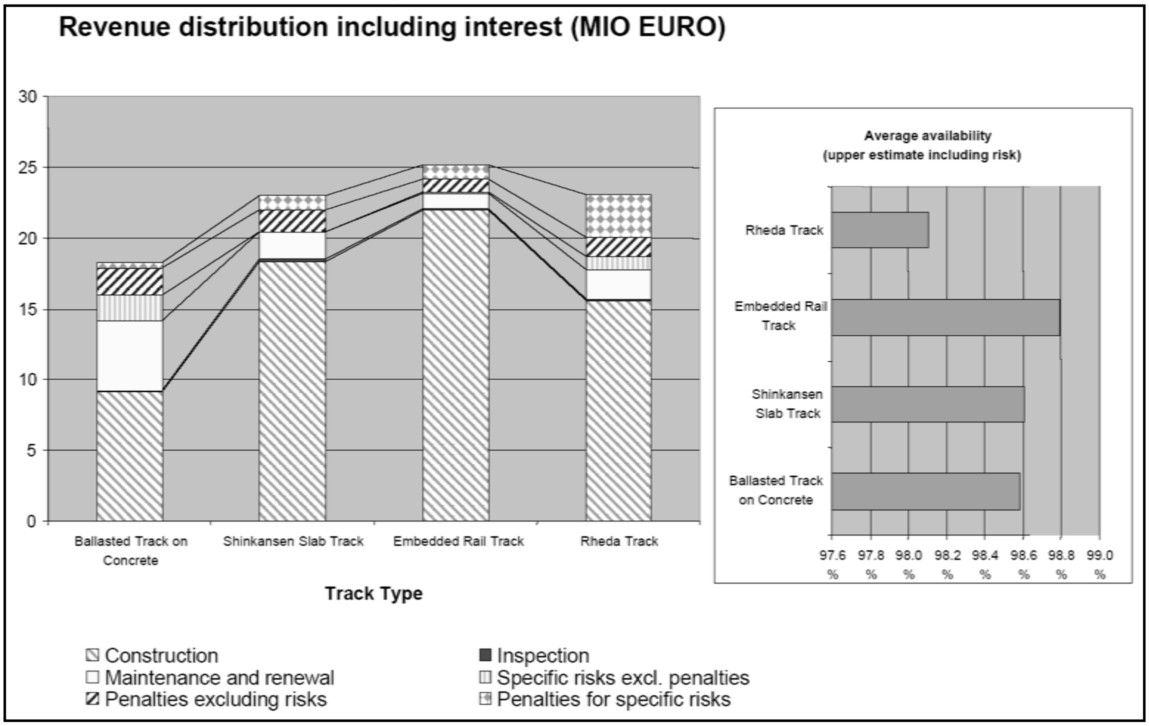

Figure 1 A chart of the composition of the Life Cycle Cost for four different track-types of the HSL-Zuid and the average availability, adopted from (Zoeteman, 2001)

Balancing performance requirements and costs

Life Cycle Management refers to the decision making process on the trade-off between the value of capital assets, its performance and costs, and finding the best option. Life Cycle Costing (LCC) and RAMS are the methods to be used to provide data on which a trade-off can be made. Life Cycle Costing is also a forecasting method that is used to compare or evaluate design alternatives with the aim of ensuring the best value from capital assets (Taylor, 1981). Sherif & Kolarik (1981) define LCC as "an analysis technique which encompasses all costs associated with a product from its inception to its disposal." The goal of LCC is to minimize the cost of obtaining a certain level of output.

Life cycle costs are often divided into different categories, such as design costs, construction costs and operational costs. Calculation of each category is often done based on time, using the Net Present Value (NPV) method, where future costs are discounted back to the value at present. According to Taylor (1981) "It becomes apparent that when an attempt has been made to evaluate all significant costs arising during the life cycle of a physical asset and these costs (cash flows) are expressed in present day values, managers have the means to quantify options and to select the optimum asset configuration". For example, this is possible by reducing the cost of maintenance by designing assets which are easy to maintain during their life spans.

An important step in Life Cycle Costing is to identify the interests and objectives of the client over a period of time so that the boundaries of design alternatives can be identified. There are basically two types of requirements that can influence trade-off decisions, mandatory and trade-off requirements. Mandatory requirements ensure that a system satisfies the customer's operational needs or in other words specifies the necessary and sufficient conditions that a minimal system must have in order to be acceptable. They are usually written with the words shall or must. These requirements can either pass or fail and there is no middle ground. Trade-off requirements should state conditions that makes the customer more satisfied. They should use scoring functions to evaluate the criteria and should be evaluated with multicriterion decision aiding techniques because there will be trade-offs between these requirements. (Bahill & Dean, 2009). In this case the procedure considers trade-off requirements to find the best solution, which goes beyond the minimal asset configuration that is stated with mandatory requirements.

In a trade-off there is interaction between initial expenditure, operation, maintenance and disposal, whereby the impact of one cost element upon another can be weighed. Low initial costs for example could result in high maintenance costs. The team that facilitates the trade-off therefore should be multidisciplinary to ensure a consensus within the organizational sections responsible for different functions like design or maintenance. The choice of best value should be made after a comparison of many variables viewed from the different points of view of the functional interests represented by the design team. Figure 2 illustrates the trade-off between initial capital cost and operating costs in relation to the total life cycle costs. As the acquisition costs of an item represented by curve A increase, the operating cost, including cost of downtime and maintenance, for an item represented by curve B, decreases. Curve C are the total costs of acquisition and operating. The optimal life cycle cost is at the lowest point of curve C. For example between points X and Y the total life cycle costs is at minimum and hence a choice between capital and maintenance costs will not significantly affect the total life cycle costs. (Taylor, 1981)

Probably the best way to reduce the total cost of an asset is to reduce the costs of its maintenance and required logistics support. A reduction of downstream costs could result in an increase in initial cost (Wübbenhorst, 1986). Clients do not always have the opportunity to increase initial costs in favor of future benefit due to limited capital budgets or cost limits. However, this problem is only the case in a short term approach and in practice a cultural change is required to accept higher initial costs to improve future revenue. Another problem is the uncertainty of information about costs, potential performance and life span of a system at the very early stage exactly when the decisions with far-reaching consequences are to be made (Wübbenhorst, 1986). Eventually a trade-off assumption will only be as reliable as the information supplied (Taylor, 1981). For example it is difficult to forecast the inflation ratios and interest rates over a large period of time. Therefore it is necessary to predict future developments of environmental change and to permanently monitor changes in time to ensure that the decision making is based on as much information as possible.

Within some infrastructural projects the client demands several performance and cost requirements. In the design process for these projects a set of alternative designs is created that satisfies the mandatory performance and cost requirements, but satisfies the trade-off requirements to varying degrees. Moving from one alternative to another will usually improve at least one criterion and worsen at least one criterion, therefore trade-offs will be necessary.

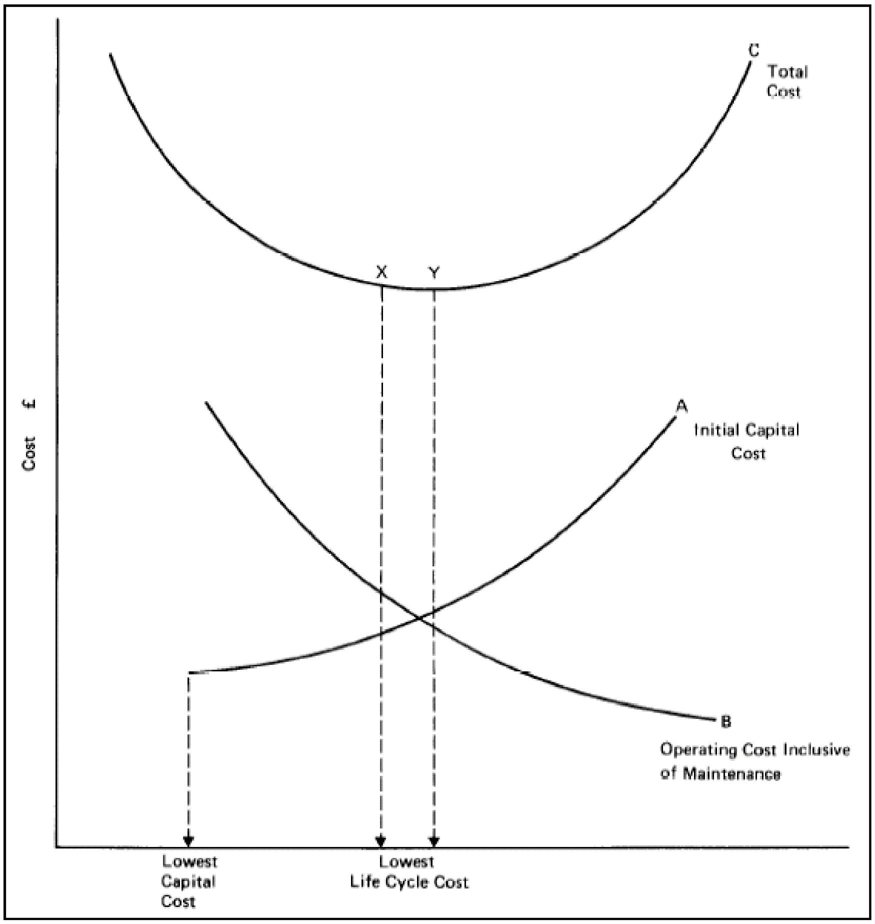

Figure 2 The cost of asset ownership (Taylor, 1981)

RAMS elements

In this section individual performance indicators (i.e. RAMS) are described. These indicators determine the performance for an asset in terms of reliability, availability, maintainability and safety. RAMS elements are mutually related and safety and availability are inter-linked in the sense that a weakness in either or the mismanagement of conflicts between their requirements may prevent achievement of a dependable system (CENELEC, 1999). Reliability and maintainability are also strongly related to operation and maintenance. For example when more traffic loads passes a road than was predicted in the design phase, more maintenance needs to be done because of higher degradation and a decrease in reliability will take place. On the other hand a higher maintainability means higher effectiveness and a positive influence on reliability.

RAMS is deployed in Systems Engineering to provide an indication of the performance of the designed systems. Although Systems Engineering is used more by clients and contractors, most cases show that RAMS is frequently only a qualitative part of Systems Engineering, where it could also be used as a quantitative indication of the performance of an asset. There are however some cases in which quantitative RAMS is used by clients to demand certainty from the contractors that the chosen design solution will meet the requirements over a systems life cycle. In the following sections the individual RAMS elements are described in more detail.

The elements of RAMS can be defined in different ways but in the following sections the definitions of those elements are based on CENELEC (1999) to illustrate their meaning.

Reliability

Reliability is defined as "The probability that an item can perform a required function under given conditions for a given time interval". A failure is defined by Todinov (2005) as "the termination of the ability to perform the required function". Reliability is measured by the probability that a system or component will work without failure during a specified time interval, with consideration of given operating conditions and environment. The failure rate is often described as the Mean Time Between Failure (MTBF) which determines the time of the average period between failures. In practice a general formula to determine the reliability is (Blanchard & Fabrycky, 1990):

$$(1) \qquad R = 1 - \left(\frac{\text{Number of failures}}{\text{Total operating time}} \right)$$

The reliability of a tunnel is for example 99.1%. This means that there is a certainty of 99.1% that traffic can get past the tunnel on a given time.

Availability

Availability is defined as "The ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided". The availability component is strongly related to reliability and maintainability. A reliable system requires less maintenance and good maintainability shortens the repair time. Availability is a function of uptime and downtime as shown in equation 2, where uptime is the time that a system works and downtime is when the system does not work.

$$(2) \qquad \textbf{Availability} = \frac{\textbf{Uptime}}{\textbf{Uptime+Downtime}}$$

There are different ways to determine a systems availability such as inherent availability, achieved availability and operational availability. Inherent availability for example only takes corrective maintenance into account and is calculated by dividing the MTBF by the MTBF plus the MTTR (Mean Time To Repair). Inherent availability is based on an ideal support environment, which assumes that tools, spare parts and personnel is readily available (Kawauchi & Rausand, 1999). Achieved availability is based on the fact that a system needs maintenance and considers preventive and corrective maintenance. It is determined by dividing the MTBM (Mean Time Between Maintenance) by the MTBM plus the MAMT (Mean Active Maintenance Time). Achieved availability is also based on an ideal support environment but with consideration of preventive or scheduled maintenance. Operational availability includes preventive and corrective maintenance, logistics delay time and administrative delay time. It indicates the availability in an actual operational environment (Kawauchi & Rausand, 1999). Operational availability is calculated by dividing the MTBM by the MTBM plus the MDT (Mean Down Time), which includes preventive and corrective maintenance, logistics delay time and administrative delay time.

The availability of a tunnel is for example 98.5%. This means that the tunnel should be operational 360 days of 365 days per year.

Maintenance

Maintenance is defined as: "The probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources" (CENELEC, 1999).

There are two forms of maintenance, preventive and corrective maintenance. Preventive maintenance is maintenance which is scheduled or planned, it generally requires shutdown of an operational system. Corrective maintenance is when actions are taken to restore a failed product or system in an operational state (Blischke & Prabhakar Murthy, 2003). Predictive maintenance is also sometimes used when maintenance is performed based on monitoring (Kawauchi & Rausand, 1999). Maintainability is calculated with the mean time to repair (MTTR), which represents the downtime in time units such as hours because of maintenance done. Problems with minimizing the downtime can arise because there are a lot of dependencies such as speed in diagnosing the problem or the speed of the supply chain for spare parts or the educational level of the maintenance personnel.

Safety

The S-component in RAMS refers to Safety in this work, but in other sources and applications it has also been used to refer to supportability. For the construction industry Safety is an important issue because of the close relationship with infrastructural systems and public services. Safety is defined by CENELEC (1999) as “Freedom from unacceptable risk of harm”. Safety is not easy to quantify because of the diversity of unsafe situations or accidents. The calculation of the safety component is most often performed by risk analysis, where the risks of a specific situation are identified, the occurrence and impact is determined and the total risk is calculated.

Applications of RAMS and LCC in the design process

There are a number of conceptual models for the integration of RAMS and LCC in the design process that have been proposed by other researchers. In this section some conceptual models are described to show how RAMS and LCC are implemented in other sectors such as the production industry.

One of the first applications of RAMS and LCC in design process was proposed by Kaufman (1970). The model is based on an eight-step approach with the purpose of obtaining a complete LCC for an asset. Performance is taken into account as parameters which control the degree of costs incurred during the life of a system, as illustrated in Figure 3 . The trade-off is done on the basis of the total cost of an asset represented by the various categories such as initial acquisition costs, operating costs, maintenance costs, overhaul costs and initial spares costs.

The operating profile describes the periodic cycle through which an asset will go and indicates which components will, or alternatively will not be working. The utilization factors indicate in what way the components will be functioning within each mode of the operating profile. When used for transport for example, the operational phase of a road will consist of certain hours when traffic lights will not be working due to performed maintenance. This will be described in detail in the operating profile and utilization factors. The third step describes that each cost category needs to be identified, such as initial acquisition costs, operating costs and maintenance costs. After the identification of the cost categories RAMS parameters are being determined and transferred into cost parameters, which is an important step in this model. Performance is quantified in terms of costs incurred, for example maintenance costs for unscheduled downtime. Following this step costs are being calculated for all categories with current prices. The inflation rate is taken into account, and all costs are discounted to present worth. In the last step all cost categories are summed and a trade-off can be made.

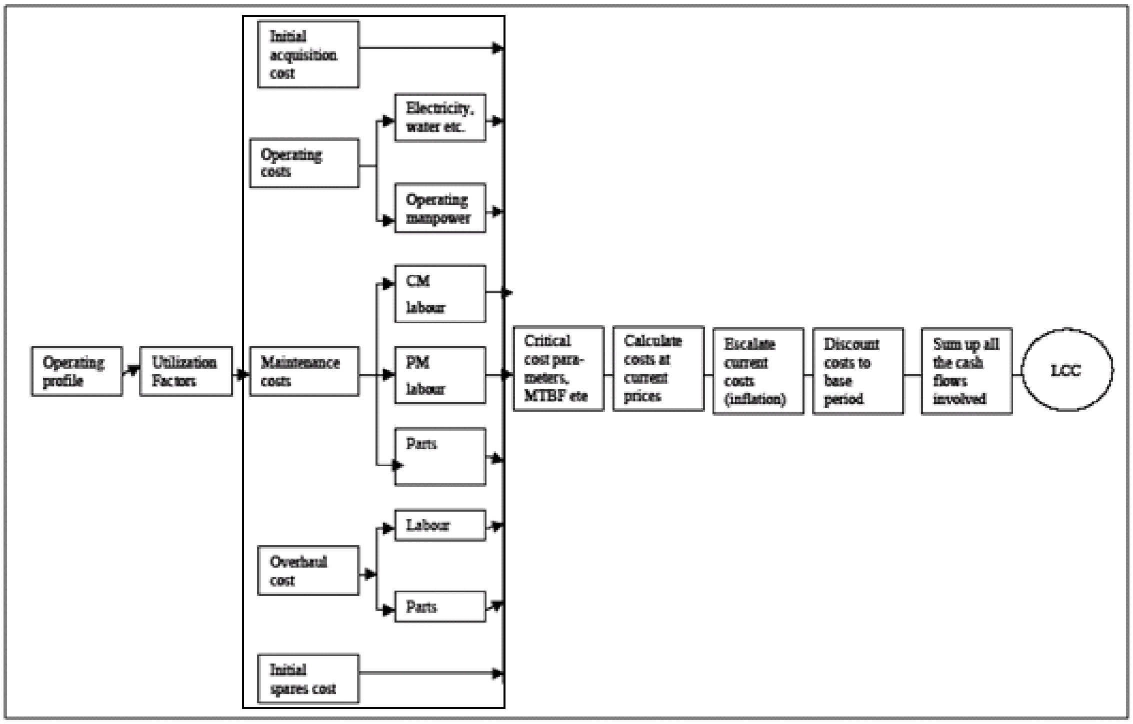

Figure 3 Model to calculate total costs for physical assets by Kaufman (1970)

A more RAMS oriented but a rather abstract model was described by Markeset & Kumar (2003). The model was developed for a manufacturing company of industrial systems to create a more reliable and predictable product. The goal of the model is to deliver products with documented quality, reliability, maintainability and competitive LCC. Markeset & Kumar identify a cultural change is needed within the design and development of products in order to introduce a model that emphasizes a risk-based process. The companies work process and product problems are caused by a lack of understanding and awareness of why things are done in the way they are done. To facilitate needed change and create understanding and awareness among personnel a RAMS coordinator is installed. The RAMS coordinator provides a basis of knowledge in RAMS and risk analysis for the company and assists in product development on a risk-basis. The FMECA (Failure Mode Effects and Criticality Analysis) tool is used to identify the events resulting in failures, their frequency and analyzing their effects on the components and systems of a product. The results of FMECA provide a basis for decision making such as recommendations for preventive maintenance, spare parts and maintenance tools, documentation (procedures, failure diagnosis, routines and checklists) and LCC predictions. In figure 4 the product development process is shown where in every stage coordination with risk oriented methods is done.

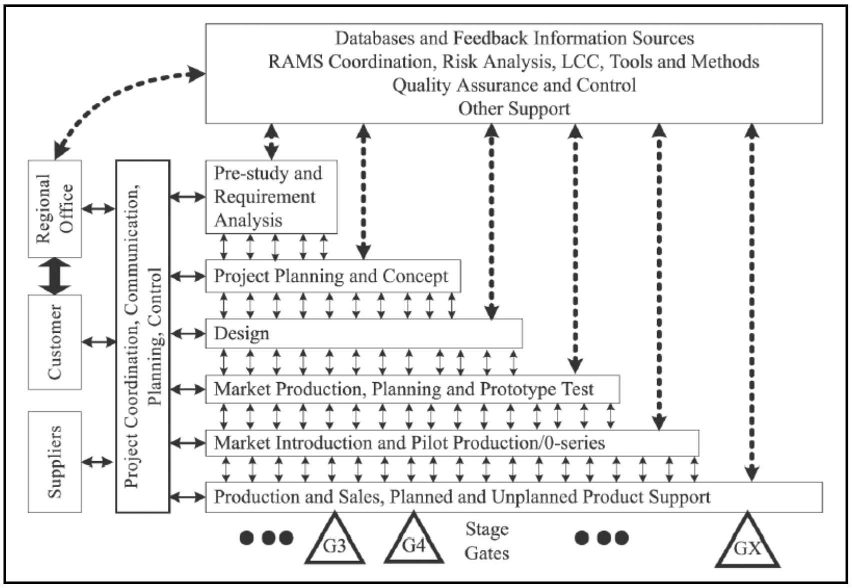

Figure 4 Dynamic product development process model by Markeset & Kumar (2003)

More recently another model for application of RAMS in infrastructural projects was described by Ogink & Al-Jibouri (2008). The model attempts to integrate both LCC and RAMS to evaluate different design alternatives. It is based on a standard design process for infrastructural projects that is used in the Netherlands. In the model RAMS is part of the design process rather than only a control tool. Evaluation of alternatives does not only takes place on the basis of RAMS, but on all other specified requirements. There are two models proposed, one for contracts without maintenance, such as Design & Construct, and one for contracts that include maintenance such as Design, Build and Maintain. Figure 5 illustrates the model for contracts where maintenance is included. There are a number of tools proposed to be used to provide data to evaluate alternatives such as FTA (Fault Tree Analysis), FMECA (Failure Mode Effects and Criticality Analysis) and ETA (Event Tree Analysis).

In this research the model described by Ogink & Al-Jibouri (2008) will be adopted, because a strong fit with the construction industry exists due to the fact that the model is based on the standard design process from Systems Engineering. Furthermore RAMS and LCC are specifically proposed to evaluate several design alternatives based on performance and costs, but with consideration of the clients requirements (i.e. mandatory and trade-off requirements).

Application of the adopted model

The adopted model is applied in a Dutch engineering company called Breijn. Breijn is part of a large construction company (Heijmans N.V.) which is active in Western Europe. The companies area of activities varies from infrastructural projects to real estate and project development. One of the projects of Heijmans is related to the redesign, reconstruct and maintenance (15 years maintenance and a minimal residual life of 5 years) of the A-road N-302 in a Design, Build and Maintain contract (DBM). Breijn is responsible for the design process. The adopted model is implemented within this project. The model describes four different phases of the design stage, namely Conceptual design phase (tender phase), Preliminary design phase, Definitive design phase and Execution phase. For the preliminary design phase within the project N302 several alternatives for the sub-system road pavements are being considered. Each alternative has different characteristics and needs a different maintenance strategy. In figure 5 the model is shown and more specific the preliminary design phase.

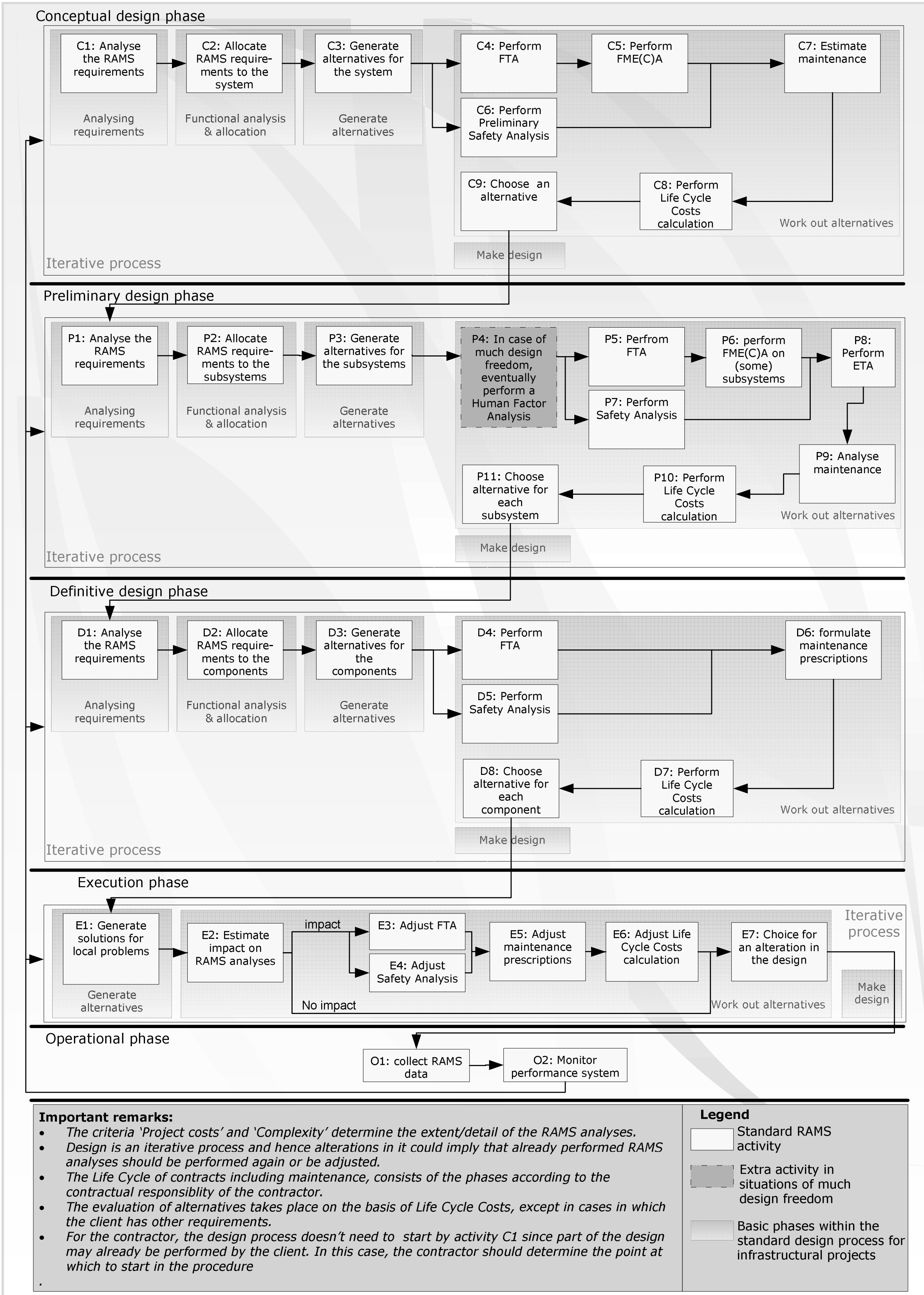

Figure 5 Alternative trade-off based on RAMS and LCC, model by Ogink & Al-Jibouri (2008)

P1: Analysing requirements

The first step in the model for preliminary design phase is to analyze the RAMS requirements. Within the project N-302 several requirements are being considered and these requirements can then be allocated to the several subsystems, such as road pavements in this case.

P2: Functional analysis and allocation

In the second step the evaluation criteria that are used to evaluate several alternatives are described and the trade-off requirements can be determined. The evaluation criteria within the project N302 are: Reliability, Availability, Downtime, Initial cost, Maintenance cost and cost for specific risks. These evaluation criteria are derived from the RAMS requirements specified by the client. Within these criteria Breijn developed the trade-off requirements that are used within the trade-off to evaluate the alternatives:

1. The reliability of road pavements should be 99,8%.
2. The availability of road pavements should be 99,8%.
3. The downtime should be less than 350 hours.

For the contractor the lowest total costs are also important to gain a competitive advantage over other contractors. The total costs (in present worth) of road pavements can be divided into initial costs, maintenance costs and costs for the risks that can occur during the life span of the road pavements. A risk for example is that large maintenance needs to be done earlier than was expected in the design phase.

P3: Generate alternatives

Five different types of road pavements for an area of 5000 m^2 are identified in this project to be evaluated. Road pavements are build in multiple layers, starting from the foundation. In the Netherlands roads are mainly based on sand and in some situations founded on piles. On top of the layer of sand a foundation material is used to spread the loads from traffic. Depending on the market price a choice is made between a bounded or unbounded foundation. A bounded foundation is mostly cement treated and the cement is used to make a whole out of the foundation. A bounded foundation is more expensive than an unbounded foundation due to the cement treatment. Bounded foundations require less asphalt layers or a thinner concrete layer than unbounded foundations, because of the better load spreading characteristics of the bounded material. Therefore road pavements built with bounded foundations can eventually be cheaper than unbounded foundations.

On top of the foundation, three or four layers of asphalt or one layer of concrete is spread. In case of asphalt each layer has different characteristics. The bottom layer has a leveling and a load spreading function. The one or two layers between the bottom and top layer are used to form a bond between these layers. Sometimes two layers are used to ensure a reliable asphalt system (mostly when unbounded foundations are used). The top layer must have specific functions such as sound reduction, water drainage and durability.

The first and second alternative both have a top layer of dual ZOAB. ZOAB is a very open asphalt mixture with good sound reduction and water drainage qualities but has only an estimated life expectancy of around 10 years. The difference between alternative 1 and 2 is that alternative 1 has an unbounded foundation, and therefore an extra layer of asphalt between the bottom and top layer, and alternative 2 a bounded foundation, which results in only one layer between bottom and top layer. The bottom and middle asphalt layers of all alternatives are made of asphalt mixture STAB, which is a very stable asphalt mixture with a high loading power. Alternative 3 and 4 both have a top layer of Microflex, which is an asphalt mixture with a little less sound reduction than ZOAB but with a higher life expectancy of around 20 years. Alternative 3 has a bounded foundation and alternative 4 an unbounded foundation. Alternative 5 is a pavement made of a 234 mm thick layer of concrete. The foundation of alternative 5 is an unbounded foundation. In Table 1 an overview of the five alternatives and their construction is shown.

Table 1 Alternatives in road pavements

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Top layer	Dual ZOAB	Dual ZOAB	Microflex	Microflex	Concrete
Middle layer	40mm STAB	40mm STAB	65mm STAB	60mm STAB	-
Middle layer	60mm STAB	-	-	70mm STAB	-
Bottom layer	70mm STAB	65mm STAB	70mm STAB	70mm STAB	-
Foundation	Unbounded	Bounded	Bounded	Unbounded	Unbounded

P4: (optional) Human Factor Analysis

A human factor analysis is useful when human or human decisions influence the functioning of the system. In this case human factors have very little influence in the functioning of road pavements. Accidents on the road caused by human failure for example could influence the functioning of the road, but traffic accidents are excluded in the performance requirements. Also no data is available on how human factors influence the execution phase where some of the pavements characteristics are determined. The rolling on asphalt pavements by a machine man for example has influence on the compactness of the material and thus influences the life span of asphalt. However no data is available about how big the influence of the machine man is on the compactness of the road pavement. Therefore a Human Factor analysis is not performed in this case.

P5: Perform FTA

A Fault Tree Analysis can be done to model and analyze the failure processes of systems by graphically developing a tree starting from one top cause of a failure into smaller failure causes. In this case little knowledge exists about failure processes of road pavements. Experienced designers of road pavements have a global idea how and when road pavements will fail in their life. They do not have specific data about the root causes of failures and therefore an FTA cannot be made in this case. Specific data about the failure processes is still under development within the organization.

P6: Perform FMECA on subsystems

An expanded FMECA sheet is used to determine the effects of the main failure modes that can occur during the life of a road pavement. Seven main failure modes are identified using data from experienced designers in road pavements. These seven failure modes are:

1. Raveling: stones are less attached on the binder and leave separately from the asphalt layer resulting in a hole in the road pavement;
2. Transverse unevenness: distortion of the transverse profile;
3. Longitudinal unevenness: distortion of the longitudinal profile;

4. Cracking: Cracks in the top layer of the pavement;
5. Edge failure: distortion or cracking of the side of the pavement;
6. Irregularities: Little damage to the top layer of the road pavement, can be small distortion, small cracks or bumps;
7. Longitudinal joint: Raveling or cracking alongside the joint of two pavements.

The occurrence of a certain failure mode is determined with the experiences from the past that have been identified by the designers of road pavements. The state of each failure mode will occur in practice in several stages which are identified in Dutch regulations. The stages vary from A (high quality level) to F (Worst quality level) and in practice clients mostly demand a minimal quality level B of their road pavements. Every state of the road below this quality is considered to be a failure and needs maintenance. When the quality level reaches below level B the effects of a failure mode can be determined by what is necessary to restore the required quality level.

With the occurrence and effect of a failure mode the risks for one failure mode and the total risk of all failure modes for one alternative can be calculated. The first alternative for example, has a double layer ZOAB on top. The occurrence of the failure mode raveling is different for every alternative. The expectancy is that for alternative 1 raveling will be below quality level B after 10 years. Alternative 3 has Microflex as top layer which is better resistant against raveling and therefore the expectancy is that raveling will be below quality level B after 20 years. For alternative 5 raveling is not an issue because on concrete raveling does not exist. It is possible that raveling will occur earlier than expected and therefore a certain risk is taken into account on the basis of an estimation graph of occurrence. In Figure 6 the occurrence of raveling for all alternatives is shown. For alternative 1 raveling eventually results in replacement of one or two layers of asphalt of the total 5000 m^2. The costs of such replacement are €48.500,- and it takes 16 hours in total to repair.

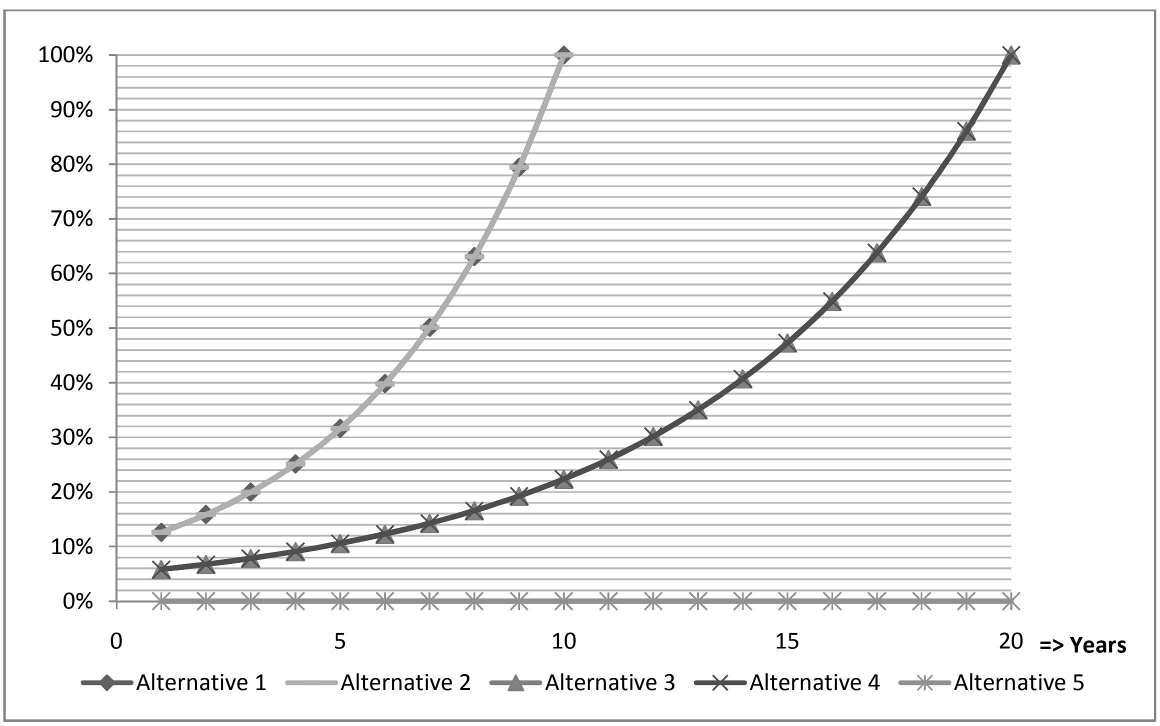

Figure 6 Occurrence of raveling in %/year on asphalt mixture ZOAB

P7: Perform Safety Analysis

A safety analysis is not performed in this case because for the subsystem road pavements safety is not really an issue. Human factors in traffic have a major influence on the safety of roads and in this case only the materials used for roads are considered.

P8: Perform ETA

An Event Tree Analysis is not performed in this case due to the fact that events, such as accidents or falling loads, that could cause the road pavement to fail are excluded in the maintenance contract.

P9: Analyze maintenance

The maintenance period is 15 years, with, for road pavements, a residual life of 5 years. The contractor is free to determine a maintenance strategy. For example: The technical life of asphalt mixture ZOAB is 10 years, and the technical life of asphalt mixture Microflex is 20 years. Here it is possible to choose for ZOAB which needs to be replaced after 10 years to ensure a proper quality level within the maintenance period or for Microflex which does not have to be replaced within the specified period but needs more maintenance during its technical life.

The maintenance plan for each alternative is partly based on the results of the FMECA that is done in P6. With the information of the effects of the failure modes for an alternative the amount of downtime can be calculated and the number of failures during the maintenance period can be estimated. The total operation time in this project is 175205 hours. Alternative 1 for example has an estimation of 27 failures during the maintenance period of 20 years. In the first 6,5 years only one time per year maintenance has to be done to repair small failures such as cracks. The last 3,5 years consists of 2 times maintenance per year. After 10 years replacement of the top layer is necessary and the same rates of maintenance are done in the last 10 years of the maintenance period. With this information the reliability of alternative 1 can be calculated as 99,98%. The downtime of alternative 1 follows from the estimated time that the maintenance for this alternative will take. Availability is calculated with the uptime and downtime of a system (see equation 2). The expected downtime in this example is 252 hours. With this downtime and the total operation time, the uptime can be determined and the availability is calculated as 99,86% for alternative 1.

In this case downtime is transferred into cost with the use of the lane rental principle. Lane rental is used to minimize the impacts of a project on the travelling public. It is a method of transferring the road user costs to the contractor. The contractor must rent a lane in order to close it. This creates a financial incentive for the contractor to minimize the duration of lane closures. In this case the client demands a minimum amount of maintenance and disturbance for the road user. Therefore when a lane of the road is shut down for maintenance purposes a penalty of €3000,- per hour is given to the contractor.

In table 2 all alternatives are shown with the trade-off requirements that indicate the performance. The other alternatives are calculated in the same way as the example above.

Table 2 Alternatives with characteristics

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Reliability	99,98%	99,98%	99,99%	99,99%	99,99%
Availability	99,86%	99,86%	99,89%	99,89%	99,91%
Downtime	252 hours	252 hours	188 hours	188 hours	156 hours
Downtime in €	€ 756.000	€ 765.000	€ 564.000	€ 564.000	€ 468.000

P10: Perform Life Cycle Cost Calculation

The costs in this research are proportionally adjusted for confidentiality reasons. In this step the relevant cost categories for this case are calculated, which are initial costs, maintenance costs and costs for certain risks. The initial costs and maintenance costs can be calculated with information from the contractor on how to construct the alternatives and the required maintenance. The risks are calculated on the basis of the results from the FMECA. In Figure 7 the total costs and all cost categories are shown.

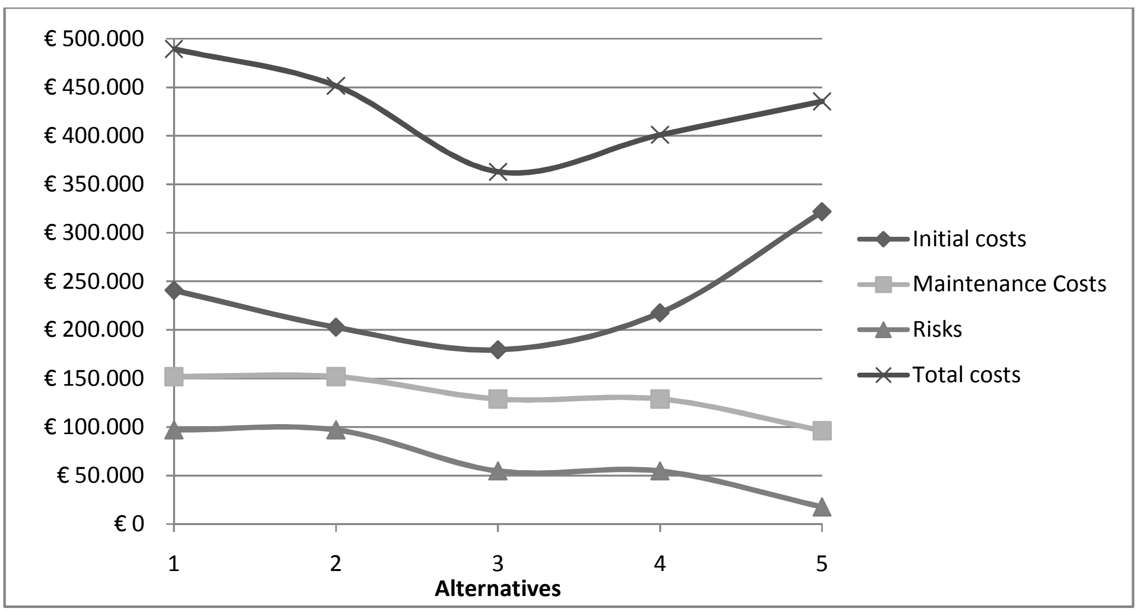

Figure 7 Cost categories for several alternatives

P11: Choose alternative for subsystem

On the basis of the calculated performance and total costs the five alternatives are evaluated. In Table 3 the criteria to evaluate the alternatives are shown.

Table 3 Evaluation of alternatives

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Reliability	99,98%	99,98%	99,99%	99,99%	99,99%
Availability	99,86%	99,86%	99,89%	99,89%	99,91%
Downtime	252 hours	252 hours	188 hours	188 hours	156 hours
Downtime in €	€ 756.000	€ 765.000	€ 564.000	€ 564.000	€ 468.000
Initial cost	€ 240.750	€ 202.700	€ 179.550	€ 217.600	€ 321.800
Maintenance cost	€ 151.800	€ 151.800	€ 128.687	€ 128.687	€ 96.086
Risks	€ 97.000	€ 97.000	€ 54.620	€ 54.620	€ 17.578
Total costs	€ 1.245.550	€ 1.216.500	€ 926.527	€ 964.907	€ 903.464

Table 3 shows that alternative 5 is the overall cheapest alternative and also has the best reliability, availability and downtime characteristics. Alternative 3 is close to alternative 5 but is a bit more expensive and has lower availability and downtime characteristics. Alternative 4 is more expensive than alternative 3 because of the use of an unbounded foundation which makes the initial costs higher. Alternative 1 and 2 are significantly more expensive than alternatives 3, 4 and 5. This is partly due to the fact that more maintenance is required in these alternatives which results in a high amount of downtime and lane rental costs. For this specific case the best choice is considered to be alternative 5. It is the cheapest alternative and at the same time has the best overall performance.

Discussion

The previous section has shown that the adopted model allows a systematic evaluation of different design alternatives in infrastructural projects, though it should be used more as a guideline. For example, tools like ETA and safety analysis could not be used in this specific case due to the fact that human factors do not have a major influence on the performance of the subsystem road pavements.

The trade-off in the presented case is made on the basis of total costs and performance. The penalty for the compensation of downtime has a major influence on the total costs of every alternative. It is however a good way to quantify performance. The overall performance (reliability, availability and downtime) differs only minimal between the alternatives and every alternative performs better than minimal.

The standard in the Netherlands for road pavements is very high and therefore designers ensure a very high reliability by expanding the thickness of the pavement layers. It is very likely that when the whole infrastructural system is regarded the performance is lower than described in this case where only the subsystem road pavements are considered. Evidence from other infrastructural projects shows that technical subsystems, such as traffic control, have a high influence on the performance of the total system and are more sensitive for failures. Therefore RAMS analysis should be done as early as possible in the design stage to ensure the performance calculations are done for the whole system, including all existing subsystems and not only for one subsystem which could be influenced by other subsystems.

Conclusions

The model used for this specific case worked well in practice and is of great value when used to assist in management decisions when a trade-off has to be made within infrastructural projects on the basis of performance and costs. A very detailed report can be made about performance and costs of alternatives which can be used to choose the best alternative for a specific situation. Furthermore the model can be used to evaluate alternatives of the whole system on performance and costs resulting in best value for infrastructural construction projects.

Research has showed that the implementation of RAMS and LCC concepts in the Dutch construction industry is still not common practice. There are also only a few models available for the implementation of RAMS and LCC in design processes of infrastructural projects. Contractors have little knowledge nor experience on how to estimate maintenance or operational costs. This is partly due to the fact that more knowledge has to be developed on the degeneration of materials used. A historical database should be developed to assist in the decision making by means of trade-offs. Also more knowledge of the tools used in RAMS and LCC needs to be developed to improve the use of these methods in the design process of infrastructural construction projects to ensure that the contractors are capable of calculating the performance of their designs.

Trade-offs between performance and costs could better be made in conceptual design phase where functional choices are based on an abstract level, such as the choice between a bridge or a tunnel, because in that case the whole system can be measured on the basis of its performance. In the preliminary design phase choices are made on sub-system level where more detail in design is available and performance is less dependent on other subsystems.

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