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SWECO

A GENERALIZED RISK-BASED MAINTENANCE MODEL TO PLAN ROAD MAINTENANCE

Master thesis Industrial Engineering and Management

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Colofon

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Management summary

The goal of this research is to support Sweco by designing a generalized Risk-based maintenance (RBM) model that provides a maintenance planning (MP) for any asset while considering the aspects of risk, cost, and performance. Because of the increasing demand to improve the efficiency of road MP, mainly caused by a limited budget, the generalized RBM is applied towards roads. The corresponding research question is formulated as:

How can a generalized RBM model be used to plan corrective maintenance actions for roads by taking aspects such as total risk, performance, and cost into account?

Currently, the municipality plans road maintenance by a multi-year period planning, based on the condition of the top layers. By identifying the damage of the road, the plan year and maintenance activities are determined. A budget released for road maintenance is often limited, which results in the incapability of executing all desired maintenance activities. Besides, the current MP provides a disliked cost peak in the first year.

The generalized RBM model is generated by the RBM model, according to Krishnasamy et al. (2005) and considers the cost, performance, and risk of the asset. This research proposes four phases to develop an MP, formulated as:

I. Scope identification
II. Failure evaluation
III. Risk assessment
IV. Maintenance planning

The objective function optimizes the total risk, cost, and performance for each decision variable and is formulated by using a Lagrange relaxation. Constraints ensure the budget is not exceeded, and the cost is equally spread during the planning horizon. The generalized RBM model is applied for roads that are managed by a municipality in the Netherlands. The roads are divided into lane sector that is inspected based on the level of damage.

Four failure distributions are considered as reasonable failure functions. The analysis of the failure distributions shows no significant differences, and the increasing distribution is selected to analyze the generalized RBM model. The current MP is exceeding the budget that restricts the total cost of the generalized RBM model. By using the same budget, the current MP shows lower risk and higher performance concerning the generalized RBM planning. This is due to the budget constraint that ensures that the cost per year is equally distributed. If both budget constraints are removed, the generalized RBM model provides an MP with the lowest possible risk and the highest possible performance. The results show that the generalized RBM is optimizing road maintenance related to the cost, performance, and risk concerning the current MP. However, removing the budget constraints provides an MP that is not representative for road maintenance, since too many maintenance activities are planned in the first year. It shows that the effect of both budget constraints in the generalized RBM model are significant. By analyzing the case study, we can conclude that the correlation between, performance and risk is approximately -70%. The cost has no significant correlation with the performance and risk of the lane sectors. The study to the Lagrange multipliers shows that variating the Lagrange multipliers between zero and one has no impact on the MP and the risk, cost, and performance.

Further research to the implementation of the generalized RBM model for other assets is suggested. Considering uncertain influences such as climate changes that effects the deterioration of roads will improve the generalized RBM model for roads. The generalized RBM model is accountable in the future to determine other restrictions for the risk, performance, and cost in line with the preferences of the asset manager.

Preface

With this research, I finish my master Industrial Engineering and Management, and my student time in Enschede. I look back to an amazing time where I met many interesting people and learned a lot about the field of industrial engineering and research. The University of Twente provides me a great environment and interesting topics to study.

It was a pleasure to write my thesis at Sweco in the main office in De Bilt. I felt really home and had nice colleagues that support me. The internship gives me the opportunity to have a look into the world as an engineer. It was a challenge to define the thesis proposal, but my colleagues of Sweco supports me by creating valuable research.

I would like to thank my supervisors from the University of Twente and Sweco for all the support, collaboration, feedback, and time. It was always interesting to receive your feedback and to learn so many details about asset management, risk-based maintenance, and road maintenance. I enjoyed working with you! Besides, I want to thank my friends, family, colleagues at Sweco, and fellow students that support me during my study and master thesis. You help me to finish this final report, which I am really proud of.

Inge van der Weg
09-07-2019

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1. Introduction

In this first chapter, the company Sweco is introduced in section 1.1. The research motivation and the research objectives are addressed in section 1.2 and section 1.3, respectively. In section 1.4, the research scope and limitations are given, which leads to the research questions in section 1.5. Finally, an overview of this master thesis is given in section 1.6 by providing the chapter content.

1.1 Company description

This master thesis is executed for the company Sweco, an architecture and engineering consultancy. With circa 15 000 engineers and architects, Sweco is located in Northern Europe, with its roots in Sweden. Sweco's vision is 'to become Europe's most respected knowledge company in the fields of consulting engineering, environmental technology, and architecture' (Sweco, 2018). As an architecture and engineering consultancy, Sweco is involved in many different projects. An example is the ice rink in Leeuwarden, were Sweco advises about the installation concept, the construction, and the energy design. Another case is the project for Northwest Europe, related to gas pipelines. Sweco was responsible for the engineering and equipment of several installations and supplies the design. As a broad specialism in roads, the business line Transportation & Mobility of Sweco investigated in the integration of the highway A27, the environmental impact and the quality of life measurements. We end with an industrial project that is performed for the company AkzoNobel. The request was to advise dismantling the factory. It is a complex process, because of safety and environmental requirements related to the materials. Sweco delivers an action plan and procures the buyers for parts of the factory.

Sweco is a country-based organization. Sweco Nederland B.V. started in 1913 as Grontmij (ConsultancyNederland, 2018). In 2015, Grontmij was taken over by Sweco. In the Netherlands, Sweco consists of circa 1.800 employees. The three divisions of Sweco Nederland B.V. are Transportation & Mobility, Water & Energy and Urban & Regional Development. Each division consists of multiple departments, all with their own specialty. In total, circa 18 departments are divided over offices in nine cities in the Netherlands. In appendix 9.1, the organogram of Sweco Nederland B.V is shown.

The department that is involved in this research is Asset Management (AM). The main activity is advising on optimizing performance, costs, and return of assets by focusing on investment cycles and life cycles (Sweco, 2018). The department consists of the teams Asset Data, Asset Management Consulting, and Asset Management Roads. According to ISO 55.000, an asset is defined as 'an item, thing or entity that has potential or actual value to an organization' (NEN, 2014, p. 2). Assets Sweco focus on are bridges, roads, sewerage, cables, and pipes.

1.2 Research motivation

The department Asset Management (AM) focusses on assets in the infrastructure. The infrastructure supports the economic development of a country (Schraven & Hartmann, 2010). Performing the optimal condition of the asset is important for among other things, the safety and public environment. An asset manager is engaged in building and planning, as well as maintain and innovate the asset. To guarantee a structured and efficient maintenance planning (MP), a maintenance concept can be selected.

The maintenance concept provides a strategy for the MP for the total life cycle of the asset. In the past, maintenance was only seen as costs without any value adding activity (Tinga, 2013). Nowadays, many strategies are developed to perform optimal maintenance. These strategies have different focus. Some well-known strategies are time driven maintenance, usage-based maintenance, and risk-based maintenance (Tinga, 2013). The maintenance concept risk-based maintenance (RBM) is considered to be one of the concepts that support performing AM. The demand towards RBM by municipalities is increasing, especially towards the AM consultants. According to Arunraj and Maiti (2007), the purpose of RBM is to minimize the occurrence of high-risk failure modes. Municipalities argue they want an RBM methodology because the budget that is available to perform maintenance is limited. Therefore, not all the mandatory maintenance activities can be performed, and prioritization is needed to select the maintenance activities that are scheduled. A risk-based method is defined as a cost-effective maintenance policy (Krishnasamy, Khan, & Haddara, 2005), because the technical features like reliability characteristics are analyzed by considering economic and safety consequences. Scenarios can be used to provide a holistic overview by comparing the cost of every maintenance decision (Krishnasamy, Khan, & Haddara, 2005). Therefore, municipalities and Sweco suggest RBM as an efficient methodology to deal with fixed budgets.

According to Krishnasamy et al. (2005), the RBM model consists of the identification of the scope, a risk assessment and the risk evaluation to provide an MP as output. The RBM model is used for an industrial case study. Even if the methodology is the same for all types of systems/assets, performing the scope, risk assessment and risk evaluation depends on the type of asset, and so modifications are needed. Secondly, one of the principles of AM is to take, next to risk, also cost and performance into account by making decisions. The request is to design a generalized[1] RBM model that can be used for any asset while considering the three key performance indicators (KPI's) risk, cost, and performance. Besides, the model should be applicable for roads, to analyze if RBM supports the asset manager to deliver the required performance on a reliable and optimal way. The generalized RBM model is applied for roads are because of:

- High demand to implement RBM for roads, mainly caused by the limited budget.
- A lot of standardized data related to inspection/condition is available.
- Clear risk definitions by CROW[2].
- Municipalities are liable for damage if the roads do not fulfill the requirements.
- Easy to compare RBM with the current maintenance concept.

Besides the scientific arguments for this master thesis is the research valuable for Sweco since it connects the RBM methodology with AM to provide knowledge for the team. Secondly, the comparison between the current MP and the RBM model can be used to advise municipalities about road MP.

[1] The RBM model is generalized since it will be developed in general by inferring from the specific case of road maintenance, discussed in more detail in chapter 4.
[2] CROW is a knowledge platform for the Dutch infrastructure, public spaces and traffic and transportation.

1.3 Research objectives

The research objective is to propose a model to plan corrective maintenance actions that takes the aspects of risk, performance, and cost of a system into account. The RBM[3] methodology is developed based on literature. By performing a case study for road maintenance, the generalized RBM model will be analyzed. The case study supports the asset manager with developing a multi-year maintenance planning by using the generalized RBM model that makes decisions objective rather than subjective. A remark towards the generalized RBM model is that the model should be generalized by using a systemic approach. To facilitate a systemic approach, RBM described in literature will be considered. To implement the generalized model for roads, the RBM model is combined with the AM aspects risk, cost, and performance. Therefore, the risk aspect will be combined with cost and performance. The model should give maintenance activities by a priority list for planned maintenance activities.

1.4 Research scope and limitations

The study focuses on roads that are managed by municipalities in the Netherlands only. In 2008, this was about 85% of the total road network in the Netherlands (Molenaar & Houben, 2010). Notice that highways in the Netherlands are excluded since it is the responsibility of Rijkswaterstaat. Secondly, only the tactical road MP is considered. While the strategic road planning focuses on cyclical maintenance activities and the operational on the small maintenance activities, this study concentrates on the maintenance activities that are based on the quality/inspection results. The maintenance activities that are scheduled are given, and so the determination of the maintenance activities is out of the scope. During the model development, many assumptions are made. If the impact on the results can be significant, the assumption is considered in the discussion.

[3] Other approaches than RBM are not considered because of preferences of Sweco.

1.5 Research questions

To achieve the research objective, the following main research question is defined:

How can a generalized RBM model be used to plan corrective maintenance actions for roads by taking aspects such as total risk, performance and cost into account?

To answer the main research question, four sub-questions are developed, each consisting of several additional questions. A literature review provides insights into RBM, as well as the relation between AM, MP, and RBM. To develop the generalized RBM model that improves the MP of an asset, literature is used to approach a model. The first sub-question is:

1. What is written in the literature about RBM?
1a. What is the relation between AM and MP?
1b. What is written in literature about developing an RBM model?

Road maintenance that is performed by municipalities is analyzed in the current situation. The CROW guide describes the MP for roads from beginning to end. The conclusion is that the MP is deterministic, and decisions are based on experience and subjective. The available data of roads in the current situation is analyzed to investigate whether the data is useful as input for the generalized RBM model. The second sub-question is formulated as:

2. How is maintenance currently planned for roads?
2a. What does road maintenance imply?
2b. What data is gathered and used for the current MP?
2c. What decisions are made to develop the MP for roads?

The generalized RBM model is developed based on the four phases of RBM, according to Krishnasamy et. al. (2005). The phases are outlined as 'Identifying the scope,' 'Risk assessment,' 'Risk evaluation' and 'Maintenance planning.' In the last phase, the MP is developed by relating the decisions with optimizing risk, performance, and cost. Because we implement the generalized RBM model for road maintenance, the failure and remaining useful lifetime of a road should be determined. The risk determination should be specified for roads. The third research question addresses the development of the generalized RBM model and the implementation for road maintenance and is formulated as:

3. What actions should be taken to use the generalized RBM model to plan maintenance for roads?
3a. How can we use the literature to develop a generalized model for RBM?
3b. How can the generalized model be related to the aspects of risk, cost, and performance?
3c. What is a failure in relation to road maintenance and how can it be modeled?
3d. How to calculate the remaining useful lifetime distributions?
3e. How to determine risks?

After the generalized RBM model is developed, we will implement the model for a case study, related to road maintenance. Depending on the completeness of the case, the RBM model will be implemented for one road type or a road network to compare the RBM model output with the current MP. The results also provide suggestions for improving the generalized RBM model. The final sub-question is formulated as:

4. How does the generalized RBM model perform compared to the current model in relation to the aspects cost, risk, and performance?
4a. What are the results of the case study?
4b. How can we compare the generalized RBM planning concerning the current MP?

Figure 1 shows the research framework and relations between the chapters and research questions. The next section provides a reading guide by providing the content of each chapter.

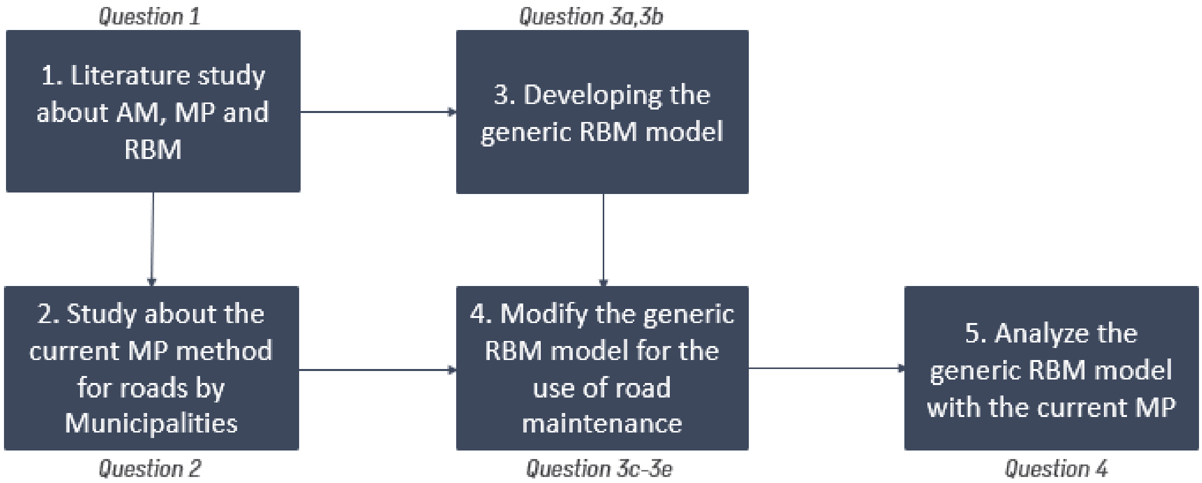

Figure 1: Research framework

1.6 Reading guide

The structure of the report is based on the research questions. In chapter 2, the literature review is presented to provide insight into AM, MP, and RBM. In chapter 3, we discuss how the current MP for roads is build up and what data is used, and decisions are made. With the literature background, the generalized RBM model that is implementable for all types of assets is given in chapter 4 and specified for road maintenance. The implementation of the case study for road maintenance is addressed in chapter 5. The discussion is provided in chapter 6. Finally, the study is concluded, and the recommendations are presented in chapter 7.

2. Literature review

To develop the generalized RBM model, relevant literature is studied in the literature review. In this chapter, we will address an answer to the research question:

'What is written in the literature about RBM?'

In section 2.1, we discuss AM by focusing on the three aspects of risk, performance, and cost. The history of MP and strategies that are used in practice will be addressed in section 2.2 to answer research question 1a. Literature is used to address how the maintenance concept RBM can be modeled, presented in section 2.3, to answer question 1b. Finally, section 2.4 covers the conclusion of the literature review.

2.1 Asset management

In the seventies, maintenance activities were planned by a corrective policy, meaning that components are fixed/repaired only after failure is indicated (Tinga, 2013). In the eighties, the demand for other maintenance concepts grown because of the building peak between 1930 and 1940 and the increase of big cities (iAmPro, 2018). Also, corporate social responsibility was introduced in the 80s, which results in the growing importance of environmental aspects instead of only taking profit into account (CROW, Kennisplatform CROW, 2018). The issues related to infrastructural problems about social responsibility is the origin of AM in England by the PAS 55. The PAS 55 became a standard for AM and is replaced in 2015 by the ISO 55.000. ISO is an international organization for standardization and is used worldwide to provide international standards (NEN, 2014). Nowadays, the ISO 55 000 series provides an overview of AM and AM systems and is developed for all types of assets and organizations (NEN, 2014).

As mentioned in section 1.4, the research will focus on the infrastructure and includes public assets. The financial value of public assets in the Netherlands has estimated around 400 billion euros (Ruitenburg, Braaksma, & Dongen, 2017). The high financial value of public assets supports, together with the social value, the importance of public assets in the Netherlands. Finding the right balance between performance, risks, and costs of an asset should be managed to provide availability for the users, which is the leading focus of AM. Figure 2 shows the relationship between the main AM aspects cost, risk, and performance.

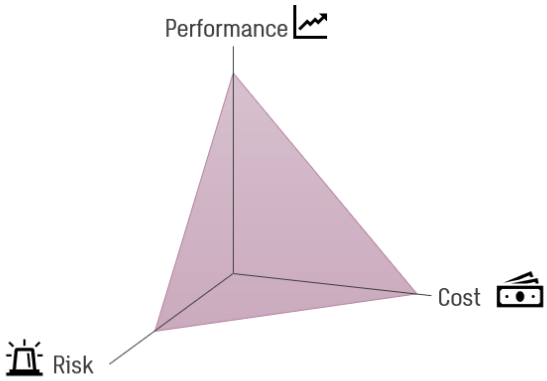

Figure 2: The three main aspects of AM

According to Robert Davis (2012), investigating AM is needed to deal with three challenges:

- To receive the maximum possible benefit for the asset by combining the lowest costs and the highest return on investment.
- To provide an understanding of the life cycle cost of the asset.
- To create the maximum life cycle while taking global challenges like climate changes into account.

The challenges can be related to the goals of AM and express by risk, performance, and cost that were mentioned earlier (Davis, 2012).

To define AM, the definition of an asset should be mentioned firstly. According to ISO 55.000 (p. 2), an asset is defined as ‘an item, thing or entity that has potential or actual value to an organization.’ In the dictionary, an asset is defined as ‘any item of economic value owned by an individual or corporation.’ Both definitions mention that the asset should add value. The value can be on the corporation’s balance sheet or by delivering a process or service (Davis, 2012) and should be defined by the organization.

The main key aspects risk, cost, and performance are the bases of AM and used in many definitions in the literature. The definition of AM applies to many disciplines (Pudney, 2010). According to Pudney (2010), AM is “an organization’s coordinated multidisciplinary practice that applies human, equipment and financial resources to physical assets over their whole life cycle to achieve defined asset performance and cost objectives at acceptable levels of risk whilst taking account of the relevant governance, geo-political, economic, social, demographic and technological regimes” (Ruitenburg, Braaksma, & Dongen, 2017, p. 261). The standardized definition of AM in the Netherlands is ‘coordinated activity of an organization to realize value from assets’ (NEN, 2014).

According to Davis, there are seven main key activities for an asset manager (2012). The AM strategy specifies the approach and objectives by the organizational principles defined in the policy. By the principles in the policy and the concepts and strategies, the asset manager can compose the AM planning. The planning should be executed by delivering the plans. To be able to deliver, or to improve the delivering of the activities, skills, and competencies of the people should be developed, and the risks should be managed. Finally, gathering and analyzing the data supports improvements by managing asset information.

Davis (2012) identifies nine benefits of AM and claims that AM can be optimized by optimizing the nine benefits. The nine benefits are (Davis, 2012):

1. Reduce the total costs of operating the asset.
2. Reduce the capital costs of investing in the asset base.
3. Improving the operating performance of the asset (reduce the failure rate, increase availability).
4. Reduce the potential health impacts of operation the assets.
5. Reduce the safety risks of operating the asset.
6. Minimize the environmental impact of operating the asset.
7. Maintain and improve the reputation of the organization.
8. Improve the regulatory performance of the organization.
9. Reduce legal risks associated with operating assets.

The benefits are shown in Figure 3 in a simplified overview to provide an overall picture of the aspects that should be improved or reduced to optimize AM. The benefits are grouped by cost, risk, impact, asset, and organization. Minimizing costs, risks, and impacts in combination with maximizing the asset and organization performance support optimizing AM.

Reduce		Improve	
Cost	Operating cost	**Asset**	Operating performance
	Capital cost		
Risk	Safety risk	**Organization**	Regulatory performance
	Legal risk		Reputation
Impact	Health impact		
	Environmental impact		

Figure 3: Nine benefits of AM (Davis (2012))

We can relate the benefits with the aspects of AM. The asset and organization that should be maximized can be related to performance. We can combine the benefit impact with the benefit risk if we look closer to the definition of risk. Risk is defined by Khan & Haddara (2003) as:

$$Risk = probability\ of\ failure * consequence\ of\ failure$$

The consequence of failure can be the impact of the failure, for example, the health impact or environmental impact. The benefits impact and risk are both related to risk.

This section can be concluded by assuming AM can be optimized by minimizing costs and risk while maximizing the performance. This will always be a trade-off since higher performance will often lead to higher cost, see Figure 2. Simultaneously, lowering the risk leads to higher cost. The variables risk, cost, and performance are important for the rest of the study since they are presented in the objective function and important by optimizing the MP of roads. We will now take a closer look at one of the aspects of AM, namely MP.

2.2 Maintenance planning

The European standard EN13306 defines maintenance as 'the combination of all technical, administrative and marginal actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function' (Tinga, 2013, p. 162). Another expression of maintenance is 'fixing and/or replacing components either when they have failed or when they are found to be failed' (Tinga, 2013, p. 167).

The available budget for maintenance is often minimal, whereby not all the technical, administrative, and marginal actions can be performed during the life cycle. The decisions should be made about the performances and risks of the system to stay within the budget, where the trade-off between availability and cost is often the case (Tinga, 2013). We define an MP as 'a set of related activities directed to restoring or keeping a system or object in the desired condition, so that it will function within specified quality norms' (Worm & Van Harten, 1996, p. 307).

According to the 'Nederlandse Vereniging voor Doelmatig Onderhoud' (NVDO), the maintenance costs in the Netherlands are around 30 to 35 billion euros per year (NVDO, 2018) and expected to increase. The increasing in maintenance field is caused by the growth of size, complexity, and variety of assets (Khan & Haddara, 2003) and results in a leading control priority (Arunraj & Maiti, 2007). Maintenance consists of a strategic, tactical, and operational level (Tinga, 2013). The strategical level covers the business goals by formulating the priorities and setting up the targets. The requirements, planning, and scheduling according to the resources are represented at the tactical level. Finally, the operational level plans and executes the tasks in the scheduled time according to maintenance.

At the strategical level, typically a maintenance concept[4] is developed. A reduction of around 40% to 60% can be achieved by selecting an effective maintenance concept (Krishnasamy, Khan, & Haddara, 2005). Selecting a maintenance concept that maximizes the availability and efficiency of the asset, controls the deteriorations, safety, environment, and performance, and minimizes the total cost of the operation is the major challenge of selecting and implementing a maintenance concept (Krishnasamy, Khan, & Haddara, 2005).

A maintenance concept aims to determine how the maintenance process is organized by selecting one or more maintenance policies[5] and the general structure of combining policies (Wayenbergh & Pintelon, 2002). Figure 4 provides an overview of the policies by the classifications reactive, proactive, and aggressive.

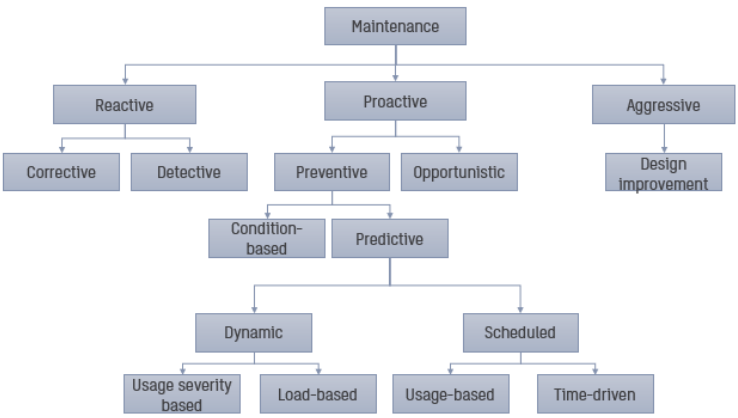

Figure 4: Classification of maintenance policies (Tinga, 2013)

[4] In literature, the words maintenance concept and maintenance strategy are both used (Tinga, 2013, p. 164). In this report we will use the word concept to avoid confusion with the term strategic level of maintenance.
[5] Maintenance policies are also called maintenance interventions.

The first classification is related to the budget of the total maintenance. Reactively executing maintenance means that it takes place when a component fails or when it is detected to be failing. Proactive means that replacing/repairing of components take place before a failure occurs. One way is called opportunistic, where maintenance activities are clustered to take advantages of, for example, downtime cost. Well-known examples of proactive are predictive, preventive, condition based, and time-based. The aggressive policy is more design-oriented and is based on improving the components so that failures can avoid/reduced. The maintenance policies can be combined while defining a maintenance concept, and are therefore also used as a guide in the tactical and operational level of maintenance. (Tinga, 2013)

Besides the maintenance policies, a maintenance concept includes the decisions about identification and allocation of resources, upgrading and back up of the assets and determining actions about repair, inspection, and replacement (Tinga, 2013). In the past decades, maintenance concepts pass through many changes because of the development of maintenance philosophies.

Figure 5 provides the timeline for the last decades and shows an overview of the modifications in maintenance strategies (Arunraj & Maiti, 2007).

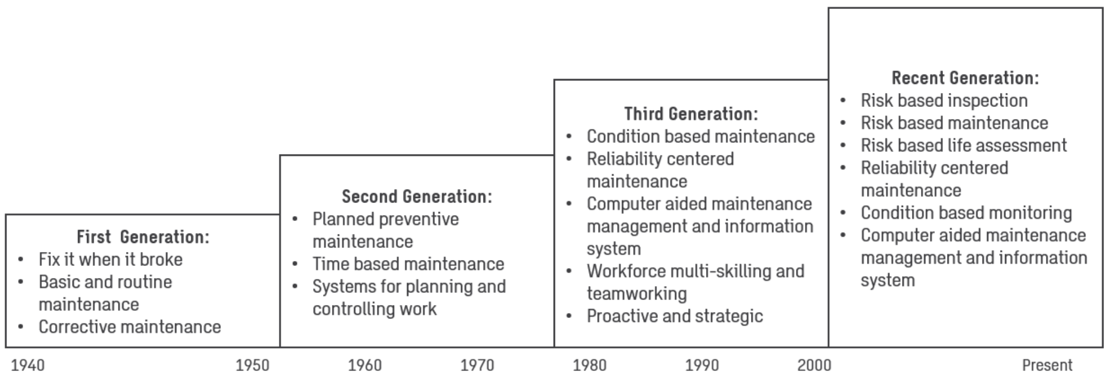

Figure 5: Timeline maintenance philosophies (Arunraj & Maiti, 2007)

Between 1940 and 1950, equipment was designed simple, and repair could be done easily. The first generation can be related to the reactive maintenance policy where maintenance was only done when it was broken. The second-generation become more expensive because of the growth of complexity of machines. Therefore, proactive maintenance policies started to be more integrated. Between 1980 and 2000, the third generation arises and is characterized by 'just-in-time,' automatization, and the growth of quality demand. Maintenance strategies become more condition based and based on historical data. The recent generation (started in 2000) is characterized by risk-based maintenance and inspection. Before, safety and maintenance were not considered together. The growth under companies/organizations of RBM can also be seen in the literature is related to the recent generation. (Arunraj & Maiti, 2007).

2.3 Risk-based maintenance

RBM is developed to identify the high-risk components of the system to be able to maintain those components with a higher priority to achieve a better overall risk profile (Arunraj & Maiti, 2007). According to Arunraj and Maiti (2007), inspection and maintenance that is based on risk analysis minimize the probability of failure and the related consequences. Secondly, it supports decision making according to the investments in maintenance. A risk is defined as 'the considered expected loss or damage associated with the occurrence of a possible undesired event' (Arunraj & Maiti, 2007, p. 656). The organization is free to define risks for the system and the related consequences. A risk can be classified as quantitative or qualitative. A quantitative risk is numerically expressed and easy to prioritize. A well-known tool to quantify risk is Fault Tree Analysis (FTA), discussed in the next sections. A qualitative risk is determined by the probabilities and consequences and provides a subjective value (Khan & Haddara, 2003). Besides the risk definition, it is important to emphases why to take the risk into account by developing the MP in the first place, in other words, why to use an RBM policy.

Many maintenance concepts are focusing on the reliability of the system and/or the components. The reliability is the probability of survival. However, it is also important to take the risk into account, because a low probability of failure (so high reliability) does not give information about the consequences of that failure (Arunraj & Maiti, 2007). In some situations, the reliability can be around 95%, but the risk of failure that people get injured is also 95%. In that case, reliability of >99% is preferred, and so maintenance on that part has a high priority.

According to Arunraj & Maiti (2007), Tixier et al. (2002) show 62 ways of risk analysis, indication that there is not just one way of performing RBM. In literature, authors developed standardized approaches about performing RBM, although the approaches need customization based on the type of system. In this study, the RBM approach, as described in Krishnasamy, Khan, and Haddara (2005), is used as a background. The RBM model, according to Krishnasamy et al. (2005), studies the failure modes, determines the corresponding risk, and finally develop the MP (Arunraj & Maiti, 2007). Figure 6 visualizes The RBM model according to Krishnasamy et al. (2005), consisting of the four phases 'Identification of the scope', 'Risk assessment,' 'Risk evaluation' and 'Maintenance planning.'

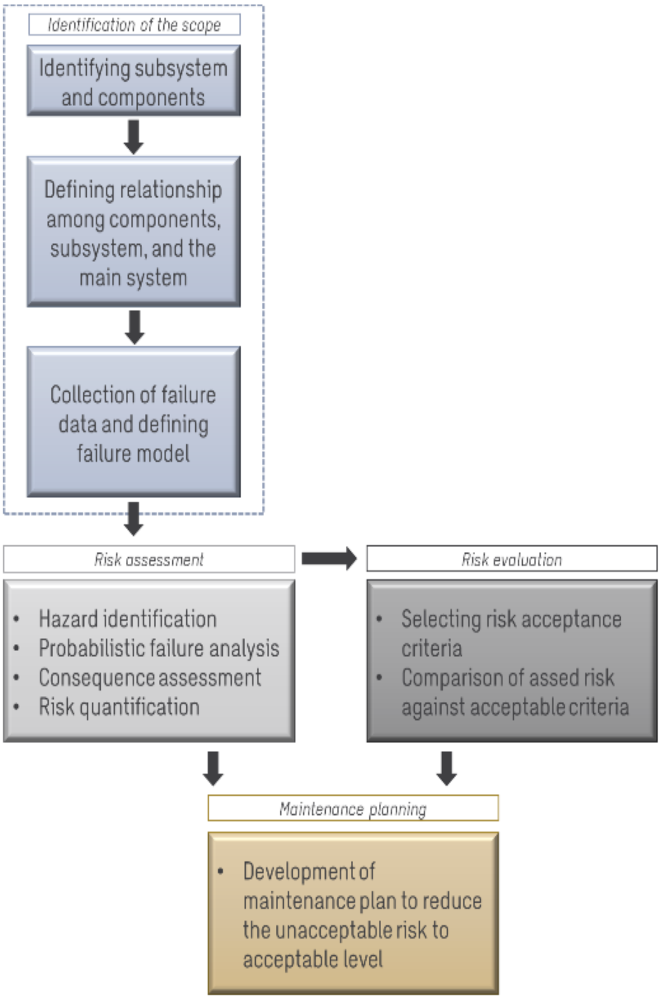

Figure 6: RBM-model (Krishnasamy et. al. 2005)

In the subparagraphs below, the four phases will be explained in more detail.

2.3.1 Identification of the scope

First, for a certain system, all the subsystems and components are identified. A structured way to show the relationships among system, subsystems, and components is a system breakdown structure (SBS), also called a tree diagram. For each component, the failure model is determined by using (historical) failure data, an experience-based approach. A failure mode is a way or mode an asset can fail concerning the undesired top event (Schüller, 1997). The data can be provided by the suppliers of the component or is available by historical data. A method to select the best fitting failure model is the least square method that selects the distribution with the smallest sum of squared distances.

Well-known probability distributions to model the lifetime of a nonrepairable item are exponential, Gamma, Weibull, Normal, Lognormal, Birnbaum-Saunders, and the inverse Gaussian distribution (Rausand & Høyland, 2004). The two most used failure distributions are Weibull and exponential distribution (Tinga, 2013). The Weibull distribution is the most popular method to analyze failures (Jardine & Tsang, 2013) and is flexible to model life distributions with a decreasing, increasing or constant failure rate function (Rausand & Høyland, 2004).

The corresponding distribution function for a component with time to failure (T), scale parameter (λ), and shape parameter (α) is given by:

$$F(t) = PR\ (T \leq t) = \begin{cases} 1 - e^{-(\lambda t)^{\alpha}} & for\ t > 0 \\ 0 & otherwise \end{cases}$$

(Rausand & Høyland, 2004)

If the shape parameter α = 1, the distribution equals the exponential distribution.

2.3.2 Risk assessment

To assess the risk for each component, the asset manager should identify the relevant hazard by failure scenarios, analyze the probabilistic failure, assess the consequences, and finally quantify the risk. To identify the hazard, failure scenarios describes which series of events lead to system failure (Khan & Haddara, 2003). Generally, various failure scenarios are possible, while not all are relevant or likely to happen. Therefore, we should select the relevant failure scenarios. Methods are available in the literature to select the most important failure scenarios. Well-known methods are maximum credible accident scenarios MCAS) and worst-case scenario. After selecting the relevant failure scenarios, the probabilistic failure needs to be quantified.

The probabilistic failure analysis can be applied by developing a probabilistic fault tree, an analytical simulation. Fault tree or decision trees determines the probability that events (in a certain sequence) result in consequences (Khan & Haddara, 2003). A fault tree analysis (FTA) provides a diagram with the basic failures and the relations between the failures that causes system failure (Tinga, 2013). The system failure is the top event in the tree. Figure 7 shows a fictive fault tree.

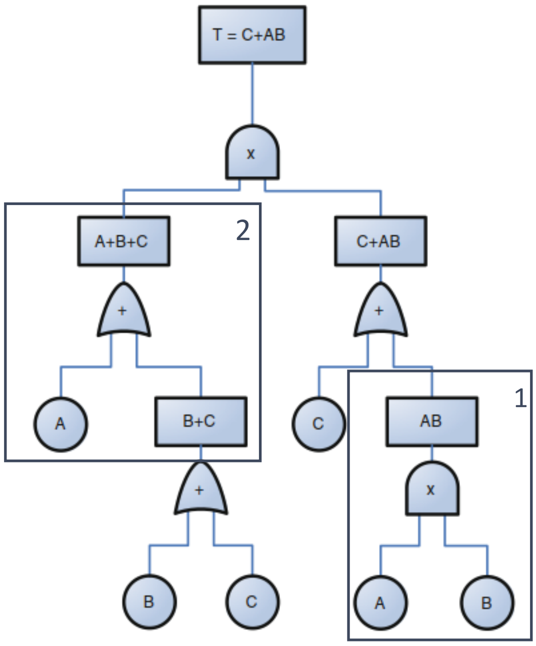

Figure 7: FTA example (Tinga, 2013)

The circles (A, B, and C) are the basic events that may result in the occurrence of the top event (T). The gates (x and +) indicates if one or more events are leading to the failure (OR-gate) or that all the events should happen (AND-gate). Boolean algebra is used to express the higher events. An AND-gate as shown in box one is expressed by AB so that only if A and B are true, the event is also true. The OR relation as in box two is determined by the sum of the events. In the example, the top event is equal to (A+B+C) (C+AB).

To determine the minimal cut sets (MCS) of the system, the equivalent fault tree (EFT) determines the top event, expressed as:

$T = \sum_{i=1}^{n} MCS_i = \sum_{i=1}^{n}(\prod_{j=1}^{m_i} C_{ij)}$ (Tinga, 2013)

By using the rules of Boolean algebra and the corresponding laws, the top event of the example can be reduced to T= C + AB. Software tools determine the minimal cuts and the top event for a fault tree, e.g., PROFAT. The probability of failure for the system equals the probability of the top event. The probability failures of the events can be estimated by, e.g., Monte Carlo Simulation and by failure parameters.

For the top events, the consequences for the system are identified and analyzed. Examples of the consequences are system performance losses, financial losses, human health losses, and environmental losses (Khan & Haddara, 2003). The consequences are calculated by mathematical models, to make it quantifiable, and based commonly on maintenance. By the consequences, the effect of the occurrence of the top events is provided.

Finally, the risks are quantified by multiplying the probability with the consequences, so that:

$$Risk = probability\ of\ failure * consequence\ of\ failure$$

The quantification is made by ranking the risks from high to low.

2.3.3 Risk evaluation

To evaluate the risks, a risk acceptance criterion decides whether a risk is acceptable. The risk acceptance criteria can be selected by using as low as reasonably possible (ALARP) or Dutch acceptance criteria (Khan & Haddara, 2003). The components for which the risk exceeds the risk acceptance criteria are selected to improve by modifications in the maintenance plan. To quantify the effect of the improvements on the MP, we will use the risk index (Krishnasamy, Khan, & Haddara, 2005). The risk index equals the actual risk divided by the risk acceptance criteria. The risk index should be lower than one to be acceptable. All the risks indexes that are higher than one are considered in the next phase.

2.3.4 Maintenance planning

For the components that exceeded the risk acceptance criteria, the MP needs improvements to reduce the risk index below one. A study of the failure causes provides insights on how to decrease the probability of failure. To identify how much the probability of failure should be decreased, a reverse fault tree analysis (RFTA) can be used. The RFTA calculates the maintenance intervals based on the risk. The desired failure probability for the top event conducts the probability failure of the basic event (Arunraj & Maiti, 2007). Modifications in the maintenance interval and/or the type of maintenance will reduce the probability of failure and so the risk. Another possibility is to reduce the consequences of the failure to reduce the risk. However, reducing the consequences is not in the scope of this thesis.

2.4 Conclusion literature review

According to Pudney, AM is “an organization’s coordinated multidisciplinary practice that applies human, equipment and financial resources to physical assets over their whole life cycle to achieve defined asset performance and cost objectives at acceptable levels of risk whilst taking account of the relevant governance, geo-political, economic, social, demographic and technological regimes” (Ruitenburg, Braaksma, & Dongen, 2017, p. 261). The standardized definition of AM used in the Netherlands is ‘coordinated activity of an organization to realize value from assets’ (NEN, 2014). Finding the right balance between the risk, performance, and cost of asset supports performing AM optimal. Coordinating the whole life cycle of an asset includes performing maintenance which is defined by ‘fixing and/or replacing components either when they have failed or when they are found to be failed’ (Tinga, 2013, p. 167). Maintenance supports the nine benefits of AM, according to (Davis, 2012).

At the strategical level, a maintenance concept is selected that maximizes the availability and efficiency of the asset, controls the deteriorations, safety, environment, and performance. Minimizing the total cost of the operation is the major challenge of selecting and implementing a maintenance concept (Krishnasamy, Khan, & Haddara, 2005). In the last decades, many maintenance concepts were developed and used to schedule maintenance activities. In the last 20 years, maintenance concepts focus on RBM and inspections, to combine safety with maintenance.

This study focusses on RBM, which is developed to identify the high-risk components of a system to be able to maintain those components with a higher priority to achieve a better overall risk profile (Arunraj & Maiti, 2007). Risk is quantified by multiplying the probability of failure with the consequence of failure.

To develop the generalized RBM, the model from Krishnasamy et al. is selected (2005). Figure 8 shows the four steps that create the MP of a certain phase. The phases are defined as:

1. Identification of the scope
2. Risk assessment
3. Risk evaluation
4. Maintenance planning

The identification of the scope defines the relationship among the components and determines the failure models. In the second phase, the risks are quantified. A risk acceptance criteria prioritize the selection of components that are considered while improving the MP. In the last phase, the MP is improved so that the unacceptable risks are reduced to an acceptable level.

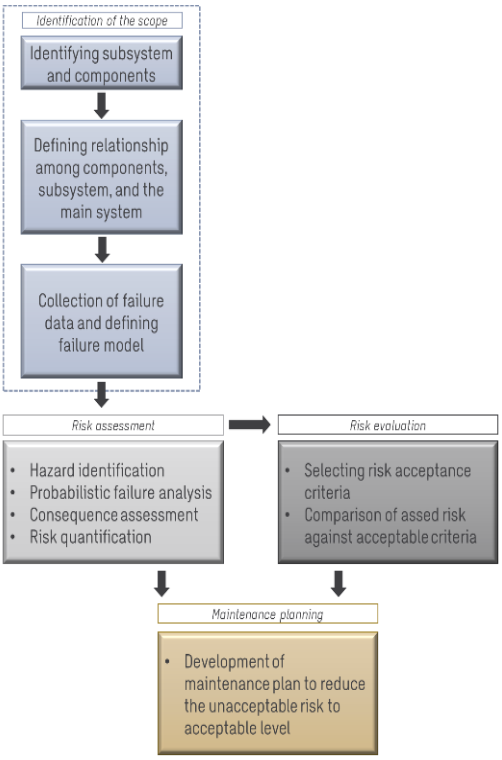

Figure 8: RBM model framework

3. Current maintenance planning

This chapter aims to describe the current method that is used to plan maintenance activities for roads that are included in the portfolio of a municipality. The conclusion answers the second sub-question:

'How is maintenance currently planned for roads?'

To be able to explain the current method, we first discuss the main characteristics of roads and the variables that influence the deterioration, resulting in a need for maintenance. The first section 3.1 discusses roads and road maintenance in general, to answer question 2a. The current method to plan road maintenance for a municipality in The Netherlands is based on the CROW road maintenance publications (CROW, Wegbeheer, 2011). Standardized variables are used as input for the MP. In section 3.2, the characteristics are discussed to provide an answer on question 2b. The decisions that are made for the current road MP are presented in a flowchart and explained in section 3.3, answering question 2c. This chapter is concluded in section 3.4.

3.1 Road maintenance

In general, a road consists of several layers, as shown in Figure 9 (Sirvio, 2017).

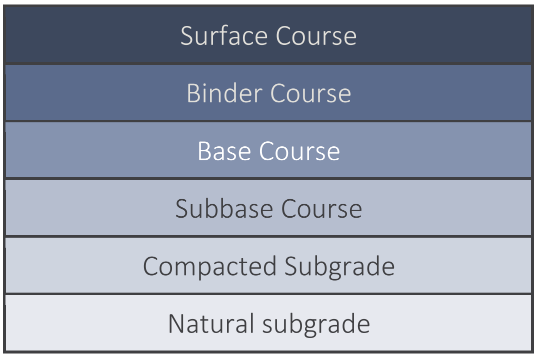

Figure 9: Layer of a road (Sirvio, 2017)

The lowest two layers, the subgrades, are the native/original ground. The next layer is the subbase (optional) and the base course, which consists of aggregate materials. The surface course is the top layer, optional above a thin binder course. Jointed plain concrete, jointed reinforced concrete and continuously reinforced concrete pavements are classified as rigid surfaces. Asphalt concrete and full-depth asphalt concrete pavements are flexible surfaces. Both rigid and flexible surfaces are often sealed, while earth and gravel roads are not (Sirvio, 2017). In this study, three types of pavement are considered. In Figure 10, the deviation of the three pavements is shown to indicate the proportions.

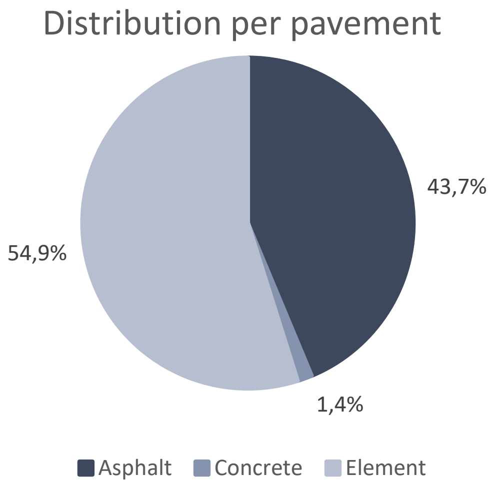

Figure 10: Division per pavement at municipalities in 2007

Multiple characteristics and measurements are used in literature to express the condition of the road and to be able to analyze the deterioration and quality. The main effect of deterioration is decreasing driving comfort and a shorter service life. The main factors that influence the deterioration process for roads are traffic density, type of pavement, and climate conditions (Worm & Van Harten, 1996). Sirvio (2017) takes the variables serviceability (comfort), safety, and structural capacity into account by analyzing the effects of the deterioration. Currently, the influences by climate condition are not considered in the road MP designed by the municipality, although they have big effects on the deterioration of the road. In this study the climate conditions are not considered because of the unpredictability compared with the other factors.

The asset owner of roads in the Netherlands is the municipality, 'Rijkswaterstaat,' 'Provincies' or 'Waterschappen.' As mentioned, we focus only on municipalities, who manage most of the roads of the total road network in the Netherlands, namely 85,3% in 2008 (Molenaar & Houben, 2010). The municipality is responsible for the state of the road (Sirvio, 2017). In the thesis, we define a road as 'A line of travel communication using a stabilized base other than rails or airstrips, primarily for the use of road motor vehicles running on their own wheels' (Sirvio, 2017, p. 14). The service life of a road without renovation varies between 10 and 50 years, depending on the road class and the design standards (Sirvio, 2017). With a size of 10 000 kilometers of highways and main regional roads, the importance to perform maintenance for Dutch road network as optimal as possible is increased (Worm & Van Harten, 1996).

In general, the purpose of road maintenance is to keep the capacity and the value of the road optimal (Sirvio, 2017). At the municipalities, the MP for roads is the responsibility of the local road authority (Dutch: wegbeheerder) (Rijksoverheid, 2019). The expenditures for road maintenance are maximized by a budget. The size of the budget for road maintenance is regulated by the city council (gemeenteraad). The road authority should demonstrate how much money is needed to keep the asset performance on a predetermined level, based on the CROW guideline. In a technical sense, there is a minimum limit to prevent capital loss. The study considers the tactical MP.

The MP is based on the condition of the road. Most of the maintenance activities are corrective. The condition of the road is indicated by visual inspection. The inspector identifies the damages on the surface, which is discussed in more details in the next sections. The inspection frequency differs per municipality but is often once per year/per two years. Besides visual inspection, other inspection results are available in some cases, e.g., by inhabitants who reports to the municipality if they notice damages or random inspections by the municipality in between the visual inspections. These other inspections are not considered in the report since in many cases those results are not accessible. We will discuss the current method to plan road maintenance in section 3.3. Notice that road can still be used, even if the inspector identifies damage. The output is a multi-year period planning and is structured by an empirical model. The planning horizon for the current MP is five years. Each year the MP is reconsidered, so only the next year plan is fixed. To be able to explain the current MP model, we will discuss characteristics of roads in the next section.

3.2 Characteristics of roads

The characteristics of roads that are used to develop the MP are categorized by roadway, roadway sector, and lane sector[6] (Worm & Van Harten, 1996). Figure 11 visualizes the difference between a lane and a roadway. It shows that the road in Figure 11 consists of two roadways and four lanes.

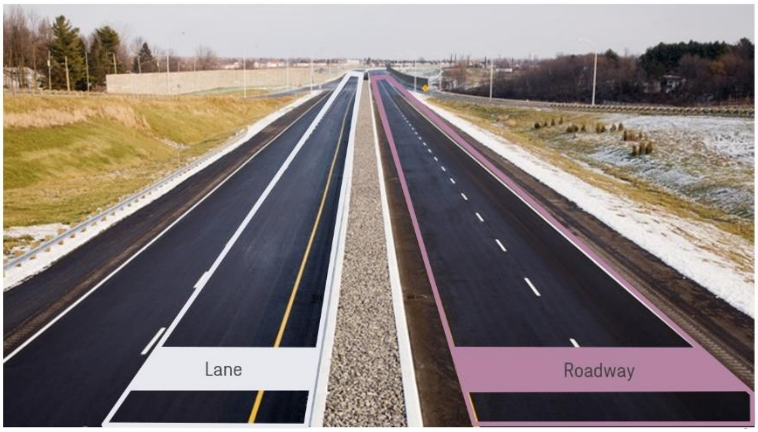

Figure 11: Breakdown of a road

In practice, many roads managed by the municipality are in the urban area and consists of different components like a curb or a junction with different pavements, and are not that clear as the road in Figure 11. Because of the different pavement and usage, the road cannot be divided into equal size lane sectors. The common breakdown is on roadway sectors, based on the same pavement and usage. If the roadway sector is too big, the roadway sectors are divided into lane sectors as well. Figure 12 visualizes an example of the breakdown of roadway sectors and lane sectors.

Figure 12: Roadway breakdown in the urban area

As shown in the figure, not every roadway sector has (multiple) lane sectors. That is why the inspection is explored for roadway sectors in the first place, and, if accessible, for lane sectors as well. Regulations are available to break down the road correctly. The breakdown is often based on logical points, e.g., at a crossing street point or a streetlight. The roadway/lane sectors are around 100 meters in the urban area, and 200-500 meter outside the urban area.

[6] In the report 'Wegbeheer 2011', other words (in Dutch) are used for roadway, roadway sector and lane sector. However, because of the clearity, we will use the words used in the paper of Worm & Van Harten (1996).

The MP is based on characteristics of the road, and data that is gathered by inspection. The characteristics are available for the categories roadway, roadway sector, and lane sector are presented in Table 1. This categorization is made since some characteristics can only be gathered correctly for one of the categories, e.g., the traffic intensity. A roadway can have multiple traffic intensities. Therefore, the traffic intensity is determined for each roadway sector. The characteristics are divided into required and optional. The required characteristics should always be available and used as input for the current MP. The optional characteristics are not always available, depending on the municipality.

Table 1: Characteristics (required and optional)

	Roadway	Roadway sector	Lane sector
required characteristics	Road number	Roadway sector number	Type lane sector
	Name	Soil	Road type
	Total length	Length	Surface
	Number of road sections	Start point	Length
	Start point	Endpoint	Pavement
	Endpoint	Geographical location	Age
		Traffic intensity	Length joints
		Freight traffic intensity	Maintenance type & date
		Bus route	Width component
			Construction type
			Thickness construction
			Thickness and type foundation
			Type joint filling
optional characteristics		Traffic sign	Sprinkle route
		Lighting	Marks
		Street name sign	Cables and pipes
		Exit driveway	Gully tops
		Traffic regulations	

Since the road types are important in the rest of the report, the seven road types that are considered are mentioned in Table 2. In the rest of the report, the numbers are often used to refer to the road type.

Table 2: Road types

Road type name	Road type number
Heavy road network	1
Heavy duty roads	2
Mean duty roads	3
Light duty roads	4
Residential area	5
Public area	6
Cycle track	7

Besides the characteristics, data is gathered to provide information about the quality of the road. The quality of a road is quantified by visual quality (Dutch: beeld kwaliteit) and technical quality (Dutch: technische kwaliteit). The visual quality is quantified by a picture of the state of a road. The quality is assessed by A+, A, B, C, and D, indicating the quality by respectively very high to very low[7]. CROW

[7] A+ is not used often in practice since this quality is related to new build roads.

publication 232 *('Kwaliteitscatalogus openbare Ruimte 2018')* and 147 *('Technische kwaliteit')* provides an identification of the costs for each ambition level for a certain road type, as an indication for the feasibility for the municipality. Table 3 indicates the meaning of each letter.

Table 3: Quality levels

Quality	Explanation	
A+	No damages	
A	Small damages	
B	Warning limit is exceeded	sufficient
C	The threshold is exceeded with 1	moderate
D	The threshold is exceeded with more than 1	insufficient

As Table 3 shows, the letters B, C, and D are categorized by sufficient, moderate, or insufficient. The municipality decides how much of the total should be quantified as sufficient, moderate, or insufficient. The technical quality is determined by inspectors. The inspection process is described in detail in the 'Handleiding globale visuele inspection 2011'. The results of the inspections are value based on the severity and size of the damage and gathered in a structured way. The damages that are assessed during an inspection are shown in Table 4.

Table 4: Damages that are inspected per pavement type

	Damage by visual inspection	Damage by measurements
Asphalt	Raveling	-
	Rutting (dwarsonvlakheid)	Rutting (spoorvorming)
	Bumps	Comfort index[8]/shoving
	Cracking	-
	Prolapse	-
	Edge damage	-
Element	Rutting (dwarsonvlakheid)	Rutting (spoorvorming)
	Bumps	Comfort index/shoving
	Joint width	-
	Prolapse	-
Concrete	Bumps	Comfort index
	Cracking	-
	Joint filling	-
	Prolapse	-

Table 4 shows that the damage types depends on the pavement of the lane sector. Three damages can be measured and provided reliable, as shown in Table 4 as well. However, in practice, those three measurements are not used much by municipalities, because of the costs. If the damages are measured, they will replace the visual inspection data. This will be explained in more detail in the MP description. The other damages can only be measured visually since it is not possible to provide reliable values by measuring with equipment.

[8] Comfort index are only measured for the road type cycle tracks.

The damages based on the inspection are assessed by size and severity. The size is expressed by 0,1,2, or 3 and is based on the size of the damage in % or meters. The severity is expressed by L (light), M (medium), and E (serious) and is also based on a % of the total lane sector or the length in mm. The guideline is provided in Appendix 9.2. In practice, the results are written by 1 to 9, as shown in Table 5.

Table 5: Inspection results

Severity	-	L	M	E
Size				
0	G			
1		1	4	7
2		2	5	8
3		3	6	9

The inspection data is gathered on a year to year basis. The visual quality notation is used to indicate the desired quality of the roads, called the ambitions. The ambitions are often related to areas (e.g., centrum vs. rural) and similar for each roadway. The technical quality shows the actual quality of the roads. The technical quality can be translated to the visual quality by using standards, provided by the CROW as well. In the current MP strategy, a road fails if the level of damage is exceeding the threshold that is determined by the municipality, which will be discussed in the next section.

3.3 Creating maintenance planning

Creating the MP consist of roughly three main steps: determine the plan year, determine the maintenance activities with corresponding costs, and finally assess changes in the MP. In the flowchart in Figure 13, all the process steps and decisions are shown. The three main process steps are explained in the subsections below. The processes (rectangles) in the flowchart are numbered and used in the clarification of the MP model. For the MP, we use the required characteristics shown in Table 1 and the damages summarized in Table 4. The output is an MP for five years and is reconsidered every time new inspection results are provided (often every two years). We assume that the MP is reconsidered every two years, which means that the planning is fixed for the upcoming two years, while the last three years are just as indication/orientation (e.g., to analyze the distribution of the cost per year).

Sweco developed the software tool OBSURV that supports the MP roads. OBSURV is an integrated management system for public assets like roads, bridges, tunnels, and parks that are used by customers like municipalities, the province, and Rijkswaterstaat. Sweco uses OBSURV to calculate the cost and determine, e.g. maintenance activities and plan years, which we will discuss in more detail in the next subsections.

The MP that is described in the report is based on the tactical MP, as already mentioned in the scope. The strategic MP for roads identifies the cycle maintenance activities that are fixed and should be executed, e.g. every ten years. The tactical MP consists of the maintenance activities that are scheduled for a time horizon of five years and are more specific, as explained in detail in this section. The operational MP is related to small maintenance activities. These activities are performed to adjust small damages that should be fixed as soon as possible and are not scheduled on any regular basis.

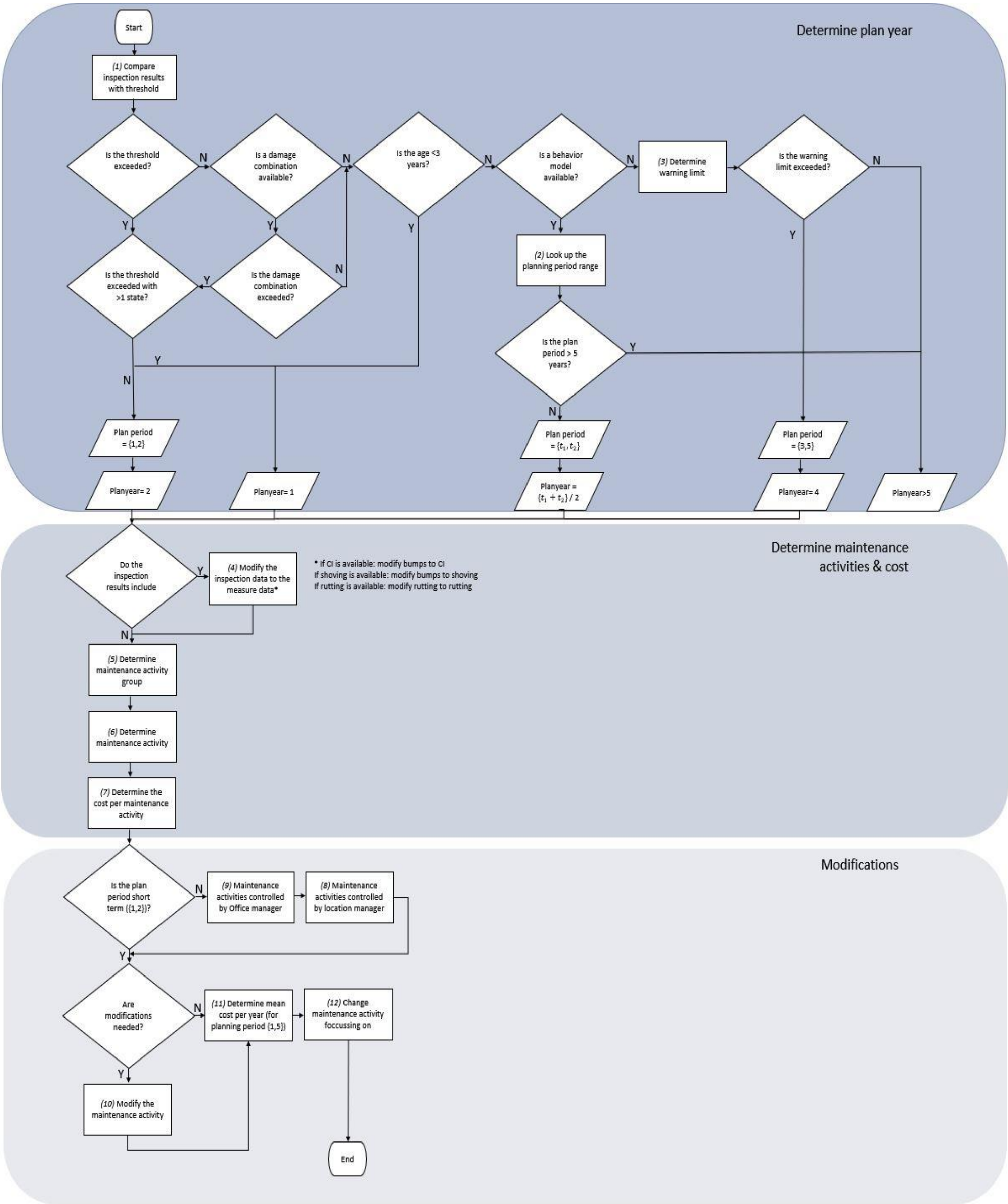

Figure 13: Flowchart current maintenance planning

3.3.1 Determine plan year

The plan year notifies the year that the municipality should take a maintenance activity to avoid exceeding the threshold. The threshold is the maximum acceptable value for the damage, defined by the municipality. The threshold is expressed as a number, which is a function of the size and severity; the same expression as for damages mentioned in section 3.2, see Table 5. If for a certain lane sector, the threshold equals M2 (so 5), the threshold is exceeded if the inspection result is M3 (so 6). If the damage result equals L1 (so 1), the threshold is not exceeded. The CROW guideline provides for each damage and road type a minimum threshold. The municipality is only allowed to set the threshold higher.

To determine the plan year, first the plan period is determined. The plan period provides a period in which the maintenance activity should be planned and is present as '{minimum plan year, maximum plan year}.' To determine the plan period, the inspection results are compared with the threshold *(1)*[9]. If the threshold Development, the plan period is at most {1,2}. The plan year is one if the threshold is exceeded with more than one state or if the age of the lane sector is less than three years old[10]. Otherwise, the plan year is the mean of the plan period {1,2}, which is 1,5 year. If the plan year is not an integer, the plan year is round up.

A damage combination exists if, on a certain roadway sector/lane sector, both two damages are initialized. A threshold is determined for each damage combination as well. If the threshold for the damage combination is exceeded, the plan period is set on {1,2} as well, and if the threshold is exceeded with more than one state, the plan year is 1. Exceeding the threshold means that maintenance is not accomplished during the technical optimal moment. Executing the maintenance activity too late can result in unsafe traffic situations resulting in increasing chance on liability. In the case of asphalt, it can also relate to capital destruction.

If both the threshold is not exceeded for the damages or the damage combinations (if possible) and the age is not smaller than three years, the **behavior model**[11] is used to determine the plan period *(2)*, if accessible. See Table 6 for an example of one of the behavior models.

Table 6: Behavior table (for damage type raveling, threshold M2, Road type 1 and 2)

		Plan period																
		AGE																
		≤ 3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**≥ 20**
inspecton results	**G**	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*
	L1	*2-6*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*
	L2	*2-5*	*2-6*	*2-6*	*3-6*	*3-6*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*	*> 5*
	L3	*1-4*	*1-4*	*1-4*	*1-4*	*1-4*	*1-4*	*1-4*	*1-4*	*2-5*	*2-6*	*2-6*	*3-6*	*3-6*	*3-6*	*3-6*	*> 5*	*> 5*	*> 5*
	M1	*1-2*	*1-2*	*1-2*	*1-3*	*1-3*	*1-3*	*1-3*	*1-4*	*1-4*	*2-4*	*2-4*	*2-4*	*2-4*	*2-4*	*2-4*	*2-4*	*2-4*	*2-4*
	M2	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*	*1-2*

9 As mentioned in the introduction of section 3.3, we refer to the processes by the numbers provided in the flowchart.

10 The age equals the year of inspection minus the year maintenance is executed or, in case no maintenance is executed before, the building year.

11 The behavior models are used for developing the RBM model for roads later in the report and are important to understand.

For a certain inspection result and age of the road type, the table provides the expected time maintenance activities are needed, also called the remaining useful lifetime. It depends on the type of damage, the threshold, and the road type. The behavior model is only accessible for the pavement asphalt. To make the use of the behavior model clearer, we illustrate the following example:

- Pavement: Asphalt
- Damage type: Raveling
- Threshold: M2
- Road type: 2
- Age: 10
- Inspection result: M1

The characteristics are circled in Table 6 and show that the corresponding planning period for those characteristics and inspection results is equal to {1,4}.

The behavior model also provides a plan period of >5. This planning period is not specific since a proper indication of the remaining useful lifetime is unknown. Therefore, the planning horizon of the MP is made for the upcoming five years. As shown in the example in Table 6, the behavior model provides the plan period, and the plan year again is determined by the mean of the plan period.

Since the behavior models are only accessible for asphalt, the pavement element and concrete remaining useful lifetime should be determined by a warning limit *(3)* which is provided by the CROW guideline as well. A warning limit is used if the damage does not exceed the threshold but is expected to exceed the threshold within the upcoming five years. The warning limit is a state for each damage and road type. If that state is exceeded, the plan period is set to {1,5}. If the warning limit is not exceeded, no maintenance activities are needed within the five coming years and the plan period is set to >5.

Now that we determine the plan year for each roadway sector/lane sector, the next process is to determine the maintenance activities and the corresponding costs. Notice that we do not go in more detail about which month/day the maintenance activity is executed since this depends on many factors like weather, lead time materials, communication with environment and accessibility for companies. These factors are outside the scope of the research.

3.3.2 Determining maintenance activities and the corresponding cost

The maintenance activities and the costs depend on the plan period that is determined in the previous step. Determining maintenance activities depends on whether the plan period is greater than five years or not. If the inspection results include measurements (presented in the third column in Table 4), the visual inspection results are replaced by the measurement results *(4)*[12]. For each roadway sector/lane sector, the maintenance activity group can be determined by the CROW guideline *(5)*. The maintenance activity group is a collection of similar maintenance activities and indicates the type of maintenance. Selecting the maintenance activity group is done by unique relations between the damage inspection results and is often implemented in a tool. Sweco uses its application tool OBSURV. An example of a maintenance activity group for asphalt is ‘conserving’ (In Dutch: conserveren). For each road type, the maintenance activity group provides if the surface course should be replaced or a surface treatment is needed. Based on the maintenance activity group and the road type, the maintenance activity is selected *(6)*, often again by using a tool/application like OBSURV. We assume that the state of the lane sector is as good as new after a maintenance activity is executed. Since the

[12] The measurement results are not expressed as the inspection results provided in Table 5. The CROW guidelines provide a transformation norm for the measurement results to inspection results (see page 59).

MP planning is developed for a planning horizon of five years, we assume that the lane sector does not require another maintenance activity for the remaining time within the planning horizon.

The cost for each maintenance activity is established by the manager, by using standard cost for each type of maintenance activity that is provided by engineering consultancies, e.g., by Sweco *(7)*. The total costs for each roadway sector/lane sector are calculated by multiplying the area with the maintenance activity cost since the cost is provided per unit. The maintenance cost includes all the cost for executing the maintenance activity, so materials cost, machine cost, labor cost, preparing cost and the cost for setting of the road. The maintenance cost is excluding the inspection cost, the cost for developing the MP, and the possible extern cost because the road cannot be used while executing the maintenance activity.

The damages that require maintenance after the plan period of five years are only considered to indicate the expected cost in the future and to determine the small maintenance activities budget. The small maintenance activities are the damages that are too small to assess by an inspection result but need maintenance. Those damages are not considered by the MP but need maintenance activities. The maintenance activities are scheduled on an operational base. In a time window of five years, the situation can change, especially the policies of the municipality. Therefore, the lane sectors that are set on a plan year greater than five years are not considered for the current MP.

3.3.3 Modifications

Finally, the modification phase considers integration planning to determine the final plan year. For the short-term period (plan period {1,2}), the office manager, and the location manager, officials of the municipality, check the maintenance activity concerning cost and damage. The office manager (8) controls the size and plan year for each maintenance activity concerning the budget after each time he receives the inspection results. Secondly, the office manager controls the total portfolio and analyzes if the maintenance activities can be combined with, e.g. sewer renovation or if multiple roadway/lane sectors can be combined. The location manager (9) supervises if the damages are close to each other and if it is possible to combine maintenance activities, which often leads to postponing or more maintenance activities. If necessary, both managers can decide to choose another maintenance activity (not necessary within the same maintenance activity group) *(10)*. These decisions are manually and based on experiences. By all maintenance activities and costs within the plan period of five years, the mean costs per year are calculated *(11)*. Often, the costs are not equally spread per year. Based on real data from a municipality, Figure 14 shows that the maintenance costs are often high at the beginning of the plan period of five years, and relatively low in the middle. Therefore, maintenance activities are shifted within their plan period to create a more equally spread cost per year *(12)*.

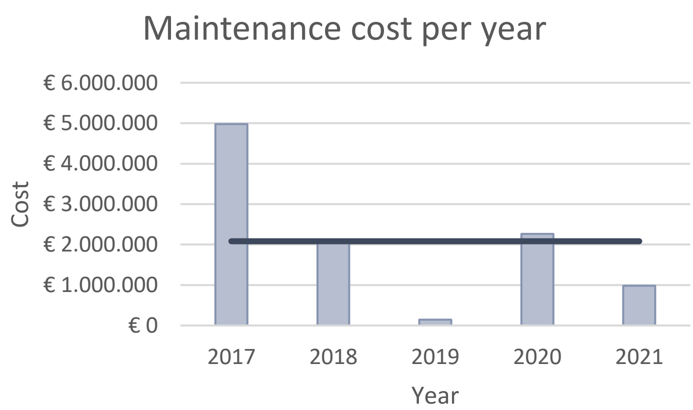

Figure 14: Maintenance cost per year

Municipalities can use policy themes, road types, the geographical location, or a combination between them to priorities which maintenance activities are shifted first. The policy themes are provided in Table 7 and are representing the core values of a municipality. Each damage should get a score on the four themes. A higher score means a higher prioritization and is therefore shifted at least.

Table 7: The four policy themes

English	Dutch	Explanation
Sustainability	Duurzaamheid	Indicates the technical condition of the pavement concerning the usage.
Safety	Veiligheid	Indicates the effect of the quality on road safety.
Functionality	Comfort	Indicates the experience of the road user on discomfort/nuisance caused by the road condition.
Aesthetics	Aanzien	The aesthetics of the road is conditioned by the visual glow of the maintenance condition.

Secondly, a municipality can decide to use the road type to prioritize roads. An example of a common prioritization is shown Table 8.

Table 8: Example prioritization based on road type

Road type (number)	Prioritization
Heavy duty roads (2)	Highest
Cycle track (7)	
Public area (6)	
Residential area (5)	
Head road network (1)	
Mean duty roads (3)	
Light duty roads (4)	lowest

Finally, prioritization based on the geographical location is possible. The order of the prioritization is divided by districts, residential area, neighborhoods, or streets. If the costs per year are equally spread, a basis MP is drawn up with the corresponding costs per year. The maintenance cost should fit with the available budget per year. Often, the available budget per year is smaller than the maintenance cost per year. This means that not all maintenance activities can be executed. To decide which maintenance activities are postponed again, the municipality can use three priority methods; based on policy themes, road types, or geographical location, as explained in the paragraph above. CROW provides the correlations between the policy themes and damages, and those correlations are used to prioritize the maintenance activities. The maintenance activities with the lowest priority are selected first.

By shifting a maintenance activity, it is possible that the activity is planned outside the planning period. If it is scheduled earlier, there are no problematical consequences, but it is not desirable. If the maintenance activity is shifted to a plan year later than the planning period, the budget for small maintenance activities increases by two, since the probability that small maintenance activities are needed in the future increases. Secondly, the total budget increases by 10% for each extra year, since the maintenance activity is expected to be more difficult to execute. For the pavement asphalt, capital loss should be considered.

In chapter 4, the generalized RBM is developed. By using the data of a municipality, the generalized RBM model is implemented in chapter 5, and the results are shown. In both chapters, we excluded the modification phase that is discussed above. Shifting a maintenance activity to another plan period or changing the maintenance activity should be done by an expert, and there are plenty of argumentations to decide a modification.

3.4 Conclusion current maintenance planning

In this chapter, an overview of the current way of MP for roads in a municipality is presented. Roads are distinguished by the pavements asphalt, concrete, and element. In general, the purpose of road maintenance is to keep the capacity and the value of the road optimal (Sirvio, 2017). The road MP is based on the condition of the top layer, provided by inspecting the damage, that is supported by the CROW guideline. Most of the maintenance activities are corrective, and the road can still be used when damage is identified. The MP provides a multi-year period planning, which is in the current situation for a planning horizon of five years. The roads are divided into roadway sectors and lane sectors. The MP provides a plan year for each lane sector. The data that is gathered and used for the MP are the characteristics from the road such as road type and pavement and the inspection results. The inspector asses each lane sector in severity and the size of the damage. A failure occurs if the level of damage is exceeding the threshold.

Creating the MP consists of roughly three steps. First, the plan period provides an interval by a minimum, and maximum year the municipality should take a maintenance activity to avoid a failure. If the threshold is exceeded, the plan period equals to the next year and the year after, expressed by {1,2}. In other cases, the behavior model or warning limit indicates the plan period. By taking the mean of the interval provided by the plan period, the plan year is determined. In the rest of the study, the total plan period, which is an interval, is assumed to be the remaining useful lifetime.

Second, the corresponding maintenance activity is selected out a maintenance group by using the inspection results. Sweco has the corresponding costs available. Additionally, the location and office manager check the total planning and pay attention to the deviation of the total cost per year, and if lane sectors from one roadway can be combined. The last step is considering if modifications of maintenance activities and/or within plan year are preferred, within the maintenance activity group and plan period. The main consideration is related to the maintenance activity that is selected for each lane sector and in which plan year the maintenance activity is scheduled. Furthermore, the municipality prepare policy decisions like the thresholds, weights for the policy themes, and the ambition levels related to the quality of the road. However, these decisions are all used as input for the road MP.

4. Generalized risk-based maintenance model

In this chapter, we develop the generalized RBM model. The chapter provides an answer to the third sub research question:

'What actions should be taken to use the generalized RBM model to plan maintenance for roads?'

The literature review is used as a background for the generalized RBM model concerning risk, cost, and performance. In the theoretical framework in section 4.1, the four phases of the generalized RBM model are developed to address research question 3a. The phases of the generalized RBM model are clarified in section 4.2. In section 4.3, the generalized RBM model is applied towards road maintenance by specifying the failure distribution and risk calculations, to provide an answer on the research question 3.c – 3.e. In section 4.4, We end this chapter by the conclusion.

4.1 Theoretical framework

The framework in Figure 6 (see section 2.3) shows that the four phases of the RBM model, according to Krishnasamy et al. (2005) are:

1. Identification of the scope
2. Risk assessment
3. Risk evaluation
4. Maintenance planning

The generalized RBM model is based on the literature of chapter 2, but some additions/modifications are applied to complete the desired RBM model. By incorporating the literature framework according to Krishnasamy et al. (2005) with the literature of AM in section 2.1, the generalized RBM model is developed that supports the research objective and motivation mentioned in chapter 1. We choose the name generalized because the RBM is designed general and is inferred from the specific case of road maintenance. The four phases are renamed, particularly to mention the content of each phase. We will discuss the modifications concerning the RBM model, according to Krishnasamy et al. (2005). The major difference is the arising of the second phase, the 'failure evaluation'. Figure 15 shows the relation between the four phases of the RBM model according to Krishnasamy et al. (2005) (first row in the figure) and the one proposed in this thesis (second row in the figure).

Figure 15: Phases of the generalized RBM model

The first phase (from now on called **scope identification** to provide consistency in the phase titles) identifies the system, subsystem, and component and visualizes the relations by an SBS. Because the study focusses on assets, a system is now called an asset. In the RBM model, according to Krishnasamy et. Al. (2005), the first phase also includes collecting the failure data and defining the failure model. Since the RBM model in this study is developed to be generalized, the failure definition requires attention as well (not part of the RBM model, according to Krishnasamy et al. (2005)). Therefore, in the second phase, the failure of the asset will be evaluated in a newly designed phase called the **failure evaluation**, to ensure the failure model is defined.

The second and third phase in the RBM model, according to Krishnasamy et al. (2005) are both focusing on determining and prioritizing the risks. In the generalized RBM model, both phases are combined in one phase, called the **risk assessment**. By combining, the total risk determination is now structured into one phase. In the RBM model, according to Krishnasamy et al. (2005), the risks are calculated by using an FTA as a tool, as explained in section 2.3.2. In the generalized RBM model, using an FTA is not required, because the relevant failures can also be identified without using the FTA method. As the implementation of the model towards roads will show, developing an FTA is sometimes not effective, e.g., because the relevant failures are already provided.

The **maintenance planning** represents the last phase of the generalized RBM model, containing the improvement of the MP for the components that are selected based on risk. The asset manager is responsible for the MP, and the objective of the study is to find the right balance between AM and the development of the MP. Therefore, in the generalized RBM model, an objective function is formulated to relate the parameters risk, cost, and performance with the decision variables, discussed in section 4.2.4. The objective function decides when to schedule the maintenance activities for each component.

4.2 Generalized risk-based maintenance model

Figure 16 presents the generalized RBM model based on the framework presented in section 4.1. In section 4.2.1 until 4.2.4, the phases will be clarified.

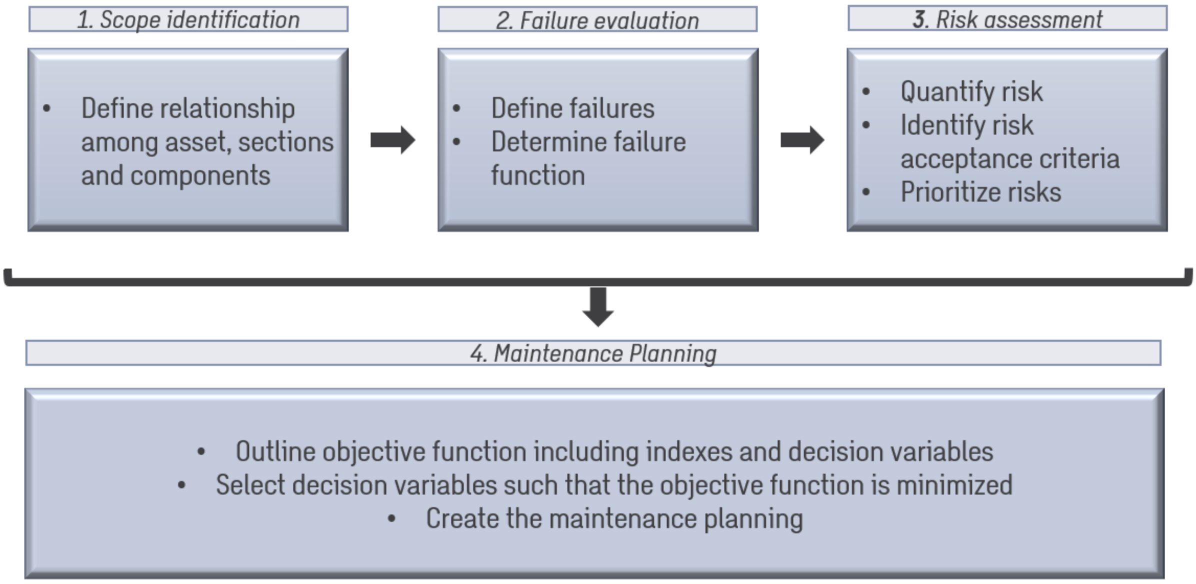

Figure 16: The generalized RBM framework

4.2.1 Scope identification

The asset for which the generalized RBM model develops an MP consists of asset sections and components. An example of an asset is the machine in a factory or an asset including in the municipality portfolio (e.g., bridge, road, tunnel). An SBS, as introduced in section 2.3.1, provides the relation between all the asset sections and components. The RBM model, according to Krishnasamy et al. (2005) also includes collecting the failure data that is required to analyze the potential failures. Since the generalized RBM model contains the new phase 'failure evaluation', collecting and determining the failure functions is displaced in the next phase.

4.2.2 Failure evaluation

It is crucial to define the failure of the asset in detail to make sure the failure functions are quantifying the relevant failures. A widespread definition for a failure is: a failure occurs if the system cannot fulfill its intended function (Tinga, 2013, p. 3). The intended function of the asset depends on the owner/user of the asset and does not necessarily mean the asset fails physically. If the definition is known, the asset owner should define how the failure occurs by developing failure scenarios. If multiple failure scenarios are defined, the relevant scenarios should be selected, e.g., by MCAS or MCS, as explained in section 2.3.2. For each failure, the failure function should be defined by including the parameters of the distribution. As mentioned in the literature study in section 2.3.2, there exist probability distributions to model the lifetime of a component, like Weibull. The definition of the asset is adjusted in the generalized RBM model. The failure evaluation mentions what is seen as a failure for the considered asset.

4.2.3 Risk assessment

As mentioned in section 4.1, this third phase is merging the second and third phase of the RBM model, according to Krishnasamy et al. (2005). The risk is calculated for each component based on the failure definition and failure function, which is:

$$Risk = probability\ of\ failure * consequence\ of\ failure$$

The probability of a failure is determined in the second phase that is clarified in section 4.2.2, while the consequences of the failure are not specified yet through the generalized RBM model. Often, multiple consequences influence risk. In that case, weights are needed to calculate the total consequence of failure. Consequences of risk can be expressed by the cost of failure, the environmental consequences or consequences on safety, as we introduced in section 2.3.2.

In many cases, it is not applicable to reduce all the risks to zero or even reduce all the risks anyhow. A risk acceptance criterion is applied to select the most relevant risks. Section 2.3.3 in the literature study provides already some suggestions. In this study, a maintenance budget is available, which has influences on the maintenance activities that can be executed. In case the budget is limited, the risks that are selected can also be based on the budget constraint. For the selected risks, a prioritization should be provided. The risk is often prioritized from highest risk to lowest risk but can also be established by the cost.

4.2.4 Maintenance planning

We developed an objective function that takes the aspects of risk, cost, and performance into account. In this section, we formulate the model that determines the final MP. The mathematical formulation is presented in the next section (section 0).

The risk is determined in the third phase of the model. The cost includes all the maintenance cost that is contributed while performing the maintenance activity. Maintenance costs often include the cost of labor, materials, downtime caused by repair and impact expressed in cost. Costs are in many cases restricted by a maintenance budget. Because the MP is developed for a planning horizon, the costs are calculated over a time window, and a discount rate is used. As an assumption, this study will use a fixed annual discount factor.

Besides the cost and risk that are determined in section 4.2.3, the performances are considered as well. According to the Cambridge dictionary, performance is defined by 'how well a person, machine, etc. does a piece of work or an activity' (Cambridge Dictionary, 2019). Accordingly, the organization should define when the asset is working and when the asset is working well. The performance can be expressed by, e.g., the number of produced units, the quality of the output of the asset or the number of working hours. Often, the performance of the asset is supported by the policy of the asset owner. Since the performance level can differ per component, the performances are expressed per component. To ensure the asset has at least the desired performance, a performance target level is introduced. In the generalized RBM model, we assume that the target value is identified for each asset, but it is also possible that the asset owner has a target performance value for each asset section.

The model selects for each component the plan year that the maintenance activity should be planned. Accordingly, the decision variable indicates if the maintenance activity is scheduled in year t or not for each component. With the (decision) variables, we define our objective function and constraints. The main objective is to minimize the risk while satisfying the budget and performance constraint. The budget constraint ensures that the total costs do not exceed the budget. The performance constraint ensures that the total performance of the road is at least the target performance. A Lagrange relaxation is used to put the performance and cost constraint into the objective function since we also prefer to minimize the cost and maximize the performance of the asset (Baxley & Moorhouse, 1984). The Lagrange multipliers are defined by the decision maker. We put a minus before the Lagrange multipliers to define the penalty costs for violating budget and performance constraints. By running the model, a decision for each component decides if the maintenance activity is scheduled in year t or not. The asset owner knows what maintenance activity to take and what the corresponding costs are. The prioritization by the risk that is proposed in section 4.2.3 decides the sequence components are considered by the objective function.

4.2.5 Mathematical formulation

The generalized RBM model is formulated with a minimization equation by using the Lagrange relaxation. Assume that the planning horizon is $|T|$ and a maintenance activity can be scheduled every year t.

Indexes

$\propto$	discount rate $\propto \in [1,0]$
λ_1	Lagrange multiplier for the budget constraint $\lambda_1 \in [1,0]$
λ_2	Lagrange multiplier for performance constraint $\lambda_2 \in [1,0]$

Sets

S	set of assets s
U	set of asset sections u with $U \subset S$
I	set of components i with $I \subset U$
T	maintenance planning years $t \in \{1..T\}$

Parameters

$R_{i,t}$	the total risk for component i in planning horizon [1,T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
$C_{i,t}$	the total cost for component i in planning horizon [1,T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
B_T	the maintenance budget in planning horizon [1,T]
$P_{i,t}$	the total performance for component i in planning horizon [1,T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
$P_{target,s}$	the target value for the performance of asset s for all $s \in \{1..S\}$

Decision variable

$x_{i,t}$	the binary variable that denotes if a maintenance activity for component i is scheduled in year t (1) or not (0)

The objective function is denoted by $\mathcal{L}$ to imply we use the Lagrange relaxation.

$$\mathcal{L}\,(i,t,s) = min\left(\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t} - \lambda_1(\sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t} * x_{i,t} * \alpha - B_T) + \lambda_2(\sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t} - P_{target,s})\right)$$

s.t.

$$\sum_{t=1}^{T} x_{i,t} \leq 1 \qquad \forall\, i \in \{1..I\} \qquad (1)$$

$$x_{i,t} \in \{0,1\} \qquad \forall\, t \in \{1..T\}, \forall\, i \in \{1..I\}$$

4.3 Applying the RBM model for road maintenance

The generalized RBM model will be applied for road maintenance by a case study in chapter 5. In this section, we present how the generalized RBM model is implemented for road maintenance by discussing the four phases of the generalized RBM model.

4.3.1 Scope identification

Since roads are often quite long, a hierarchical ordering for dividing into subsystems is needed (Worm & Van Harten, 1996). To provide the relation between the asset, asset sections, and components, the SBS for roads is provided in Figure 17.

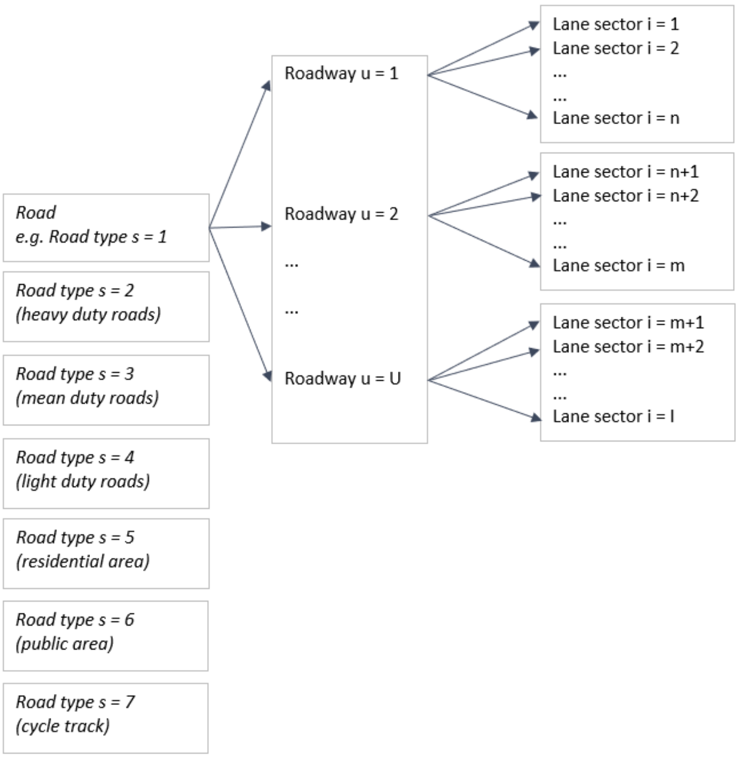

Figure 17: SBS for roads

Figure 17 is based on the road deviation that is introduced in section 3.2. In this study, the asset road consists of seven types, defined as $s = \{1,2, \ldots 7\}$. The asset sections of each road type are specified by the roadways, $u = \{1,2, \ldots U)$. Each roadway (e.g. Soestdijkseweg) consists of lane sectors, indicated as $i = \{1,2, \ldots . I)$. However, the lane sectors i are numbered continuously, i.e., the numbering of the first sector of roadway u+1 follows the numbering of the last lane sector of roadway u. The relation of the roadway *u*, as shown in Figure 17, are not required to indicate which lane sector is referred. For applying the generalized RBM model to roads, the index *u* is not considered. However, The road type '*s'* is used for the performance target.

4.3.2 Failure evaluation

We distinguish between a policy road failure and a technical road failure. Policy failure occurs if the road is not fulfilling the required level defined by the policy theme. The policy themes are used in the current MP to prioritize the maintenance activities, see section 3.3.3. By using the inspection results, the software tool OBSURV can determine the level of the lane sector of each policy theme. If the level is below the desired level, policy failure occurs. The policy failure is considered in the risk determination.

The technical failure is based on the damages of each lane sector i, determined by the inspection results. If a technical failure occurs, the road cannot fulfil its intended function, which consists of two elements in this study. First, unsafe traffic situations arise, resulting in a decreasing of liability of the municipality. Secondly, in the case of asphalt, technical failure is related to capital destruction, which means that the road cannot be maintained anymore. Even if capital destruction is not the case, more expensive and heavier maintenance activities are needed, e.g., replacing the total surface course (€15,-/m^2) instead of adopting a scuff course (€5,-/m^2). If one or both elements are true, the road section i fails. Note that technical failures (as well as policy failures) are yet soft failures, since the road can still be used, even if the failure occurs.

As discussed in the current situation in section 3.3.1, the plan period provides the remaining time to failure. We assume that after the plan period, the road fails. Furthermore, we assume that the road fulfills its function, and so no failure can occur before the plan period. In between the plan period, there is a probability the road fails. To visualize the failure horizon, an example is provided in Figure 18.

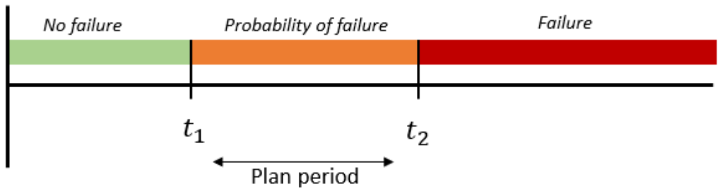

Figure 18: Failure horizon

The green part before time t_1 is assumed to have a failure probability of zero. The plan period is the time between t_1 and t_2 and is marked orange. The years within the plan period have a probability that the lane sector fails. The probability depends on the failure distribution. The red part shows the time after t_2, where the probability of failure is assumed to be one for each year.

As mentioned in the current situation in section 3.3.1, a maintenance activity is only considered if the plan year is within the planning horizon T=5, which is if:

- The threshold is exceeded,
- the behavior model indicates a plan period smaller than five years,
- the warning limit is exceeded.

(See section 3.3.1 for the determination of the threshold, behavior model and warning limit)

We assume the plan period as the mean remaining time to failure for each lane sector. However, the distribution for the plan period is unknown. We consider four scenarios for the distribution of the plan period {y_1, y_2}, with 'y_{i1}' is the start year of the plan period and 'y_{i2}' the end year. The discrete uniform distribution is considered if we assume that the probability of failure equally for every year within the plan period. The failure function is formulated as:

$$f(i,t) = \begin{cases} \dfrac{1}{(y_{i2} + y_{i1})} & for\ y_{i1} < t < yi_2 \\ 0 & Otherwise \end{cases}$$

Another possibility is to define $f(i,t)$ by using a triangular distribution. The triangle distribution corresponds to a higher probability in the middle of the plan period than at the begin and end of the plan year. This strikes with the method that is used in the current situation, namely selecting the mean to define the plan year. Finally, decreasing and increasing triangular distribution are considered. The increasing distribution seems like a logical progression because the chance of failure is often increasing if the asset is older. The decreasing distribution is considered because it is possible that the risk of failure is the highest in the first year of the plan period. To ensure the risk is the highest in the first year of the plan period, a decreasing distribution could be used. Figure 19 shows the differences between the four distributions.

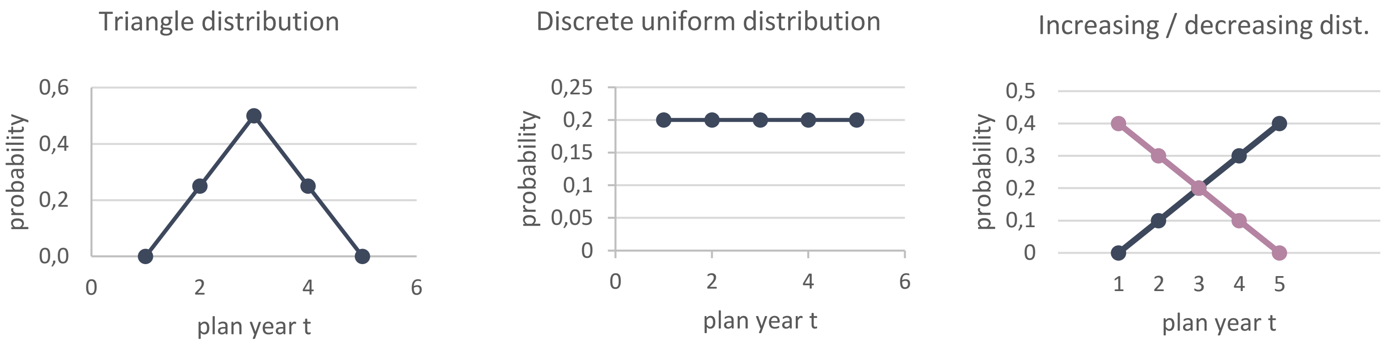

Figure 19: Failure distributions roads

The failure distributions define the probability that failure occurs in a certain year. Based on the failure distributions, the failure rate can be determined. The failure rate indicates how frequency a component fails during a time period. The triangle, discrete uniform, and increasing distribution are related to an increasing failure rate, while the decreasing distribution is referring to a decreasing failure rate.

4.3.3 risk assessment

The risk for each lane section i in year t ($R_{i,t}$) is calculated by multiplying the probability of failure with the consequence of failure. The probability of failure is determined by using the failure function. The considered distributions are the discrete uniform distribution, triangle distribution, and the increasing/decreasing distribution, as introduced in section 4.3.2. The consequence of failure is based on the four policy themes (sustainability, safety, functionality, and aesthetics) that we introduced in section 3.3.3. The software tool OBSURV determines the effect of each damage on the policy themes by using the inspection results as input. A consequence is expressed by a grade between zero and one in the current situation. The determination process of that grade is not considered in the study, and so we assume the factors as a consequence of the failure of a road. To calculate the total consequences of failure, each consequence on sustainability, safety, functionality, and aesthetics is multiplied by the weight of the policy theme. The weights are defined by the municipality for each road type and each damage. Table 9 displays an example of the weights for each road type and damage related to safety. The damages that are considered are mentioned by d {1,2,3…11}.

Table 9: Example of weights of consequences for safety

	Damage (d)										
Road type (s)	1	2	3	4	5	6	7	8	9	10	11
1	0,3	1	1	0	0,5	0,6	0,5	0	1	1	1
2	0,4	1	1	0	0,4	0,4	0,5	0	1	1	1
3	0,3	0,8	1	0	0,5	0,5	0,5	0	1	1	1
4	0	0,3	0,4	0	0	0,6	0,5	0	0,3	0,6	0,4
5	0	0,3	0,8	0	0	0,3	0,5	0	0,6	0,5	0,3
6	0	0,5	1	0	0,6	0,9	1	0	0,5	1	1
7	0	0,7	1	0,5	0,5	1	1	0,6	0,5	1	1

The prioritization of the lane sectors is arranged from highest to lowest risk. Developing the MP is discussed in the next section, where the lane sectors are considered by starting with the highest risk. The municipality presents risk by a scale from very high to very low. In the case study, we will use the expressions very high, high, moderate, low, very low to present the results.

4.3.4 Maintenance planning

The decision variable $x_{i,t}$ is a binary variable that denotes whether the maintenance activity for lane sector i is scheduled in year t. If the maintenance activity is scheduled, the decision variable takes one, otherwise zero. Since the maintenance activity can only be scheduled once in the plan period, constraint (2) is valid for road maintenance as well. The planning horizon for road maintenance of a municipality is assumed to be $T = 5$. To calculate the objective function, we should specify the risk, cost, and performance for road maintenance. The risk is calculated in the risk assessment. For all maintenance activities, the total maintenance cost is provided by Sweco. The maintenance cost includes all the cost for executing the maintenance activity, including materials cost, machine cost, labor cost, preparing cost, and the cost for setting of the road. The maintenance cost excludes the inspection cost, the cost for developing the MP, and the possible external costs because the road cannot be used. We assume that the maintenance costs are equal for each year within the planning horizon, while the discount rate considers the present value of the cost. If no maintenance activity is scheduled, the corresponding costs are assumed to be zero. However, the risk will be very high, and the total performance extremely low.
In the current MP (section 3.3), the maintenance costs per year are not equally spread over the planning horizon. The budget for road maintenance (B_T) is decided by the city council and is provided for the RBM model. We assume a constant budget for each year in the total plan period of 5 years. To ensure the maintenance costs are not too high in the first plan year compared to the others, we add a cost constraint, which secures the maintenance cost for each year by:

$$\sum_{i=1}^{I} C_{i,t} * X_{i,t} \leq \frac{1}{5} * B_T \qquad \forall\, t \in \{1..T\}, \forall\ i \in \{1..I\} \qquad (2)$$

In the case of road maintenance, the performance of the road is expressed by the **quality** of the road, which is introduced in section 3.2. The municipality decides for each road type (s = 1,2, 3...7) the part that should rate as sufficient (e.g., 40%), moderate or insufficient. The percentages provide the **performance target** of the municipality. The total of all lanes sectors within a road type is examined with the target performance. The current quality of a lane sector can be determined by multiple methods. In this study, the quality is based on inspection results. The municipality provides (based on CROW data) the desired threshold for each damage type. Each lane sector is assessed on damages by the inspection results as well. The relation between the quality level, threshold, and damage level is:

B (Sufficient): threshold – inspection results > 1
C (Moderate): threshold – inspection result = 1
D (Insufficient): threshold – inspection result < 1

E.g., for the inspected damage raveling, the threshold equals M1. For the inspection results L1, L2, and L3, the quality is sufficient. The quality is moderate if the inspection result is M1. For the other inspection results (M2, M3, E1, E2, and E3), the quality is insufficient. For the objective function and linear programming constraints, we use instead of A+, A, B, C, D respectively 5, 4 until 1.

In contrast with the performance constraint that is defined per asset, we will determine the performance target level for road maintenance for each component. The objective function and corresponding constraints are implemented in Excel. For lane sector i, the decision variable is set on 0 or 1 while considering the constraints. The model selects the optimal decision that minimized the objective function. The final MP is now provided. In the next section, we assess the mathematical formulation for road maintenance.

4.3.5 Mathematical formulation

Assume that the planning horizon is $|T|$ and a maintenance activity can be scheduled every year t.

Indexes

$\propto$	discount rate $\propto \in [1,0]$
λ_1	Lagrange multiplier for the budget constraint $\lambda_1 \in [1,0]$
λ_2	Lagrange multiplier for performance constraint $\lambda_2 \in [1,0]$

Sets

S	set of road types s
I	set of lane sectors i with $I \subset S$
T	maintenance planning years $t \in \{1..T\}$

Parameters

$R_{i,t}$	the total risk for lane sector i in planning horizon [1, T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
$C_{i,t}$	the total cost for lane sector i in planning horizon [1, T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
B_T	the maintenance budget in planning horizon [1, T]
$P_{i,t}$	the total performance for lane sector i in planning horizon [1, T] if the maintenance activity is applied in year t for all $t \in \{1..T\}$ and $i \in \{1..I\}$
$P_{target,s}$	the target value for the performance of asset s for all $s \in \{1..S\}$

Decision variable

$x_{i,t}$	the binary variable that denotes if a maintenance activity for lane sector i is scheduled in year t (1) or not (0)

The objective function is denoted by $\mathcal{L}$ to imply we use the Lagrange relaxation.

$$\mathcal{L}\,(i,t) = min\left(\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t} - \lambda_1(\sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t} * x_{i,t} * \alpha - B_T) + \lambda_2(\sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t} - P_{target,i} * I)\right)$$

s.t.

$$\sum_{t=1}^{T} x_{i,t} \leq 1 \qquad \forall\, i \in \{1..I\} \qquad (1)$$

$$\sum_{i=1}^{I} C_{i,t} * X_{i,t} \leq \frac{1}{5} * B_T \qquad \forall\, t \in \{1..T\}, \forall\, i \in \{1..I\} \qquad (2)$$

$$x_{i,t} \in \{0,1\} \qquad \forall\, t \in \{1..T\}, \forall\, i \in \{1..I\}$$

4.4 Conclusion generalized risk-based maintenance model

The generalized RBM model is based on the RBM model, according to Krishnasamy et al. (2005) and the three key aspects of AM: risk, cost, and performance. Four phases contribute to the generalized RBM model that is developed in this chapter. We defined the phases as:

1. Scope identification
2. Failure evaluation
3. Risk assessment
4. Maintenance planning

The generalized RBM model determines an MP for the considered asset. The failure evaluation is included in the generalized RBM model to ensure the failure definition is specified towards the asset. An objective function is built to optimize the AM aspects after the asset components are prioritized by risk. The objective function that decides for each asset component if the maintenance activity is scheduled in a certain year t is formulated as:

$$\mathcal{L}\,(i,t,s) = min\left(\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t} - \lambda_1(\sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t} * x_{i,t} * \alpha - B_T) + \lambda_2(\sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t} - P_{target,s})\right)$$

s.t.

$$\sum_{t=1}^{T} x_{i,t} \leq 1 \qquad \forall\, i\, \in \{1..I\} \qquad (1)$$

$$x_{i,t} \in \{0,1\} \qquad \forall\, t \in \{1..T\}, \forall\, i \in \{1..I\}$$

The decision variable $x_{i,t}$ equals one if the maintenance activity for component i is scheduled in year t and becomes 0 if not. In the case of road maintenance, the generalized RBM model should support the asset manager by dividing the total budget equally within the planning horizon. The constraint that ensures the cost per year does not exceed 1/5th of the total budget is introduced, formulated as:

$$\sum_{i=1}^{I} C_{i,t} * X_{i,t} \leq \frac{1}{5} * B_T \qquad \forall\, t \in \{1..T\}, \forall\, i \in \{1..I\} \qquad (2)$$

The failure evaluation defines failure and determines the corresponding failure distribution. In this study, we assume that a road fails by a technical failure, which, if the damage for lane sector i is exceeding the threshold, the warning limit or if the plan year according to the plan period is below five years. A road failure results in unsafe traffic situations and in case of the pavement asphalt to capital destruction. We assume that a lane sector fails within the determined plan period by a probability, while it fails certainty after the plan period. This means that the plan period provides the remaining useful lifetime of a road. The failure probability during the plan period is unknown. We will consider the triangle, discrete uniform, increasing and decreasing distribution in this study to be suitable distributions.

To prioritize the lane sectors, the total risk is calculated by multiplying the failure probability with the total consequences. Based on the current MP, we will distinguish between consequences on sustainability, safety, functionality, and aesthetics, each multiplied by a certain weight. The performance is determined by the quality of the road. Finally, the MP is developed by running the generalized RBM model so that the objective function is minimized. The risk prioritization determines the sequences of the lane sectors that are considered.

5. Case study

The case study aims to test the generalized RBM model to analyze the effect compared to the current model. Furthermore, the case study provides recommendations for further improvements. By presenting the results, the last sub-question is addressed, which is:

'How does the generalized RBM model perform compared to the current model in relation to the aspects cost, risk, and performance?'

In section 5.1, the case is introduced. In section 5.2, we cover the implementation by go through the phases of the generalized RBM model. The results of the case study are provided in section 5.3 and answer the additional questions 4a and 4b. The conclusion of the case study is covered in section 5.4.

5.1 Case description

To verify the generalized RBM model by applying it to road maintenance, we use data from an existing municipality. The case municipality is a middle size municipality located in the middle of the Netherlands and manages a total of almost 3.400.00 m^2 of roadways. In the last decades, the quality of the roads was below the required level, leading to the demand for an improvement MP methodology.

The case municipality is selected since it provides a good representation of Sweco's future interests, namely, to implement RBM for municipalities. Some years ago, Sweco implemented an RBM methodology to improve the current MP. That RBM methodology is based on risks, and the risk determination is provided in an organized Excel file with suitable data. The RBM model that is developed and implemented by Sweco for the case study differs from the RBM model according to Krishnasamy et al. (2005) and with the generalized RBM model that is developed in chapter 4. The Sweco RBM model uses the weights and consequences on the policy themes as risk determination, explained in section 4.3.3. The risks are prioritized by high, medium, and low. The high-risk lane sectors are reconsidered first in the modification phase (that we explained in section 3.3.3). However, the determination of the plan year is performed in the same way as in the current MP (see section 3.3.1). Since the modifications are not in the scope of the research (as mentioned in section 3.3.3), we assume the Sweco RBM model equal to the current way of planning maintenance for roads. Therefore, we will not take the RBM model developed by Sweco into account while analyzing the results. The generalized RBM model determines the plan year based on risk, performance, and cost, and the modification phase is excluded in the model as well. The generalized RBM model is implemented in Excel. In the next section, we will describe how the generalized RBM model is implemented for the case study.

5.2 Case study: generalized RBM model

In section 0, we specified the generalized RBM model towards roads. In the following four subsections, the implantation of each phase is proposed by considering the case municipality and by clarifying the decisions and calculations that are executed in the Excel file. Each step is presented in a new worksheet to structure the case study. We will refer to the worksheets by the title of the worksheet. In Table 10, each worksheet is related to the corresponding step from the generalized RBM model, and a short clarification is provided.

Table 10: Explanation worksheets Excel File

Name worksheet in Excel	The corresponding phase of generalized RBM model	Clarification of the worksheet
''Start screen''	-	The input data and explanation of variables.
''Policy data''	-	The decisions that are obtained by the Case municipality about the policy decisions.
''Scope identification''	1. Scope identification	All information that is available and suitable for the generalized RBM model.
''Failure dist.''	2. Failure evaluation	The determination of the four failure distributions for each lane sector.
''Consequences''	3. Risk assessment	The determination of the total consequences for each lane sector.
''Risk''	3. Risk assessment	Calculation of the risk for each lane sector, depending on the failure distribution.
''Sort Risk''	3. Risk assessment	Sort the lane sectors based on risk from highest risk to lowest risk.
''Cost''	4. Maintenance Planning	The determination of the cost for each lane sector and each plan year as input for the objective function.
''Performance''	4. Maintenance Planning	The determination of the performance for each lane sector and each plan year as input for the objective function.
''MP_TD''	4. Maintenance Planning	The maintenance planning for the triangle failure distribution.
''MP_UD''	4. Maintenance Planning	The maintenance planning for the uniform failure distribution.
''MP_ID''	4. Maintenance Planning	The maintenance planning for the increasing failure distribution.
''MP_DD''	4. Maintenance Planning	The maintenance planning for the decreasing failure distribution.
''Results''	-	Evaluating the results.

5.2.1 Scope identification

Table 11 shows the indexes and sets of the case municipality as presented in worksheet ''Start screen''.

Table 11: Characteristics case study

Notation	Definition	Value
i	lane sector	{1, 2…,7230)
u	roadway	{1, 2….629)
s	road type	{1, 2….7)
T	Planning period	5
$\propto$	discount rate	3%[13]
Y_1	Start year plan period	1 (2017)
Y_2	End year plan period	5 (2021)
B_T	Budget for the total planning period	€ 7.500.000,00
P_{target}	Performance target	7.772.250
λ1	Cost Lambda	0,8
λ2	Performance Lambda	0,6

The Lagrange multipliers λ_1 (related to cost) and λ_2 (related to performance) are respectively 0,8 and 0,6. The cost is provided by Sweco, and we assume the cost realistic and sufficient. Section 3.3.2 mentioned what costs are included and excluded. Section 4.3.4 shows how the performances of each road section are determined. The performance indication is developed in this study, based on the quality of the road. Assumptions are made to fit the performances into the model, mentioned in section 5.2.4. The Lagrange multipliers affect the allocation of the cost and performance on the total objective function. Because the cost is considered to be more reliable then the performances (mainly because of the assumptions), the cost are weighed with 0,8 and the performance with 0,6. Note that the risk is considered complete by the objective function. A study of the effects of the Lagrange multipliers is provided in section 5.3.6.

The policy data determined by the municipality is used to calculate the risk and performance, provided in the worksheet ''Policy data''. In the worksheet ''Scope identification'', we present the first phase of applying the generalized RBM model to the case municipality. The lane sectors with no identified damage, do not have a plan period and maintenance activity since no maintenance activity is required. Assumptions to make the scope identification complete are necessary since variables are missing. Unfortunate, the plan period is not available in the data file. Therefore, the plan period is estimated in a structured way by using the plan year that is selected in the Sweco RBM planning and the current MP. If the plan year in the Sweco RBM planning differs from the plan year in the MP, the lowest plan year is set as y1 and the highest plan year is set as y2. If both plan years are equal, the plan year is set as y1, and y2 equals a random number that is higher than y1 and lower than six. A second assumption is required because lane sectors without damage do not have a quality level. In case no damage is inspected, we assume that the quality for that certain lane sector equals A. The highest quality level (A+) is not allocated in this case study since A+ is only provided for newly built roads in practice. We assume that there are no new built roads in the portfolio of the case municipality. An argument is that if the quality level should be A+, it is only in the advantage of the quality that the level is determined lower. Besides, the municipality does not take the level A+ into account for the performance target.

[13] The discount rate is assumed to be 3 %, based on the literature according to Sirvio (2017).

In total, 7230 lane sectors are inspected on damages. For 1325 of the total lane sectors, the inspection results are provided. We assume that the lane sectors with no inspection results (in total 5905) are performing as they should, and no maintenance activity is required in the planning horizon of 5 years. We will exclude those lane sectors after the lane sectors are sorted based on risk in the third phase of the generalized RBM model (see section 5.2.3) since it ensures that not the wrong lane sectors are removed.

5.2.2 Failure evaluation

The failure definition for roads is provided in section 4.2.2, as well as the failure distributions that are considered in this study. In the worksheet ''Failure dist.'', the failure probabilities are calculated for each lane sector i based on the plan period. The triangle distribution, discrete uniform distribution, increasing distribution, and decreasing distribution are considered. In section 4.3.2, we already discussed the formulas that calculate the probabilities. The formulas are implemented in Excel for each year within the plan period. The probabilities before the plan period are zero since we assume no failure will occur. The probabilities after the plan period are one since the lane sector fail certainly. If the plan period is not provided (because no damages are identified), the failure probabilities equal zero for each plan year.

5.2.3 Risk assessment

The consequences are determined in the worksheet ''Consequences''. In section 4.3.3, the determination of the consequences of road maintenance is discussed. The total consequences for each lane sector are established by summing the consequences on Aesthetics, Functionality, Safety, and Sustainability. The inspection results are transformed into calculation values and multiplied by the weight (that differs per road type and damage) and by the relation between damage and consequence. Finally, each consequence is multiplied by the general weight of the policy theme. If the lane sector has no identified damage, the consequences cannot be determined because no inspection results are available. The weights and relations are determined by the municipality, provided in worksheet ''Policy data''.

The risks are calculated by multiplying the total consequence provided in the worksheet ''Consequences'' with the failure probability provided in the worksheet ''Failure dist.''. The worksheet ''Risk'' provides the risk for each lane sector in each plan year. The total risk equals the sum of the risk per plan year. To prioritize, the risks are sorted from high to low in worksheet ''Sort Risk'', for each failure distribution. To scale the risk values with the cost and performances, the risks are multiplied by factor 100.000, to keep the objective function in balance. Now the risks are sorted, the last rows with risks that equal zero are removed, as mentioned in section 5.2.1.

After a maintenance activity is executed, the risk cannot be determined until new inspection results are available, since that is the input for the consequence determination. As mentioned in section 3.3.2, we assume the lane sector as good as new after executing a maintenance activity for the remaining time within the planning horizon. The corresponding risk for that lane sector is neglectable in comparison with the other risks. Therefore, we assume that the risk equals zero if a maintenance activity is executed.

The risks are expressed by very high, high, moderate, low, and very low to analyze the effect of performing the generalized RBM model in section 5.3. The total risk of each lane sector is used instead of the risk per year since the generalized RBM model focusses on the total planning horizon. To create the intervals, the outliers are excluded, so that the risks are scaled. The outliers equal 1,5* the differences between quartile 1 and quartile 3 (Mes, 2017). Table 12 presents the intervals that are used in the rest of the case study.

Table 12: Risk intervals

Risk	Range in RBM model
Very high	> 1.468.125
High	(978.750, 1.468.125)
Moderate	(489.375, 978.750)
Low	(0, 489.375)
Very Low	0

5.2.4 Maintenance planning

Since the risk per year differs per failure distribution, an MP is made for each failure distribution separately. The risks are already determined in the previous step to prioritize the lane sectors. The cost and performance are determined in a separate worksheet. The costs are shown in worksheet ''Cost'' and equals the cost discussed in section 3.3.2. We assume that the costs provided by Sweco are the costs of plan year one. The discount rate that is introduced in section 4.2.4 is used to calculate the cost for plan year two to five.

The performances are determined in the worksheet ''Performance'' and based on the quality of the lane sector. As mentioned in section 4.3.4, the quality is expressed by A+, A, B, C, and D, and they are quantified as 5, 4, 3, 2, and 1, respectively. The corresponding values are presented in Table 13.

Table 13: Performance values

Quality	Value	interval in RBM model			Target performance in % of total
A+	5	(5000-4000)	very high	no damage	
A	4	(4000-3000)	high	small damages	
B	3	(3000-2000)	moderate	warning limit is exceeded	
C	2	(2000-1000)	low	threshold - inspection result = 1	35%
D	1	(1000-0)	very low	threshold - inspection result < 1	30%

The performances are multiplied by factor 1000 to stay in proportion with the cost and risk values. The third column presents the range that is used in the RBM model to determine the performance level of the lane sector. The last column provides the target performance. Only 25% of the total lane sectors can have performance level D. For performance level C, maximum 35 % is allowed. The remaining lane sectors should be quantifying with performance level B or higher. It is not preferred to schedule a maintenance activity before the plan period since the quality of the road is still acceptable. To ensure the model does not schedule a maintenance activity before the plan period, the performances are turned to zero if the maintenance activity is scheduled in a year outside the plan period. We do not schedule any maintenance before the plan period in order to waste the useful lifetime of components. The quality of the lane sector is expected to decrease one level every five years. To implement the degradation of the performance level into the model, we assume that the performance level decreases with 10 % every year if no maintenance activity is scheduled. If the level is already D, the performance level cannot decrease. However, since the model uses numbers instead of the expression that is used in the current MP, the value will turn into zero.

We present the MP for each failure distribution in the worksheets ''MP1_TD'', ''MP_UD'', ''MP_ID'' and ''MP_DD''. The total cost, total performance, and total risk are calculated as described in section 4.3 and implemented in the objective function that is minimized. For each lane sector and plan year, the Visual Basic for Applications (VBA) code decide whether the decision variable equals zero or one so that the objective function is minimal. In appendix 9.3, the VBA code is provided, including descriptions. The MP worksheets include the determination of the risk (which turns into zero if the maintenance activity is scheduled) and the performance (which turns into 4000 is the maintenance activity is scheduled and equals zero if the maintenance activity is scheduled outside the plan period). The constraint related to the budget is implemented in the VBA code. In the results, we will refer to the constraints by (2) and (3),[14] as:

$$\sum_{i=1}^{I} C_{i,t} * X_{i,t} \leq \frac{1}{5} * B_T \qquad \forall t \in T \qquad (2)$$

$$\sum_{t=1}^{T} \sum_{i=1}^{I} C_{i,t} * X_{i,t} \leq B_T \qquad (3)$$

The output of the MP provides the year that the maintenance activity should be executed. In the next section, we describe how the current MP is implemented to validate the effect of the generalized RBM model.

5.2.5 Current maintenance planning

The current MP selects for each lane sector with an identified damage a plan year. The plan year is determined as described in section 3.3.1 by taking the mean of the plan period. If the plan year is not an integer, the plan year is round up. If we import the plan years into the generalized RBM model, the total risk, performance, and cost can be determined, as well as the objective function. By selecting one of the failure distributions, which is done in the next section, the effect of using the generalized RBM model instead of the current MP can be analyzed by comparing the risk, cost, and performances and by analyzing the number of maintenance activities that are scheduled each plan year.

In the current MP, manually modifications are executed after the MP is developed by considering the cost and amount of maintenance activities per year. The modifications consider collaborations between maintenance activities for the roadway or postponing maintenance activities. To compare the current MP with the generalized RBM MP, these modifications are excluded in both MP's.

[14] The two budget constraints could be combined as one. However, to analyse the effect of both budget constraints on the results, we decided to keep them separated.

5.3 Results

The four MP's that are created by distinguishing between the failure distributions are analyzed in section 5.3.1. We conclude the analysis by selecting one of the failure distributions. In section 5.3.2, the current MP is compared with the generalized RBM planning. In section 5.3.3 and section 5.3.4, the model is analyzed by excluding the budget constraints. The correlation between the risk, cost, and performances is discussed in section 5.3.5. The effect of the Lagrange multipliers on the MP are analyzed by running the generalized RBM model with multiple lambda's, presented in section 5.3.6. Finally, the verification and validation of the generalized RBM model are discussed in section 5.3.7.

To present the results, we provide for each analysis a table with the cost, risk, performances, and objective value. In Table 14 we show the structure of the table and explain how each variable is calculated. Some comments are provided to explain why the corresponding results are presented in the table.

Table 14: Presentation of the results

	Formula	explanation	comments
Total cost	$\sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t} * x_{i,t}$	The total maintenance cost for T =[1, 5]	
Total risk	$\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t}$	The total risk for T =[1, 5]	The total risk is not used to analyze the results. We only provide the total risk so that it can be used as background by analyzing the mean risk. Accordingly, the total risk is presented since it affects the objective value.
Mean risk	$\frac{\sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t}}{I}$	The mean risk per lane sector for T =[1, 5]	The mean risk is presented by 'Very Low, 'Low',..'Very high' as shown in Table 12,
Total performance	$\sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t}$	The total performance for T =[1, 5]	The total performance is not used to analyze the results. We only provide the total performance so that it can be used as background by analyzing the mean performance. Accordingly, the total performance is presented since it affects the objective value.
Mean performance	$\frac{\sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t}}{I}$	The mean performance per lane sector for T =[1, 5]	The mean performance is presented by A, B,..D, as shown in Table 13.
Objective value	$\sum_{i=1}^{I}\sum_{t=1}^{T} C_{i,t} * x_{i,t} + \lambda_1 \sum_{i=1}^{I}\sum_{t=1}^{T} R_{i,t} * x_{i,t} - \lambda_2 \sum_{i=1}^{I}\sum_{t=1}^{T} P_{i,t} * x_{i,t}$	The value for the Lagrange objective function	The objective value is presented since it is easy to compare the total differences between models. However, the value by itself does not has a unity and does not say something about the MP.

5.3.1 Failure distributions

In this section, we focus on the differences between the failure distributions by analyzing the risk, performance, cost, and the total MP. At the end of the section, one of the failure distributions is selected so that the results of the generalized RBM can be compared with the current MP. In section 5.3.2, we will go into more detail about the results in general. The results for each failure distribution are presented in Table 15.

Table 15: Results for considered failure distributions

	MP_TD	MP_UD	MP_ID	MP_DD
Total cost	€ 7.499.610,32	€ 7.499.599,69	€ 7.499.599,69	€ 7.499.683,35
Total risk	438.521.625	438.601.033	393.785.117	479.952.950
Mean risk	330.960 (Low)	331.020 (Low)	297.196 (Low)	362.229 (Low)
Total performance	12.226.248	12.198.248	12.198.248	12.250.248
Mean performance	1.845 (C)	1.841 (C)	1.841 (C)	1.849 (C)
Objective value	437.185.564,7	437.281.764,5	392.465.847,9	478.602.548,1

The results are by taking a quick look similar. Table 15 indicates that there are no major differences in results concerning the considered failure distributions. To ensure the differences are not significant, we will now take a closer look into the risk, performance, and cost for the MP. The cost, risk and performances that are presented in Table 15 will be discussed below. In Table 16, the differences between the total risk and mean risk are presented.

Table 16: Results risk for each failure distribution

Risk	MP_TD	MP_UD	MP_ID	MP_DD
The total Risk with no MP	1.155.195.000	1.155.195.000	1.155.195.000	1.155.195.000
The total risk with MP by generalized RBM model	438.521.625	438.601.033	393.785.117	479.952.950
Reduction:	-62%	-62%	-66%	-58%
Mean Risk with no MP	871.845 (Moderate)	871.845 (Moderate)	871.845 (Moderate)	871.845 (Moderate)
Mean risk with MP by generalized RBM model	330.960 (Low)	331.020 (Low)	297.196 (Low)	362.229 (Low)

The reduction of the total risk shows that the generalized RBM model decreases the total risk with roughly 60% for each failure distribution, compared to the risk with no MP. The mean risk for the case study is calculated by taking the average of the total risk per lane sector. The mean risk for the case municipality is currently moderate. The MP developed by the generalized RBM decreases the mean risk to low. We conclude by the results provided in Table 16 that there are no major differences between the failure distribution in relation to the risk.

The asset manager presents the performance of the road by the performance levels provided in Table 13. The total performance is the sum of all the performances per year for each lane sector. In Table 17, the results for the performance among each failure distribution are presented.

Table 17: Results performance for each failure distribution

Performance		MP_TD	MP_UD	MP_ID	MP_DD
Total Performance with no MP		6.437.640	6.437.640	6.437.640	6.437.640
Total performance with MP by generalized RBM model		12.226.248	12.198.248	12.198.248	12.250.248
Increasing:		*90%*	*89%*	*89%*	*90%*
Mean performance with no MP		972 (D)	972 (D)	972 (D)	972 (D)
Mean performance with MP by generalized RBM model		1.845 (C)	1.841 (C)	1.841 (C)	1.849 (C)
% of lane sectors and amount in each performance level					
A	% of total (amount)	13% (186)	13% (168)	13% (168)	13% (168)
B	% of total (amount)	44% (582)	44% (585)	44% (585)	44% (583)
C	% of total (amount)	15% (205)	15% (195)	15% (195)	15% (209)
D	% of total (amount)	28% (370)	28% (377)	28% (377)	28% (365)

In Table 17, the increasing in performances shows that the total performance increases by approximately 90%. To be sure the results can be considered as equal, Table 17 presents the percentage of the total lane sectors for each performance level. We conclude that the effect of the failure distribution on the performance is neglectable. Even though the mean performance is level C, the mean value shows that the performance level almost equals level B. That is in line with the high percentage of lane sectors with level B (namely 44 %) that is shown in Table 15.

The two budget constraints (2) and (3) have an impact on the total cost and cost per year. Table 18 presents the total cost and cost per year for each failure distribution.

Table 18: Total cost and cost per year for each failure distribution

cost	MP_TD	MP_UD	MP_ID	MP_DD
Total cost	€ 7.499.610,32	€ 7.499.599,69	€ 7.499.599,69	€ 7.499.683,35
Cost year 1	€ 1.499.940,91	€ 1.499.940,91	€ 1.499.940,91	€ 1.499.940,91
Cost year 2	€ 1.499.971,57	€ 1.499.971,57	€ 1.499.971,57	€ 1.499.971,57
Cost year 3	€ 1.499.896,87	€ 1.499.896,87	€ 1.499.896,87	€ 1.499.896,87
Cost year 4	€ 1.499.931,14	€ 1.499.931,14	€ 1.499.931,14	€ 1.499.931,14
Cost year 5	€ 1.499.869,83	€ 1.499.859,21	€ 1.499.859,21	€ 1.499.942,87

We can conclude that the total cost equals the budget, restricted by (3), and that the cost per year is equal because of budget constraint (2). Only the cost in year 5 are not equal for each distribution, but the differences are negligible. By analyzing the risk, performances, and cost for each failure distribution, we see no major differences. In Table 19, we present the amount of maintenance activities that are scheduled in total and per year. The only differences between the failure distributions is seen in year five, where the discrete uniform and increasing distribution scheduled fewer maintenance activities than the triangle and decreasing distribution.

Table 19: Number of maintenance activities scheduled in year t

Amount scheduled maintenance activities	MP_TD	MP_UD	MP_ID	MP_DD
Total scheduled	665	658	658	671
# scheduled in year 1	84	84	84	84
# scheduled in year 2	79	79	79	79
# scheduled in year 3	162	162	162	162
# scheduled in year 4	229	229	229	229
# scheduled in year 5	111	104	104	117

The analysis towards the results for the considered failure distributions shows that the differences are negligible and the total risk, performances, and cost are insensitive to the failure distributions used in the experiments. We will now continue the presentation of the results by considering the increasing distribution. The increasing distribution is the most accountable failure distribution, as we discussed in section 4.3.2.

5.3.2 Current maintenance planning analysis

The current MP is created, as discussed in section 5.2.5. In Table 20, the total cost, risk, performances and the value for the objective function for the current MP and the generalized RBM MP are shown. The objective value indicates the effect of the MP on the total cost, risk, and performances and is minimized by running the generalized RBM model.

Table 20: Results current maintenance planning vs RBM planning

	Current MP	Generalized RBM MP
Total cost	€ 11.026.007,58	€ 7.499.599,69
Total risk	15.908.367	393.785.117
Mean risk	12.006 (Low)	297.196 (Low)
Total performance	19.510.794	12.198.248
Mean performance	2.945 (B)	1.841 (C)
Objective value	13.022.696,5	392.465.847,9

The objective value of the current MP is much lower than the objective value of the generalized RBM planning, indicating that the current MP is more optimal. This is due to the total cost of the MP. The generalized RBM model is restricted by the budget with budget constraint (3), resulting in contributing less money than the current MP does. The current MP contributes more money since it schedules more maintenance activities, which effects a decreasing risk and increasing performance. This is in line with the literature of AM, provided in section 2.1. If the cost increases, more maintenance activities are executed that results in less risk and higher performance. The current MP spend more money, and so the total risk and performance are better. To compare both MP's fairly, the generalized RBM model should be restricted by the same budget as the current MP uses. The budget for developing the generalized RBM planning is now adjusted to € 11.026.0078, =. In appendix 9.4, all the results are presented. Table 21 shows the results on the cost, risk, performance, and objective value for the same budget.

Table 21: Results of current maintenance planning vs. RBM planning with the same cost

	Current MP	Generalized RBM MP
Total cost	€ 11.026.007,58	€ 11.025.311,37
Total risk	15.908.367	143.647.600
Mean risk	12.006 (Low)	108.413 (Low)
Total performance	19.510.794	17.009.153
Mean performance	2.945 (B)	2.567 (B)
Objective value	13.022.696,5	142.262.357,2

In contrast with the expectations towards the effect of the generalized RBM model, the objective value of the current MP is still smaller than the objective value of the generalized RBM planning. Likewise, the total risk is not decreased, and the performances are lower. That the current MP seems to be better than the generalized RBM planning is due to the budget constraint (2) that is applied, that ensures the cost and amount of maintenance activities are equally spread within the planning period. Therefore, we will investigate more detail on the effect of budget constraint (2). The cost per year for the current MP and the generalized RBM planning are visualized in Figure 20.

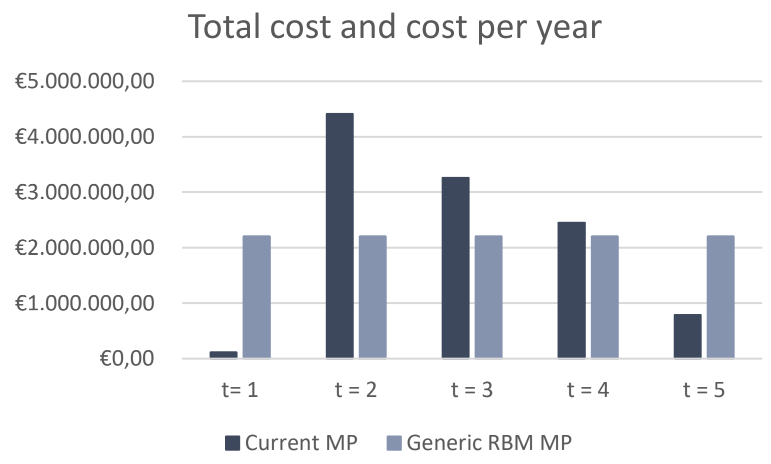

Figure 20: Distribution cost per year

The total cost is the same for both MP's. The cost per year for the generalized RBM planning is equally spread, caused by budget constraint (2). The cost per year for the current MP is fluctuating. Figure 20 shows that budget constraint (2) achieves the goal to deviate the budget equally within the planning horizon, which is not the case for the current MP (as mentioned in section 3.3.3). Implementing the budget constraint into the generalized RBM model ensures that the decisions do not only consider budget constraint (2) but also takes the risk and performance of the road into account.

The current MP shows low cost in year 1, while the cost in year 2 are significantly higher. The major differences are due to the number of plan periods resulting in plan year 1 or 2. The current MP selects t=1 only if the plan period equals {1,1}. However, t=2 is selected if the plan period equals {1,2}, {1,3} or {2,2}, and so t=2 is selected much frequently. The cost per year are correlated with the number of maintenance activities that are scheduled per year. In Figure 21, the number of maintenance activities that are scheduled each year is presented for the current MP and the MP developed by the generalized RBM model.

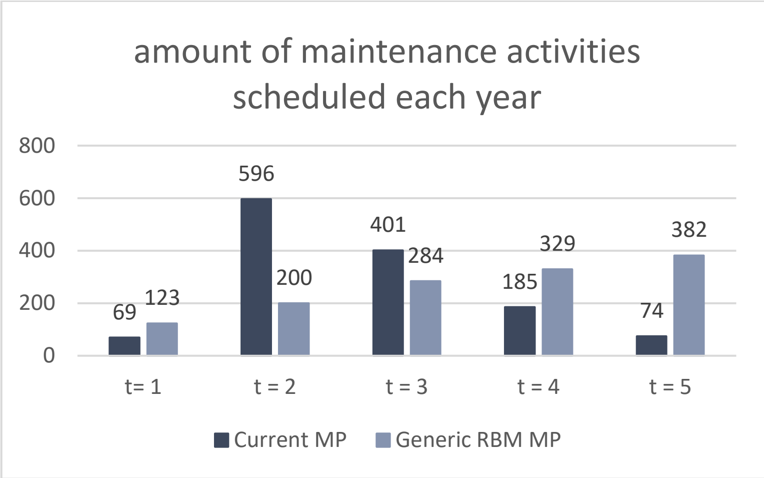

Figure 21: Amount of maintenance activities scheduled each year

The current MP shows the same deviation as the deviation for the cost per year as in Figure 20. The amount of maintenance activities scheduled for the generalized RBM planning is slowly increasing, while the cost per year is equal. This can be clarified by the average cost per year per scheduled maintenance activity in each year. The average cost per scheduled maintenance activity is decreasing every year for the MP developed by the generalized RBM model, as provided in Table 22.

Table 22: Average cost per scheduled maintenance activity per year

year	Current MP	Generalized RBM MP
t=1	€ 1.633,69	€ 17.928,36
t=2	€ 7.401,22	€ 11.025,41
t=3	€ 8.133,04	€ 7.764,61
t=4	€ 13.251,62	€ 6.702,53
t=5	€ 10.665,62	€ 5.771,62

We can conclude that the generalized RBM model schedules the more expensive maintenance activities at the beginning of the planning horizon and the cheaper maintenance activities later in the planning horizon. An argument is that the model only considers the maintenance activity if it optimizes the total risk and performances. The maintenance activity with high maintenance cost is not scheduled in the end of the plan period since it does not outweigh the improvement on risk and performance for the total planning horizon. This would be the case if the maintenance activity is scheduled earlier in the planning horizon, but due to the budget constraint (2), only the end of the plan period is available. In the next section, budget constraint (2) and (3) are excluded in the generalized RBM model and compared with the current MP.

5.3.3 Generalized Risk-based maintenance planning without budget constraints

The total cost of the current MP is much above the original budget (€7.500.00, =), and do not meet budget constraint (2) and (3). We run the generalized RBM model without budget constraint (2) and (3) as well, so with no budget constraints. Appendix 9.5 presents the total overview of the results. In Table 23, the results on cost, risk, and performances concerning the current MP and generalized RBM planning are provided.

Table 23: Results on cost, risk, and performance without budget constraint (2) and (3)

	Current MP	Generalized RBM MP	Generalized RBM MP without (2) and (3)
Total cost	€ 11.026.007,58	€ 11.025.311,37	€ 10.640.783,58
Total risk	15.908.367	143.647.600	0
Mean risk	12.006 (Low)	108.413 (Low)	0 (Very Low)
Total performance	19.510.794	17.009.153	21.520.668
Mean performance	2.945 (B)	2.567 (B)	3.248 (A)
Objective value	13.022.696,5	142.262.357,2	-4.399.774,2

The total cost is lower than the total cost for the current MP, because the generalized RBM model schedules the maintenance activity as soon as possible, which leads to lower cost (due to the interest rate, as discussed in 5.2.4). The total risk is as low as possible (total risk equals zero), and the total performance is as high as possible (discussed later in more detail). We will look into more detail to the effect on the risk and performance in comparison with the current MP.

The mean risk is decreased from low to very low compared with the two MP's. The generalized RBM model schedules every maintenance activity such that the total risk for the lane sector within the planning horizon equals zero, the lowest possible risk. This is the case when the maintenance activity is scheduled in the first year of the planning horizon. The current MP schedules the maintenance activity in the mean of the plan period. Therefore, in case the plan period is longer than one year, there will always be some risk during the planning horizon, as explained in section 5.2.3.

In Figure 22, the performances for the current MP, generalized RBM planning and generalized RBM planning without budget constraint (2) and (3) are presented.

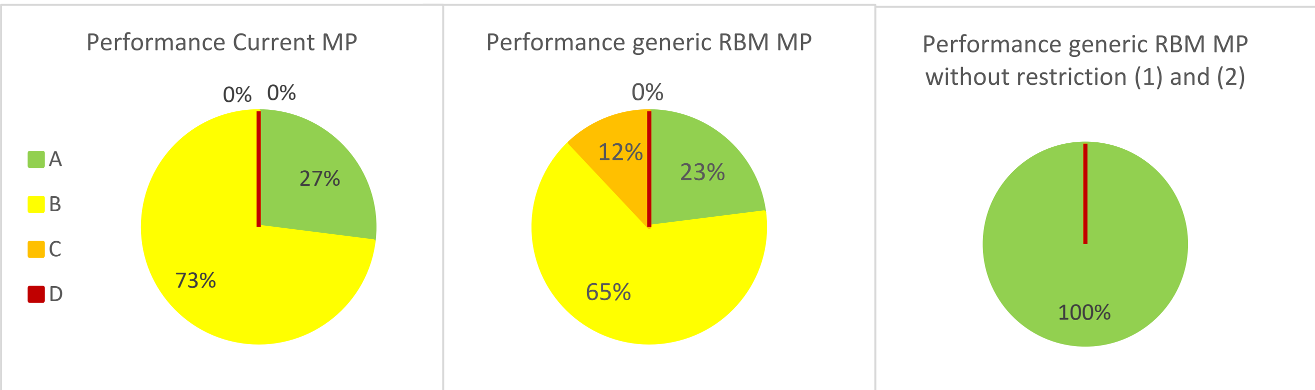

Figure 22: Performance comparison

The performances for each lane sector are the highest as possible (A) if the generalized RBM model is applied without budget constraint (2) and (3). For the current MP, the performances are always higher than performance level C, which is restricted by the municipality (see 5.2.4). The generalized RBM MP shows that 12% of the total lane sectors has performance C, which is still within the target level of 35%.

Even though the MP that is developed by the generalized RBM model without budget constraint (2) and (3) seems to be the optimal planning (since the cost are lower than the cost for the current MP, the risk is the lowest possible, and the performance are the highest possible), we can conclude that the MP not realistic. In Figure 23 the number of maintenance activities that are scheduled each year is visualized.

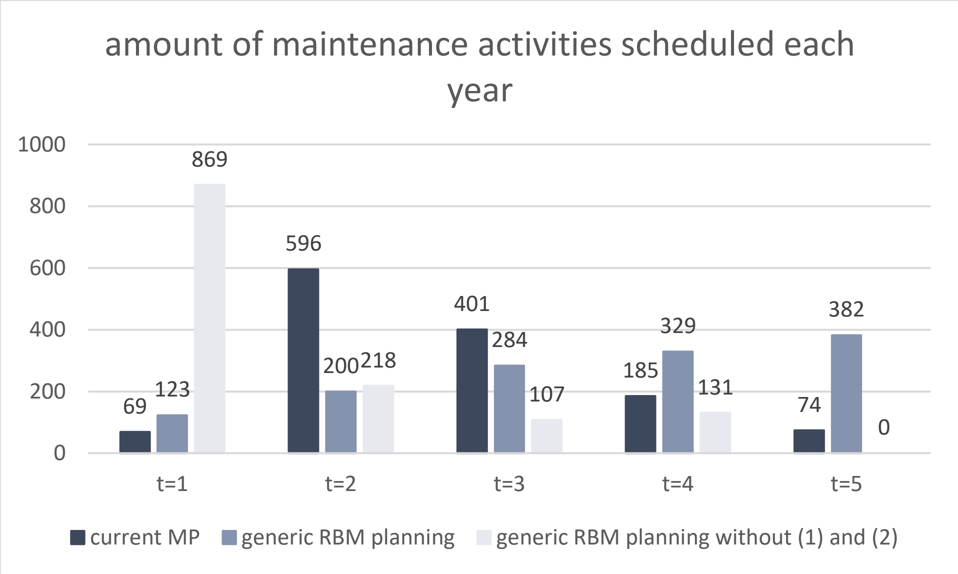

Figure 23: Amount of maintenance activities scheduled per year

As the graphic shows, 869 maintenance activities are scheduled in the first year of the planning horizon if the generalized RBM model is implemented without budget constraint (2) and (3), while no maintenance activities are scheduled in year 5. We can conclude that this amount is not possible to execute in year 1, which will result in many required modifications in the MP, which we introduced in section 3.3.3. That modifications result in higher risk and lower performance. In the next section, the effect on the risk, performance, and cost while excluding only budget constraint (2) is analyzed.

5.3.4 Generalized risk-based maintenance planning without budget constraint (2)

Unfortunate, we cannot compare the current MP with the generalized RBM planning if we exclude budget constraint (2). This is because Table 23 shows that the generalized RBM planning does not spend the total budget if we exclude budget constraint (2) and (3). This will also be the case if we exclude only budget constraint (2). To analyze the effect of only excluding budget constraint (2), the generalized RBM model should still be restricted by the total budget (constraint (3)). Accordingly, the results of the generalized RBM planning are compared with the generalized RBM planning without budget constraint (2) for the budget of € 7.500.000, =. Appendix 9.6 provides an overview of the results. The total cost, risk, and performance are presented in Table 24, compared with the generalized RBM planning.

Table 24: Results generalized RBM planning without budget constraint (2)

	Generalized RBM MP	Generalized RBM MP without (2)
Total cost	€ 7.499.599,69	€ 7.499.993,56
Total risk	393.785.117	229.007.000
Mean risk	297.196 (Low)	172.835 (Low)
Total performance	12.198.248	15.025.648
Mean performance	1.841 (C)	2.268 (B)
Objective value	392.465.847,9	225.991.605,8

The total costs are for both cases the same as the budget. The total risk and the total performances are scoring better compared to the generalized RBM planning, but the mean risk is in both cases low. We will take a closer look at the performance of the lane sectors and the distribution of the cost per year. In Figure 24, the percentage of lane sectors for each performance level is visualized.

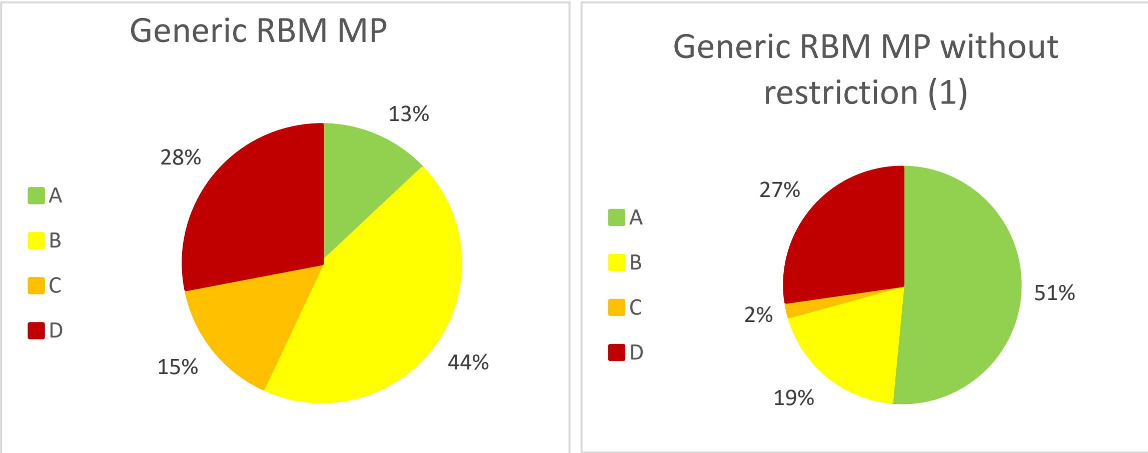

Figure 24: Distribution lane sectors for each performance level

The differences between the MP's for the lowest performance level (D) is negatable. The relevant differences are between the level C and A. level C is restricted by the performance target, as discussed in section 5.2.4. Even the performance target is met in both cases; the generalized RBM model provides a higher percentage. More than half of the lane sectors have the highest performance level if we leave out budget constraint (2). While it seems valuable to leave out the budget constraint (2) in the generalized RBM model for the performance, the amount of maintenance activities that are scheduled per plan year shows the disadvantage. Figure 25 confirms the effect of budget constraint (2) again.

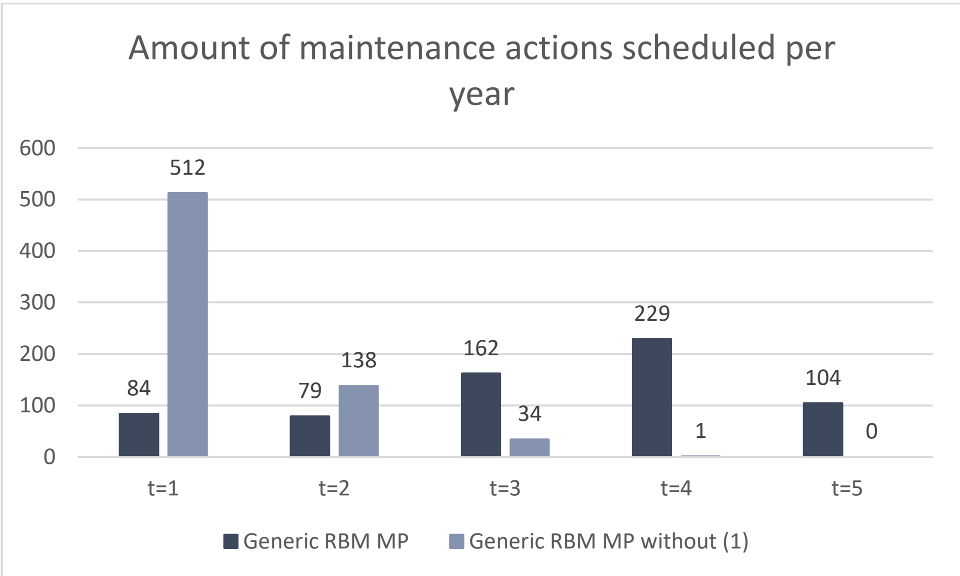

Figure 25: Amount of maintenance activities scheduled per year

The generalized RBM planning without budget constraint (2) shows an unfair and unrealistic deviation of the amount of maintenance activities per year. Even though budget constraint (2) results in lower performances, the budget constraint is required to ensure the MP has approximate the same amount of maintenance activities per year. In the next section, the correlation between the risk, performance, and cost for the generalized RBM model is analyzed.

5.3.5 Correlation

By comparing the results for the MP that is developed by the generalized RBM model with the original budget of € 7.500.00,=, the correlation between the cost, risk, and performance for each lane sector is determined, presented in Table 25.

Table 25: Correlation between Risk, Cost, and Performance

	Risk	Performance	Cost
Risk	1		
Performance	-0,69125	1	
Cost	-0,28303	0,289795	1

The correlation between the cost and the performance/risk is limited in comparison with the correlation between performance and risk. The correlation between the performance and risk shows that if the performance increase, the risk decreases most of the time (69%). It is simultaneously with the theory of AM discussed in section 2.1 and the characteristics of roads discussed in section 3.2.

5.3.6 Lagrange multipliers

A study to the Lagrange multipliers is applied to analyze the effect of the Lagrange multipliers on the cost, risk and performances, and the MP. We run the generalized RBM model for values between 0 and 1 for the Lagrange multipliers. The analysis is performed for a constant λ_1, a constant λ_2, and the same proportion between λ_1 and λ_2. The values for the Lagrange multipliers are presented in Table 26.

Table 26: Values for Lagrange multipliers analysis

Constant λ_1		Constant λ_2		Same proportion $\lambda_1 - \lambda_2$	
λ_1	λ_2	λ_1	λ_2	λ_1	λ_2
0,8	0,2	0,2	0,6	0,4	0,2
0,8	0,4	0,4	0,6	0,6	0,4
0,8	0,6	0,6	0,6	0,8	0,6
0,8	0,8	0,8	0,6	1	0,8
0,8	1	1	0,6		

The results for the three analysis show that the cost, performances, and risk do not change if the Lagrange multipliers are variating. For all the runs that are executed as presented in Table 26, the MP is the same. We conclude that the objective value differs because the cost and performance are multiplied with another factor, while the generalized RBM model makes the same decision to optimize the risk, cost, and performances. Figure 26 presents the relation between the objective value and the Lagrange multipliers.

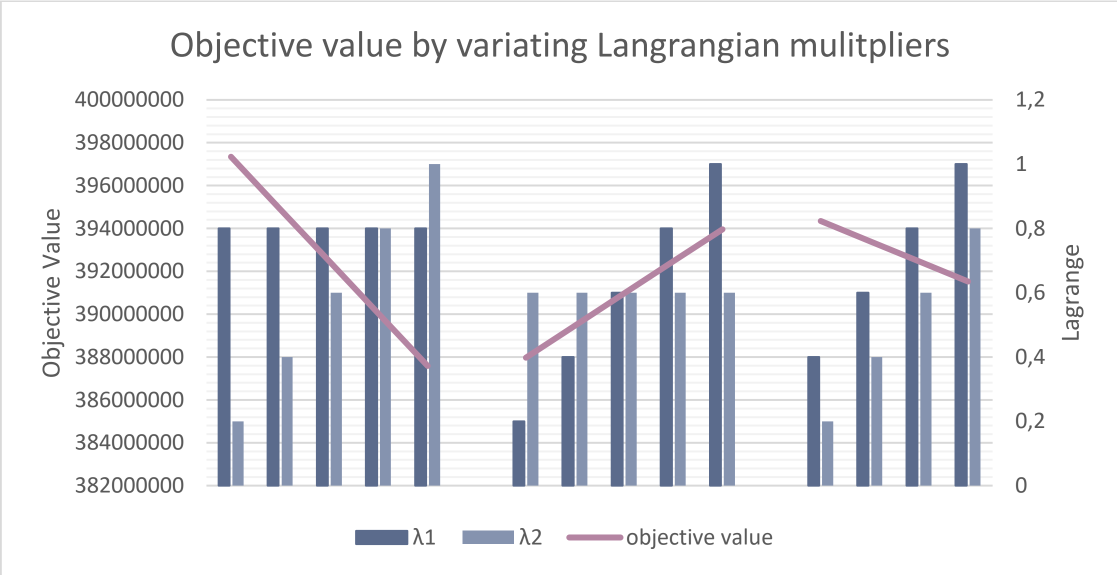

Figure 26: Objective value by variating Lagrange multipliers

Figure 26 shows that the objective value is increasing if the second Lagrange multiplier is increasing. The second multiplier is related to the weight of the performance that the model maximizes. If the performance has a higher impact on the objective value, the objective function is decreasing, since the performance is subtracted. The middle part of the graphic is the other way around, where the Lagrange multiplier that weighted the cost is increasing. The total cost increases if the weight is increasing, and so is the objective value is increasing as well.

Finally, we see that if the cost and performance weights are increasing, the objective function decreases slowly. This suggested that the impact of the risk on minimizing the objective function is higher than the impact of the performances and cost. By comparing the impact of the cost and performances on the objective value, Figure 26 shows that the decreasing in the left part is higher than the increasing of the middle part about objective value. If both λ_1 and λ_2 are increasing, the impact of the performance is higher than the impact of the cost, and so is the objective function slowly decreasing.

5.3.7 Validation and verification

The asset manager demands to develop an MP that optimizes the main aspects of AM, namely, risk, cost, and performances. The MP should provide a planning that presents the plan year and corresponding maintenance activity. By prioritizing the lane sectors on risk, the intention of RBM is supported. The objective function that is minimized supports optimizing the AM aspects. The asset manager can develop the MP by running the model, assuming that the data such as cost, risk, and performances is available. Section 5.3.3 shows that the generalized RBM model is optimizing the risk, performance, and cost if the budget constraints (2) and (3) are excluded. The total cost is lower compared to the current MP, and the risk and performance have the best level as possible. Some suggestions for further research that are related to the trade-off between risk, performance, and cost are addressed in section 7.1.

The generalized RBM model is restricted by (2) and (3) so that the amount of scheduled maintenance activities is equally spread through the planning horizon and the cost is not outreaching the budget. Section 5.3.2 shows that the budget constraints improve the MP compared with the current MP towards the deviation of the total budget every year. The implementation of the generalized RBM towards roads shows that still customizations in the model are required to implement the variables, e.g., factorizing the variables risk and performance so that the proportion is balanced in comparison with the cost. In the case study, some indexes are excluded because they are not used, e.g., the asset sections u. This implies that the generalized RBM model could be too adequate.

Verification implies that the designed model should correspond to the RBM model, according to Krishnasamy et al. (2005) and that the software meets the specifications. The code is verified by debugging and testing the steps that are executed by the model. The results of the model are considered to be realistic. The objective of the model is to develop an MP that minimizes the risk and cost while maximizing the performances of the asset. The objective function is designed to meet the specifications. The budget constraints are not implemented in the objective function as the designed model suggested. However, by adding the budget constraint in the code so that the budget limit is considered by every decision is covered the budget constraints.

5.4 Conclusion case study

In chapter 5, we provide an answer to question 4. The case study that is implemented in the RBM model is based on real data from a middle size municipality in the Netherlands. The discount rate is assumed to be 3 % every year, and for λ_1 and λ_2, we select a value of respectively 0,8 and 0,6. Missing variables results in assumptions towards the plan period and performance. Since the plan period is not provided, the plan period is determined by the plan year provided by the current MP and by the Sweco RBM planning. If only one plan year is available, the end of the plan period is selected randomly between 1 and 5.

By running the VBA code, the model determines for each lane sector at most one plan year. In case no damages are identified or if the objective function is not minimized by scheduling a maintenance activity, no plan year is selected. The output of the model provides a total risk, cost and performance, and an MP. By analyzing the results presented in section 5.3, we conclude:

- The analysis among the four failure distributions shows no major differences in results. The increasing failure distribution is selected to analyze the differences between the current MP and the generalized RBM planning.
- By using the same budget, the generalized RBM planning shows a better spread towards the cost per year concerning the current MP. The risk and performances are not improved for the generalized RBM planning since the budget constraints towards the budget and maximum cost per year delimit the model with always selecting the optimal plan year.
- To analyze if the generalized RBM model performs better concerning risk and performance, the budget constraints (2) and (3) are removed. The results show the highest possible performance and lowest risk level. The generalized RBM planning performs significantly better concerning the current MP. The excluding of budget constraint (2) and (3) leads to an unrealistic MP since too many maintenance activities are scheduled in the first plan year, while the last plan year has no maintenance activities at all.
- The generalized RBM model always selects the earliest plan year within the planning horizon, if the budget constraint (2) is not contributing.
- The correlation analysis shows the significant relationship between the performance and risk with approximately -70%. The cost is not considered to be correlated with risk and cost.
- Experimenting with the Lagrange multipliers shows that there is no effect on the risk, cost, performance, and MP if the Lagrange multiplier is within the range of {0,1}. Analyzing the objective values shows that the performance has a slightly higher impact on the objective value compared with the cost.

After analyzing the case study, some recommendations for further research are made. More research towards determining the performances will result in a stronger implementation of the RBM model. Secondly, the results would be more representative if the plan period is provided instead of the randomness for some plan periods.

6. Discussion

In the presented study, a generalized RBM model is developed. The literature study focusses on AM, MP, and is used as input for the generalized RBM model. The maintenance concept RBM is seen as the newest generation (see section 2.2). However, the timeline provided in Figure 5 already indicates that a new generation of maintenance concept is possibly deriving, which could have another focus rather than risks. Studying the current developments of maintenance could lead to another focus of the study and the model rather than RBM, that is more in line with the future demand of maintenance concepts.

In chapter 3, the current method of developing the road MP by municipalities is proposed based on the CROW guideline. According to the experience of Sweco, municipalities use the guideline as to the method of planning road maintenance. Evaluating municipalities according to the development of the MP could provide other insights, e.g., by the background in knowledge and the differences in interests. Perhaps, the municipalities adjust the CROW maintenance concept, and the current MP that is developed in the case study in chapter 5 is in contrast with the realistic way of road MP. The discussion is in line with some suggestions from engineers who suggests the CROW guideline is not used in practice in the same way as it is presented. An example is that the modifications in the maintenance activity or plan year are not always argued by the original reason (as described in section 3.3.3), but sometimes because of drawing up the budget. An argument is that the municipality receives a smaller budget if the government figures out that the total budget is not spent, which suggested a smaller budget can cover the maintenance demand. It is suggested that the request from municipalities towards RBM is to convince the government to provide a larger budget so that the total risks can be reduced. This would make the study less relevant for municipalities to implement since the results show that the risks could be reduced while reducing the total cost.

The RBM model is developed with a generalized intention. The implementation should be accessible for any assets so that Sweco can implement the generalized RBM model for other assets like bridges and tunnels. For the study, roads are selected because of the demand for RBM and accessible data. In section 4.3 the generalized RBM model is modified to apply the generalized RBM model for road maintenance. It shows that proper modifications are required towards the generalized RBM model such as failure evaluation. By the case study, we cannot draw significant conclusions about the extent of the generalization of the RBM model. The study is not considering if road maintenance is representative for applying the generalized RBM model. The literature study towards RBM shows that papers focus mostly on machines.

The generalized RBM model optimizes the risk, performances, and cost of the asset. Constraints are applied to control the distribution of the maintenance activities that are scheduled each year. Even though the number of maintenance activities is controlled, the asset manager should still reconsider the MP according to merging the maintenance of lane sectors of a roadway, so that the roadway is not endured maintenance every year. Maintenance activities of lane sectors should be combined to disturb, e.g. inhabitants. The generalized RBM model is not fully eliminating the modification part, as discussed in section 3.3.3.

Finally, some improvements towards the model could be considered according to reliability. In the Excel file, unknown modifications could easily be made accidentally, which affects the optimality of the MP. Implementing the model into a software tool like OBSURV could control the reliability of the data. In this thesis, the case study should be validated with the original data to control the reliability of the output.

7. Conclusion and recommendations

This research studies how a generalized RBM model can be used to plan corrective maintenance activities for roads by taking aspects such as total risk, performance, and cost into account. The Asset Management department from Sweco focuses on optimizing AM by considering the risk, cost, and performance of the asset. The literature review shows that an RBM model focusses on identifying high-risk components and plan the maintenance activities with a higher priority to decrease the total risk of a system (Arunraj & Maiti, 2007).

The current MP of roads is based on the CROW guideline. By inspecting the damage level of a lane sector, the plan period, plan year, maintenance activity, and corresponding cost are determined. The main constraint is the available budget and an equal deviation of the total cost per plan year. Manually modifications according to the plan year and maintenance activities are improving the total MP to fulfill the constraints. The generalized RBM model is developed by combining the literature review of RBM and AM with the available data from the current MP. The aim of implementing the generalized RBM model is to prioritize the components on risk and select the plan year for each component that minimizes the total risk and cost while maximizing the performance of the asset. The generalized RBM model consists of four phases. In the scope identification, the assets and its corresponding components are defined. The failure evaluation defines failures and calculates the remaining useful lifetime. The risks are calculated and prioritized by the risk assessment. The MP is developed by running the generalized RBM model.

The generalized RBM model is specified for roads to analyze if the generalized RBM model improves the current MP. A failure can be identified if the inspection results provide a plan period within a planning horizon of five years. The remaining useful lifetime distribution is based on the plan period and is considered to be a(n) triangle, uniform, increasing, or decreasing distribution. The risk is calculated by multiplying the probability of failure with the consequences of aesthetics, safety, functionality, and sustainability of the lane sector. The generalized RBM model provides an optimization function that decides for each lane sector, whether the maintenance activity is planned in the considered plan year.

A case study provided by a municipality in the Netherlands is used to analyze if the generalized RBM model supports the asset manager with planning road maintenance and improves the current MP method. The analysis towards the failure distributions shows no significant differences, and the increasing distribution is selected. The current MP is exceeding the budget that restricting the total cost of the generalized RBM model. While using the same budget, the current MP still shows lower risk and higher performance concerning the generalized RBM planning. This is due to the budget constraint (2) and (3) that ensures the cost per year are equally distributed. If both budget constraints are removed, the generalized RBM model provides an MP with the lowest possible risk and the highest possible performance. Concerning the current MP, the generalized RBM model has a lower cost. It shows that the generalized RBM is optimizing road maintenance related to the cost, performance, and risk concerning the current MP. However, the MP is not representative for road maintenance, since too many maintenance activities are planned in the first year. It shows that the effect of both budget constraints is significant. By using the case study, we can conclude that the correlation between performance and risk is approximately -70%. The cost has no significant correlation with the performance and risk of the lane sectors. The study to the Lagrange multipliers shows that variating the Lagrange multipliers between 0 and 1 has no impact on the MP. The generalized RBM model provides an MP for roads by optimizing the total risk, performance, and cost and ensures the total cost is equally spread over the planning horizon.

7.1 Suggestions for further research

During the implementation of the generalized RBM model for road maintenance and by analyzing the results, suggestions for further research are derived. The discussion in chapter 6 suggests that the RBM concept could be replaced by a new maintenance concept soon. Further research towards the future of MP could be interesting for the development of the generalized RBM model. Furthermore, implementing the RBM model for other assets rather than roads is needed to analyze the capability of the generalized RBM model and to underpin the conclusions of this study. We suggest selecting assets within the infrastructure, but also to implement the generalized RBM model for an industrial case to validate the model.

The main improvement concerning the RBM model according to Krishnasamy et al. (2005) is the purpose of the objective function. The indexes that are used to calculate the objective function in the case study are based on many assumptions. Variating the values of the indexes would provide more insights into the effect of the indexes on the total minimization of the objective function. Secondly, the estimations that are made for the plan period incompletes the data of the case study — estimating the remaining lifetime distribution of a lane sector more significant will results in a better calculation of the total risks. This will affect the decisions of the model to plan a maintenance activity in a certain year and would approach a more accurate MP concerning the risks.

The study towards road maintenance in section 3.1 shows that many factors have an impact on the deterioration of a road. It would be interesting to implement uncertainties such as climate changes and traffic density into the determination of the risk of road failure. Both have a negative effect on the risk of failure. Further research could implement the uncertainties in the model to provide a more realistic and precisely MP. Besides the risk determination of a road, the cost and performances are optimized in the generalized RBM model. The cost is determined based on real-time data and is considered reliable. However, calculating the performances required a more reliable argumentation. Although the calculation of the performances is based on the available data, i.e., the quality of the lane sectors, many other determinations are suggested in the literature. To improve the effect of the performances on the total minimization of the model, the performance determination needs a complete study.

Some further research on the effect of implementing penalties could be interesting. In the current generalized RBM model, the penalties are implemented in the determination of risk and performance. Many kinds of literature are available to implement penalties in an objective function. Besides, the model is now used to improve the MP, but could also add value towards the decisions on the strategical level. By applying the model, an asset manager can determine what the effect on risk and performance could be if he allows more cost. We suggest adding a risk constraint to the model. The trade-off between the three KPI's could be analyzed in more detail concerning the practical use by an asset manager.

The generalized RBM model is executed by using Excel and code the decisions into VBA. The determination of the risk, cost, and performances is formulated in Excel. As the discussion in chapter 6 already suggested, the possibility of an unintentional change in the data is significant. The model will be more reliable of the input data cannot be changed during the development of the MP. A suggestion is to implement the generalized RBM into OBSURV because municipalities use the software tool to create a road MP.

8. References

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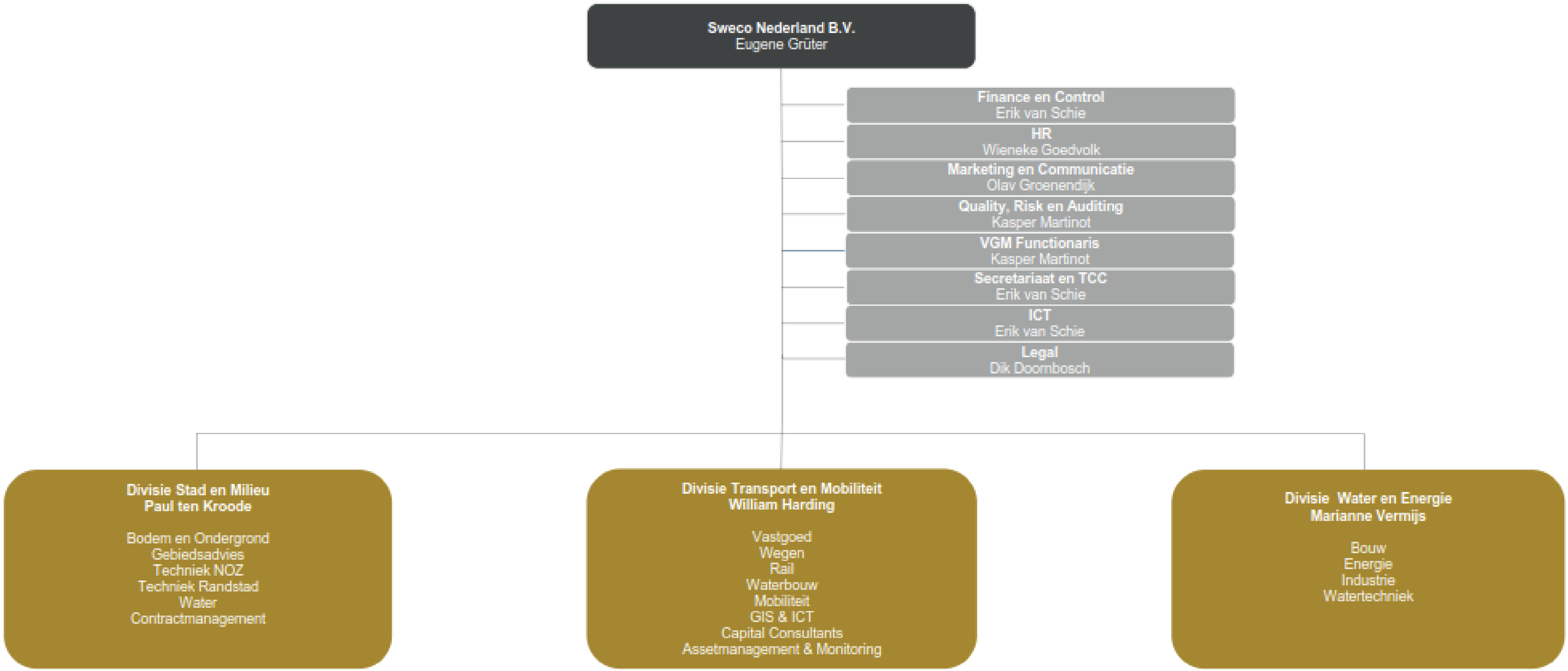
9. Appendix

9.1 Organogram Sweco Nederland B.V.



9.2 Inspection guideline from CROW

Afkortingen

Benaming wegvakonderdeel

RB: Rijbaan
RBL: Rijbaan Links
RBR: Rijbaan Rechts
FP: Fietspad
VP: Voetpad
PS: Parkeerstrook
L: Links
R: Rechts

Weersinvloeden

Niet inspecteren:
- Asfalt en cementbeton bij nat wegdek

Let op bij:
- Scheurvorming bij asfalt- en cementbeton bij opdrogend wegdek
- Plasvorming
- Lichtinval

Inspectieuitrusting

- 'Handleiding globale visuele inspectie'
- rei, 1,20 meter lengte met waterpas
- wig (met schaalverdeling)
- (metalen) stiften met diameter 3, 5, 10, 15 en 20 mm doorsnede
- meetwiel
- meetlat
- veiligheidsvest of -jas
- eventueel een fotocamera
- bord 'WEGINSPECTIE', goed zichtbaar op de auto
- oranje zwaailicht
- eventuele vergunningen en ontheffingen
- wegafzetting of pijlenwagen, afhankelijk van de verkeerssituatie

Inspectiekaart globale inspectie (versie febr. 2013)

C·R·O·W

Praktische kennis direct toepasbaar

GLOBALE INSPECTIE KAART

CROW-publicatie 146b 2013

				Ernst				
Asfaltbeton		Omvang		L	M	E		
Textuur	Rafeling asfaltbeton en oppervlakbehand. (in %)	≥5 – <30% ≥30 – <50% ≥ 50%	1 2 3	>5 – ≤20%	>20 – ≤50%	>50%	% van de maatgevende m² vertoont schade Alléén steenfractie > 2 mm	Niet in verh.rand
	Rafeling zoab (in %)	≥5 – <30% ≥30 – <50% ≥ 50%	1 2 3	>5 – ≤10%	>10 – ≤20%	>20%		Niet in verh.rand
Vlakheid	Dwarsonvlakheid (m/100 m)	≥5 – <15 m ≥15 – <35 m ≥ 35 m	1 2 3	>10 – ≤20 mm	>20 – ≤30 mm	>30 mm	mm hoogteverschil	Niet in verh.rand Alleen > 5 m Beide sporen 1x
	Oneffenheden (st./100 m)	≥3 – <8 st. ≥8 – <15 st. ≥ 15 st.	1 2 3	>5 – ≤15 mm	>15 – ≤30 mm	>30 mm	mm hoogteverschil Opm. Fietspaden licht vermelden onder matig	Niet in verh.rand Alleen < 5 m²
Samenhang	Scheurvorming (m/100 m) **Let op :** Dwarsscheuren bij opmerkingen	≥5 – <25 m ≥25 – <50 m ≥ 50 m	1 2 3	ja ≤10 mm ≤5 mm nee nee nee	nee >10 – ≤15 mm >5 – ≤10 mm ja ja nee	nee >15 mm >10 mm nee nee ja	Gevulde scheuren Lengtescheuren, hoogteverschil in mm Scheurwijdte in mm Meerdere parallel lengtescheuren Lengtescheuren met zijtakken Lengte- en dwarsscheuren verbonden (craquelé)	
Verhardingsrand (facultatief)	Randschade (m/100 m)	≥5 – <25 m ≥25 – <50 m ≥50 m	1 2 3	Afzonderlijke schades dwarsonvlakheid, oneffenheden en scheurvorming die in de verhardingsrand voorkomen				
Elementen		Omvang		L	M	E		
Vlakheid	Dwarsonvlakheid (m/100 m)	≥5 – <15 m ≥15 – <35 m ≥35 m	1 2 3	>10 – ≤25 mm	>25 – ≤40 mm	>40 mm	mm hoogteverschil	Tot aan goot Alleen > 5 m Beide sporen 1x
	Oneffenheden (st./100 m)	≥3 – <8 st. ≥8 – <15 st. ≥15 st.	1 2 3	>5 – ≤15 mm	>15 – ≤30 mm	>30 mm	mm hoogteverschil Opm. Fietspaden licht vermelden onder matig	Alleen < 5 m² < 3 st. E K.O. < 3 st. M Niets
Samenhang (facultatief)	Voegwijdte maatvast (in %)	≥5 – <15% ≥15 – <30% ≥30%	1 2 3	>5 – ≤10 mm	>10 – ≤20 mm	>20 mm		
	Voegwijdte niet maatvast (in %)	≥5 – <15% ≥15 – <30% ≥30%	1 2 3	>10 – ≤15 mm	>15 – ≤20 mm	>20 mm	Opmerking: houd rekening met grilligheid natuursteen	
Cementbeton		Omvang		L	M	E		
Vlakheid	Oneffenheden (st./100 m)	≥2 – <5 st. ≥5 – <10 st. ≥10 st.	1 2 3	>5 – ≤10 mm	>10 – ≤15 mm	>15 mm	mm hoogteverschil Opm. Fietspaden licht vermelden onder matig	
Samenhang	Scheurvorming (aantal platen/100 m)	≥1 – <3 st. ≥3 – <8 st. ≥8 st.	1 2 3	≤3 mm ≤5 mm nee ja	>3 – ≤10 mm >5 – ≤10 mm ≤50 mm nee	>10 mm >10 mm >50 mm nee	Scheurwijdte in mm Hoogteverschil in mm Afbrokkeling scheurrand Gevulde scheuren	Langs- en dwarssch.
Waterdichtheid	Voegvulling (m/100 m)	≥10 – <30 m ≥30 – <50 m ≥50 m	1 2 3	n.v.t. n.v.t. n.v.t. n.v.t.	deels deels ja nee	geheel geheel n.v.t. ja	Verlies hechting a.d. rand Noodzaak vervanging Plaatselijke uitstulping Voegvulling ontbreekt	
Divers - facultatief		Omvang		L	M	E		
Zetting	(in m)	n.v.t.		≤0,20	>0,20 – ≤0,40	>0,40	Opm.: Gelijkmatig of ongelijkmatig	

Veelgebruikte afkortingen t.b.v. asfalt- en elementenverhardingen

AI: aansluiting inspectieput	BG: boorgaten	PO: plaatselijke ophoging
AK: aansluiting kunstwerk	BP: bezweken plek	PV: plaatselijke verzakking
DS: dwarsscheuren	BW: boomwortelopgroei	RV: ribbelvorming

Extra t.b.v. cementbetonverhardingen

DS: hoogteverschil bij dwarsscheuren
DV: hoogteverschil dwarsvoegen
LV: hoogteverschil langsvoegen
BP: bewegen betonplaat

9.3 VBA code

```
Sub SolverInge()
Dim YearBudgetMax As Boolean
Dim TotalBudgetMax As Boolean
Dim BB As Boolean
RowCounter = 3
ColumnCounter = 2
ObjectiveFunction = 0
bestObjectiveFunction = 1E+18
PickedColumn = 0

Do While RowCounter < 1328 '1328

    Do While ColumnCounter < 7
        TotalBudgetMax = False
        YearBudgetMax = False
          OldValue = Cells(32, 12).Value                                                   'the Old value indicates value for the obj function
        Cells(RowCounter, ColumnCounter) = 1                                               'decision variable = 1
        ObjectiveFunction = Cells(32, 12).Value

        If ObjectiveFunction = OldValue Then Cells(RowCounter, ColumnCounter).Value = 0    'if old and new obj value are the same, dec variable = 0
        If ObjectiveFunction > OldValue Then Cells(RowCounter, ColumnCounter).Value = 0    'if new obj value is bigger then old obj value, dec variable=0
        If ObjectiveFunction < OldValue Then                                               'if new obj value is smaller then old obj value, then

            If Cells(14, 9) <= Cells(14, 12) Then TotalBudgetMax = True                    'TotalBudgetMax=True if budget is exceeded
            If ColumnCounter = 2 Then If Cells(9, 12) > (Cells(14, 9) / 5) Then YearBudgetMax = True   'YearBudgetMax= True if cost in t is higher then 1/5 of TotalBudget
            If ColumnCounter = 3 Then If Cells(10, 12) > (Cells(14, 9) / 5) Then YearBudgetMax = True
            If ColumnCounter = 4 Then If Cells(11, 12) > (Cells(14, 9) / 5) Then YearBudgetMax = True
            If ColumnCounter = 5 Then If Cells(12, 12) > (Cells(14, 9) / 5) Then YearBudgetMax = True
            If ColumnCounter = 6 Then If Cells(13, 12) > (Cells(14, 9) / 5) Then YearBudgetMax = True


                If TotalBudgetMax = False And YearBudgetMax = False And ObjectiveFunction < bestObjectiveFunction Then
                    PickedColumn = ColumnCounter                                           'If budgetsconst is not exceeded, then select that year
                End If

                If TotalBudgetMax = False And YearBudgetMax = False And ObjectiveFunction < bestObjectiveFunction Then
                    bestObjectiveFunction = ObjectiveFunction                              'If budgetsconst is not exceeded, then best plan year so far
                End If

            Cells(RowCounter, ColumnCounter) = 0                                           'Turn dec variable to 0

         End If

        ColumnCounter = ColumnCounter + 1                                                  'Test next plan year

    Loop

    If PickedColumn > 0 Then Cells(RowCounter, PickedColumn).Value = 1                     'make dec variable that improves obj value 1


    RowCounter = RowCounter + 1                                                            'Go to next lane sector
    ColumnCounter = 2                                                                      'Start in year 1
    bestObjectiveFunction = Cells(32, 12).Value
    YearBudgetMax = False                                                                  'Reset
    TotalBudgetMax = False
    PickedColumn = 0

Loop

End Sub
```

9.4 Results current maintenance planning vs generalized risk-based maintenance planning

	Current MP	Generalized RBM MP
Total cost	€ 11.026.007,58	€ 11.025.311,37
Total risk	*15908367*	*143647600*
Total performance	19510794	17009153
Objective function	*13022696,57*	*142262357,2*
Total cost	€ 11.026.007,58	€ 11.025.311,37
Cost year 1	*€ 112.724,77*	*€ 2.205.187,87*
Cost year 2	€ 4.411.129,49	€ 2.205.081,92
Cost year 3	*€ 3.261.347,50*	*€ 2.205.149,26*
Cost year 4	€ 2.451.550,20	€ 2.205.131,66
Cost year 5	*€ 789.255,62*	*€ 2.204.760,66*
Mean risk	*12.006*	*108.413*
	Low	Low
Performance		
A	*27%*	*23%*
B	73%	65%
C	*0%*	*12%*
D	0%	0%
Total scheduled	1325	1318
# scheduled in year 1	*69*	*123*
# scheduled in year 2	596	200
# scheduled in year 3	*401*	*284*
# scheduled in year 4	185	329
# scheduled in year 5	*74*	*382*

9.5 Results running generalized risk-based maintenance model without budget constraints

	Current MP	Generalized RBM MP	Generalized RBM MP without (2) and (3)
Total cost	€ 11.026.007,58	€ 11.025.311,37	€ 10.640.783,58
Total risk	*15.908.367*	143.647.600	0
Total performance	19.510.794	17.009.153	21.520.668
Objective function	*13.022.696,6*	142.262.357,2	-4.399.774,2
Total cost	€ 11.026.007,58	€ 11.025.311,37	€ 10.640.783,58
Cost year 1	*€ 112.724,77*	€ 2.205.187,87	€ 5.711.340,69
Cost year 2	€ 4.411.129,49	€ 2.205.081,92	€ 2.659.530,08
Cost year 3	*€ 3.261.347,50*	€ 2.205.149,26	€ 1.586.864,82
Cost year 4	€ 2.451.550,20	€ 2.205.131,66	€ 683.047,99
Cost year 5	*€ 789.255,62*	€ 2.204.760,66	€ -
Mean risk	*12.006*	108.413	0
	Low	Low	Very low
Performance			
A	*27%*	23%	100%
B	73%	65%	0%
C	*0%*	12%	0%
D	0%	0%	0%
Total scheduled	1325	1318	1325
# scheduled in year 1	*69*	123	869
# scheduled in year 2	596	200	218
# scheduled in year 3	*401*	284	107
# scheduled in year 4	185	329	131
# scheduled in year 5	*74*	382	0

9.6 Results running generalized risk-based maintenance model without budget constraint (2)

	Generalized RBM MP	Generalized RBM MP without (2)
Total cost	€ 7.499.599,69	€ 7.499.993,56
Total risk	393.785.117	229.007.000
Total performance	12.198.248	15.025.648
Objective function	392.465.847,86	225.991.605,81
Total cost	€ 7.499.599,69	€ 7.499.993,56
Cost year 1	€ 1.499.940,91	€ 4.554.099,18
Cost year 2	€ 1.499.971,57	€ 2.297.410,21
Cost year 3	€ 1.499.896,87	€ 570.417,37
Cost year 4	€ 1.499.931,14	€ 78.066,80
Cost year 5	€ 1.499.859,21	€ -
Mean risk	297.196	172.835
	Low	Low
Performance		
A	13%	51%
B	44%	19%
C	15%	2%
D	28%	27%
Total scheduled	658	685
# scheduled in year 1	84	512
# scheduled in year 2	79	138
# scheduled in year 3	162	34
# scheduled in year 4	229	1
# scheduled in year 5	104	0