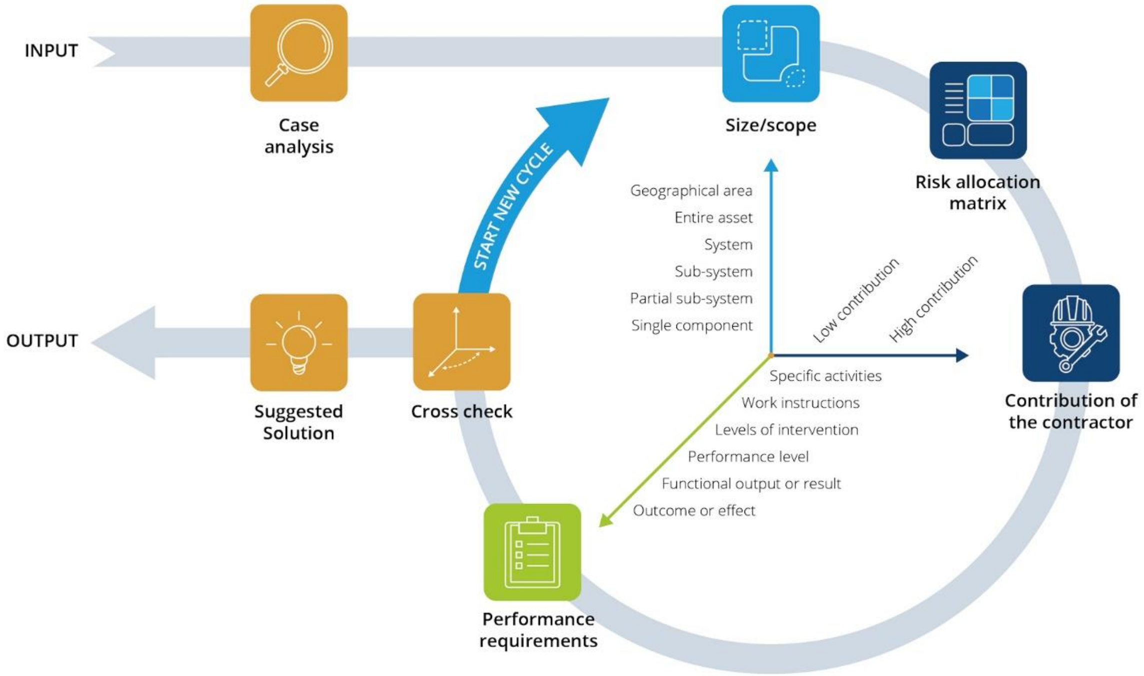
Master thesis

Outsourcing maintenance using PBMC

Introducing a decision-support method for performance based maintenance contracts



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Introducing a Decision-Support Method for Performance Based Maintenance Contracts

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Preface

This report is the result of my graduation research for the completion of the Construction Management and Engineering Master at the Delft University of Technology. It introduces a decision-support method for performance based maintenance contracts. With this method the contract design teams working on civil infrastructure contracts can get more insight in the options that are available within performance based contracting, helping them optimize the contract designs.

This has not been the first thesis that I have written in my educational career. This was however my first, and hopefully last, master thesis. Though it has been a challenging rollercoaster of achievement, disappointment, tension and relief. Just as I did in my previous thesis, I wanted to use this research create something new. In this case a new method will be created by using the knowledge of different sources and areas of expertise, combining it with already existing and recently developed tools within the field of performance based contracting.

I soon came to realization that creating something new was quite difficult within the timespan that was available. With the help and guidance of Marco at Rijkswaterstaat and the graduation committee I was able to stay on track for a long time. However, the closer I got to the end, the further I diverted from the expectations of the rest. This resulted in a difficult period where my internship opportunities with Rijkswaterstaat expired and I had to find my own workspace. But therefore I owe a great deal of gratitude to Marco Dreschler, who kept supporting and helping me, even though I wasn't working for Rijkswaterstaat anymore. It was at that same period that I had some major changes in my life. I decided that I wanted leave the world of construction behind me and start a new career in law enforcement.

Through some personal setbacks and the passing of my grandpa, I didn't manage to finish my thesis before my admission to the police academy. It was however a final wish of my grandpa that I finished my master thesis, no matter what. The combination of the police academy and finishing a master thesis is one I wouldn't recommend anyone to try. Considering the circumstances, it therefore feels like a great relief that I can finally finish this chapter of my life.

I would like to take this opportunity to thank everyone who has helped and supported me during the writing of this thesis. From Rijkswaterstaat I would like to thank Marco Dreschler for providing the opportunity to perform this research at Rijkswaterstaat and even when working at Rijkswaterstaat wasn't possible anymore, he kept supporting me in finishing this thesis. I would also like to thank Rob Schoenmaker, who delivered an important contribution to the content of this thesis. Not only through his own previous works, but during the vivid discussions that we had about this thesis. You really helped me keep my eye on the finish line throughout the thesis. I'd like to thank Leon Hombergen for encouraging me in times that things didn't go that well and taking Rob's place during his absence. I would also like to express my gratitude to Marleen Hermans for keeping a critical view during the entire process and therefore managing the quality of the eventual work. But also for showing understanding for the choices I made regarding my future and consequential delays for this thesis in the process. I would like thank Robert Bijvank for proofreading this work and for assisting me with very helpful comments. A special thanks goes to Dennis Osseweijer for helping me bringing the decision-support method to life.

Finally, I would like to thank my family for the fact that they gave me this opportunity. Without them this wouldn't even be possible. The support, encouragement and help of my parents, my brothers and everyone around me made all of this possible.

I dedicate this work to my late grandpa, Henk Osseweijer (1939-2018) , who sadly passed away during the writing of this thesis. The last time I had the opportunity to speak to him, he encouraged me to finish my master thesis and I promised him to do so. I can't describe how happy I am that I'm finally able to deliver on that promise. Grandpa, this one is for you!

Michael Osseweijer, 22-12-2019

Abstract

When it comes down to building or maintaining civil infrastructure commissioned by a governmental body, a lot has changed during the last couple of years. The government made a turn from all determining body, to a cooperative partner and later even to an organization that's outsourcing most of the construction and maintenance work to second and third parties. Changing the working methodology requires a change in the contracting strategy. Nowadays, the contract of choice for maintenance used by governmental and semi-governmental organizations is the performance-based maintenance contract (PBMC).

There are many risks and important factors that influence the outcome of the use of PBMC in a negative way. Organizations that use them seem to overlook those negative influences and just focus on the potential cost savings. This results to a contract that hasn't really been updated since it was first introduced. This leaves a situation where the effectiveness of the contract form is less than optimal; the contract does not deliver its full potential and the writers of the contract have no standardized way to approach the PBMC. The goal of thesis is to therefore find a structured way that can assist the contract design teams in making informed decision when drafting a PBMC.

In order to find that structured way, the ingredients that would make up the structure had to be found. To achieve that, a literature study was performed in which all the criteria that would influence the outcome of a PBMC where gathered and categorized into five main decision criteria: predictability, plannability, measurability, responsibility and criticality. Next up, the parameters of the PBMC had to be found. These parameters would enable the user of the method to change the way an object would be outsourced based on the five main decision criteria. The parameters that where found are: size/scope, contribution of the contractor and the performance requirements. In order to provide the user with sensible information about a certain object to base their decisions on about the way of outsourcing, a trustworthy and function information gathering tool/method was needed. Within the area of reliability centered maintenance (RCM), the failure mode, effects and criticality analysis (FMECA) method was found to be very useful to gather the required information to base these decisions on. Another method that was found to be useful was the risk allocation matrix by Brommet. This method was created to give the user insight in possible outsourcing and payment solutions for DBFM contracts, but a redesign of the original matrix proved just as useful in making suggestions about outsourcing and payment methods for PBMC.

All this information led to the creation of the decision-support method. This method, which contains 7 steps, was created to help contract design teams in making their initial decision about the way a certain object should be outsourced. The first step is designed to find the necessary information and prepare the risk allocation matrix to make it usable for this specific case. Steps 2 to 7 are designed to give a step by step answer on how to interpret each parameter and to reach a decision on how to outsource a certain part of an object. These steps are repeated for every single part of the object until a suggested outsourcing decision is made for every single part.

The decision-support method is tested twice on a real case. During these case studies improvements were made to the initial model. Eventually the method is presented during an expert meeting within Rijkswaterstaat and another set of improvements was implemented.

It can be concluded that the method can be successful in helping the contract design team is making a PBMC. Both by using the entire method of utilizing parts of it during the contract design process. The method helps the user to think of more options and assists in weighing these different options against each other. Although, the methods needs further testing and can definitely be improved. The potential of a method like this was definitely recognized during the expert meeting. The last part of the thesis is therefore dedicated to the limitations of the method at this time and the future research and improvements that can be made.

Summary

This master thesis focuses on finding a method to assist contract design teams in their decision-making process when designing a performance-based maintenance contract (PBMC).

Traditionally, the government was the all-determining body for the entire process, from the initial design, construction, delivery, maintenance, operation until the eventual demolition and/or replacement. The government had the in-house expertise, knowledge and man-power to manage all these activities themselves. During the early 70's, this behavior has changed and the government took a more collaborative role, working together with market parties. This resulted in more work being given to the market parties. Over time, many different ways of outsourcing and many contract variations are used.

Nowadays, the contract of choice for maintenance used by governmental and semi-governmental organizations is the PBMC. The PBMC focuses on the performances requirements that need to be achieved by the contractor. The contractor is then paid based on the delivered performances. The potential benefits of using PBMC are a trigger for many organizations to use these contracts, both here in the Netherlands and abroad. The main reason is the potential cost saving of 40% compared to regular contracts. It must however be pointed out that this amount of cost savings is not achieved most of the time.

There are many risks and important factors that influence the outcome of the use of PBMC in a negative way, but the organizations that use them seem to overlook that and just focus on the potential cost savings. This results in a contract that hasn't really been updated since it was first introduced. This leaves a situation where the effectiveness of the contract form is less than optimal; the contract is not delivering its full potential and the writers of the contract have no standardized way to approach the PBMC.

With this problem in mind, the goal was set to find a method that can help the contract design teams approach the PBMC in a standardized way in order to optimize the potential outcome of the use of PBMC. In order to achieve that goal, the following research question is used during this thesis:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

The structured way that was introduced to assist the contract design teams is called the decision-support method. There is an important reason why this method is called a decision-support method, rather than a decision-making method or model. The use of this method is not by making simple yes or no decision. A great amount of expert judgement and knowledge about the assets is still necessary to make the eventual decision. The method, however, supports the contract design team in searching and finding necessary information, evaluating the options and come up with an informed conclusion about the suggested way of outsourcing through a number of steps. During these steps the most important decision criteria and important considerations are brought up in a structured way. That is how the decision-support method will help the contract design team in their decision-making process.

In order to create the decision-support method, the necessary data and information was gathered by literature research.

To help the contract design teams in making informed decision about the PBMC, it is important to know what considerations need to be made when dealing with PBMC. Through different sources, a list of over 60 considerations was compiled. In order to create a manageable decision-support method, the main decision criteria were introduced.

The main decision criteria for the PBMC are found by grouping the 63 original considerations and covering most of them. These are five main decision criteria that were found:

- Predictability
- Plannability
- Measurability
- Responsibility
- Criticality

Now that the important decision criteria are found, the focus was on the decisions themselves. What exactly needed to be decided when outsourcing is done through a PBMC. This lead to the introduction of the three main parameters that are used throughout the decision-support method. In order to help the contract design team in their decision-making process, the decision-support method should tell them something about what is being outsourced, who will be responsible for the outsourced part and how will it be managed. This resulted in the following three main parameters:

Size/scope

Contribution of the contractor

Performance requirements

For each individual parameter a range is defined from which the user of the decision-support method can choose the most appropriate setting. The combined range of all the parameters is the solution space in which the eventual solution can be found. The solution space can be visualized as a three-dimensional cube between the three main parameters.

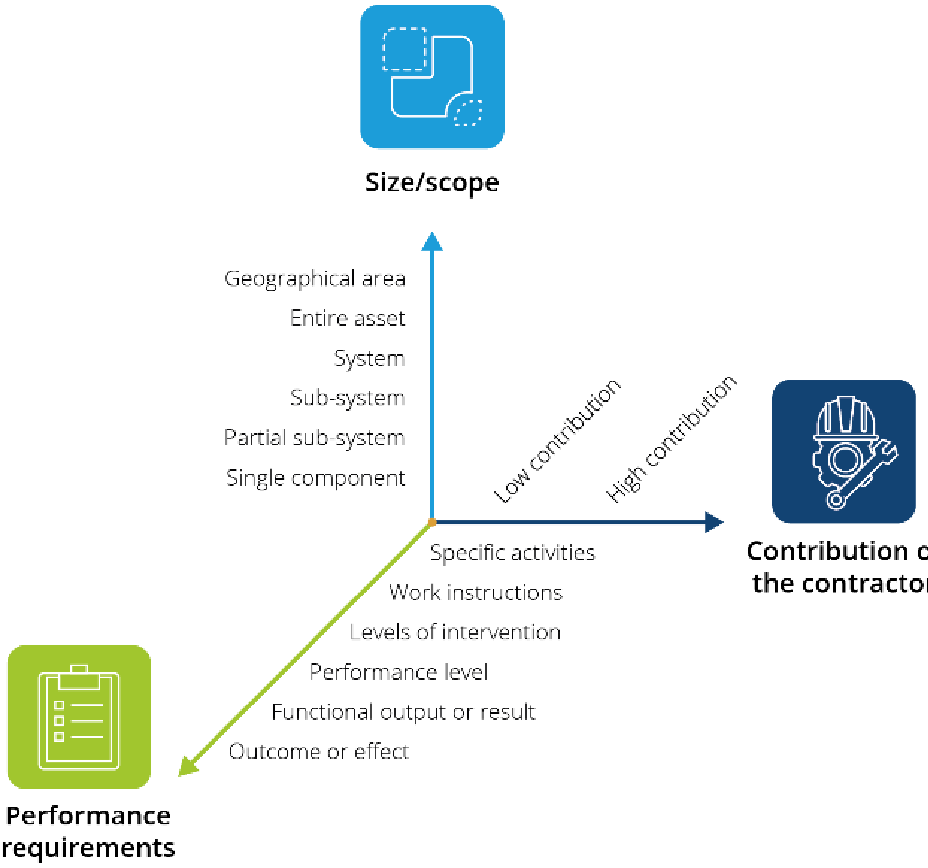

Figure (S) 1: The solution space of the decision-support method based on (Schoenmaker, de Bruijn, & Herder, 2013)

In order to help the contract design team make informed decisions, several models are added to the method. For the contribution of the contractor, the six stage model by Rob Schoenmaker was introduced. This model helps to understand and decide the maintenance cycle and help the design team decide the contribution that each party can deliver under certain circumstances.

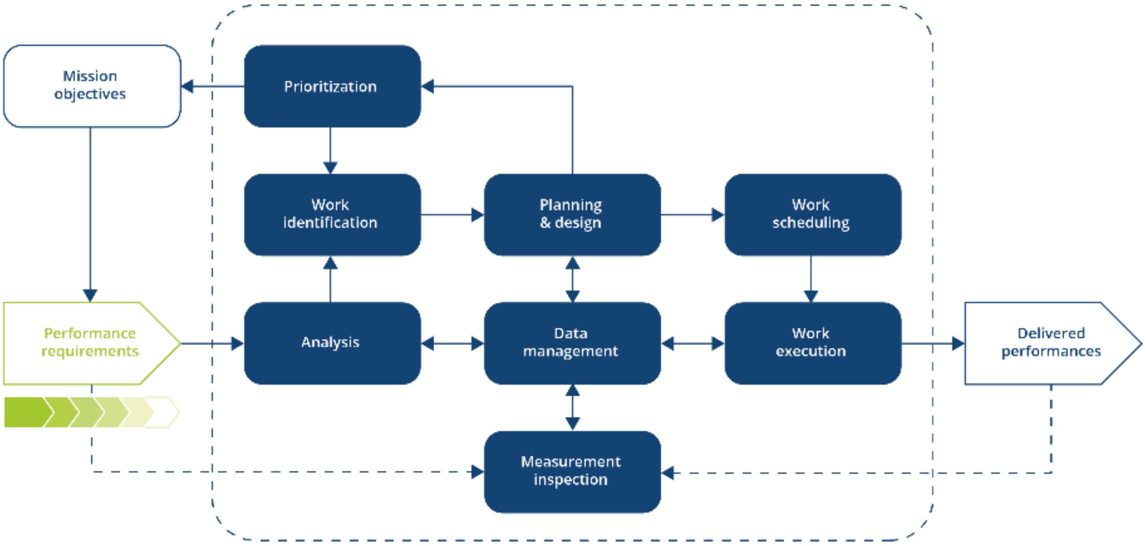

Figure (S) 2: Model of the cyclic maintenance process based on (Schoenmaker, de Bruijn, & Herder, 2013)

Another model that was introduced to help the contract design team was a model explaining the different levels of outsourcing. This was also derived from the work of Schoenmaker. This image helps understand the range of performance requirements.

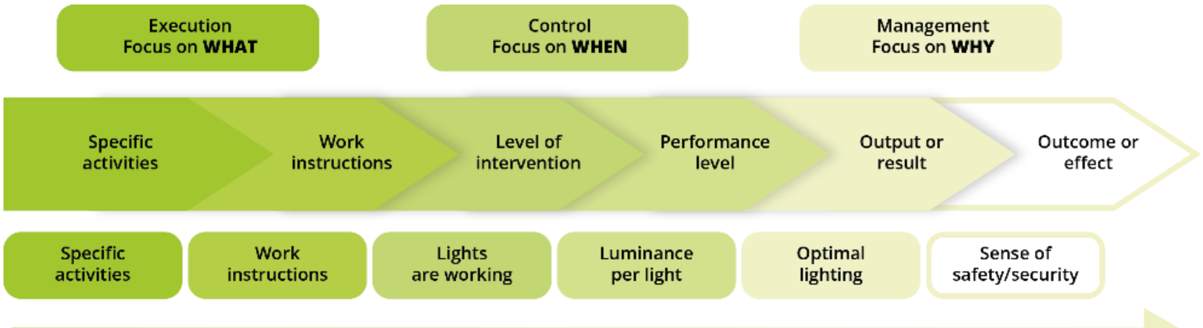

Figure (S) 3: Performance requirement levels based on (Schoenmaker, 2017)

In order to get the information that is needed to take the informed decisions about the three main parameters, the reliability centered maintenance (RCM) method has been introduced to fulfill the task of information gathering. This method is defined by Moubray (1997) as 'a process used to determine the maintenance requirements of any physical asset in its operating context' and 'a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context'. An important part of this method is the failure mode effects & criticality analysis (FMECA). By using this tool, a risk matrix and risk register is made which gives a lot of insight in the predictability, plannability and criticality of the maintenance measures of an asset.

Another tool that was introduced during this thesis was the risk allocation matrix by Brommet (Managing the Dutch Waterworks using long-term Maintenance Contracts, 2015). The risk allocation matrix was designed to help with risk allocation when outsourcing maintenance contracts of sluices. Because this matrix can help identify the risks and gives an appropriate outsourcing solution in various circumstances, an added value for decision-support method was seen in this tool. It was however not possible to use the matrix in every case because it was made for sluices in particular. Therefore a method has been designed to transform the matrix to fit the case it is being used in. The risk matrix from FMECA has played an important role in this transition process.

At that point in time, all the criteria, parameters, tools and techniques were found to start designing the actual structure that would bring it all together, the actual decision-support method. The first conceptual model consisted of a 6 step linear process. In this first conceptual model, the information gathering and use of FMECA was left outside of the process itself. The steps were purely focused on the decision-making.

- Step 1: Determining the size/scope
- Step 2: Using the risk allocation matrix
- Step 3: Determining the extent of contribution of the contractor
- Step 4: Determining the level of performance requirements
- Step 5: Cross-check the three chosen parameters to see if they work together
- Step 6: Present the proposed solution for the three parameters and expected outcome

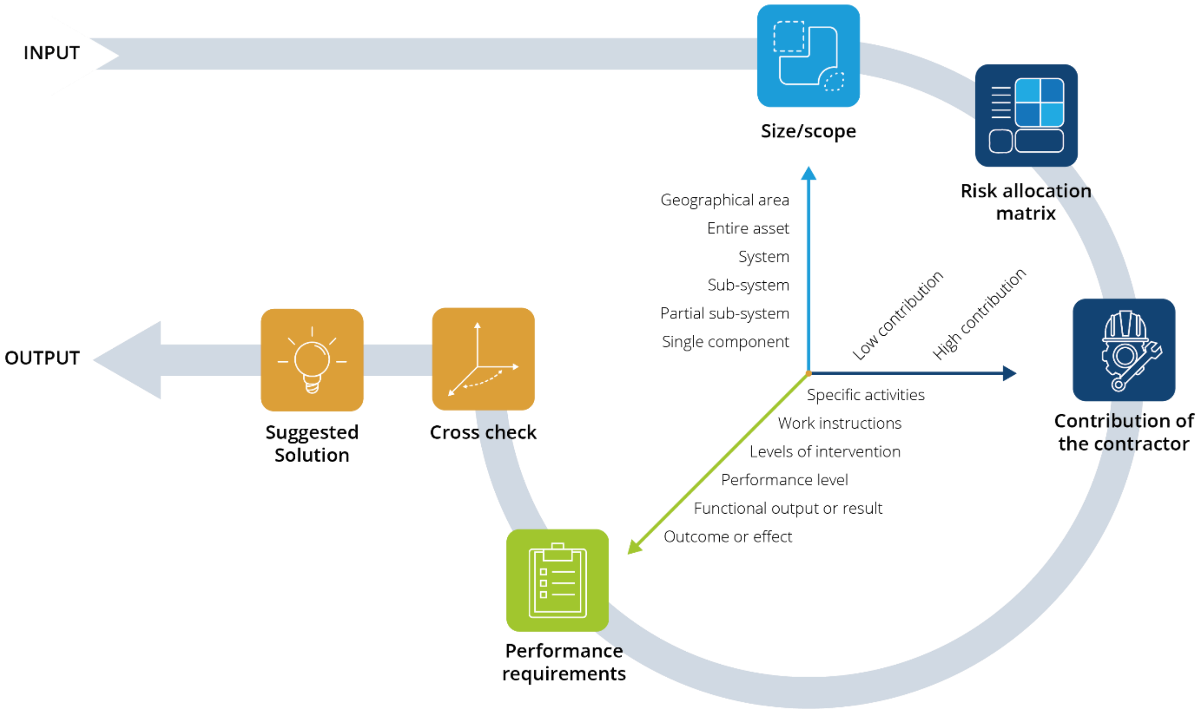

Figure (S) 4: Conceptual design of the decision-support method

The conceptual design is tested two times during a case study. The case study was used to see if the method performed as expected and to see where improvements were needed. Based on the two runs of the case study, the design has been improved twice. FMECA has been integrated into the method itself as the first step of the process because it became clear that the information that is gathered during that process is crucial to the success of the decision-support method. This also meant that the decision-support method has become a 7 step method instead of the previously mentioned 6 steps. The transformation process for the risk allocation matrix that was mentioned before has further been developed during the case study and got a permanent place during the first step of the decision-support method right after the execution of the FMECA. The explanation of the individual steps has become more strict than it was during the first conceptual design to improve the validity of the method. By doing so, it became more clear what is to be expected from the user when working with the decision-support method.

Another big thing that was found out during the case study, was the influence that expert judgement still has on the outcome of the method. The expert judgement is and will remain an important part of using the decision-support method. The method only helps the user to take certain steps and consider certain factors, but it will not take the decisions itself, that will still be the responsibility of the experts.
All these changes eventually lead to the final design of the decision-support method. Contrary to the first conceptual design, the method consisted of 7 steps instead of 6 and was no longer linear. The new cyclic design did more justice to the way the method actually works in practice.

The new final decision-support method was designed as follows:

- *Step 1: Performing FMECA and executing the transition of the risk allocation matrix*
  An FMECA is performed to gain insight in the failure modes of an asset/system/object. During the FMECA, information about the predictability, plannability and criticality can be found and used in the remainder of the steps. This step is also used to perform the transition of the risk allocation matrix to the object that is being evaluated while using the decision-support method.
- *Step 2: Determining the size/scope*
  The information from the FMECA, as well as the criticality analysis will be used to find a suitable size/scope. This is the first parameter that is set and the other parameters will be adjusted accordingly.
- *Step 3: Using the risk allocation matrix*
  The risk allocation matrix requires input from the FMECA like frequency of failures and effects that occur. The matrix can be used to suggest a way of outsourcing and a suggested payment regime.
- *Step 4: Determining the extent of contribution of the contractor*
  The extent of contribution of the contractor is based on the information from FMECA and the risk allocation matrix. This information is used as input for the six-stage model where predictability and plannability are taken into account, as well as the suggested way of outsourcing and payment regime.
- *Step 5: Determining the level of performance requirements*
  The chosen level of performance requirements are based on the measurability of the performances and the ambition of the organization. Easily measured performances result in a higher levels of performance requirements while performances that are hard to measure result in simple performance requirements. The options depend on the ambition and strategy of the organization. If they want innovative and progressive solutions, outsourcing on a higher level, using performance levels or output-based performance requirements is a possible solution.
- *Step 6: Cross-check the three chosen parameters to see if they work together*
  This step is aimed at checking whether the suggested level of performance requirements work in combination with the proposed level of contribution of the contractor. If a certain performance level is requested, a certain level of freedom for the contractor might be needed. This way the allocation of responsibility is checked in order to make sure that the request is realistic. If either one of the variables is too high, and therefore not compatible with the other, an adjustment needs to be made to either one of them.
- *Step 7: Present the proposed solution for the three parameters*
  This last step of the process summarizes the eventual proposed solution that is the result of the process. The proposed solution will be the chosen parameters for the size/Scope, contribution for the contractor and the performance requirements.

Step 1 of the method is meant to acquire the necessary information and prepare the tools (risk allocation matrix) for the remainder of the process. After the first step a cycle of 6 steps (step 2-7) keeps repeating itself for all the different parts of the asset until the entire asset is evaluated. Every cycle however produces a separate proposal on how to outsource that specific part of the asset.

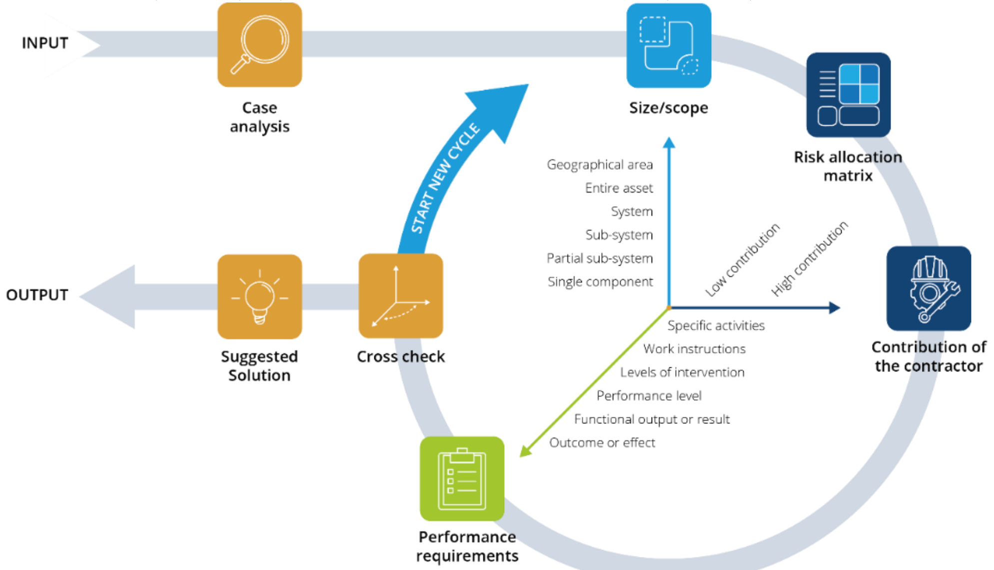

Figure (S) 5: Final design of the decision-support method

During the last case study, it also became clear that more information was needed about the circumstances around the asset to take an informed decision about the outsourcing of that asset. What is meant by this is the information about direction that the contracting authority (CA) is willing to take, the capacity of the organization and the goals that they want to achieve and willing to invest in. This is something that was not taken into account in the design of the decision-support method. To overcome that lack of information, the decision-support method is placed within a bigger decision-making process. Within this process, the decision-support method is preceded by a few steps before it is actually started. The following steps are included in this process:

- ***Step 1: Determination of ambition and goals***
  At the start of the process, the organizational ambition and goals they want reach with the new contract need to be expressed and have to be clear. They will determine the direction that is taken during the decision process.
- ***Step 2: Exploration***
  During the exploration phase the total scope of the contract is determined, the current state of the assets (and asset information) is established. As well as the current state of the organization and the market. This is set out against the ambition and goals that were set.
- ***Step 3: Determination of strategies***
  During the exploration, opportunities and problems are found. A strategy needs to be determined to show which opportunities should be taken, intentions to solve certain problems, and decide which problems are left as is.
- ***Step 4: Decision-support method***
  The decision-support method is used to guide every individual part of the asset through the solution space in order to give a suggestion about the way of outsourcing that might work best for that particular part of the contract.
- ***Step 5: Concept decision and conclusions***
  A list of conclusions and concept decisions comes from the decision-support method and need to be evaluated through expert judgement and converted to final decisions that can be used in the contract.

This process is briefly explained during this thesis but not yet implemented and tested. For the sake of telling the complete story and highlight the information shortcomings that were found during the case study it was included in the appendices.

After the final version of the decision-support method was designed based on the results of the case study. The result was presented to experts of Rijkswaterstaat during an expert meeting. The overall reaction was positive towards the line of thought that was used to create the decision-support method. They were very enthusiastic about the use of FMECA, the way the decision criteria were found and the method of finding and tuning the three main parameters. There were however also some things that needed further attention. The decision-support method ends with a list of individual decision for specific parts of the asset that is being evaluated. Realistically the CA and the contractor do not look at the asset as individual pieces, but as a whole. The decision-support method doesn't contain a step that brings all the individual recommendations back to one big picture. Because this is a major intervention within the total view of the decision-support method, this is taken as a recommendation for further research, but it is not yet implemented in the current designs.

Another comment that was made during the expert meetings was the request for a procedural model for the decision-support method containing the input for the method, the steps and the output that should be there when the step is completed. This request was captured in the procedural approach to the decision-support method which can be found in appendix 10.

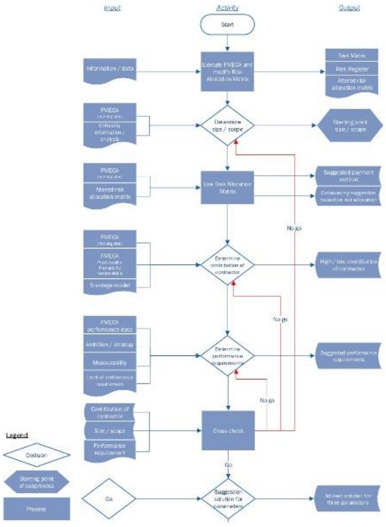

Figure (S) 6: Procedural approach to the decision-support method as found in appendix 10

Conclusion

During this master thesis a 7 step decision-support method has been designed that can successfully be used in assisting contract design teams in writing new performance-based maintenance contracts. The case studies have shown that the individual steps of the method perform as they are supposed to. It has also shown the value of good information management. The information that is gathered through FMECA about predictability, plannability and criticality plays an important part in the design of new PBMC. This thesis therefore also encourages organizations to use FMECA or as similar method to acquire good information to make informed decision about the outsourcing of maintenance work.

Throughout the thesis also became clear that the decision-support method wasn't going to be able to provide clear and concise answers to the outsourcing dilemmas, meaning that expert judgement still plays a very important role in the overall decision-making process. Also, the viewpoint of the CA, state of the organization and the willingness to invest are influential to the decision-making process and can't be ignored when starting to use the decision-support method. Therefore the decision-making process, structuring the gathering of that circumstantial information, becomes very important and more research in that area will be recommended.

The last major point that was found during the execution of the decision-support method during the case study and whilst on review by the experts during the expert meeting was the fact that the decision-support method only focuses on individual elements, rather than the asset as a whole during the outsourcing process. This last crucial step of combining the individual results and bringing the focus back to the bigger picture has not been taken into account at this point. This issue has to be resolved in the future to improve the capabilities of using the decision-support method on real cases.

Even though the decision-support method doesn't yet take the bigger picture into account, the individual steps help the contract design teams in approaching the design of the PBMC in structured way considering all the important decision criteria and making decision about the three main parameters of a PBMC. It will therefore help them in the decision-making when designing a PBMC and can help improve the quality of the outcome of the contracts.

Recommendations

In order to improve the current design of the decision-support method and improve the quality of use on real cases, the following recommendations are given. Some of these recommendations focus on the actual use and some focus on improving the method by doing more research into this area.

The decision-support method has to be seen as part of the decision-making process that is introduced briefly in this thesis. This ensures that information about the goals and ambition of the company, information about the capabilities of the organization and the strategy of the organization are known. This information is needed to take informed decisions during the decision-support method.

A structured way needs to be found to collect all the results from the decision-support method and put them in one clear framework. Then research has to be done in order to create a way that can combine all those individual results in one overlapping conclusion that will be the final suggestion for outsourcing the asset. Until such a way is found, the outcome will be heavily depended on the expert judgement of the people using the decision-support method and delivering the eventual results.

More testing of the steps of the decision-support method and the decision-making process is recommended. The method has been tested on a tunnel case, but needs more testing to see if it can be used under different, perhaps more difficult, circumstances. Also the decision-making process needs to be tested and refined to be used on real cases.

In the end, the decision-support method can mean a lot to the contract design teams, but there is even more to discover in the future and we shouldn't stop looking for more opportunities.

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Chapter 1

Introduction

This chapter will introduce the context and the background of this thesis. Based on that, a problem statement and research objectives are found for which suitable research questions are then formulated.

1

1 Introduction

This chapter will elaborate the context and background of this research. It will also define the problem that triggered this research and explain the theoretical and practical relevance of this master thesis.

1.1 Research context

Civil infrastructure is an important part of the communities, cities and country. This consists of our transport infrastructure such as road, rail and waterworks, but also our public buildings, public spaces, public services and other long-term physical assets and facilities that are constructed, owned and managed by the government meant for public use. This research will focus on the asset management of public works that are related to our transport infrastructure. The government is responsible for designing, constructing, maintaining and managing most of the infrastructure network throughout the entire lifecycle. To make sure that the network performs to the set standards, the government uses separate bodies like municipalities and provinces for regional and semi-national infrastructure, Rijkswaterstaat for national road and water infrastructure and governmentally controlled bodies like Pro-Rail for the rail infrastructure, to manage the day to day operations within the network.

1.1.1 Development of the government's role in the transport infrastructure sector

Traditionally, the government was the all-determining body for the entire process, from the initial design, construction, delivery, maintenance, operation until the eventual demolition and/or replacement. The government had the in-house expertise, knowledge and man-power to manage all these activities themselves. Nowadays however, this is long gone. Due to budget cuts, the government was forced to shrink their departments and could not maintain the position of the all-determining body in the transport infrastructure sector. Although they are still in charge of managing the infrastructure network and bear the responsibility for the network's performance, they are no longer able to prescribe and control everything themselves when it comes to designing, building and maintaining the network. The government has been shifting towards a partnering role, where the collaboration with private parties has become increasingly important. Within this new collaboration structure, which originated from the early 70's and has been developing ever since, the government takes on a higher management role, while the market is managing the execution of the projects themselves (Rijkswaterstaat, Onze historie, 2017).

Another good example of the development of government's role is the Dutch railway infrastructure. Until late 80's, the Dutch Railway Infrastructure, both the exploitation and the managing of the railway infrastructure, was done by the government. During that late 80's and early 90's the Dutch Railways (NS) became increasingly more independent of government intervention. In 1995 the NS splits its businesses into a commercially owned group responsible for the exploitation of the railway network (now known as *Nederlandse Spoorwegen*), and another organization responsible for the maintenance and development of the railway infrastructure. This last organization became Pro-Rail in 2003. This semi-governmental company is responsible for further development and maintenance of the railway infrastructure, in the same sense as Rijkswaterstaat is developing and maintaining the road infrastructure (NS, 2018) (Prorail, 2018).

Until 2000, the government was gradually shifting work and responsibility towards the market. In the early years of the 21st century, the philosophy that they used was: 'the market, unless…'. This meant that the contracts were put on the market, unless the government organization thought that the market was not able to do the complex assignments because the lack of knowledge, skill or capabilities (too much risk). In that case the government will stay in charge (managing party) and the work is not given to the market. Nowadays, another development is occurring. 'The market, unless…' philosophy is already outdated because it led to unwanted results, mainly caused by the crisis, a crowded market and too little assignments. The market competition led to very low and unrealistic bidding, which made private parties crumble under their contracts and a lot of long-lasting juridical procedures where needed to keep these contracts going. The relationship between the private and public parties (and the private contractors between themselves) sank to an all-time low and needed to be restored.

With a new view on how the construction industry should function, Government tried to turn the tide during the following years. The conclusion was that the market was not able to operate on its own. 'The market, unless…' had to change and became: 'with the market'. The emphasis is not to keep more of the work in-house (with the government), but to invest in the relationship and collaboration with the private parties. These parties work together to manage and build the infrastructure network in a smart, safe, durable and sustainable way by using the knowledge and know-how of all the partners. This was eventually put into writing in a new market-vision (2015). A better and more realistic allocation of the risk is an important step in that process. As well as using the knowledge of all partners to reduce the risks as much as possible. Another important matter that is pointed out is the fact that within this new vision the goal is to align the scope and the complexity of the contracts with the capabilities of the market to make the work more manageable for the contractors and reduce the risks of disappointing results. (Cobouw, 2016)

1.1.2 Outsourcing maintenance using performance contracting

The development described in the previous sub-chapter applies to the construction of new infrastructure, as well as the maintenance of existing infrastructure. The focus of this thesis will be on the maintenance of existing infrastructure and the impact of these developments on that maintenance.

The existing network needs to perform according to the required standards and therefore be maintained in a qualitative and cost-efficient way. The government traditionally managed all the maintenance tasks themselves, but this changed over time. In the beginning it was still done through task-based contracts, where the public body prescribed certain activities and the contractor was hired to perform these activities. Currently, outsourcing maintenance of infrastructure is mainly done through performance contracting.

To get a better understanding of the goals, the meaning and the function of these performance contracts, 'performance contracts' must clearly be defined. This clear definition has been formulated based on a presentation given by Schoenmaker (2017, p. 22) about performance-based outsourcing of maintenance work. In this presentation of Schoenmaker the following definition was given:

'Performance Contract'

- ➢ *the contracting authority:*
    - o *describes a desired situation through performance requirements*
    - o *is holding back on prescribing all the activities*
- ➢ *the contractor:*
    - o *has freedom of choice for the design and execution of the activities,*
- ➢ *a link is created between delivered performance and payment*
- ➢ *the performance requirements need to be maintained for a pre-determined period of time.*

Instead of focusing on what should be done (tasks and activities), the emphasis lies on what the result should be (performances and services of structures). This method allows the contractor to use the provided freedom to come up with new, innovative and efficient solutions to maintain the requested performance. This way of contracting is currently used by many major government (or governmentally controlled) organizations like ProRail, Rijkswaterstaat, municipalities and provinces (ProRail, 2017) (Rijkswaterstaat, Prestatiecontracten, 2017) (Avans, 2017) (Dienst Beheer Infrastructuur Provincie Zuid-Holland, 2016).

Public organizations are often driven to use performance-based maintenance contracts by the prospects of a better performance - value ratio. They want to achieve equal or better performances at less costs. The use of performance-based maintenance contracts can in some cases contribute to achieving those goals (Schoenmaker, De ingeslagen weg, 2011, p. 6).

The contract can be steered by the contracting authority (from now on will be defined as CA) using several mechanisms, for instance through payment regimes, certain requirements, specific forms of responsibility or freedom and sharing or transfer of risk. By managing the contract through these mechanisms, they can influence the outcome of the contract. This outcome can either have positive or negative effects for all parties involved.

By managing the contract through these mechanisms, the following effects can occur:

- Transfer of risk
- More innovation
- More flexibility
- More budget security
- Better maintenance management
- Use of more integrated services
- Better deals when dealing with larger quantities
- Strengthen and promoting the sector
- Less administration for the contractor (smaller government)

(Schoenmaker, De ingeslagen weg, 2011, p. 6)
(Original sources: Austroads, 2003; ERANet, 2009; FHWA, 2002; Koppinen & Lahdenpera, 2004a, 2004b; NCHRP, 2003, 2009; Pakkala, 2002; Pakkala et al., 2007)

Because this thesis focuses on the maintenance contracts, the definition of maintenance is needed to get a better understanding of the context of this work. Therefore, it is defined by the CEN-EN 13306 as follows:

‘Maintenance’

- *Combination of all technical, administrative and managerial 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*

(European Committee for Standardization, 2010)

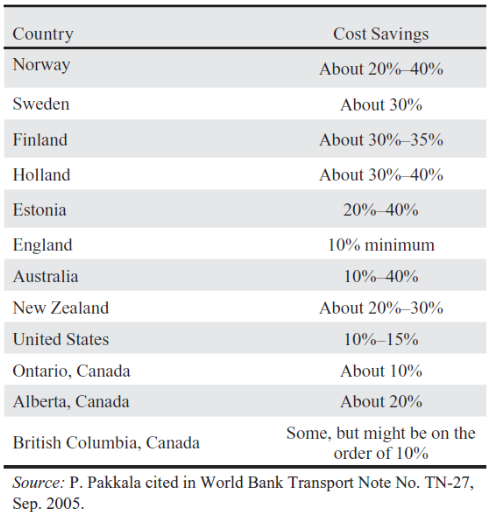
A lot of decisions must be made when designing a performance contact for maintenance. However, the considerations when being compared to the construction of new infrastructure are different. Uncertainty about the current state and the behavior over the following years of existing infrastructure make it hard to predict the necessary maintenance and with it the design of the maintenance contract. The performance-based maintenance contract makes the prediction even harder because the goal is to use the performance as a measuring tool for good, acceptable of bad effort of the contractor. But when the Performance Levels are unpredictable, acceptable expectations for the contractor will be hard to come up with. The CA will therefore need certain tools and mechanisms to deal with this uncertainty without burdening the contractor with unrealistic demands and expectations, together with the goal of reaching an acceptable outcome of the contract for all involved parties.

Within these performance-based maintenance contracts (from now on, PBMC) the CA can steer the outcome of a contract by building in a variety of mechanisms. A few variables through which the client can steer the contract are the size or scope of the contract, the contribution of the contractor (degree of autonomy) and the performance requirements that are used (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017). These variables will largely determine the way the client and the contractor will be collaborating during the contracting period and will have great influence on the outcome of the contract.

1.1.3 Reasons and risks of using performance-based maintenance contracts

The potential benefits of using PBMC is a trigger for many organizations to use these contracts, both here in the Netherlands and abroad. The decision to do this is strengthened by an international research performed by the American NCHRP (National Cooperative Highway Research Program). In this research, cost savings of up to 40% are shown when outsourcing using performance contracts relative to using traditional contracts.

When looking at the figures, as defined in Figure 1, the outcome of the use of PBMC with respect to cost savings is very promising. The numbers however are almost certainly derived from expert judgement and originate from several different contracts. Because every contract is made with different goals, executed under different circumstances, having a different input, different measurement methodology and different degree of efficiency, it is hard to compare them with one other. In the end it remains unknown which criteria were used to select the projects that were examined during this research and how the results were interpreted before they ended up as cost saving percentages in this table.



Country	Cost Savings
Norway	About 20%–40%
Sweden	About 30%
Finland	About 30%–35%
Holland	About 30%–40%
Estonia	20%–40%
England	10% minimum
Australia	10%–40%
New Zealand	About 20%–30%
United States	10%–15%
Ontario, Canada	About 10%
Alberta, Canada	About 20%
British Columbia, Canada	Some, but might be on the order of 10%

Source: P. Pakkala cited in World Bank Transport Note No. TN-27, Sep. 2005.

Figure 1: Cost savings of PBMC relative to conventional contracts in selected countries

Because of the positive attitude towards these contracting types, they're now frequently used in the Netherlands. The PBMC are often used to organize the multi-year maintenance of transport infrastructure assets owned by major players like Rijkswaterstaat (2017), ProRail (2017), provinces and municipalities (Dienst Beheer Infrastructuur Provincie Zuid-Holland, 2016). But these types of contracts are not just popular in the Netherlands. Especially when it concerns road maintenance there is a worldwide interest in using these contracts. Amongst other countries, the performance-based maintenance contracts are used in developed and developing countries such as Argentina, Australia, England, Finland, USA, Uruguay, Chile, New Zealand, Columbia, Brazil and Peru (Zietlow, 2005) (Pakkala, 2005).

Besides the potential benefits that the performance contracts have to offer, there are also a considirable amount of possible downsides and risks. Furthermore, some benefits can even become downsides or risks when they are handled incorrectly. The challenge therefore is to draft the contract in such a way that the maximum amount of the benefits will be achieved, with a minimal amount of downsides and risks. In figure 2, a list of potential risks that can occur when using a PBMC is shown. The list was put together by Schoenmaker (2011) using various sources as shown in this figure.

Wrong Performance Requirements
Reduced Market Forces
Reduced Flexibility
Reduced amount of (technical) knowledge with the client
Reduced control of the client
Reduced ability for innovation of the market
Less consistent approach across the market
Misunderstanding and wrong interpretation of the requirements
Determining the right performances
Correct use of performance measurement
Costs of procurement
Lack of experience on one of either side (Contractor/Client)
Lack of willingness at one of either side (Contractor/Client)
Insufficient data on the assets
Information about the current/future state of the assets
Regional development and employment opportunities
Incorrect transfer of risk to the contractor
The consequences of failure

Original source: (AustRoads, 2003), (Highway Agency, 2003), (NHCRP, 2009), (Rijkswaterstaat, 2004)

Figure 2: Risks of performance contracts

1.1.4 Important factors when using performance-based maintenance contracts

The previous sub-chapter shows that there are potential benefits to gain by using PBMC and several players in the infrastructural sector being triggered by this. This is confirmed by the fact that Pro-Rail is engaging in a new set of PBMC (ProRail, 2017), Rijkswaterstaat is using PBMC as their main maintenance contracting method for all their assets (Rijkswaterstaat, Prestatiecontracten, 2017) and WTC Schiphol Airport which started using PBMC for their assets (Platform Duurzame Huisvesting, 2016). The popularity of these contracts provides all the more reason to make sure that these contracts perform at their best, but this is currently not always the case.

The use of PBMC does not always guarantee success and does not always deliver a win-win situation for both the client and contractor. According to van Rhee (2011) this can in most cases be traced back to bad implementation or by pursuing the wrong goals. This is comparable to the conclusion that was drawn by the Public-Private Infrastructure Advisory Facility (PPIAF, 2014) that concluded that the design of the contract is very important to the eventual outcome. Since many aspects influencing the outcome of a contract are already laid out in the design, it can be assumed that an unsatisfying outcome of a contract has (accidently) already been built into the contract from the start.

This is due to the inherent aspects, processes and risks that are being outsourced based on performance specifications. Poor judgement or making the wrong considerations can result in bad implementation of the performance contract. Setting wrong targets or using unrealistic allocation of risk can also lead to unwanted results. Furthermore, it can happen that unfavorable chosen performance indicators or wrongly used incentives can lead to contradictory/paradoxical behavior of the contractor during the contract period. This can lead to unsatisfactory, or at least sub-optimal, results. Because of the pre-determined (long) periods of most contracts, this is most undesirable. It is therefore very important to know what should be in the contract, why it should be in the contract and how to put it in de contract.

These opinions are shared by Hennes de Ridder, who wrote an article about the concerns they have on the use of performance contracts within Rijkswaterstaat. According to de Ridder (2006), the effort it takes to make these performance-based contracts work is underestimated by all involved parties. The contracts will only be successful if they are well thought through on a strategic, tactical and operational level. This means that careful considerations must be made on how the work is being outsourced. At the time of publication of this article, Rijkswaterstaat did not leave enough room for the contractors to be creative or innovative. Rijkswaterstaat continued to prescribe many of the activities and the possible advantages of the performance contracts were harder (if not impossible) to be achieved by the contractors.

During the creation of the contracts, there should be enough knowledge and experience about the decisions that need to be made, and the fact that they are fundamental to the outcome of the contract. The room for innovation and creativity is already being demarcated there. This demarcation is not inferior, but there must be a good reason to decide whether to prescribe an activity, rather than request a performance or vice versa. Fair and realistic allocation of risk can be a good reason to choose one over the other. Eventually the goal is to create a contract where both prescribed activities and required performances are balanced which work together to reach the goals that were set.

Decisions that need to be made during the design phase of the contract have to do with, its financing, the length or duration of the contract, division of risks and the contents of the contract (PPIAF, 2014). Another important aspect of using performance-based contracts, is the ability to measure certain performances. The way the performances can be measured, combined with a certain payment structure, will influence the way the contract will function (Schoenmaker, De ingeslagen weg, 2011).

To outsource an object using a performance-based maintenance contract, four questions need to be answered:

1. What is being outsourced?
2. Who is performing which tasks (responsibility)?
3. What are the performance requirements that will be used?
4. How will the contract be governed?

The combined answer to these questions will enable the people responsible for writing the contract to do just that. But getting the answers to these questions requires a lot of considerations, decision making, information gathering and interpretation of results. Considerations about certain aspects that are relevant are the following:

- The object that is being outsourced
- Performance indicators and incentives
- The governance
- The division of roles

(Schoenmaker, De ingeslagen weg, 2011)

In order to give an answer to these questions, whilst making the right considerations during the development of the contract, a good process is needed to make sure that all the available and necessary information is used. But at this time there is no clear overview of all the information that could be used, how certain data could be used and what considerations are important to make when designing a performance-based maintenance contract. There are many different data sources available (depending on the object that is being outsourced) that might be useful. Many different tools and techniques to gain information about a certain object can help in the decision-making when writing a PBMC. The big problem however is there is no literature on how these different sources of information, tools and techniques can be used to provide support in making a functioning PBMC.

1.2 Problem statement

The use of performance-based maintenance contracts is becoming an important part of outsourcing maintenance and will become increasingly important for maintenance in the infrastructure sector. The aforementioned statements however suggest that the outcome of a PBMC is highly dependent of the many difficult considerations that are involved during the contract design. The decisions during the contract design phase are influenced by the huge load of information and the use of many different tools and techniques to process that information. The outcome of that process will define the way objects are outsourced and for a great part also define the success or failure of these maintenance contracts.

While the use of PBMC is getting increasingly popular, the knowledge about the process of creating these contracts is still marginal. Literature that helps the designers of these contracts with the process of creating a PBMC is missing. Information about the possibilities within the contract and the variables that are available to manage the contract are spread out through several books and papers. The same goes for the considerations that need to be made when making decisions on how the outsourcing of certain objects will be put in the contract. The main problem is that there is a lot of information and data available, but no structured way to process that information and data in such a way that it becomes helpful when developing a new PMBC. In other words, there is no standardized method that tells the contract design team what information or data is useful and how to use it. Furthermore, a structured method that helps them to determine suitable parameters based on which a PBMC can be drafted are not clearly defined in literature.

The following problem statement is formulated.

> ‟There is no standardized way in literature that helps to find suitable parameters for drafting a Performance-Based Maintenance Contract.ˮ

1.2.1 Research objective

The objective of this research consists of two separate parts, both necessary to find the solution to the problem. The first objective is to find the suitable parameters to draft performance-based maintenance contract. The second part consists of finding a structured method to find information that helps making informed decisions about the use of the parameters based on which a performance-based maintenance contract can be drawn. The structured process should be used in an early stage of the contracting phase, in order to provide early indications on what the eventual contract will look like.

The research objective is formulated below.

> ''The objective is to find a structured way for the contracting team to find suitable parameters in an early stage of the process in drafting the Performance-Based Maintenance Contract.''

1.2.2 Main question

The main research question is aimed at creating a way to assist contract design teams finding suitable parameters for the design of performance-based maintenance contracts by helping them find usable information to make informed decisions about the parameters while designing the contract.

The main research question is therefore formulated as follows:

> ''Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?''

1.2.3 Sub-research questions

To find a good answer to the main research question, it will be supported by several sub research questions. These questions are aimed at finding the necessary theory needed to answer the main question.

1. What parameters should be used by the contracting team during the design phase of a performance-based maintenance contract?
   Provides a set of solutions that can be used to assist the contracting teams when designing new performance-based maintenance contracts.
2. What information should be available, and how should this be used to assist the contracting design team in setting the parameters in such a way that they suit the individual and specific needs of an object?
   focuses on the kind of information that is necessary, how to gather, analyze and interpret it to help the contracting teams take informed decisions in setting the parameters for individual cases.
3. What steps should be taken to find informed answers in a structured way based on which a performance-based maintenance contract can be drawn?
   Design a support method that consists of steps that help the contract design team when making decisions about the use of the parameters based on which a PBMC can be drawn.
4. What are the results of the technical application of the support method to real case examples?
   A case study is used to find out how it performs during the application of real case examples. Based on these results, improvements can be proposed to the original design.
5. What are the expert opinions on the practical application of the decision-support method on real case examples?
   The possibilities of the practical application of the support method are discussed during the expert meeting in order to get their findings for further improvements of the method. The expert meeting is also used to confirm the applicability of the method to real cases.

Chapter 2

Research design

This chapter is used to explain the plan of execution for this research. For this purpose, the research framework and research methodology is introduced. The chapter concludes with the reading guide, providing a detailed overview of contents found in the three main parts of this report.

2

2. Research design

The main research question of this thesis is formulated in the previous chapter. This question reads as follows:

''Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?''

Sub-research questions will be used during the thesis in order to come up with a reliable and satisfying answer to the main research question. This chapter of the thesis will elaborate the research design and the plan of execution that is used for this thesis. The research framework is designed, followed by the methodology that is used during the execution of the research. In the end, a reading guide and a section about the research approach is added to give a more details about the contents of this thesis.

2.1 Research framework

The research framework is following around the steps described by Verschuren en Doorewaard (Designing a Research Project, 2013). The method described divides the research into four separate steps:

1) Find the theories needed to create a perspective to start working from. This theoretical framework (literature study) will help create a 'to be' situation. In the case of this thesis, the first conceptual model of the support method will be formed.
2) Confront the conceptual model of the 'to be' situation with the current 'as is' situation during the case study. This step entails the collection of results of the case study. The results are then pushed on to step 3, where the results are analyzed. It remains possible that the results of this analysis suggest the need to redesign the conceptual model, in which case the information is pushed back to step 2.
3) Compare and analyze all the results, after which one of two options will be available. The possibility remains to apply changes to the current model, either by going back to step b, or by making minor changes and continue in the process of validating the current model.
4) The last step is the conclusion of the model. The eventual result of the previous steps is presented here.

The research that is conducted in this thesis elaborates the earlier works by Rob Schoenmaker about the dynamics of outsourcing maintenance within the Civil infrastructure sector (Schoenmaker, De ingeslagen weg, 2011). This literature is complemented by works on the use of the Six-Stage model (Schoenmaker & Verlaan, Analysing Outsourcing Policies in an Asset Magement Context: A Six-Stage Model, 2013), the dynamics of outsourcing through PBMC (Schoenmaker, de Bruijn, & Herder, The dynamics of outsourcing maintenance of civil infrastructure in performance based contracts, 2013) and the use of PBMC in general (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017). Within this literature collection a start will be made on how these PBMCs should be designed, or at least what options are available. There is, however, no clear structure available to use when designing the PBMC. The goal of this thesis is to continue the way of thinking that is presented here and try complement it with a structure that will help the contract design teams in drafting new PBMC. Because this work continues previous works that are associated with civil engineering domain, this thesis is also written from a civil engineering perspective.

2.2 Research methodology

The research framework shows that there are roughly 4 main steps during the research. This sub-chapter will elaborate the details of the individual steps. These steps are based on the 4 steps of Verschuren en Doorewaard (2013). Step 1 is used to define a 'to be' situation based on literature study. Step 2 is used to confront the design with reality in a case study. Step 3 is used to analyze these results and gain new insights on how to optimize the original design. The original design is then refined during step 2 and the same process is repeated. Eventually, the conclusion presented in step 4.

During step 1, different theories will be analyzed in order to define a theoretical framework to be used during this thesis. A clear definition of the PBMC for this report needs to be established, as well as decision criteria which need to be used when designing one. Next, the parameters that will be used to navigate the solutions space of a PBMC need to be found, defined and explained in order to be used in a later stage of the thesis. The last part of the literature study is used to explain the Reliability Centered Maintenance (RCM) and the use of a risk register and FMECA (Failure Mode Effects & Criticality Analysis). Also, the use of the risk allocation matrix will be introduced. These last parts are used to gain information and/or help making decisions within the solutions space of the PBMC.

Based on the information gathered during this first step, a conceptual model of a decision-support method can be designed. This conceptual model will then function as the initial input for the case study which will be performed during step 2. The case study is (initially) used to test the technical application the conceptual model. The results are then analyzed during step 3. If the results suggest that changes or redesign of the conceptual model is necessary, that input is given back to step 2. Based on these suggestions changes can be made to the conceptual model, creating a version 2. After the redesign is done, a second run of the case study will be performed to test the technical application of this enhanced model. The results of the second run are then analyzed during step 3. This can result to a repetition of the previous steps, if radical changes are still suggested. If this is not the case, an expert meeting can be arranged to validate the latest model by discussing its practical application.

Based on the results of the case study and the outcome of the expert meeting, a final design for the decision-support method will be made. This version will be presented in the conclusion of the thesis. This will be done along with recommendations about further research and things that still need to be improved on the current model. There will also be a section that shows what elaboration these results have on the initial work by Rob Schoenmaker and the domain of civil engineering.

The next sub-chapter will elaborate on the case study and the validation using an expert meeting.

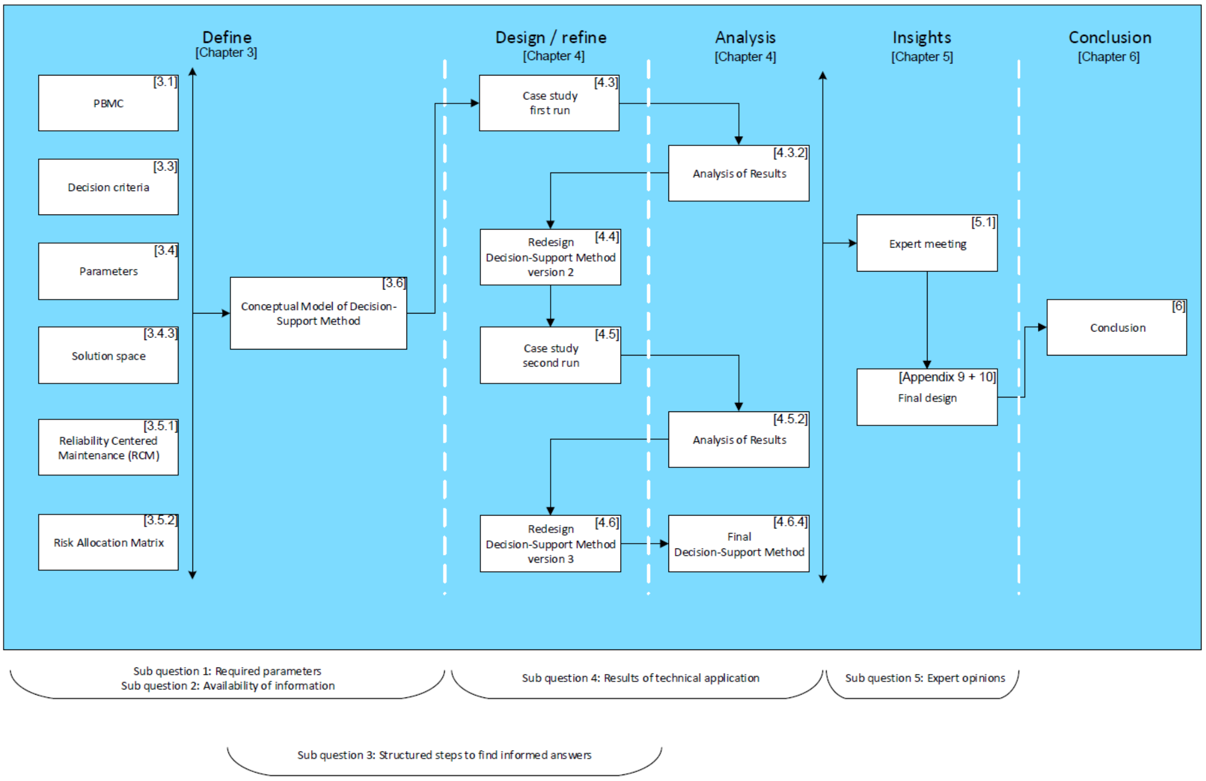


Figure 3: Methodology flowchart

2.3 Case study methodology

The literature found and evaluated during the first part of the thesis is used to create a conceptual model for a decision-support method. When the first conceptual model has been realized, the case study is introduced. The goal of this case study is to test the technical performance of the conceptual model and use the results to improve the method. The improved model will then be tested again during a second run of the case study. The results of this second run will be used to improve the method once more. The result of the case study is a model that technically works and provides a 'to be' situation.

The case study is done during the development of the decision-support method right after the design of the conceptual model is finished. This is when the initial steps of the method are chosen and worked out based on the theoretical framework. At that point, the theory supporting the steps should be clear before to ensure that the steps can be executed during the case study. The boundary conditions of the case study are decided in consultation with the experts of Rijkswaterstaat to have a realistic case, without having to find the actual information or making realistic assumptions. This suffices the goal of this case study, which is checks whether the chosen steps technically work as they supposed to and what information or steps might still be missing. Because the main intention of the case study is to check the technical performance of the decision-support method, it was decided that one case will suffice. It was however decided that at least two separate runs would be needed to make the necessary adjustments to the decision-support method in order to improve the method along the way. At this stage is spoken of 'at least two runs' because this will also depend on the results that are found during these first two runs of the case study.

2.3.1 Case selection

The case that is chosen for this case study should fit within a range of boundary conditions. In order to select a suitable case that will deliver usable results, a selection needs to be made based on several criteria. These criteria are chosen to provide a case of which enough data can be found, has enough depth to perform a thorough case study and able to test all the steps of the decision-support method and be an 'average' case of civil transport infrastructure. Besides the previously mentioned criteria, the case must have a connection to the main research question. These criteria are the following:

- The case should involve an asset or partial asset related to civil transport infrastructure
- The asset is currently subjected to a performance-based contract
- The asset is managed by a (semi-)governmental organization
- The asset is in the operation and maintenance phase
- The asset is NOT in the first or last 15 years of the projected lifetime
- The asset is NOT currently subject to renovation

Most of the criteria above are chosen to ensure that a general case is selected. With these criteria the chance of getting anomalies during the case are kept to a minimum, improving the reliability of the results. The criteria also fit the main research question in ensuring that the field is PBMC and stays within the area of civil infrastructure. For this thesis, it is chosen to limit to one case and performing two runs of the case study. This is done to be able to compare the results of the two runs and be able to see whether the improvements did work. The case study is mainly used to test the technical functioning of the steps that are introduced and provide input for improvements.

The type of asset that chosen for the case study is a tunnel. The decision is made because this thesis is written at Rijkswaterstaat as part of *PPO Tunnelteam II*. Furthermore, tunnels provide a lot of challenges within many fields of expertise that can be found throughout the domain of civil engineering. Within the portfolio of Rijkswaterstaat, several tunnels can be chosen. Based on the criteria that were set, some tunnels are not suitable.

The next table shows the criteria which were used to decide which tunnel was most suitable for use during the case study. After the that, the eventual decision is taken and explained.

Tunnel	Civil infra	PBC	Governmental	Operational	Age	Renovation
1st Heijnenoord	+	+	+	+	+	-
2nd Heijnenoord	+	+	+	+	+	-
Sytwende	+	+	+	+	-	+
Ketheltunnel	+	+	+	+	-	+
1st Benelux	+	+	+	+	-	-
2nd Benelux	+	+	+	+	-	+
Drechttunnel	+	+	+	+	+	+
Noordtunnel	**+**	**+**	**+**	**+**	**+**	**+**

Table 1: Tunnel criteria for the case study

- 1st and 2nd Heijnenoord tunnels are now subject to renovation and therefore not suitable as a case
- Sytwende tunnel is relatively new (just 15 years old).
- Ketheltunnel has just been delivered and is therefore too young

Three (technically four) tunnels seem to be meeting all the criteria
- 1st and 2nd Beneluxtunnel (1967 and 2002)
- Drechttunnel (1977)
- Noordtunnel (1992)

The eventual choice is made between the three cases above. The Beneluxtunnel will be excluded because there are technically two tunnels with different ages. This leaves the Drechttunnel and the Noordtunnel. The Noordtunnel is youngest of the two. This tunnel is old enough to be past all problems that relatively new tunnels have and old enough to have enough available data. The Drechttunnel is a bit older and therefore closer to renovation. To get an 'average' result that can be used and analyzed without having to deal with anomalies, the decision was made to choose the Noordtunnel as case for the case study during the development of the decision-support method.

2.3.2 Practical execution of the case study

The case study will be performed on the Noordtunnel. Before any further steps of either the decision-support method can be taken, basic information about the tunnel is needed. Every run of the case study is started with an introduction of the case/subject, finding basic information and already start with the collection of data that will be useful during the remainder of the process.

After the case introduction, the steps of the decision-support method are used. During the first run of the case study, the step of the conceptual model is used. During the second run, the improved steps are used, perhaps complemented with extra steps that were introduced based on the results of the first run. Every step is seen separately. Each step should be clear on how it is done, how it performed and what comments can be made on the performance of that step. Based on that information a proposal for improvement can be made and documented.

After the first run, the comments and proposals for improvement are analyzed. That information will be used as input for the second version of the decision-support method. The same routine will then be used during the second run of the case study. Proving yet another set of comments and proposals for improvement. This will then lead to a third improved version of the decision-support method.

It is important that every step and every consideration that is made is written down during the case study. All to ensure that the reason for all changes can be traced back and motivated during the conclusions of this thesis.

2.4 Expert validation methodology

The validation is an important part of this thesis. During the case study the technical performance of the decision-support method is tested through expert meetings. During the expert meeting both the technical performance and the practical application will be topic of discussion. The emphasis during the meeting will be, however, on the practical application.

During the expert validation meeting the decision-support method that has been developed during this thesis is presented. Every step of the method is introduced, explained and discussed. During the discussion, the experts will comment on the technical use of the steps and the practical application of the steps on real cases. The goal is to do this by referring to the case study that was done during this thesis. The goal of the expert meeting is to learn whether they think that the decision-support method can help them while designing a PBMC in the future. Which steps are promising, and which steps might need further research? Eventually the case study and the expert meeting will be the base of the conclusions and recommendations that will be given about this thesis.

2.4.1 Expert meeting

For the validation to commence, the decision-support method should be in its final form after the case study. Minor textual changes can still be made, but the core of the method should be there and should be clear and ready to use. The validation is done through a group session with experts responsible for drafting a PBMC. People working on contract design teams, technical advisors and the managers within Rijkswaterstaat will be invited to comment on the method during this meeting. The meeting will start with a presentation where the overall idea of the decision-support method is presented. Then every individual step will be discussed amongst the experts that are present during the meeting. During the discussion, valuable information that is gained will be documented. The suggestions that the experts make will be used to perform a last improvement will be made on the decision-support method, delivering the final version of the method. Improvements that could not be implemented anymore at this time will be added as comments in de final conclusions of this thesis.

During the meeting, all comments and suggestions are categorized per step in order to trace back all changes that are made to reach the final version of the method.

2.5 Reading guide

The reading guide is used to provide more insight in the detailed contents of the report. The execution of the research is roughly divided into three main parts. Those are explained below. A visual representation of the thesis is added in the next part.

The execution of the research is the core of this thesis and can be divided into three main phases:

➢ Phase I	(1)	Literature Research & Conceptual Design	[Chapter 3]
➢ Phase II	(2)	Case study & Redesign	[Chapter 4]
➢ Phase III	(3)	Analysis & Validation	[Chapter 4 + 5]

1. **Literature research & conceptual design [Chapter 3]**

   During phase 1, all prerequisites for the decision-support method should be brought together. Finding the theories needed to create a perspective to start working from. Creating a theoretical framework (literature study) that helps creating a 'to be' situation. In the case of this thesis, the first conceptual model of the support method will be formed.

2. **Case study & redesign [Chapter 4]**

   During the second phase, the conceptual model of the 'to be' situation is confronted with the current 'as is' situation during a case study. This step entails the collection of results of the case study. The results are pushed on to phase 3, where the results are analyzed. If the results of the analysis suggest the need for redesign of the conceptual model, the information is pushed back to step 2 where redesign of the model will be done. Another run of the case study on the improved model will then be performed.

3. Analysis & validation [Chapter 4 + 5]

   During phase 3, all the results are compared and analyzed, and one of two options are available. Based on the results, a redesign of the conceptual model might be needed. In that case the model is pushed back to phase 2 for improvements and the improved model will be used in the case study. The second option is finalizing the model (minor changes can still be applied) and have the method validated during an expert meeting. The practical application of the method will be discussed during this meeting. The improvements that will be suggested during this meeting can either be integrated in the final model before the conclusion of the thesis is written or added as comments in the conclusion.

2.5.1 Research approach

During this research, the assumption is made that the decision to outsource maintenance using a PBMC has already been made by the contracting authority (CA). The scope of the work has been demarcated and the boundary conditions of the organization of the CA have been set. This means that the research is limited to how the work is being outsourced using a PBMC and not if or what is going to be outsourced. The focus will be on the decisions that need to be made by the contracting team of the CA when drafting the contract.

The first step is to get more knowledge about **performance-based maintenance contracts (PBMC) [3.1]**. Information about the use of PBMC is acquired through literature study and used to find out how these contracts work. Knowledge about how the contracts work is necessary to discover parameters that can be used while designing such a contract. It is also important to find out what possibilities are available using the mechanisms that can be built into the contract. By doing so it should become clear how much margin is available to the contracting team for maneuvering during the design of the contract.

The information about the PBMC is used to find **suitable parameters [3.4]** that are necessary to design a contract. The parameters are very important for this thesis because the eventual decision-support method will be designed around those parameters. The parameters are used to understand what decisions need to be made by the contracting team of the CA in order design a functional contract. These parameters will be found by looking at the **considerations [3.3]** that the contract design teams need during the design of the contract. These considerations will be narrowed to a set of **decision criteria [3.3]** that are being used to find suitable parameters and as a guideline during the entire decision-support method.

Having suitable parameters alone doesn't help the contracting team of the CA to make the decisions on how to outsource certain objects. In order to support them in their decision-making process, a range needs to be determined for the parameters. **The range of the parameters [3.4]** are the combined options that the contracting team can use when designing the contract. This can be described as some sort of solution space in which the most suitable answer can be found. This is where the work of Schoenmaker (2011) about the **six-stage model [3.4]** is introduced.

The task of the contracting team is to find a suitable solution by **tuning the parameters [3.4]**. In order to make an informed decision, a lot of information need to be processed. During this thesis, one of the goals is to find out which factors influence the decision-making. Furthermore, attention is given to the tools and techniques that can be used to acquire and interpret information about these factors. Tools and techniques that are being highlighted for this purpose during the literature study are: **reliability centered maintenance (RCM), the risk matrix , the risk register and the risk allocation matrix [3.5].**

In order complete the tuning process, all factors that influence the parameters need to be evaluated based on the information that has been found. This is where the beforementioned **considerations and decision criteria [3.3]** come in again. During the literature study an indication on the most important subjects that need to be considered when designing a PBMC can be found. Using the literature study, a list of considerations will be compiled at categorized by the subject it influences. The most important subjects, and thus the subjects that are expected to have the greatest effect on the outcome of the contract, are embedded in the decision-support method. It is not said that less important subjects are neglected, but they are less prominent when using the method.

At this stage, enough information should be gathered to develop a **conceptual model of the decision-support method [3.6]**. The method combines all the findings from the previous parts and brings it together in one clear walkthrough. An important part of the success of the method is the ability to use and reproduce the methodology without prior knowledge of this method. The explanation of the various steps and the specifications of all the information, tools and techniques that are used need to become clear.

The **first case study [4.3]** can then be performed with the conceptual model. During the case study, the technical application of the first version of the decision-support method is tested. Results are then analyzed and used to suggest improvements on the method. These improvements are then implemented, and a **second version of the decision-support method is created [4.4]**. This version is then used during a **second run of the case study [4.5]**. The results of the second run are also analyzed and used to make some last improvements to the method. This will result in a **third version of the decision-support method [4.6]**. This version is then ready to be checked for its practical applicability.

The practical application of the decision-support method is up for discussion during the **expert meeting [5.1]**. During this meeting, the steps of the method are **evaluated [5.1]** by an expert group and provided with comments and suggestions for improvement. The results of the meeting are used to make last improvements to the method and create the final version of the decision-support method and **validate [5.2]** the work that has been done during this thesis. The comments and improvements that are not taken into the final method will be mentioned during the conclusion or suggested as future improvements.

Based on the results of the case study and the expert meeting, the final version of the decision-support method is presented during the **conclusion [chapter 6]** of this thesis and the **main research question [6.4]** will be answered. A conclusion is given about the use and applicability of the method in its current state and in the future. Besides commenting on the results, **recommendations [6.6]** are given about **future improvements** and **new research angles [7.2]** that might be wort looking into.

Chapter 3

Literature study

This chapter is used to explain and introduce the decision-support method for the first time. Literature is used to find the most important steps and information that is needed when designing a performance-based maintenance contract. The result of this chapter is a conceptual model of the decision-support method combining all those steps.

3

3. Literature study

The literature study marks the beginning of finding information to answer the main research question of this thesis. The main research question reads as follow:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

The literature study consists of 6 separate parts and a conclusion. In the main research question, the PBMC is specifically mentioned. The first part of the literature study is therefore meant to find out what a PBMC is and how it can be used within the domain of civil infrastructure.

The goal of this thesis, which is also defined in the main research question, is to find a structured way to help contract design teams in drafting a new PBMC. The structured way that will be designed during this thesis is called: the decision-support method. The decision-support method will be introduced in the second part of this literature study and thoroughly explain the definition, design and final goal.

The main body of the literature study is dedicated to find what informed decisions regarding PBMC are and how these informed decisions can be taken. Finding this information is crucial to the design of the decision-support method and will be covered in part three and part four of the literature study. The third part is therefore dedicated to finding decision criteria for designing a PBMC. These criteria and information about the PBMC in general are then used to find the parameters that should be used during the design phase of the PBMC in the fourth part of the literature study. The following sub-research question is answered during parts three and four:

'What parameters should be used by the contracting team during the design phase of a Performance-Based Maintenance Contract?'

These two parts indicate the start of answering the second sub-research question, which discusses the information that is required to make informed decisions, as well as where to find enough information finalized by determining a structured way to process it. The second sub-research question reads as follows:

'What information should be available, and how should this be used to assist the contracting design team in setting the parameters in such a way that they suit the individual and specific needs of an object?'

The fourth part defines the range of the parameters and how the decisions need to be made using these variables. The considerations and factors which have direct impact on the decision process will be elaborated as well.

The fifth part of the literature study continues answering the second sub-research question by finding and explaining additional tools and techniques that help obtain and process the information that is needed for the design, development and the practical use of the decision-support method. The use of reliability centered maintenance (RCM) and some corresponding tools are introduced to assist in gathering information and the use of the risk allocation matrix to assess risks when outsourcing (maintenance) work within the domain of civil infrastructure. This tool was found in earlier thesis works by Brommet (2015).

The sixth part of the literature study is the development of the conceptual design of the decision-support method. This part continues answering the second sub-research question mentioned before, and initiates the start of answering the third sub-research question that reads as follows:

'What steps should be taken to find informed answers in a structured way based on which a Performance-Based Maintenance Contract can be drawn?'

Based on the information found during steps one to five, the conceptual design which will be used during the case study will be formulated.

The last part of this chapter is used to summarize the information found during the literature study and define how it will be used in the following steps of the process.

3.1 Performance-based maintenance contracts

A performance-based contract (PBC) is a contract where parties agree on delivering performances instead of performing activities. The PBC is used to define agreements on quantifiable & measurable goals and manages the responsibilities for achieving those goals. The starting point for defining the required performances is usually the goals specific to CA and the user. Examples of these starting points are the availability, reliability and maintainability of the product and the lifecycle cost. These goals are then used to define the following goals for the contractor, which are then broken down into performances that must be delivered. Through incentives and penalties, the contractor will be motivated to deliver the required performances. Through this type of contract, the CA and the contractor have aligned interests which leads to the determination of the responsibility for the execution of the work. The strong points of both parties will be maximized and the risks are assigned to the party who can manage them best. (van Rhee, Kaelen, & van de Voort, Performance Based Contracting - Waarom, wanneer, wat, hoe?, 2009)

The client is free to use any methods or materials (provided that minimal requirements set in the contract are achieved) to achieve the goals when using PBC. The CA specifies performance indicators (or levels of service) that the contractor is required to meet when delivering maintenance services. The payment mechanisms are linked to the performances of the completed work or delivered services. Payments are made for measured output and not for the quantity of input by the contractor.

An important note is that within the PBC, there is room for more traditional methods of outsourcing as well. This means that the CA can choose for a 'hybrid' form, where both PBC and traditional contracting methods can be used altogether. Some services will be paid on a unit rate basis, while others based on performance indicators. This also means that different levels of performance requirements can be used within one contract. (Stankevich, Qureshi, & Queiroz, 2005)

A performance-based maintenance contract (PBMC) may cover only individual assets (only traffic lights or road signs) or all road assets within a corridor. The complexity of a PBMC can be classified as 'simple' or 'comprehensive', depending on the number of assets and the range of services that are included in the contract. A 'simple' PBMC would cover a single service (e.g. only mowing) and could be awarded for relatively short periods of time (between several months to a year). A 'comprehensive' PBMC would cover all road assets and a full range of services needed to manage and maintain the contracted corridor. Such services are very flexible and can include routine maintenance, periodic maintenance and traffic accident assistance, etc. The contracting period of these contracts is usually 3 to 10 years (Stankevich, Qureshi, & Queiroz, 2005). Both Stankevich and van Rhee describe comparable steps: the preparation, the draft of the PBMC and eventual implementation. The decision-support method will be designed to be used during the first steps of the preparatory process of drafting a PBMC. For this reason, only these steps are highlighted in this report. The remaining steps can be found in literature of Van Rhee and Stankevich (van Rhee, Kaelen, & van de Voort, 2009) (Stankevich, Qureshi, & Queiroz, 2005).

According to van Rhee (2009) the first step is to decide the scope and the phasing of the PBMC strategy. This means that a decision needs to be made on two essential questions:

- What performances need to be guarded?
- What will be the scope of the contract?

Stankevich, Qureshi, & Queiroz (2005) starts off with an 'Inventory of potentially contracted assets and determination of their condition' and 'finding performance indicators'. This is roughly the same as van Rhee is suggests.

Important decisions about the scope and content of the contract need to be taken in a very early stage of the contract design phase. These decisions will have a great impact and decide how the contract will be designed, how it will work and what potential outcome it will have. choices need to be made on many aspects, for instance the sub-scope of the work, the amount of risk each party can and will bear, the amount of dependency that is acceptable, the way performance requirements can and will be used and the payment mechanisms that can and will be used. According to van Rhee, determining the scope is finding the balance between controllability, dependency, flexibility, cost and risk.

3.2 Introducing a decision-support method for designing a PBMC

The goal of this thesis is to find a structured way that can help the contract design teams in making informed decisions when designing a PBMC. During this literature study, the tools, techniques and information that is necessary to be able to help the contract design teams in their decision making will be gathered. In order to make these tools and techniques accessible, a structured method is needed to act as a framework. A new methodology therefore is introduced here. This methodology will be known as:

'The decision-support method'

As the name suggests, this method is meant to support the contract design teams in their decision-making process. The decision-support method consists of several steps and uses different tools and techniques to assist the contract design in making the same considerations about different parts of the contract repetitively. That way every part of the contract is evaluated in the same way and decisions can be made based on the same decision criteria. The outcome of the method is a list of suggestions on how to outsource specific parts of the entire contract. This means that for every specific aspect, the decision-support method will suggest in what way it should be outsourced based on relevant considerations and decision criteria. What these are will be found out during the literature study. The experts within the team can use the information that is obtained through the decision-support method as a base to write the eventual contract. It is impossible to take all considerations into account in just one method, thus the outcome is always a suggestion for a solution. This suggestion is based on technical information about the object that is available. Therefore, it can happen that expert judgement will decide that there is a better or more suitable solution for that specific part based on information that was not provided as input for the decision-support method. Company orders, for instance, might be a reason to deviate from the suggested solutions.

The decision-support method can be implemented when a PBMC is going to be used. The method serves its goal best when it is used in a very early stage of the contract design process. This method encourages to find specific useful information to aid the design team in making their decisions based on relevant considerations and decision criteria. Furthermore, it helps evaluate every decision in a consistent way. Eventually when the method is used, the contract design team has a strong foundation to start designing the actual contract.

In literature, no clear and unambiguous method can be found to address this issue. In order to make these informed decisions, the remaining part of the literature study is used to find the necessary unaddressed information, tools and techniques in order to make a conceptual design for the decision support method.

3.3 Decision criteria for PBMC

The decision-support method will consist of several steps, in each step, certain decision needs to be taken regarding the way of outsourcing a certain part of the contract. In this chapter the consideration factors and the decision criteria that need to be considered when designing a PBMC will be introduced.

In the first part, the consideration factors of designing a PBMC will be found based on numerous authors that have written about the problems that are encountered when designing PBMC.

The second part is dedicated to the decision criteria. The decision criteria are found when taking all the consideration factors and categorizing them into different types. The types of considerations that occur most frequently can then be used as the main decision criteria. These main decision criteria are the most important factors that 'at least' need to be considered when designing a PBMC.

3.3.1 Consideration factors

The consideration factors are found by searching for literature regarding the design of PBMC with the emphasis on the relevant aspects that need to be taken into consideration. There are many different aspects that will be mentioned during this chapter, too many to take into consideration one-by-one. But eventually, all factors will be taken into account which influence the outcome of a contract. The challenge remains to deal with all these consideration factors in a structured way. The eventual goal is to find the most important or most influencing factors. The first step is to create list of consideration factors which according to Schoenmaker (De ingeslagen weg, 2011), play a significant role in designing the eventual contract. Making decisions when designing PBMC requires the considerations on many relevant aspects:

- The object that is being outsourced
- Performance indicators and incentives
- The governance
- The division of roles

These aspect align with the first steps that van Rhee (2009) and Stankevich, Qureshi, & Queiroz (2005) suggest in their work. These are taken as the main aspects that need consideration when starting the draft of a PBMC. Although, there are many more things that need considering such as aspects that are related to the ability of the parties within the PBMC and the way the PBMC needs to be structured.

The PPIAF (2014) (Public-Private Infrastructure Advisory Facility) has published an article about the lessons learned in output- and performance-based road maintenance contracts. In this article, several factors are mentioned that need to be considered when designing output-based contracts. These considerations must be made in order to assure that the PBMC has benefits compared to traditional contracts. The important factors that are mentioned in the article are:

Affordability:	Is the government able to meet its long-term financial liabilities?
Incentive structure:	Does the contract have standards that encourage private operators to be efficient, innovative, transparent, responsible and reliant?
Risk Allocations:	Are risks allocated to the public and private parties who are most able to bear them, to optimize the efficiency of the contract?
Contract scope:	Does the scope of the contract allow for economies of scale to be achieved? Is the scope of the contract manageable for the relevant public agency? Does the scope allow for synergies to be achieved or will innovative approaches to be used?
Length:	Is the contract period long enough to transfer life-cycle risks to private operators? Is it sufficiently long for private investors to earn a return on any investment?

(PPIAF, 2014)

Another important aspect of the PBMCs that need to be considered is the performance aspect. Questions that can be asked in regards to the performance aspect are:

- To what extent is it possible to measure the performances?
- What is known about them?
- Can they be controlled?
- Can a payment mechanism be couple to a performance
- Etc.

Schoenmaker (2011), for instance, named 5 features that could make performance measuring problematic, thus important to consider before a PBMC is drafted:

- The degree of complexity;
- The degree of autonomy;
- The degree of temporal mismatch;
- The degree of innovation and dynamics;
- The degree of unknown issues – unknowns, unknowables.

(Schoenmaker, De ingeslagen weg, 2011, pp. 32-46)

To understand how these features make performance measurements difficult, the degree of complexity is explained below as described by Schoenmaker (2011).

A high level of complexity can make performance measurement problematic. The degree of complexity of a system is the result of the characteristics of the elements, the nature and the dynamics of the relations between these elements. The characteristics of the actors (CA, contractor, owner) that are involved with these systems also contribute to the overall complexity. A distinction is made between:

- **administrative complexity**: interaction between actors that influence the decision-making process;
- **technical complexity**: number of components and relation between those components and changes in these relationships;
- **constructive complexity:** the extent to which the client/contractor are able to work with the systems that are in place, low constructive complexity will make performance measurement very difficult.

Problematic performance measurement, by either of the mentioned features, will have consequences on the way the performance requirement is put in the contract. This can result in a situation where parts of the work are outsourced in different ways, using different performance requirements that fit the complicating factors of that specific activity. It therefore becomes an important consideration when writing the contract.

More on the decisions that need to be made, or at least the requirements for using PBMC are written in articles by Pakkala (2005) and Sultana (2012). Pakkala described a set of eight key requirements that need to be met before introducing PBMC:

- Robust and good data of existing road network;
- Good funding stream for maintenance;
- Expertise for good tendering, clear and concise contract language;
- Having common standards on performance measures;
- Good understanding and relationship between client and service providers;
- Partnering or partnering board;
- Head to head competitions among service providers;
- Good communication and sharing of knowledge with all parties.

(Pakkala, 2005)

Sultana already described a similar set of requirements in 2012, bringing up seven issues that need to be considered before introducing PBMC:

- Performance specifications and set up a standard;
- Expertise of the private sector;
- Deciding the initial project;
- Risk exposures;
- Performance monitoring;
- Employee issue;
- Payment and termination of the contract.

(Sultana, Rahman, & Chowdhury, An Overview of Issues to Consider Before Introducing Performance-Based Road Maintenance Contracting, 2012)

To make sure that the full benefits of the performance contracts are being maximized, it is important to create some sense of awareness for the requirements that need to be met when using these contracts for maintenance work. To achieve this, all consideration factors that were found in the literature is compiled in one list of considerations. Every consideration is grouped into different types, clearing out what aspect it would influence. The 14 types that were identified were the following: predictability, plannability, measurability, responsibility, criticality, risk division, available knowledge, prioritizing, suitability, financial, capacity, preparation, diversity of the work and adjustability. Some are found more frequent that others and some will have greater influence than others, but in the end, all of them will be essential and influence the outcome somehow.

The list consists of 63 consideration factors that were subdivided into the 14 types. The table on the right shows the number of occurrences for each type. The complete list of considerations can be found in appendix 1. When analyzing the list, it becomes clear that predictability is the most common type of consideration. Followed by plannability and measurability, both gaining a score of 7. Then responsibility and criticality with 6 points each. Even though all consideration types that come after that are also very essential, the focus will be on the top 5. This does not mean that the other types of considerations are forgotten. Many of them overlap or at least align with the top 5. They will therefore be considered, but not explicitly mentioned in this report.

As previously mentioned, the following types of consideration factors are found to be the most important and will therefore be used as leading consideration factors during the remainder of this thesis: predictability, plannability, measurability, responsibility and criticality. These consideration factors and their corresponding typology will now be used to find suitable parameter that based on which a PBMC can be drafted. Because they have an important role in the decision-making when designing PBMC, they will from now on be referred to as: 'the main decision criteria'. Before the decision criteria can be used in the decision-support method, they need to be clearly defined. This is done in the next part of this chapter.

Type of consideration	Number of occurrences
Predictability	16
Plannability	7
Measurability	7
Responsibility	6
Criticality	6
Risk Division	4
Available knowledge	4
Prioritizing	3
Suitability	3
Financial	2
Capacity	2
Preparation	1
Diversity of work	1
Adjustability	1
TOTAL	63

Table 2: Considerations

3.3.2 Decision criteria

Based on the literature of Pakkala (2005), Schoenmaker (2011) , Sultana (2012) and the PPIAF (2014) more than 60 different considerations were found that are important when outsourcing using PBMC. These five main considerations will be used as the most important decision criteria while using the Decision-Support Method.

The five main decision criteria are: predictability, plannability, measurability, responsibility and criticality.

It is however important to notice that these criteria are made up of several individual consideration factors and therefore represent a group of aspects. It is hard to cover all the individual consideration factors in just one criterion. The next part is used to explain how to interpret these decision criteria and what considerations they are based on. This is done to ensure that it is clear what they mean and how to use them correctly. The explanations are based on information of the 4 sources mentioned before: (Pakkala, 2005), (Schoenmaker, 2011), (Sultana, Rahman, & Chowdhury, 2012) and (PPIAF, 2014). Because the different considerations per category originate from different individual sources, the sources are not mentioned in every occurrence.

The definition of the different decision criteria is found using the consideration factors from which the decision criteria originates, the definitions that are given by several dictionaries and formulated in such a way that they are usable for creating the decision-support method. Only the final definition for each decision criteria is given in this chapter. The elaborate explanation and reasoning behind these definitions can be found in appendix 2

Predictability

To what extent is the behavior of an asset (technical and/or influenced by outside forces) predictable enough to know what maintenance work needs to be done during the contract period, what replacement work can be expected and can count as a base for a cost estimate?

Plannability

To what extent is enough specific technical information and enough financial certainty present to be able to plan maintenance interventions, of which they are confident that will be necessary, throughout the entire length of the contract?

Measurability

To what extent are common standards, specifications and norms on performance measuring available to base measurable performance requirements on and is the Contracting Authority able to monitor those performance requirements sufficiently in relation to the payment regime?

Responsibility

To what extent is a party accountable or to blame for things that happen (negative effects) during the contract period, considering whether these effects were to be expected, are part of the agreement (or not) & therefore the duty of that party and whether this party had decision-making authority to prevent the negative effect from happening?

Criticality

To what extent is a part (of a system) of crucial importance for the functioning of a system or even the entire asset based on the effects it has on downtime, malfunctions, safety issues, costs and nuisance for the users?

3.3.3 Conclusion

This section was used to collect and analyze the many considerations that are present when dealing with, and designing in particular, a PBMC. It was concluded that the eventual list of considerations was too big to integrate in the decision-support method, creating infeasibilities. To avoid the problem of having to deal with too many individual considerations, the considerations where categorized into 14 groups. In order to design an easy to use and clear method, the decision was made to decrease the amount of categories even further. It is important to understand that the remaining categories are not being forgotten, but are not seen as the main decision criteria when designing and using the decision support method. Based on the amount of considerations that were categorized into certain groups, five main decision criteria were found: predictability, plannability, measurability, responsibility and criticality.

The last part of this chapter was used to find clear definitions for these five decision criteria. These definitions will be used for the design of the decision-support method and will give the users a sense of direction on how to use these criteria while using the decision support method when designing a PBMC.

3.4 The parameters of PBMC

The essence of the decision-support method is to help the contracting team of the CA to decide which parameters are suitable for outsourcing a specific set of maintenance activities through a PBMC. This chapter will define the parameters that will be used. During this chapter, sub-research question one will be answered:

'What parameters should be used by the contracting team during the design phase of a Performance-Based Maintenance Contract?'

The definition of the parameters is not just a list of the parameters themselves, but also a suitable range of the parameters that can be used in the decision-support method. The range of the combined parameters will provide the options that will then be used in the decision-support method. In this chapter the main parameters that will be used in the decision-support method will be found. After that, the range of these parameters is defined. The combined range of the parameters provides all options that can be used by the contract design team when drafting a PBMC. During this thesis, this will be referred to as the solution space of a PBMC. consecutively, a part of this chapter is devoted to make the connection between the chosen parameters and the decision criteria. This part describes which decision criteria influences which parameter and why. This information is necessary to understand how to use and interpret the decision-support method. When that is all clear, the last part will explain how the parameters should be tuned.

3.4.1 The three main parameters

The parameters of the decision-support method are adjustable variables that can be used to propose a solution based on a set of consideration factors. These parameters should at least be able to adjust accordingly when dealing with the five main decision criteria which are: predictability, plannability, measurability, responsibility and criticality. The result of the decision-support method is a proposed set of parameters based on which the contract can be written.

The parameters that are chosen, originate from the work of Schoenmaker (2017) about outsourcing maintenance using performance-based contracts. Three parameters are introduced in this work and used as an important part of the contracting process of a PBMC. The three parameters tell something about what parts need to be maintained according to the contract, who is responsible for maintaining those parts and to what extent and how will the maintenance contract be managed. But this is not the only work where this is done. Both the 'what' and 'how' that are used above are mentioned by van Rhee (2009, pp. 29-31) as important steps at the start designing a performance-based contract. In the work of Stankevich (Stankevich, Qureshi, & Queiroz, 2005, pp. 4-5) all three boxes are ticked regarding the parameters above. Both the work by van Rhee and Stankevich, Qureshi & Queiroz elaborate on even more steps than the three that are mentioned here, but there is significant overlap between the steps that are mentioned and the steps that are added in the other works.

For this thesis it has been decided to go with and continue the work from Schoenmaker. Therefore, the following questions need to be answered by the three parameters during the design phase of a PBMC:

- What needs to be done?
- Who is going to be responsible for it?
- How will it be managed?

This will be the starting position for the parameters that will be used for the decision-support method. The **'what'** says something about the **size or scope** of the individual part that will be described. The criticality of certain components of a system may result in different choices than used for the rest of the system. In that case a smaller scope is used to adjust the other parameters accordingly. The size or scope can also be influenced by the amount of information or complexity of a system. With a simple, predictable system it might be easier to adjust the other parameters than with more complex and unpredictable system. How this works in practice will be treated at a later stage.

The **'who'** should give insight in the responsibilities of the different parties that are involved, mainly the CA and contractor(s). By adjusting this parameter, the contribution of each party can be shifted to one another to fit the specific situation. Because the model is aimed at outsourcing the work, this parameter shall describe how much of the work is shifted towards the contractor. The parameter will therefore describe the **contribution of the contractor**. When looking at the five main considerations, this parameter will take the predictability, plannability and responsibility into considerations when adjusting it.

The **'how'** is aimed at finding out which way the contract can be managed best. Because of the performance-based nature of the contract that is being used, the way the performances are requested, measured and used to reward the contractor is an essential part of this contract. It is also a very important considerations (measurability) when deciding how the contractor will be drawn. Therefore, the last parameter will be aimed at adjusting the **performance requirements** according to the specific needs.

The three parameters that will be used to construct the decision-support method will be:

- Size/Scope
- Contribution of the contractor
- Performance requirements

In earlier work of Schoenmaker (De ingeslagen weg, 2011, pp. 133,177,222,271) the relationship between Size/Scope and a suitable Performance Requirement was used and explained. In the last work in (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017) the contribution of the contractor was added and connected to the earlier found parameters. The three parameters are dependent and work together to create the complete picture of what is desired for outsourcing a certain object. Using these three dependent parameters, the 'who', 'what' and 'how' can be found and help the contract design team to start writing the contract.

3.4.2 Range of the parameters

Now that the parameters are chosen, the variety of options that the CA has when designing a contract become clear. To illustrate this, the parameters size and scope, contribution of the contractor and the performance requirements are put on separate axes and the following image appears in figure 4.

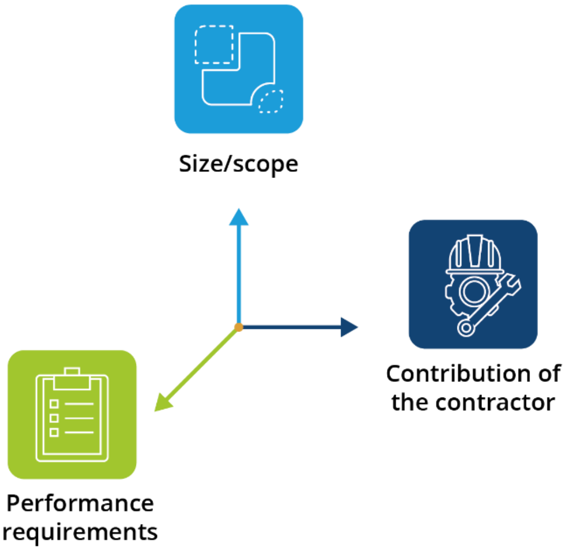


Figure 4: Parameters of the decision-support method based on (Schoenmaker, de Bruijn, & Herder, 2013)

The three axes form an imaginary cube. This cube contains all possible options that can be chosen by the contract design team when drafting the contracts. This also means that every parameter has a range of possibilities that can be used. Along the axes, a variety of options will be presented with different pre-conditions and effects that they will have on the eventual outcome of the contract. Based on the preconditions, effects and the way they affect (or are affected by) the other parameters, the decision-support method will help to find the three most suitable parameter settings for a specific situation based on which the contract can be written.

This chapter will be used to explain the range of each of the parameters and how they will be used.

Size or scope

Size/scope is a difficult concept to get a grip on. It is however an important parameter and needs some understanding to use in a correct way. According to the Oxford Dictionary, scope can be defined as follows:

Scope

- *the extent of the area or subject matter that something deals with or to which it is relevant*
- *the opportunity or possibility to do or deal with something*

(Oxford Dictionaries, 2018)

When dealing with contracts and the corresponding contract scope, the scope defines the boundaries of the work. Within these boundaries all the relevant work (for the contract) is collected and responsibilities of both CA and contractor are included in such a way that they know what can be expected of them. The scope will describe what objects and systems are part of the contract, but also the type of maintenance and the geographical size of the contract will be defined. The contract scope can therefore be described as the collection of all the relevant work that is part of the contract.

The parameter size or scope is not the same as the contract scope that is mentioned above. This parameter is meant to indicate a small part of the total (contract) scope that is treated separately from other parts of the contract. This decomposition of the total scope is necessary to reduce the complexity of the assignment and make it more manageable. The goal is to create a set of smaller parts for which a suggestion for performance requirements and the contribution of the contractor can be given.

Within the imaginary cube that was introduced previously, the size and scope is the first parameter that is set. The remaining parameters are tuned when this first one is chosen. To set the size/scope, several options are available. The options that are proposed are based on a physical decomposition of the object. To use it within the decision-support method, six different layers of size/scope are introduced. Those different layers are shown in the figure below.

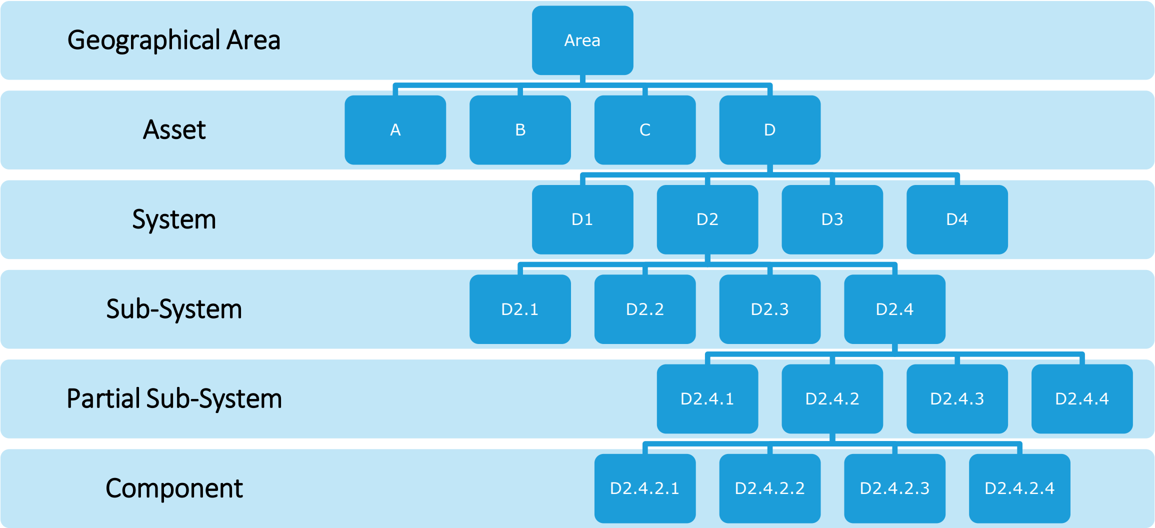


Figure 5: Six layers of size/scope (based on Werkgroep Leiddraad Systems Engineering, 2009)

With these smaller scopes, the contract scope is cut into separate parts. Those separate scopes can individually be steered by changing the performance requirements and the contribution of the contractor for each individual part. Based on the gathered information, the layers are based on the system breakdown structure that is used within Rijkswaterstaat (RWS) and modified to suit the needs of the decision-support method. This concluded in the following six-layer structure. (Werkgroep Leiddraad Systems Engineering, 2009) (Rijkswaterstaat Steunpunt ProBO, 2016)

The geographical area is the highest layer that is used. It describes an area and can contain a variety of assets. Besides the assets themselves, the area around the assets, such as grassland, water, pavement, etc., that is not specifically bound to them can be part of this scope. The second level is the assets themselves. An asset can be anything: a bridge, a tunnel, a stretch of rail or road, a service building etc. One level down, there is the breakdown of the assets into systems like: technical installations, IT-infrastructure or civil engineering etc.. The next level are the sub-systems within the systems. When looking at technical installations, sub-systems are the electrical supply system, lighting, drainage installations, ventilation system, traffic management installations, fire safety installations, communications etc. These sub-systems can then be further broken down into partial sub-systems. In the case of traffic management installations, this could for instance be traffic lights, traffic detection systems, height detection systems etc. The last level is an individual component. Continuing the last example about the traffic management installations and look at traffic lights, the individual component can be a single traffic light or just a light bulb.

Contribution of the contractor

The first variable was aimed at the size/scope of the individual part that is added to the contract. This variable defines the scale of contribution of the contractor during the contract period. The scale of contribution is the number of tasks/steps of the maintenance process that the contractor will be responsible for during the contract period. The tasks/steps that are used to determine the scale come from a model about the cyclic characteristics of the maintenance process. The model used is more commonly known as the 'Six-stage model' and for this thesis used as described by Schoenmaker (De ingeslagen weg, 2011) & Schoenmaker, de Bruijn, Herder (The dynamics of outsourcing maintenance of civil infrastructure in performance based contracts, 2013). The figure below shows the Model of the cyclic maintenance process as used by the latter authors.

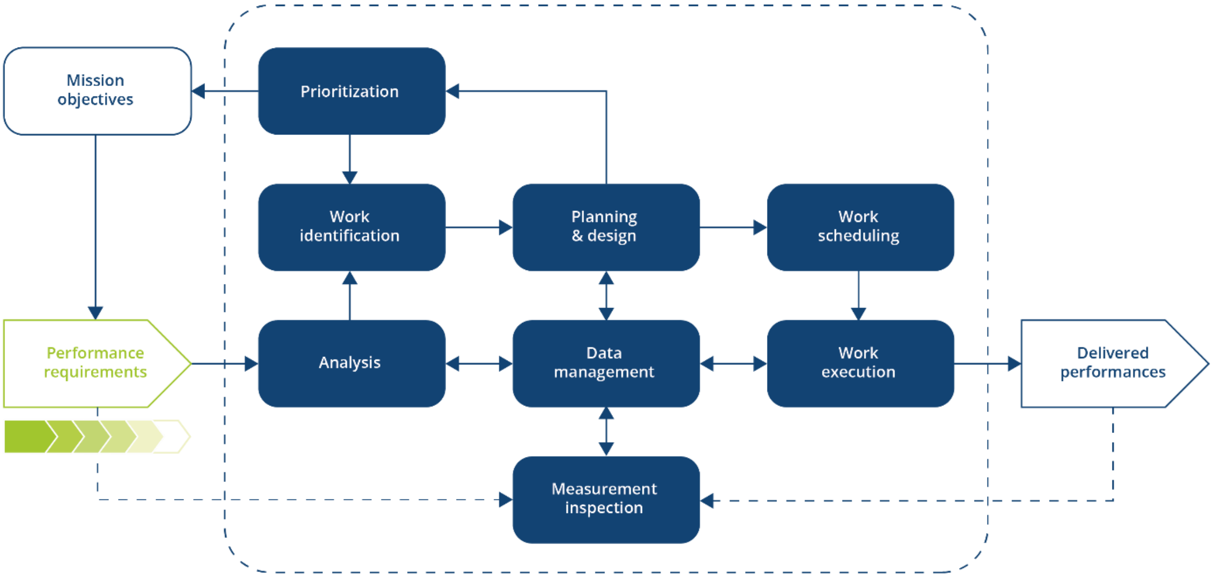


Figure 6: Model of the cyclic maintenance process based on (Schoenmaker, de Bruijn, & Herder, 2013)

An explanation of the different steps is given in the next table to get a better understanding of the functioning of the model within this thesis. The table gives the process step with short addition of the meaning of this step, followed by the actual execution of this process step. This table is based on work of Schoenmaker (De ingeslagen weg, 2011, p. 24) and Schoenmaker & Verlaan (Analysing Outsourcing Policies in an Asset Magement Context: A Six-Stage Model, 2013, p. 9)

Process step	Execution
Mission, Objectives *Development of a local strategy*	Make, implement, review and renew the translation of the corporate missions and objectives to a local level.
Performance Requirements *Set goals and requirements*	Translating the strategy into SMART goals and requirements that describe the demands of the network and the supporting processes.
Measurement, Inspection *Measure and inspect the assets*	Provide an accurate record of the current condition and the actual performance of the asset(s).
Data Management *Management of all collected data*	Establish and maintain an accurate and up to date asset inventory and associated condition and performance data.
Analysis *Identify the needs*	Analyze the data and intelligence gathered and documented to identify trends, faults, intervention levels that are in conflict or future conflict with the requirements.
Work Identification *Identify the solution*	Produce effective solutions that satisfy the identified needs to keep the assets in line with the requirements.
Planning & Design *Plan & design of the intervention*	Deliver maintenance plans and preliminary designs of the solutions.
Prioritization *Prioritize the interventions*	Weigh the proposed interventions on preset criteria, available budgets and impact on requirements. If necessary propose changes in requirements if available budgets do not cover the identified needs.
Work Scheduling *Preparing the work*	Prepare for construction to ensure the delivery is done within pre-determined budget and timeframe.
Work Executions *Deliver the work*	Efficiently deliver the maintenance work and deliver input for the data management systems.

Table 3: Explanation of steps of model of the cyclic maintenance process based on (Schoenmaker & Verlaan, 2013)

Some of the steps above are reserved for the CA only. The mission or objectives and the performance requirements are set by (the organization of) the CA. The other steps can either be done by (the organization of) the CA, the contractor, a third party or a collaboration between either combination of the three parties. This way of working allows for the CA to stay in control of certain aspects of the assets, while at the same time, transfer control of other parts of the asset to other parties. The third option is a form of shared control where the CA and the contractor share control on the same part of the asset and deliver a collaborated effort.

The blocks inside the dotted line (Figure 6) are the tasks that need to be done during the maintenance cycle and can, if this is desired, be transferred to the contractor. In fact, every step can be given to the contractor separately, but in most cases a block of multiple tasks/steps is given to them. Depending on the amount of responsibility and risk the contractor has, an amount of autonomy is given to the contractor. This is necessary because a contractor cannot be expected to take risks and bear responsibilities without leaving them the freedom to mitigate those risks and deal with the responsibilities themselves.

For this thesis and the use within the decision-support method, only two options are given. High contribution of the contractor and low contribution of the contractor. Many more variations are possible because, as mentioned before, every step can be given to the contractor independently. But within the high and low contribution range, enough room remains to have specific decisions for specific situations. High and low contribution of the contractor are explained below.

In the six-stage model, a cut between high and low contribution was chosen. This cut can be seen in the next figure (Figure 7). Low contribution of the contractor means that the contractor is depending on permission of the CA to start work scheduling and work execution. In this case the contractor can have assigned tasks like monitoring the asset and informing the CA about the status of the asset.

The responsibility and control are mainly for the CA. This form will mainly be used for variable maintenance tasks. Within this option, the contractor can for instance be paid to do standard routine maintenance and inform the CA if major repairs, breakdowns or other renovations are to be expected. The contractor solely bears the responsibility of doing routine maintenance and report expected changes in the conditions of the asset/object. When the CA wants to act on the recommendations of the contractor, they must pay separately for all variable maintenance tasks. A reason for choosing this option can be the high amount of uncertainty that goes with some variable maintenance tasks both in price and frequency of occurrence.

High contribution of the contractor includes autonomy for the contractor for work scheduling and work execution. The contractor is free to make these decisions on their own. The responsibility however is also for the contractor in this case. This form will mainly be used for routine maintenance tasks. In this option, the contractor is paid a predetermined fee to maintain the asset/object and is responsible to for all the work. In some cases, variable maintenance tasks can be part of the job description. This is mainly done when work is predictable or the probability of the occurrence of a breakdown is nearly 100%. This way, the contractor can anticipate on the repair job and plan accordingly and the CA is assured of a quick fix at a pre-determined price.

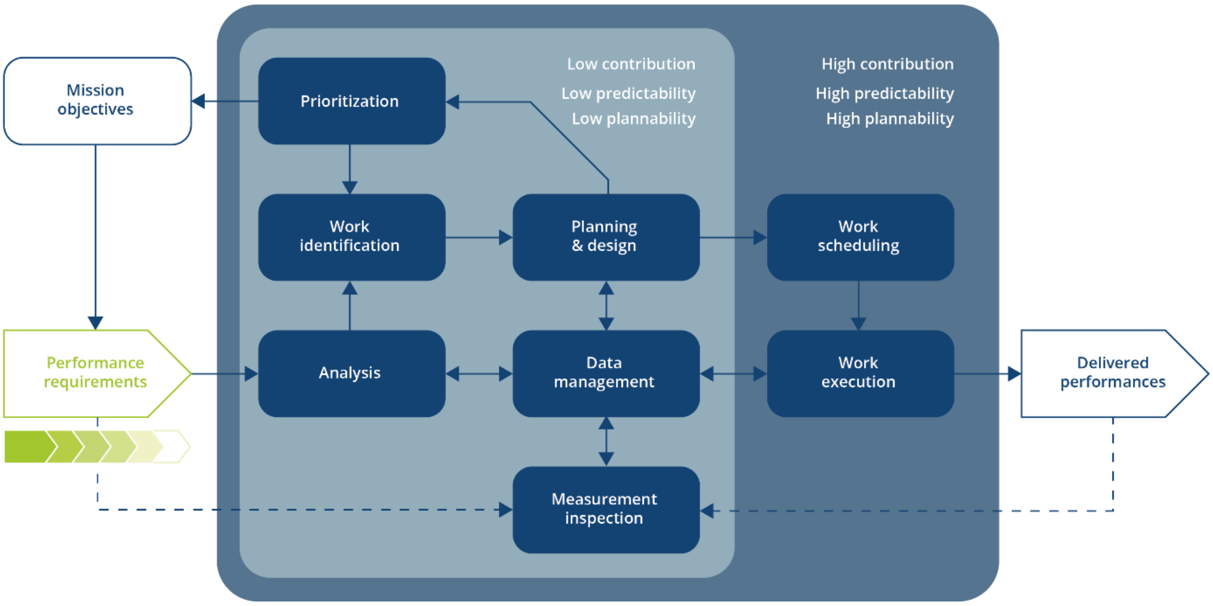


Figure 7: Model of cyclic maintenance based on (Schoenmaker, de Bruijn, & Herder, 2013)

When high or low will be chosen is highly dependent on the kind of tasks it concerns and the amount of certainty there is about the tasks that need to be performed. Important in this decision is the certainty for the CA because they don’t want to pay for things that are not necessary. On the other hand, it is important to realize to what extent the contractor can anticipate on the amount of work there will be necessary during the contract period to make a fair and realistic price. That is why the difference between the high and low contribution is directly influenced by the amount of predictability and plannability that there is for a certain part of the asset.

‘Predictable’ and ‘plannable’ sound quite the same, but two different things are meant here. Predictability describes the behavior of certain parts of the asset or system. This can for instance be decided from the malfunction history of a system. If a certain system fails every 3 months on average for the last 2 or 3 years, it can be expected that this will continue, and the system therefore behaves predictable. Another form of predictability is when systems need to be replaced because of end of life. If the end of life expectancy is in the middle of the contract period, it is almost certain that this replacement will have to take place (thus predictable), however when this will take place is not certain yet (thus not necessarily plannable). If the end of life expectancy lies on the near the end of the new contract, uncertainty may arise whether the replacement will be part of this contract or the next and is therefore unpredictable and unplannable. Predictable things (of which we are sure when they occur) are also plannable, but unpredictable events can be plannable if the goal/ambition is to prevent them. If we know that a certain system fails every 6 months, but that this failure can be prevented by a simple maintenance measure, we are able to plan this maintenance measure every 4 months (make it plannable) and by doing so prevents the failure from happening and therefore more predictable to maintain.

Performance requirements

The next parameter is the performance requirements. The performance requirements define how a certain request from the CA towards the contractor is put in the contract. Performances can either be a measurement on how well something is done, or the accomplishment of the act itself (Oxford Dictionaries, 2018) (Cambridge Dictionary, 2018). Six levels of performance requirements are therefore introduced.

The six levels of performance requirements that are used during this thesis are based on the levels that were introduced by Schoenmaker (De ingeslagen weg, 2011, p. 81) based on works by Austroads (2003, p. 9) and Porter (2005, p. 2). The translated version of that figure (Figure 8) can be seen below. The figure consists of three parts, the upper part tells what goals the performance requirements are focused on, the middle part describes the performance requirements themselves and the last part gives examples on what this should look like. An extra scale is added in this figure, showing the increasing amount of risk for the contractor when certain levels of performance requirements are used. This was based on a presentation by Schoenmaker (Prestatiegestuurd uitbesteden van onderhoud, 2017) on this subject.

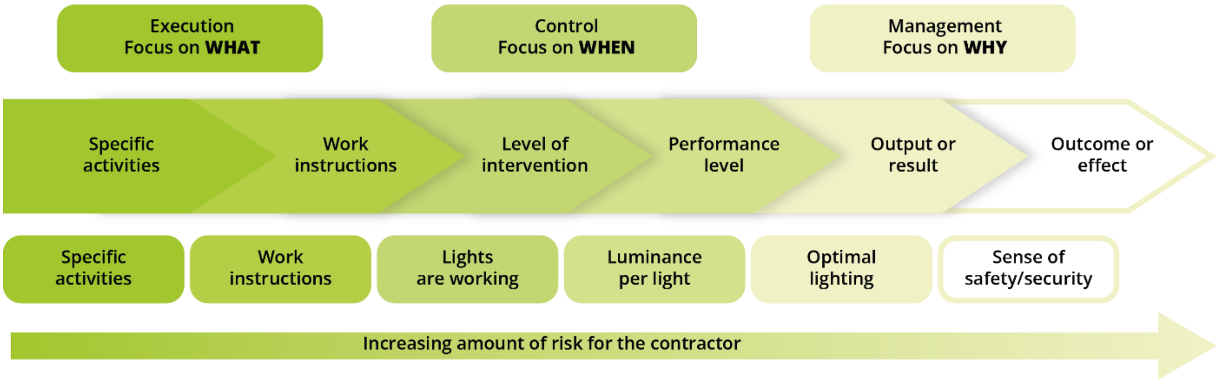


Figure 8: Performance requirement levels based on (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017)

The six levels are divided into three sub-groups. The first group focuses on WHAT should be done and HOW it should be done. The emphasis lies on the execution of a task and is known as input-based requirements. The performance is the action or process of performing a task or function. The requirements that can be found in this part are specific activities and written work instructions. The CA tells the contractor exactly what must be done and how it should be done. The performance requirement is met when the specific activity is executed or the written work instructions have been followed and carried out. Nothing is said about how well the performance should be. That is covered by the other two groups.

The second sub-group focuses on WHEN certain activities should take place. The performance requirements are described in one of two ways. One based on the level of intervention and the other on the performance level. These are both output-based. The first one focuses on the lower boundary of an acceptable performance. When that boundary is crossed, maintenance must be performed to make sure that the boundary is not being exceeded anymore. The other one focuses on maintaining certain performance levels. This is a specified, measurable performance that needs to be achieved in order to meet the performance requirements. An example for an intervention level is broken lights, when a certain number of lights are broken, they need to be replaced. An example for a performance level is the performance of the lights itself. In order to meet the performance requirements, the lights must achieve a minimum amount of luminance per lightbulb. If that is not the case the performance requirement is not met. Another difference with this group of performance requirements compared to the previous group is the increased amount of freedom for the contractor. The contractor can decide, to some extent, how they want to execute the work and when they are going to do it, given that they still meet the set performance requirements.

The last sub-group focuses on WHY things are done, what the goal is, what the targeted achievement is. That is put into a requirement and leaves it up to the contractor to figure out how this state can be achieved or maintained. The performance requirements that are used here are output or result based, or even outcome or effect based. The collective name for these requirements is outcome-based performance requirements. This type of requirements leaves the most freedom for the contractor to decide how to approach the work. The increased amount of freedom also increases the amount of risk for the contractor.

3.4.3 Solutions space of a performance-based maintenance contract

In the previous chapter the three parameters based on which a PBMC can be written are further explained. Every parameter has been assigned a range of options that can be used while designing a contract. The complete range of options of all three parameters is called the ‘solution space’. The solution space is an imaginary three-dimensional space (cube) that holds all the available options to use in a PBMC. This solution space is shown in figure 9.

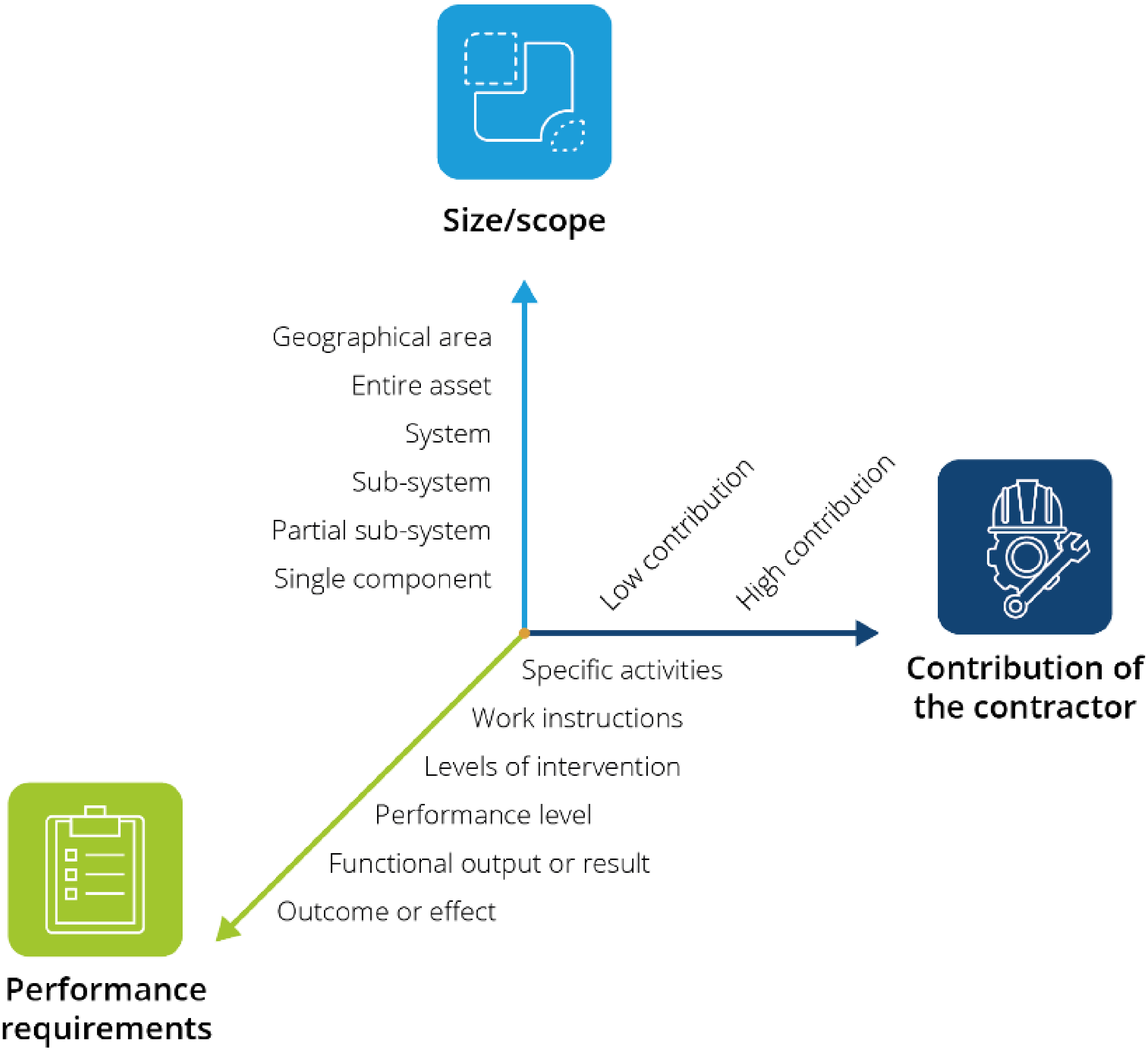


Figure 9: The solution space of the decision-support method based on (Schoenmaker, de Bruijn, & Herder, 2013)

The goal of the solution space is to visualize the available options within every parameter for the contract design teams. These teams are responsible for designing contracts based on the available information. By using the solution space, decisions concerning the contract are based on the three parameters and are made in such a way that they are based on the most important considerations that need to be made when outsourcing using a PBMC. These considerations are about predictability, plannability, measurability, responsibility and criticality.

To adjust the solution space and come up with a proposed solution to suit every specific situation, the contract design team of the CA can adjust the parameters independently. This process is called tuning. The tuning is done by sliding every parameter back and forward along the available rang until a satisfying solution is there. The process of tuning the parameters is further explained in the next chapter.

3.4.4 Connecting parameters and decision criteria

There is an important link between the parameters and the decision criteria. Different criteria will affect different parameters. In order to know what information is needed and what considerations need to be made at a certain stage of the decision-support method, it is important to clarify which criteria is affecting which parameter, why it affects that parameter and in what way it is being affected.

The size and scope of the contract is the first parameter that can be tuned. Criticality is an important consideration during this tuning process. If certain parts of the asset are of crucial importance to the function of the whole asset, they require extra attention. When analyzing the criticality of the asset, it is important to find out what level (system/sub-system/component) is critical to the function of the asset. This might influence the decision on how to outsource at later stage of the process. The second decision criteria that is interesting during the tuning of the size and scope is the predictability. When the decision is made to outsource a certain piece of the entire contract, it is important to realize what kind of interventions can be expected during the contract period. This might also influence the way the size and scope parameter is tuned.

The contribution of the contractor is based around the six-stage model by Schoenmaker. The six-stage model is hugely dependent on the amount of predictability and plannability of the work. Routine maintenance is seen as predictable and plannable work. It bears little risk for the contractor and responsibility for it can therefore easily be transferred to them. The contractor will have a high contribution because they are responsible for the entire maintenance cycle. Variable maintenance and replacement of bigger components (or systems) is often less predictable and less plannable. Therefore, it brings more risks for the contractor and the CA if outsourced in the same way. Another choice might be made with less contribution of the contractor and consequently less responsibilities. Given that the interdependency between the contribution of the contractor and the responsibility for the consequences are very strong, responsibility is also linked to this parameter.

The performance requirements are mainly based on the ability to perform measurements and the availability of suitable requirements. Therefore, this parameter is mainly dependent on the measurability. The tuning of the performance requirements is also affected by the amount of responsibility that a contractor has. Certain performance requirements ask more of the responsibility of the contractor than others, thus this needs to be aligned.

The table below visualizes the connection between the decision criteria and the three main parameters. A high dependency is depicted with a '+', influential factors are depicted with a '±' and lesser or no dependency is depicted with a '- '.

	Size/scope	Contribution of the contractor	Performance requirements
Predictability	±	+	-
Plannability	-	+	-
Measurability	-	-	+
Responsibility	-	±	±
Criticality	+	-	-

Table 4: Connection between decision criteria and parameters

When analyzing all these connections, it becomes clear that all parameters and all of the decision criteria somehow depend on one another. This only strengthens the claim that both the considerations (now decision criteria) and the parameters have interdependencies and therefore directly affect the decision-making process.

3.4.5 Tuning the parameters

During the decision-making process on how to outsource an object, the suitable parameters are chosen according to the given situation. This is done by tuning every individual parameter based on the most important considerations that need to be made. During this process, one of the three parameters is fixed, whilst the other two are tuned accordingly. This process can be very complicated because of the many variables and considerations that are present when designing a PBMC. That is why a structured method is recommended to aid the contract design team while making these decisions. By using a structured method of dealing with the most important considerations, the endless amount of possibilities can slowly be reduced to a manageable amount of possible options.

Besides the considerations that have an influence on the tuning the of the parameters, the parameters themselves affect the decision-making process. In practice it is a more difficult than simply picking three desirable parameters, put them together and have a contract. The parameters themselves have interdependencies, this means that certain choices made on one variable, will unavoidably influence the choices that can be made on another parameter. The size/scope has influence on the performance requirements that can be used and the contribution of the contractor, or at least the responsibility that the contractor can bear. The performance requirements on their turn will have an influence on the amount of freedom that the contractor should get to be able to meet these requirements. The reason these interdependencies are important come from the fact that the payment mechanisms are connected to the delivered performances, and the ability to deliver these performances are directly influenced by the freedom they get to act on a developing situation or their ability to manage a situation of a certain size.

It is not acceptable to require a certain performance from a contractor, whilst knowing they are not able to achieve that requirement due to a lack of freedom. If, for instance, a certain amount of functioning lights is required (level of intervention), the contractor will be rewarded if they can manage to keep that amount of lights working during the contract period. If the contractor can't deliver that performance they will receive less payment, balancing the end-to-end requirement and level of delivery reasonable. But what if this performance requirement is asked, but the contractor is not given the freedom to decide when and how he will replace the lighting, because the CA wants to keep control and has to give permission for repairs or replacement? Then these variables are contradicting each other. These mechanisms can make or break the ability of the performance contract to function properly. Therefore, it is very important to decide what the goals are and what is expected from the parties and the contract before writing a PBMC.

3.4.6 Conclusion

The parameters of PBMC have been found and defined during this section. At the start of this chapter, the three main parameters have been found based on which a PBMC can be written. The three parameters are based on the work of Schoenmaker (Prestatiegestuurd uitbesteden van onderhoud, 2017), van Rhee (Performance Based Contracting - Waarom, wanneer, wat, hoe?, 2009) and Stankevich, Qureshi & Queiroz (Performance-Based Contractor for Preservation and Improvement of Road Assets, 2005).

Size/scope, contribution of the contractor and performance requirements were chosen to be the three parameters that will be used during the design of the decision-support method. Based on previous research, these parameters are seen as repeating factors in many PBMC designs and are approached as deciding factors during the writing of a PBMC. These parameters will therefore be used to base the decision-support method on. This is also the answer to the first sub-research question.

Because of the fact that the parameters will be part of a structured method, the decision-support method, they had to be demarcated. The second part of this chapter was aimed at finding the range of these parameters, eventually setting the boundaries that could be implemented in the structure of the decision-support method. By setting boundaries, a limited set of solutions is created that can be used by the design teams to choose from. These solutions were highlighted in section 3.4.3.

The set of solutions that was created by combining the three demarcated parameters is known as the solution space. The solutions space is a visual representation of all possible solutions. It is a three-dimensional cube with the ranged parameters on the axes. Every spot within the cube represents a unique solution build up from the three individual parameters. The decision-support method will be built around the options that the solution space offers.

In section 3.3.2, the decision criteria where defined. The five main decision criteria, predictability, plannability, measurability, responsibility and criticality, were seen as the group of most important considerations that had to be taken into account when designing a PBMC. The parameters and the corresponding solution space creates the options that need to be chosen from during the design of a PBMC. Therefore, the connection is made between the parameters and the decision criteria: 'which criteria will influence which parameter'. This is an important factor during the design of the decision-support method, because here, the relation between the available solutions, the deciding criteria and the reasoning behind the decision making becomes clear. Also the interaction between the different parameters and decision criteria is explained.

The last part of this chapter is aimed at the tuning of the parameters. In order to move around the solutions space, the parameters are changed individually, this is known as tuning. If one parameter is changed, a new solution is created, which by definition has an effect on the outcome of the PBMC. The parameters need to be tuned in such a way that presented solution results in the most favorable outcome.

The information that is gained during this chapter is crucial to the design of the decision-support method. It creates the backbone of the method and the rest will be added around this structure. Besides the important role in the creation of the method, the information that is found here is also important for the users of the method to understand how certain choices are made and how certain considerations will affect the outcome of the PBMC. Therefore, a lot of extra information about the parameters is added in the appendices. This information is all combined in appendix 3.

3.5 *Additional tools and techniques*

The previous sections are used to define the important parameters and decision criteria that are needed to design a decision-support method for making a PBMC. The outcome of the decision-support method however, will be as good as the information that is used put in the method. This chapter is therefore dedicated to finding a reliable source of information that can interact with the decision-support method. Also, a new tool is introduced that could help the contract design teams to make estimates about the outcome that they can expect when working with the decision-support method.

The source of information that is introduced in this chapter is a risk analysis that is commonly known to be used within reliability centered maintenance (RCM) by using FMECA. The reason why this method was chosen had all to do with the connection it has with many of the main decision criteria. During this section the interaction between RCM and the decision criteria plannability, predictability and criticality is further explained.

The second tool that is introduced in this chapter is the risk allocation matrix by Brommet (2015). This tool was designed to help contract designers with deciding how risk allocation could be done best within a new contract. By using information that can be found in the FMECA, a suggestion can be made on the most suitable way of outsourcing when looking at the risk allocation. This also has ties with the main decision criteria, because in a matter of speaking, this way of working can increase the predictability, plannability and criticality of the events that are to come. More on this will be explained in the section following the RCM method.

3.5.1 *Reliability centered maintenance*

When the parameters are being tuned, information is needed to make the right considerations when dealing with the decision criteria. Tools and techniques are being used to provide that information. One of the ways to gain information about the decision criteria is the RCM method. This method is defined by Moubray (1997) as 'a process used to determine the maintenance requirements of any physical asset in its operating context' and 'a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context'. A third definition is given by Buckland (2003) based on the IEC60300-3-11 (1999) which reads: 'a systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks.'

A more recent explanation was given by Hastings (2015) and said that RCM is a systematic method for establishing maintenance policy. The technique is able to give an in-depth analysis of the asset and provide information about the maintenance work that is required (suggested) for the coming period. This technique is therefore extremely helpful in providing information about the predictability, plannability and criticality of the maintenance work. This method is therefore applied in an early stage of the decision-support method to assist the contract design team in making decision about the size/scope and lay the base for the decision about the contribution of the contractor.

According to Hastings (2015): 'The applications of RCM must involve an appropriate level of engineering authority, consistent with the technology if the application for which the maintenance policy is being developed'. At the same time, the value of this technique lies in combining knowledge of maintenance, engineering, and management staff in a structured process, providing benefits from the in-depth communication involved'.

The concept of RCM is described as a number of steps that need to be taken. Hastings (2015) identified the five steps that are shown in figure 10. In the following section the essentials of the RCM methodology are explained. This part is added to at least understand the basics of this concept, whether it is already in use or not.

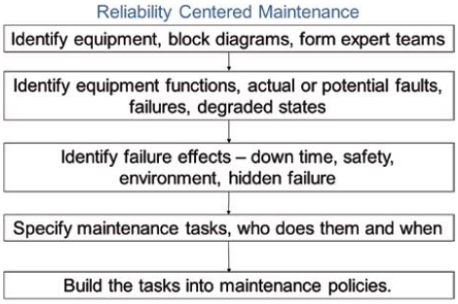


Figure 10: Reliability-centered maintenance concept by Hastings (2015)

Outcome of the RCM methodology

The goal of using the RCM methodology is getting more information about the predictability, plannability and criticality of the maintenance measures of an asset. The RCM methodology should at least identify the expected maintenance measure that are necessary to keep the asset operational in the foreseeable future. The value of RCM increases when suggestions about the type of maintenance (preventive, predictive, failure finding maintenance, modifications, run-to-failure) are given. This way the contract design team can base decisions on that information.

The RCM methodology is not implemented everywhere and the information might not be available in all situations. The basics of the methodology are therefore explained in the next section in order to either use the method, compare it to the existing method (information might be equally useful) or skip this step altogether and find another way to gain information about predictability, plannability and criticality. A more detailed explanation is added in appendix 4.

The RCM cycle

The RCM methodology is a cycle containing numerous steps. The following steps are being used in the RCM cycle: decomposition of the asset, risk determination, risk analysis, maintenance strategies, maintenance measures, implementations, monitoring, reviewing and adjusting (van den Boomen, 2015) (Colibri Advies BV, 2018). This cycle is visualized in Figure 11.

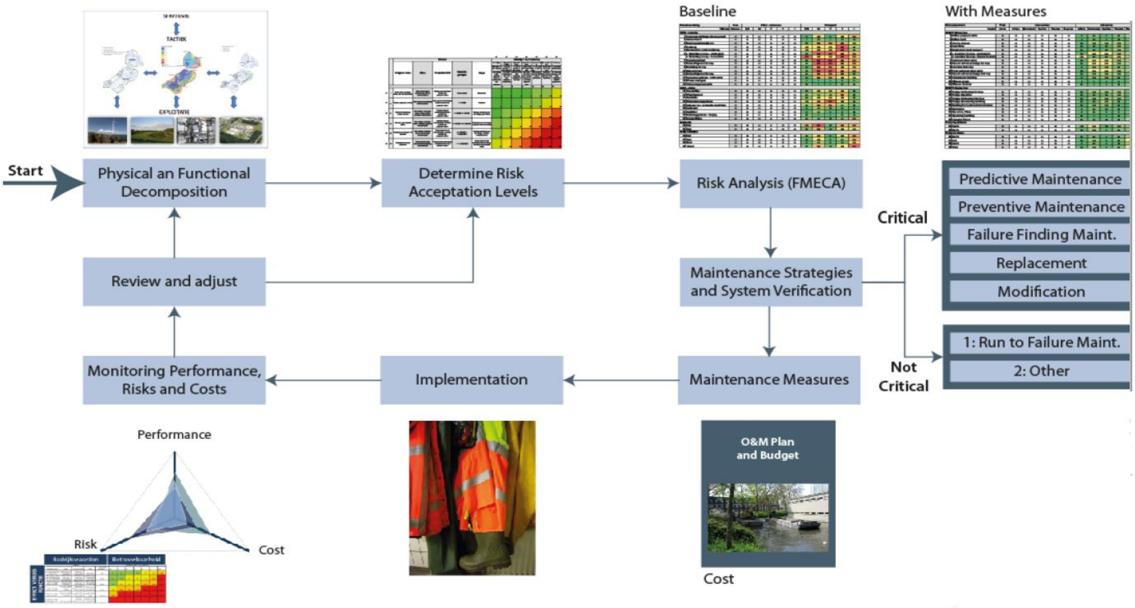


Figure 11: The RCM cycle (Colibri Advies BV, 2018)

For the use within the decision-support method, steps 1 to 5 are the most interesting because there the necessary information will be provided. During these steps, the risk analysis (FMECA) is done, generating a risk matrix and risk register, providing valuable information for use during the decision-making when designing a PBMC. It is therefore suggested to add some form of risk analysis at the start of the decision-support method in order to acquire data.

If an FMECA of a certain object is already done at the beginning of the process of creating a PBMC, this information can be used for the decision-support method. If this is not the case, FMECA is suggested to gather that information. In order to replicate the steps of FMECA, steps 1 to 5 are explained in detail in appendix 4. There could however always be a situation where FMECA or RCM can't be used. Whether it is just unpractical or there isn't sufficient information available is not that important. The important thing is that the decision-support method will be able to function properly when this is the case. So, what if RCM is not an option?

Unavailability of RCM

RCM and the FMECA were chosen for their ability to meet the need for information about predictability, plannability and criticality. The RCM method aims at improving the reliability of the maintenance work by finding the critical components, predicting the maintenance that will be required and make the work plannable for the contractors. The reason RCM was chosen had to do with fact that it can be implemented rather easy and can be applied on various levels of depth. Therefore the method is fit for almost every situation. It is however imaginable that a smaller organization has more trouble engaging in a new method like RCM (if they are not used to do so) than for instance Prorail, Rijkswaterstaat or any other government driven organization. The government driven organizations often have more resources and experience in trying new methods (given that they're not already using RCM).

An important factor to point out here is that the RCM (and FMECA) are suggested solutions for finding the necessary information. But every other method that is able to point out criticality and is the ability to predict whether maintenance work will suffice. An added bonus will be if the method is also able to give some level of plannability about the predicted maintenance work. The more information is provided as input during the use of the decision-support method, the more accurate the results will be.

Another important factor is that the use of the FMECA, and especially the depth of the FMECA can vary from case to case. In some cases, it is wise to get everything right, down to every small detail. However, in many cases a more overall view of the asset is more than enough to do the predictions that you need. By just using and analyzing the first steps of the FMECA process, a lot of important information is already gained.

The RCM methodology is not specifically what is important for the process, it is the information that it provides. If RCM is used correctly, high quality input can be used during the entire decision-making process, but the RCM method itself is not crucial. If another methodology, or a simplified version of the RCM method is used, this will still work on the condition of being able to gain reliable information about criticality of systems, predictability of maintenance work and plannability of maintenance interventions. But it is important that the quality of the information input is crucial for the level of the eventual outcome.

3.5.2 Risk allocation matrix

In 2015, a thesis was written by O.D. Brommet (Managing the Dutch Waterworks using long-term Maintenance Contracts, 2015) about risk allocation when outsourcing maintenance of civil infrastructure (sluices) through maintenance contracts. This thesis was used to develop a model that helps with evaluating the Risk Allocation within these contracts. The risk allocation model (Figure 12: Risk allocation model by Brommet (2015)) helps to understand how Frequency of failure and the expected consequences influence the decision on what method to use when outsourcing certain parts. The model suggests a payment regime and the decision-making moment to use based on the factors frequency of failure and the average repair time (consequences). The model that is presented in this chapter was designed to help contract design teams during the decision-making process for designing long term maintenance contracts for sluices. Depending on the type of infrastructure the model is used on, the Frequency of failure and kind of consequences could differ from the original model.

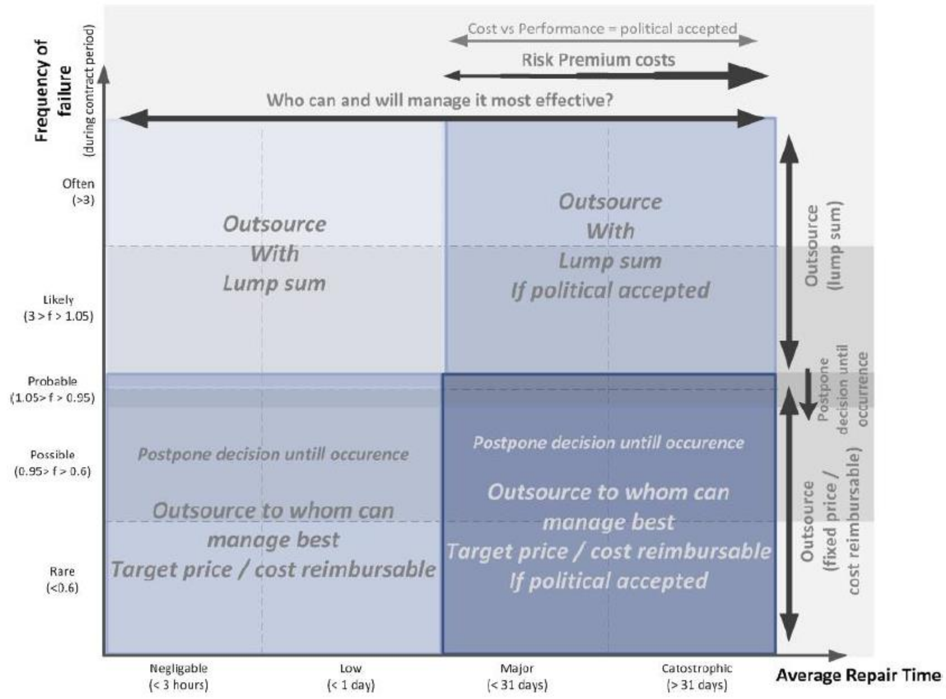


Figure 12: Risk allocation model by Brommet (2015)

This risk allocation matrix fits well within the mindset that is used in this thesis. It will defenitly have an added value within the decision-support method. The FMECA uses the frequency of failure (probability & predictability) and the effects to find the criticality and come up with proposals for a maintenance regime (plannability). The risk allocation matrix uses the frequency of failure (probability & predictability) and effects to suggest a suitable way of of outsourcing. The matrix focusses on the moment in time where a final decision (for action) should be taken and the payment method that is used. The risk allocation matrix will use the information gain from the FMECA and will result in input for the six-stage model (Schoenmaker & Verlaan, Analysing Outsourcing Policies in an Asset Magement Context: A Six-Stage Model, 2013). Based on that information decisions about the contribution of the contractor can be taken.

An indepth explaination on how the matrix works and how it was constructed can be found in the following literature: the thesis, Managing the Dutch Waterworks using long-term Maintenance Contracts (Brommet, 2015) and a paper, determining a functional responsibility allocation between public and private parties in a long term maintenance contract for waterworks (Brommet, Hertogh, Schoenmaker, Kleijn van Willigen, & Chen, 2016).

3.5.3 Conclusion

The introduction of the RCM method and FMECA in particular will be an important addition to the decision-support method. It will be used as the first and main source of data input when creating new PBMC. In the conceptual design, the use of FMECA will be a highly recommended suggestion. The case study has to point out how valuable the input of RCM and FMECA is to the final outcome of the method. Then can be decided what final form of RCM and FMECA will be used in the decision-support method.

The risk allocation matrix is seen as a tool that can be used to help gather a sense of direction to decide how to outsource certain parts of a system. It is also a good tool to assess the way risk is divided between the contractor and the CA. Therefore this tool be useful just before the decision about the contribution of the contractor has to be taken. The risk allocation matrix will definitely be in the conceptual design of the decision-support method.

3.6 Conceptual design of the decision-support method

All of the previous sections were about finding a structured way to help contract design teams in making PBMC. In the early part of this chapter the decision-support method was introduced. Throughout this chapter, the many ingredients that make up for this method are introduced, analyzed and explained. Now that all the ingredients are present, the first conceptual design of the decision-support method can be initiated. This conceptual design is based on the information that has been gathered so far. During the following chapters, this conceptual design is tested and modified until a satisfactory final design for the decision-support method is found.

The steps that make up the decision-support method are introduced and explained in the following section. This will be the first structured representation of the decision making process that contract designers have to go through when drawing a PBMC.

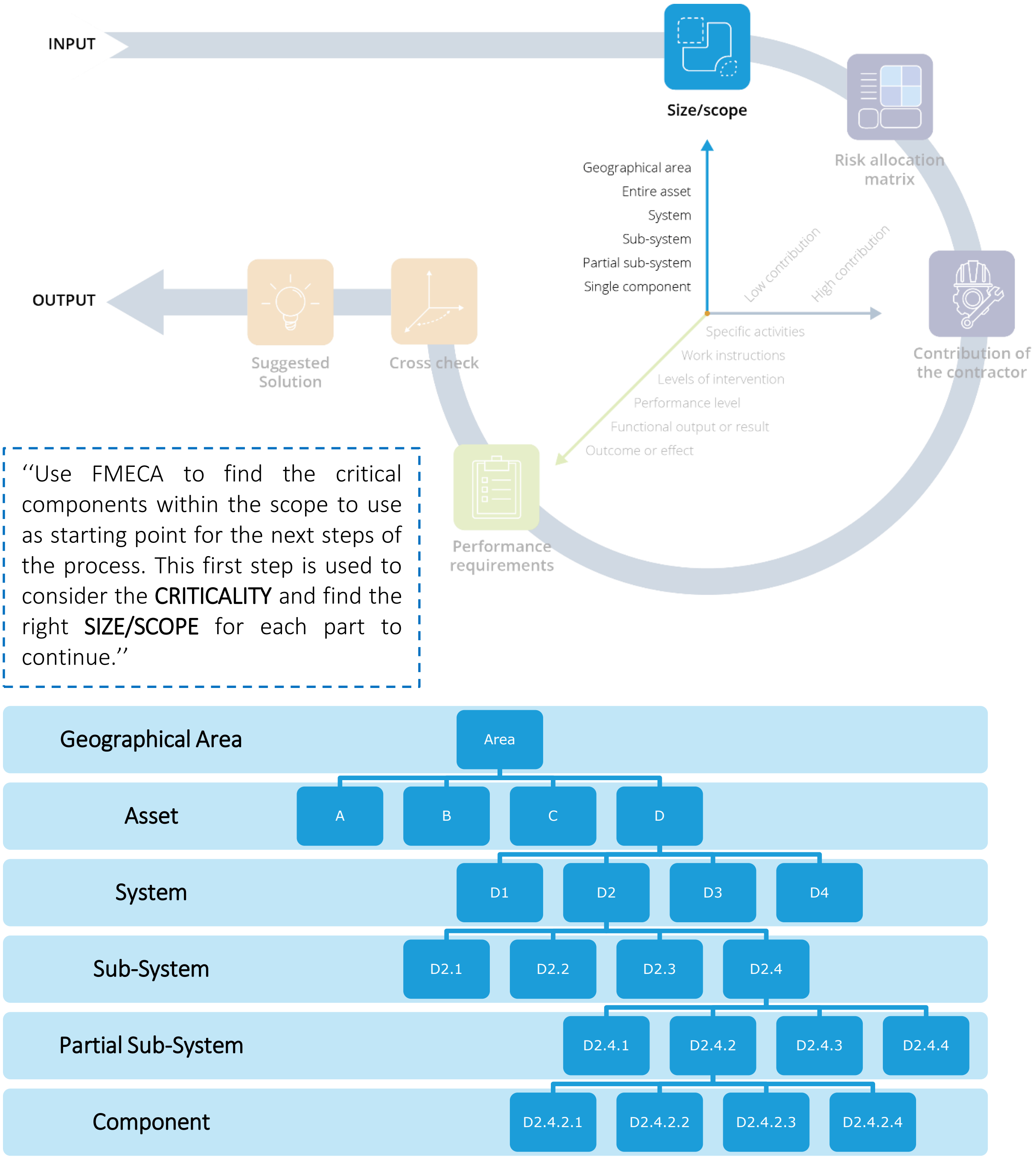
The conceptual design is based around the information that was gathered during this chapter, starting with the three main parameters. When the user reaches the end of the process, an answer on how to deal with every individual parameter should be present. The parameters will have to be tuned whilst considering the five main decision criteria and other information that is gained using the tools that where discussed during the literature study like RCM and the risk allocation matrix.

The RCM method is not integrated in the method at this time. It is used as a starting point for gathering information that can be used as input during the steps decision-support method. In an ideal situation, the user of the method has the ability to use a working risk register based on FMECA. This is not always the case, so when that occurs, the user needs to find other ways to gather information about the predictability, plannability and criticality of an object. This information gathering should always precede the actual six steps of the conceptual design of the decision-support method.

3.6.1 *Step 1: size and scope*

The first step is used to create a starting point for the remainder of the method. During this step, one of the main parameters is set. This is not final, but creates a starting point to continue on to step two. This step is used to find the biggest single element that can be outsourced as one piece. This is done by using FME(C)A to obtain information about the criticality of certain systems, sub-systems or components within the total scope. The level where the criticality originates might help determine what size/scope should be used.

During this step, the size/scope is determined using the criticality, one of the five main decision criteria of PBMC. This step is shown in figure 13.



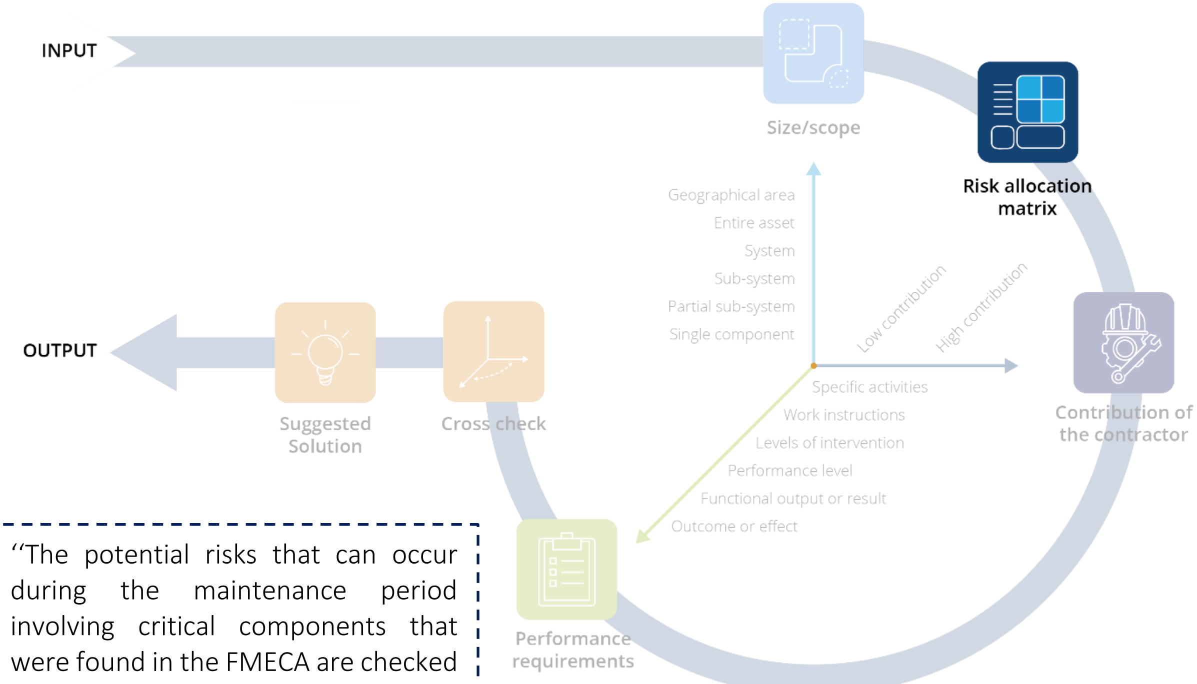
> ‘’Use FMECA to find the critical components within the scope to use as starting point for the next steps of the process. This first step is used to consider the **CRITICALITY** and find the right **SIZE/SCOPE** for each part to continue.’’

Figure 13: Conceptual design of the decision-support method: step 1

3.6.2 Step 2: risk allocation matrix

The next step is to use the risk allocation matrix by Brommet. The model however, needs to be adjusted to the object that is being evaluated. The model was originally designed for DBFM contracts for sluices. It is therefore important to see how this reflects to the object that is being outsourced when using the decision-support method. This step is shown in figure 14.

By using the risk allocation matrix, a first suggestion is done about the method of outsourcing that can be used based on predictability and plannability of maintenance of an object. Besides the two already mentioned decision criteria, risk division is also evaluated as part of using this matrix. This says something about where the responsibility for certain decision should be. The outcome of this step can be used during the next step.



''The potential risks that can occur during the maintenance period involving critical components that were found in the FMECA are checked for their **PREDICTABILITY & PLANNABILITY** using the model by Brommet.''

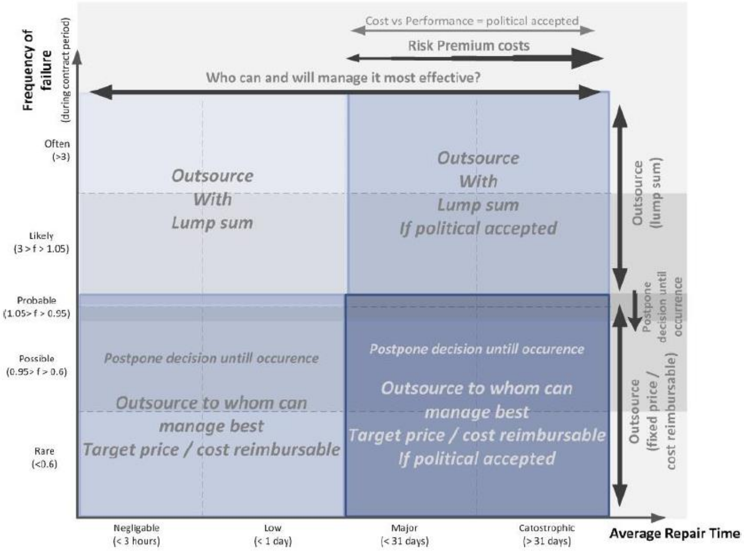
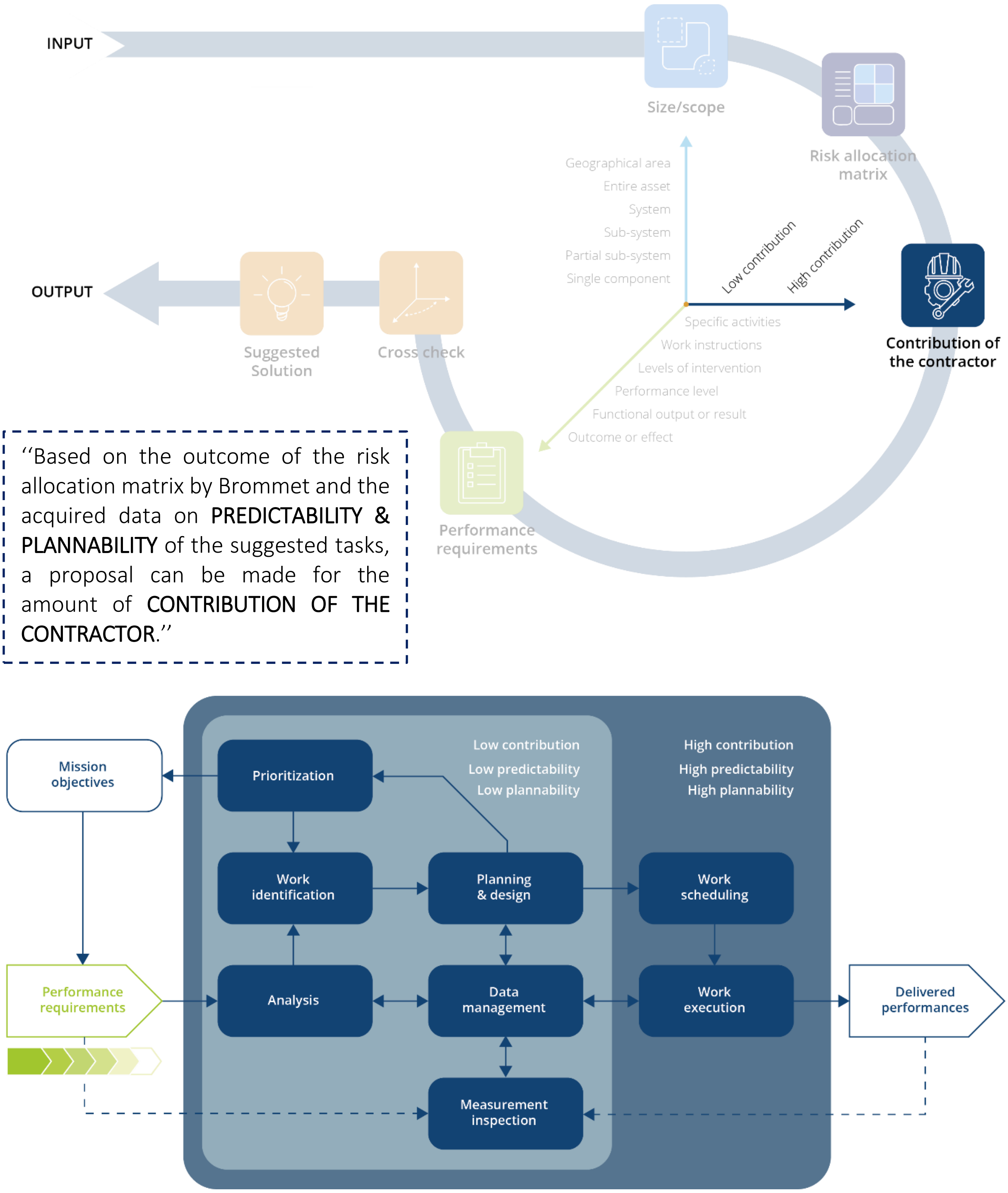


Figure 14: Conceptual design of the decision-support method: step 2

3.6.3 Step 3: contribution of the contractor

The following step takes the consideration of the predictability and plannability a step further. This is where the amount of contribution of the contractor is decided. The information that is used to decide this can also be extracted from the FME(C)A. The results of the use of the risk allocations model are also taken into account when making the suggestion here. Based on that information, a suggestion is made for high or low contribution of the contractor. This step is shown in figure 15.



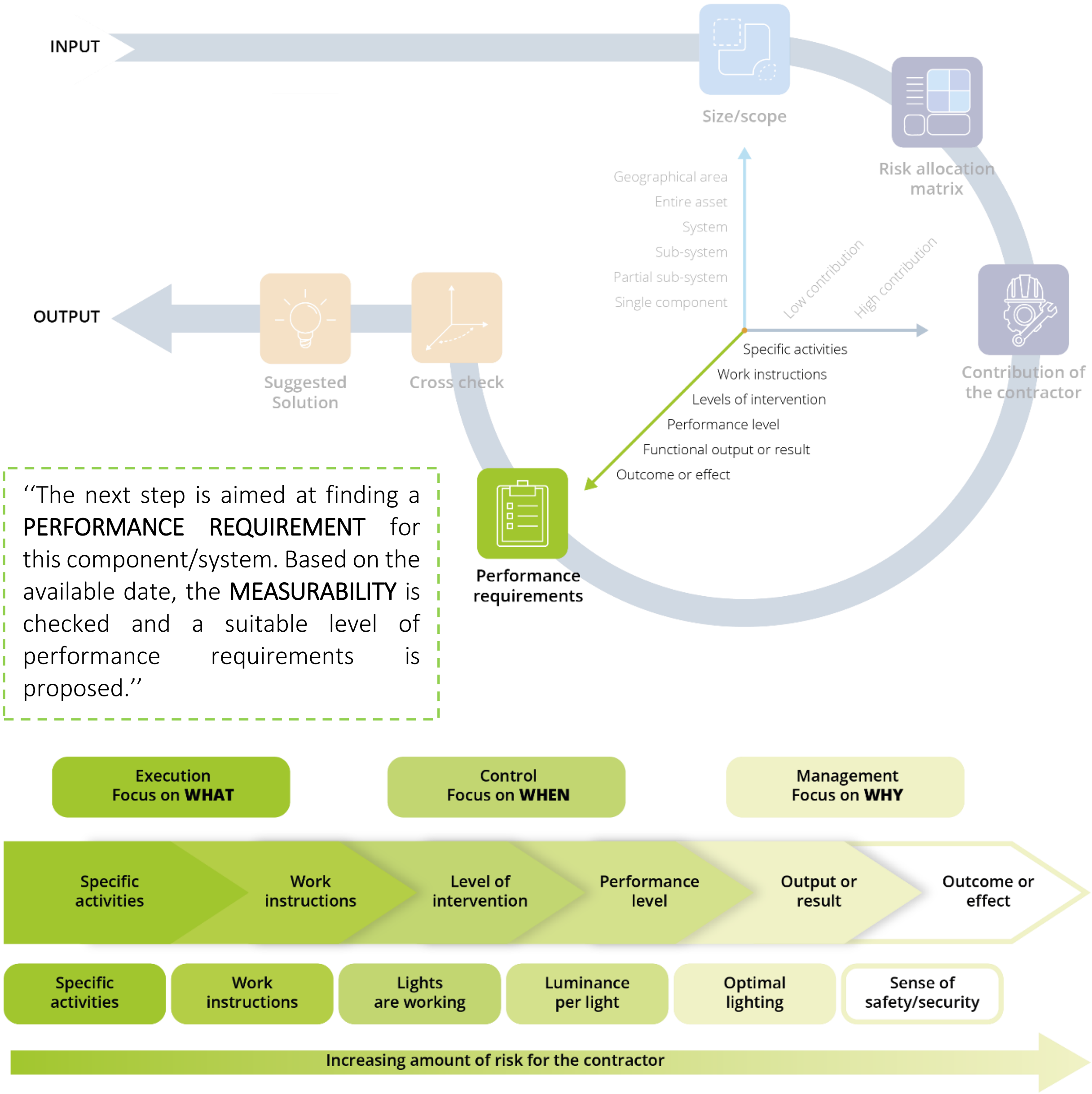
> ''Based on the outcome of the risk allocation matrix by Brommet and the acquired data on **PREDICTABILITY & PLANNABILITY** of the suggested tasks, a proposal can be made for the amount of **CONTRIBUTION OF THE CONTRACTOR**.''

Figure 15: Conceptual design of the decision-support method: step 3

3.6.4 Step 4: performance requirements

In this step, the performance requirements are chosen. These are based on the measurability of performances and ambition of the organization. If performance is easily measured, a higher level of performance requirements can be chosen. If performances are hard to measure, simple performance requirements might be more suitable.

The choices made here also heavily depend on the ambition and strategy that the organization wants to follow. If the organization has sufficient information about the behavior of an object, and is satisfied with keeping the risk and control within the organization, they can easily use work instructions to outsource the work. If the ambition is to give the contractor more freedom and challenge them to come up with innovative and progressive solutions, outsourcing on a higher level, for instance using performance levels or output-based might be a better solution. This step is shown in figure 16.

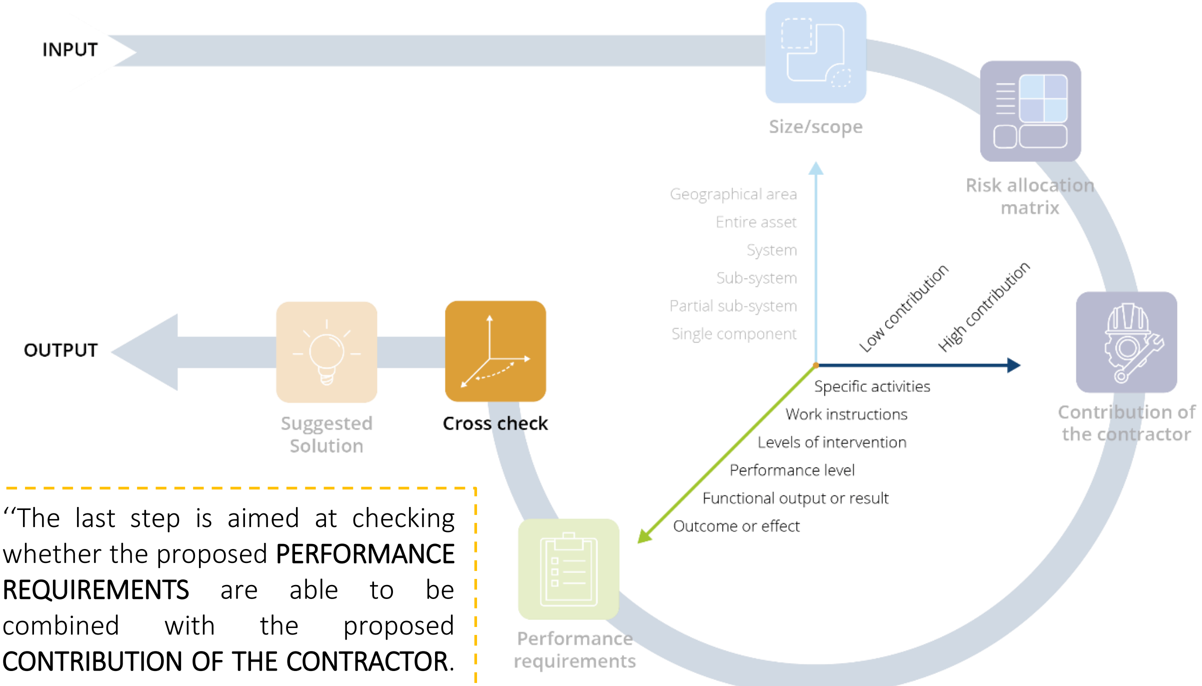


‘’The next step is aimed at finding a **PERFORMANCE REQUIREMENT** for this component/system. Based on the available date, the **MEASURABILITY** is checked and a suitable level of performance requirements is proposed.’’

Figure 16: Conceptual design of the decision-support method: step 4

3.6.5 Step 5: cross-check

This step is aimed at checking whether the suggested level of performance requirements work with the proposed level of contribution of the contractor. If a certain performance level is requested, a certain level of freedom for the contractor might be needed. This way the allocation of responsibility is checked in order to make sure that the request is realistic. If either one of the variables is too high, and therefore not compatible with the other, an adjustment needs to be made to either one of them.

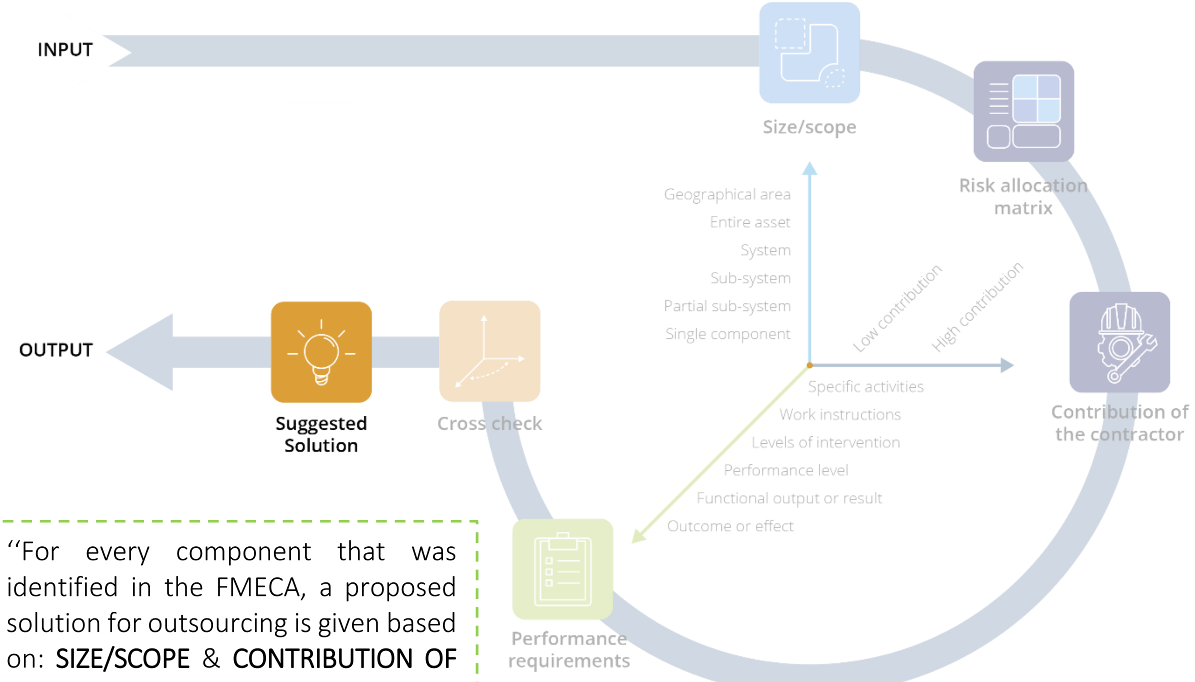


> ‘’The last step is aimed at checking whether the proposed **PERFORMANCE REQUIREMENTS** are able to be combined with the proposed **CONTRIBUTION OF THE CONTRACTOR**. The acceptable **RESPONSIBILITY** is checked here.’’

Figure 17: Conceptual design of the decision-support method: step 5

3.6.6 Step 6: proposed solution and expected outcome

This last step of the process summarizes the eventual proposed solution that is the result of the process. This part is divided into two parts. The first part is about the proposed solution for the size/scope, contribution for the contractor and the performance requirements. This step is shown in figure 18.



''For every component that was identified in the FMECA, a proposed solution for outsourcing is given based on: SIZE/SCOPE & CONTRIBUTION OF THE CONTRACTOR & PERFORMANCE REQUIREMENTS.''

Figure 18: Conceptual design of the decision-support method: step 6

3.6.7 Concept decision

The last step delivers a concept decision about the way outsourcing can be done. The model can however only take so many considerations into account and things can and probably will be missed. This concept decision is a starting point for experts to reach a final conclusion. The concept results will be discussed and tested for feasibility within the context of the contract. The final decision will be made outside of the decision-support method.

3.7 Conclusion

Three sub-research questions where set out at the start of this chapter. The goal of this entire chapter was aimed at finding the answers to those research questions and eventually making a start on answering the main research question, which was also mentioned at the introduction of the literature study. The main research question of this thesis reads as follows:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

The first sub-research question has been explored during the first sections of this chapter. The first sub-research question reads as follows:

'What parameters should be used by the contracting team during the design phase of a Performance-Based Maintenance Contract?'

During section 3.1 of this chapter, more general knowledge about the PBMC was acquired. This information was needed to understand the basics of the use, function and capabilities of these types of contracts. This information was needed to understand how this method of contracting works and how this relates to the questions that need to be answered.

Section 3.2 of the chapter was aimed at introducing the decision-support method, that could act as a framework to build the structured method around it that is mentioned in the main research question. The reason of introducing this methodology so early on in this thesis was to make sure that all the information that was gathered during the remainder of the literature study and could directly be linked to this method.

Sections 3.3, 3.4 and 3.5 help answer the already mentioned first sub-research question, but also the second sub-research question. These sections mainly provide knowledge about the information that is needed and the way the information should be used to set the parameters that are found in section three. This research question reads as follows:

'What information should be available, and how should this be used to assist the contracting design team in setting the parameters in such a way that they suit the individual and specific needs of an object?'

Section 3.3 looks at the many considerations that are linked to designing and using PBMC. From this huge list of considerations, five main decision criteria are created. This was done to keep the methodology simple. Having to consider everything whilst putting it in a structured method is nearly impossible. By grouping the considerations and finding the most important ones, the best result is expected and most considerations will still end up in the decision-support method. The five main decision criteria that where found are: predictability, plannability, measurability, responsibility and criticality. These criteria are crucial for the design of the decision-support method and were again used in section four about the parameters.

Section 3.4 was dedicated to finding the three main parameters and elaborated on the way the parameters should be used. This section provides an answer to sub-research question 1. The parameters that should be used when designing a PBMC are size/scope, the contribution of the contractor and the performance requirements. This was found by analyzing the works of Schoenmaker, van Rhee and Stankevich. The work of Schoenmaker was the biggest contributor to this section. Because the thesis continues on earlier works of Schoenmaker, this was a logical consequence. The three individual parameters were demarcated and then combined to create the solution space. This solution space represents the available outcomes that the decision-support method will have.

Another important part of section 3.4 is the connection between the decision criteria and the parameters. During this part, the influence of changing the position of the parameters on the available range on the different decision criteria is explained. This information is needed to understand how the tuning of the parameters works and will help create the structured method that is required to answer the main research question. This part of the chapter, combined with the part about the tuning of the parameters plays an important role in the creating of the conceptual designing of the decision-support method.

Section 3.5 introduces additional tools and techniques to help the contract design teams find the required information and helps them to make informed decision during the design process. For that purpose the RCM method, including FMECA are introduced. This method will help the design team to get a lot of information at the start of the design process and will be used to base decision further down the line. This method is therefore used as a source of information at the beginning of the decision-support method and will be integrated as such.

Besides the RCM method, another tool is introduced that can help the design teams make decision during the decision-support method. This second tool is the risk allocation matrix by Brommet. The risk allocation matrix is seen as a tool that can be used to help gather a sense of direction to decide how to outsource certain parts of a system. It is also a good tool to assess the way risk is divided between the contractor and the CA. Therefore this tool will be useful just before the decision about the contribution of the contractor has to be taken. The risk allocation matrix will definitely be in the conceptual design of the decision-support method.

Section 3.6 is the connecting factor that combines all the information that was gathered in chapter. The combining of gathered knowledge is presented in the form of a conceptual design of the decision-support method: the first visual representation of the structured way that is mentioned in the main research question. This is also the first time the answer of sub-research question three becomes more clear. Sub-research question three reads as follows:

'What steps should be taken to find informed answers in a structured way based on which a Performance-Based Maintenance Contract can be drawn?'

The steps that are introduced in section six, do not provide a full answer to this question yet. At this stage it represents a conceptual design for a the decision-support method and is just a way it could look in future. These steps will be tested, adjusted, refined and tested again until a satisfying method is created. The steps that are presented in this chapter and show in the figure below are the final answer to this sub-research question.

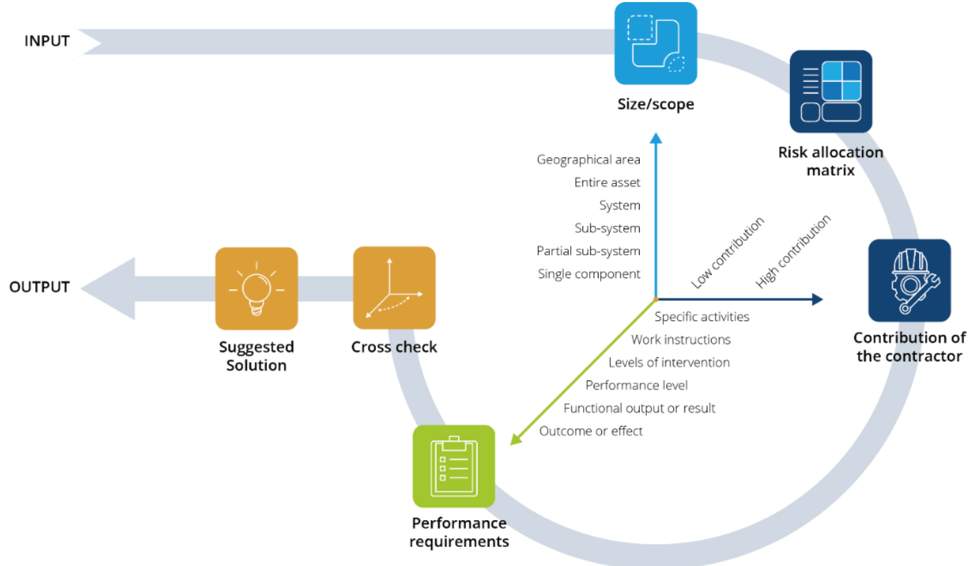


Figure 19: Schematic representation of the conceptual design of the decision-support method (as found in Appendix 5)

Before step one is started, the information gathering process should be done by either using FMECA or another risk evaluation method.

Step 1 is based on the parameter **Size/Scope** and is can be tuned using the information from FMECA about the decision criteria predictability, plannability and most importantly, criticality.

Step 2 is the use of the **risk allocation matrix** to find an appropriate risk allocation. During this procedure, the decision criteria predictability and plannability are evaluated. The outcome is then taken to the next step.

Step 3 uses the outcome of the risk allocation matrix and data from the FMECA on predictability, plannability and criticality to find a suitable and fair way to make a decision about the parameter that is about the **contribution of the contractor**.

Step 4 uses the available information about the measurability of certain performances to find a suitable level of **performance requirements** that can be used for this parameter.

Step 5 is a **cross-check** that is introduced to see whether the previously chosen combination of parameters work together as they should. An acceptable division of responsibility is checked here. If this is not the case, other decisions need to be made in the earlier steps.

Step 6 is the **conclusion** of the decision-support method and provides an answer on how to outsource a certain part of an object. It provides a proposed size/scope to use, an appropriate contribution of the contractor and a suitable level of performance requirements.

By making the conceptual design this way, the three main parameters are represented and the design is built around the solution space. All five main decision criteria are integrated in the design and connected to the steps they influence the most. The risk allocation matrix has an important advising role towards the contribution of the contractor and says a lot about the division of risk and therefore the responsibility of the contractor. The RCM method is not an integrated part of the method, but is suggested as an option to gather the needed information which is used during the execution of the decision-support method.

Every bit of information that was gathered during this literature study was used to create the conceptual design as presented before. Now it is time to put it to the test and see how it works in practice. The following chapter will be used to test the conceptual design during a case study. The findings of that case study will point out the strong points and weaknesses of the current design and will help improving the conceptual design to a next level.

Chapter 4

Case study

This chapter is used to check the performance of the conceptual design during a case study. Improvements to the conceptual design are made based on the results of this test. The performance of the improved model is then checked during a new case study. A second set of improvements is made to create a final design of the decision-support method.

4

4. Case study

During the literature study in the previous chapter, enough information was acquired to make a conceptual design for a decision-support method. Now that the conceptual design of the decision-support method is done, its applicability to a real case will now be simulated. During this chapter the answer to sub-research question 4 should be answered. This research question reads as follows:

> *'What are the results of the technical application of the support method to real case examples?'*

The goal of the case study is to gather information about the functioning of each individual step of the decision-support method on real cases. During this case study, information about the functioning provides insight on the positive and negative sides of the use of this method and will be used to improve the method. This chapter is roughly divided into eight sections.

Section 4.1 starts with a case introduction. During this introduction, the case that is used during the different parts of the case study will be presented. This includes general information about the object, the location and some technical details of the case.

Section 4.2 is an overview of the available data that will be used during the case study. This includes all documents and sources that could be found on this case and the object in particular. This is the information that the people within the contract design teams would have in a real case.

Sections 4.3 and 4.5 are the two runs of the case study. During the first run, the conceptual design is tested and the results are analyzed. After this analysis, a set of improvements will be suggested and explained. These improvements are then implemented on the conceptual design which creates an improved design of the decision-support method. This redesign is done in section four. This improved design is then used during the second run of the case study (section 4.4). The application of the design will be tested again in the same way as before, only now the new improved steps are used. The results are analyzed again and another set of recommended improvements are given. These improvements are implemented in section 4.6.

The conclusion of the chapter is given in section 4.7. During this conclusion, the final design (as a result of the two runs of the case study) is presented and will be used during the expert meeting in chapter 5.

4.1 Case introduction

The case that is used during this case study is the Noordtunnel. The Noordtunnel is a highway tunnel under the river Noord close to Hendrik Ido Ambacht and Alblasserdam. The tunnel is part of the highway A15 and consists of two tunnel tubes both containing three lanes of traffic. For the goal of testing this case, a few boundary conditions are put in place. The decision to outsource by using a PBMC is already made by the CA. The total scope of the contract will be the entire tunnel and the service buildings that are part of this tunnel system. In reality this maintenance contract is part of a larger contract containing multiple tunnels within the *West Nederland Zuid* (WNZ) area, but for the purpose of testing the decision-support method, just one tunnel is evaluated. For the purposes of this test, the PBMC that will be issued has a contract length of 5 years and will start in 2019 and will end in 2024. The information that is used for this test comes from the databases from Rijkswaterstaat (RWS) and their employees involved in day to day management of the tunnel maintenance. The information is not always completely up-to-date, but for the purpose of this test, the time of availability is defined to be sufficiently reliable to be used to gather information about the performance of the individual steps of the decision-support method during a real case, which is the eventual goal of this test.

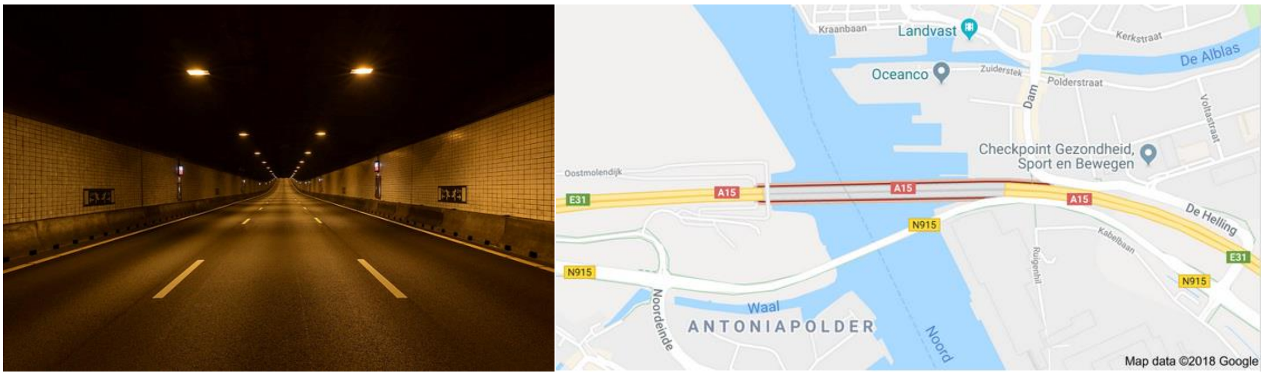


Figure 20: L: Noordtunnel (Zuid-Holland), Patrick van Dam (2017) / R: Google Maps view of the Noordtunnel (07-11-2018)

The Noordtunnel was opened for traffic in 1992 and is part of the Trans-European Network. It is an immersed tunnel with a (tunnel) length of 540m (left tube = 530m). The length of the entire asset is 1270m. The tunnel consists of two tubes (North and South) both containing three lanes of traffic, both suitable for cars and trucks on all lanes at the same time. Besides the main tunnels, there is an emergency escape (service) tunnel in between both tubes.

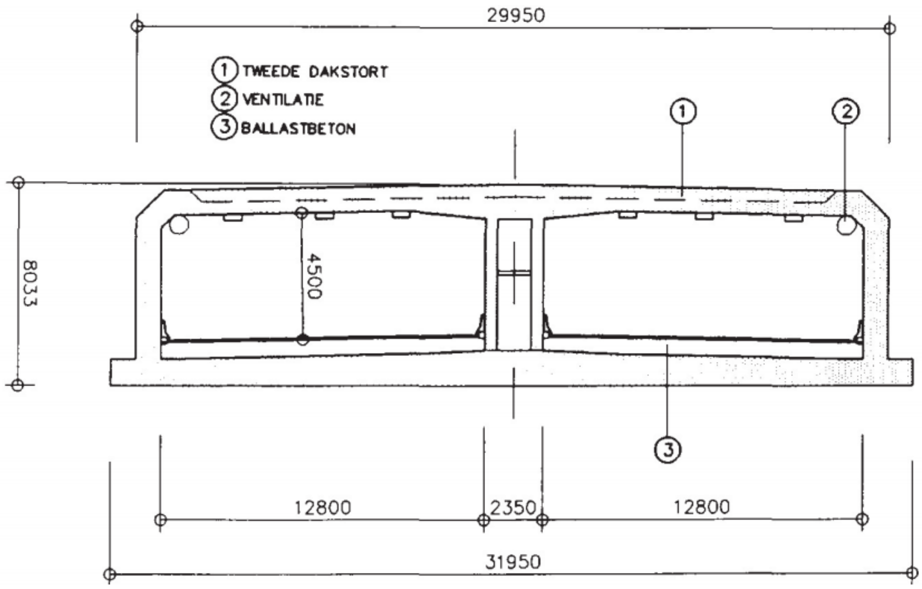


Figure 21: Cross-section of the Noordtunnel (tunnel engineering consultants, 1991)

4.2 Available data

In order to use (the conceptual design of) the decision-support method, data is required. This data is used to evaluate the different considerations that are made whilst tuning the parameters and take an informed decision on how to outsource a specific part.

For this case study, the data was acquired through talking to the experts from Rijkswaterstaat and using their databases. The following documents were found and used during the case study:

- A document called the ''tunnel passport'' of the Noordtunnel which describes the tunnel and all its components. This overview can be used to obtain the entire scope of the tunnel. *Paspoort Noordtunnel* 38c-113 Versie 1.1. (Rijkswaterstaat, 2014)

- A document to support the improved maintenance concept (the next document) of the Noordtunnel (*Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel*). This document includes the a risk matrix, a criticality analysis and the approach of the FMECA (Imtech, 2013).

- The improved maintenance concept itself. This document includes the FMECA, all failure modes for the critical (sub-)systems and much more information about the behavior of these (sub-) systems. Furthermore, this document gives a suggestion on the proposed maintenance strategy and will come in handy when making certain outsourcing decision during the decision-making process. This document is called: *Verbeterd Onderhoudsconcept* VOT2 NOORDTUNNEL (Imtech, 2013). Because this document already contained a suitable FMECA, this one was used instead of making one. The concept of using the results of the FMECA can be found perfectly while using this one. Although it is somewhat aged, the information is accurate enough to use, especially when bearing in mind that the goal is to gather information about the performance of the individual steps of the decision-support method during a real case, not to provide perfect answers on tunnel related maintenance issues.

- The risk dossier of the Noordtunnel. This document contains a list of all systems and their deviations, shortcomings, damages etc., but also the date of installation of new components and the expected remaining lifetime of the systems. To conclude, this list also tells whether performance requirements are used for certain components. Risk dossier, *Instand Houdings Plan tunnels Zuid-Holland 2013*. (Rijkswaterstaat, 2013)

- Information regarding the general system specifications of Rijkswaterstaat tunnels can be found in a separate document *Systeemspecificatie RWS Tunnelsysteem* – 1 juli 2014 – Concept B –. (Rijkwaterstaat, 2014)

- To acquire the functional requirements that are applicable to the systems and sub-systems that are used during this case study, information from the following document is used: *TOP Prestatiecontract Werkbestek WNZ* v4.0 (Rijkswaterstaat, 2016). This document contains information about the current contract and the requirements that are used in this contract.

4.3 Case study (Run 1)

During this first run of the case study the steps of the conceptual design of the decision-support method are tested to see if they work as expected. The steps that need testing are the direct result of the information that was found in chapter 3. These steps are shown in figure below (figure 22) and can also be found in section 3.6.

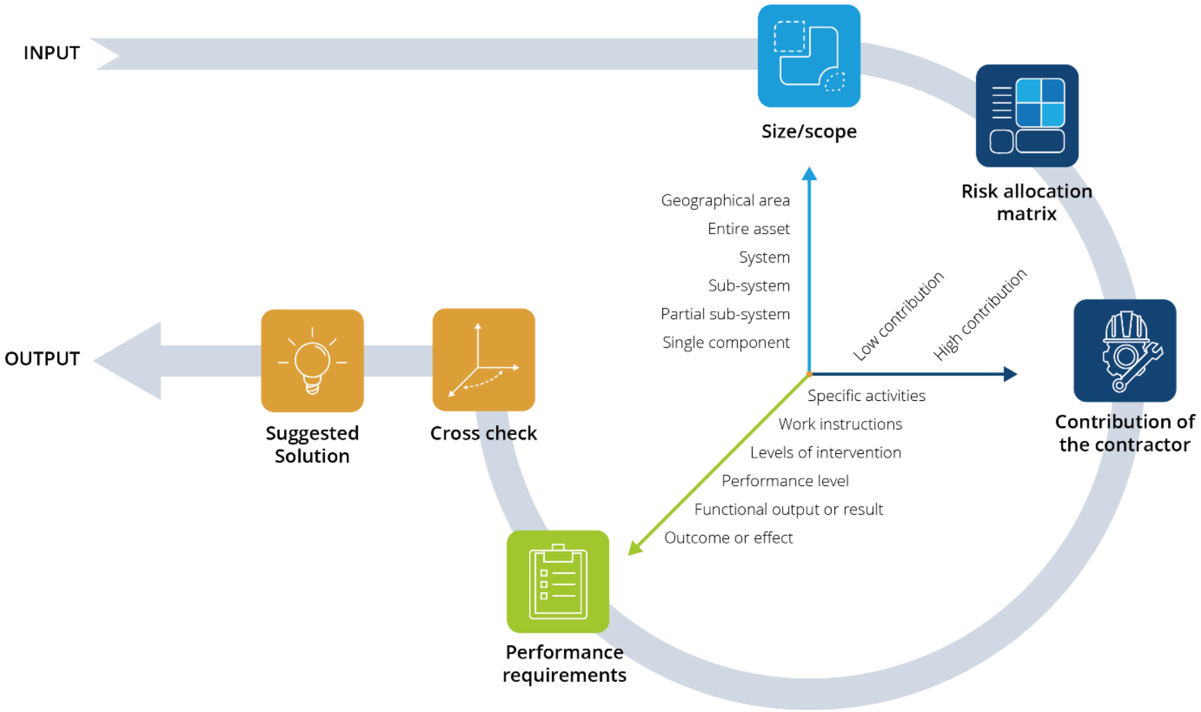


Figure 22: Schematic representation of the conceptual design of the decision-support method (as found in section 3.6)

The results of the case study are split into two parts. In appendix 5, the process description and the results of the first run of the case study found. The steps that have been taken and the data that was used along with its interpretation leading to the final results for three different systems are stated in this appendix. In this appendix, the flaws of the conceptual design are already found and visible, but are not yet discussed or solved. This is done in the other part about the case study that is found in this chapter.

In section 4.3.1, every individual step that is performed during the application of the decision-support method is reviewed based on the results that were found in appendix 5. This review mainly focuses on the functionality and practicality of the individual steps, rather than the actual outcome of the first case study. The outcome will become more important during the second run of the case study at a later stage of this report.

In section 4.3.2, a general discussion about the first run of the case study is presented. Rather than discussing the individual steps, as is already done in the previous section, the bigger picture is reviewed here.

Based on the outcome of the discussions in sections 4.3.1 and 4.3.2, recommended improvements are presented in section 4.3.3. These improvements can be for individual steps, but might as well cover a bigger range of multiple steps of significant changes in the design of the decision-support method.

The last part of this case study is the conclusion in section 4.3.4. The conclusion is a review of the findings of the first run of the case study and a list of recommended improvements that should be implemented in the method before the next run of the case study is started.

The suggested improvements will be researched and worked out in section 4.4 and a redesign will be made, which will then be used as input for the second run of the case study.

4.3.1 Review of the functionality of steps of the conceptual design

This section covers the review of the individual steps of the conceptual design of the decision-support method during the first run of the case study. This review focuses on the functionality and practicality of the steps that are performed during the case study. The outcome of each step in relation to the case and a description of the actual process can be found in appendix 5.

The first section covers the gathering of information and gradually continues into step 1. After that, every section reviews an individual step. In every section the functionality and practicality of that specific step is reviewed and the findings on that are presented. These findings can be used as input for recommended improvements, but might also be a confirmation that the steps are technically working and achieve the goals for which they are added to the decision-support method. No hard decision are taken in this section yet. This is postponed until after the general discussion of the results.

Information gathering and step 1: size/scope

For the Noordtunnel, a criticality analysis was available from 2013. This criticality analysis was used to decide which systems and sub-systems are critical to the overall function of the tunnel and/or have a direct impact on the safety of the tunnel. From this criticality analysis a list of systems came forth that are critical to the functioning of the tunnel. From this list, 3 systems were selected to apply the decision process on. These systems are: emergency power supply (NOT-Cl-14), main pump basement (NOT-Cl-31) and video and CCTV systems (NOT-N-61). Two of the three systems were central systems, having impact on the entire tunnel (emergency power supply and main pump basement), and the last system was a tube bound (video and CCTV system). During this phase, a general assessment of the tunnel was made to map out what systems were present and what should be included in the eventual contract.

Followed by the general assessment of the tunnel, the collection of the functional requirements and the reasons of existence is initiated, which is performed on each individual system. This information is necessary to understand the importance of the system and make informed decisions in the remainder of the process. Without knowing the importance of certain functions of a system, decisions that need to be made further along the decision process might be underestimated. This information was easily found in the previous contract and supplemented with information from the document holding all generally required system specifications for the RWS Tunnels. This step of information gathering was not previously specified and was done to be able to collaborate certain decisions that are to be made during the following steps.

Step 2: risk allocation matrix

The second step was using the model of Brommet. Given the fact that the risk allocation matrix was designed for a specific purpose, in this case a sluice, the first issue occurred. When using this same model on tunnels, the MTBF / frequency of failure and the impact and severity of the effects in case of a failure are completely different. The matrix therefore has to be redesigned for this specific case. This was done based on the risk matrix that was included in the documents of the FMEA. During this run two approaches were used: first the overall scores of all failure modes were combined and an average score was given. Secondly the individual failure modes were evaluated to see whether another approach was possible. The MTBF and downtime were normative in most cases, but also repair costs and hindrance were of high impact in some cases. Interpretation of the numbers is extremely difficult, because there is no hard proof and the numbers are mostly obtained from expert judgement. The risk allocation matrix was therefore used to gain a general perception of what would be sensible to do, but the real decision is made during the next step.

Step 3: contribution of the contractor

The next step is the evaluation of predictability and plannability. It was harder than expected to clearly say when something was plannable and when something was predictable or not. The information that is gained from FMECA on the suggested maintenance strategy can be used. Preventive maintenance for instance can make things plannable, and therefore also more predictable. An unpredictable system can therefore be made more predictable for the contractor and more reliable for the client. Whether this is a viable option depends on the amount of resources and capacity that is available within the organization of the contracting authority. The goals and ambition, and the corresponding strategy of a company has a major impact on the eventual decision that will be made here. The risk dossier was eventually used to get insight in the life expectancy of certain systems as a whole, impacting the decision to include or exclude the renewal of that particular system in the contract. This information was very helpful. The only thing that lacked was solid information of MTTF (mean time till failure) of certain systems measured from a certain point in time. This could help improve the predictability and make the decision even more clear.

Step 4: performance requirements

The next step was to decide the level of performance requirements that will be used for every sub-scope. During this step, the measurability of the performances was the leading factor, but this was hard to find out. In the risk dossier some information could be found about the whether or not measurable performance requirements were set, but this information was scarce. Another point that was difficult was the absence of an exact description of every level. Expert judgement might become an important factor here. Eventually it was possible to make an informed decision about the level of performance requirements that could be used and were suitable for the situation it was meant for. There were however a few instances where multiple solutions where possible, depending on the interpretation of the information. The outcome is therefore highly dependable on who was evaluating and with what goal in mind. This could also be improved in the next run. What really missed here was an overview of all measurable data of the last few years to predict a level of performance that could then be used to set new performance requirements. This is only feasible when measurable data can be acquired and this data can be used to judge the delivered performance. Keep in mind that this is only interesting if the level of performance requirements is at least higher than levels of intervention. similarly, the eventual choice is highly dependent of the ambition, goals and strategy of the organization of the contracting authority.

Step 5: cross-check

The last step in the process is the compatibility or cross -check to see whether the chosen solution can be used together. This is an important step to prevent impossible contracting solutions where the contractor is burdened with an unfair share of risk. A striking example is a situation where the contractor can be punished when not delivering a certain performance, but at the same time is not allowed to do everything in its power to deliver that performance. This situation can occur when a low contribution of the contractor is expected, but a high performance level is required. This check is important and helps fine-tuning the proposed solution in the advantage of both parties.

Step 6: proposed solution

After this step the proposed solution is presented. This is an overview of the decisions that were taken in terms of scope/size, contribution of the contractor and the level of performance requirements is proposed. This is a summary of the decision that come from the model, backed up with a short explanation on why this was the proposed solution. This provides a good overview of the outcome. This was done based on the information that was found in the previous steps and therefore easy to do.

4.3.2 General discussion

The outcome of the first case study was very positive. Although things need to be adjusted to make the method more usable, many of the goals where already achieved. The method forces the user to consider the most important decision criteria and helps to think about the variety of possible solutions. This was one of the main goals of the method. The eventual outcomes, as well as the process itself have been discussed with the technical manager and contract advisor (currently working on the new contract) and they agreed that the process indeed can help forming an informed opinion when making decisions concerning the way and level of outsourcing.

The literature study has found the three variables to design a PBMC and have brought them together in one solution space. This solutions space contains the size/scope, the contribution of the contractor and the level of performance requirements. Within this solution space the decision-support method is able to navigate to find the optimal solution for every individual situation. Navigating through the solution space requires the user to make considerations about many different decision criteria. These main considerations (criticality, predictability, plannability, responsibility and measurability) form the backbone of the decision-support method.

During the first run of the case study the decision-support method proved itself and showed, though not yet optimal, that is was possible to connect the different variables to the main decision criteria and deliver a proposal for the way of outsourcing through a structured process.

But, although many things went well, there were also things that definitely need improving. The method as it is works fine, but is still very susceptible for personal opinions and interpretation of results. The fact that this happens now, and probably will still happen in the improved versions is given, but the effect on the end result need to be reduced. There could also be some more structuring in the individual steps. Therefore a short explanation on how to approach and how to interpret the results could resolve some of the issues that were mentioned before about the influence of individual opinions.

Another aspect that will be done differently in the next version is the position of the information gathering. In the conceptual design, the information gathering was a pre-requisite for starting with the steps of the decision-support method. It is however one of the most important steps of the entire process, so it should be part of the method as well. By doing so, the information gathering and the first step of execution can be seen as two different steps and could improve the quality of information gathering and hence, the decision making.

Some issues arose during the use of the risk allocation matrix of Brommet. This matrix had to be altered to function within the tunnel case, instead of sluices. This was not taken into account when doing the literature study and was redesigned while using the decision-support method. This redesign needs to be explained and be part of the method itself.

The first run of the case study has brought many positive results, but also some improvements that are important to take into consideration to further improve the design of the decision-support method for the second run of the case study. The actual recommended improvements are discussed in the next section.

4.3.3 Recommended improvements

Based on the results, review and general discussion of this first run of the case study, a few recommended improvements are given. These improvements could affect the method as a whole, or be specified to adjust specific steps. The improvements themselves are made and explained in section 4.4. This will result in a redesign of the decision-support method that will be used during the second run of the case study.

Information gathering and step 1

It has become clear that the information that is gathered at the start of the method is very important for the execution of certain further steps of the method. It is therefore recommended that the information gathering will become the official first step of the decision-support method. The remaining steps simply won't work without this input of information. Secondly, certain requirements should be set for the information gathering and a strong recommendations for using RCM and FMECA should be given because this source of information proved to be most valuable during several steps of the process.

This then results to a modification of the total amount of steps for the decision-support method to seven, with the first step being the gathering of information and the second step being the determination of size/scope. The remaining steps therefore automatically jump up one number.

Redesigning the risk allocation matrix

During this first run of the case study, the risk allocation matrix has been changed provisionally to be usable for tunnels. This is not desirable because every individual would make this correction in a different way. Within the redesign should be clear how the risk allocation matrix should be redesigned, when this should be done and how it should be used when execution the steps of the decision-support method.

Defining instructions for steps of the decision-support method

During the execution of the steps, a certain procedure was followed and repeated. Some of these procedures are traceable to the instructions and explanation that were provided in the literature study, but some were not yet fixed. During the redesign, the goal is to fix some instruction within the steps of the decision-support method to ensure that everyone follows the same procedure and finds the same conclusions when working with this method.

4.3.4 Conclusion of case study run 1

During this first run of the case study, the conceptual design of the decision-support method has been tested for the first time. The overall outcome of this first run has been positive. It was not yet perfect, but it has the potential to become a usable tool for the contract design teams when designing PBMC. In order to improve the current version of the decision-support method, three recommendations are done:

- Introducing a separate step for the information gathering using FMECA
- Formulate a structured plan for the redesign of the risk allocation matrix
- Defining more specific instructions for using the steps of the decision-support method

The first recommendation was done to improve the quality of the information and make FMECA a more prominent part of the decision-support method. This is done because the specific information that FMECA provides plays an important role during the remaining steps of the method.

The second improvement is crucial for the function of the risk allocation matrix in cases where different kind of infrastructure is used. By designing a method to convert the risk allocation matrix to fit any case, the decision-support method becomes usable in almost any situation.

The last recommendation has to do with the specific instructions that are given with each step of the process. During the first run of this case study, the execution of the steps was not yet fixed. With this extra information, a more structured execution of the method should be achieved.

These recommendations will be explored and implemented in section 4.4. This will result in a redesign of the decision-support method that will be used as input for the second run of the case study.

4.4 Redesign of the decision-support method

This section of the report focusses on redesigning the decision-support method based on the findings in the first run of the case study. In this section, the recommended improvements from it are evaluated, researched, designed, explained and implemented. The improvements that were recommended during run one read as follows:

- Include the FMECA as separate step to the decision-support method
- Consequently the determination of a suitable size/scope becomes step 2
- Formulate a structured approach to the redesign of the risk allocation matrix
- Define more specific instructions for using the steps of the decision-support method

These sections are concluded with the actual improved version of the decision-support method where the new design is show. This improved version will be used during the second run of the case study. The improved design will also be shown in appendix 6.

4.4.1 Introducing FMECA as the new first step

During the first run of the case study it was found that the use of the information that is found using FMECA proves very valuable for using the steps of the decision-support method. Because of the major impact that this methodology has on the use of this methods, the conclusion had to be drawn that the use of FMECA is not just a pre-requisite, but should be an official step of the decision-support method. That is why the information gathering and the use of FMECA are now separated. The gathering of information is now a pre-requisite for the use of the decision-support method, but when the necessary information is gathered, the new step 1 of the decision-support method ensures that either the information of FMECA is available or an FMECA is performed. The risk register and the risk dossier that are found whilst doing FMECA are used in the steps that follow.

The information on how to perform and use FMECA was already given in section 3.5.1 and appendix 4. Thus this stays unchanged. Only the fact that the use of FMECA is now the official first step of the decision-support method was changed. After the FMECA is performed and the information is gathered can be started with step 2. Step one will be known as the ‘case analysis’.

4.4.2 Step 2: Determine a suitable size/scope

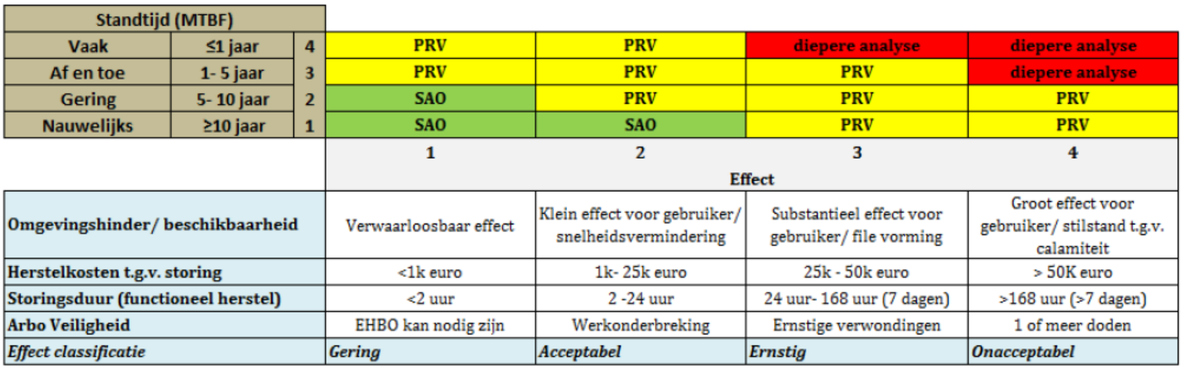
Consequently, the original first step becomes the second step of the method. But that is only part of the reason that is mentioned here. During the first run of the case study the determination of the size/scope was done by looking at the critical components and then chosen at random for this test. For this case study, that isn’t a problem, but it should be clear how the determination of the suitable size/scope works. Because there are more instructions that need to be defined extensively, these instructions are bundled in section 4.4.4.

4.4.3 Redesign of the risk allocation matrix

The risk allocation matrix can’t just be used in any case that presents itself. As part of the decision-support method, the matrix needs to be adjusted to suit the specific needs of that particular case. The matrix was originally designed with DBFM contracts in mind and specifically aimed at sluices. Therefore the frequency of failure and the effects (average repair time) are specifically applicable to sluices only. When working with other objects and systems, different frequencies of failure might be more appropriate. It is therefore recommended to adjust the risk allocation matrix accordingly.

In order to adjust the risk allocation matrix, two possible suggestions can be given. The first one is to approach the risk allocation matrix the same way as it was done in the original thesis, but this time applied to the current situation. The philisophy behind the choices of the current design are explained in the thesis by Brommet in chapter 4.2 of *Maintenance: Risk-Based Life Cycle Optimisation (effects)* and chapter 4.3 of *Risk uncertainty and classification (Frequency of Failure)* (Brommet, Managing the Dutch Waterworks using long-term Maintenance Contracts, 2015, pp. 19-26). Using these explainations, the steps can be retraced and used to adjust the matrix to the current situation.

The second option is using the already available information from the risk matrix to adjust the risk allocation matrix in a rather simple and logical way. The risk matrix is basically built up of the same variables as the risk allocation matrix. The MTBF that were chosen in the risk matrix can be transcribed as expected frequency of failure (during the contract period) and the effects can be used in accordance with the neglible to catastrophic rating that is already in place. If the risk matrix (Figure 23) that was used during the first run of the case study is used, the MTBF needs to be rated in accordance with the frequency of failure rates on the risk allocation matrix. The same has to be done with the effects that were used in the risk matrix.

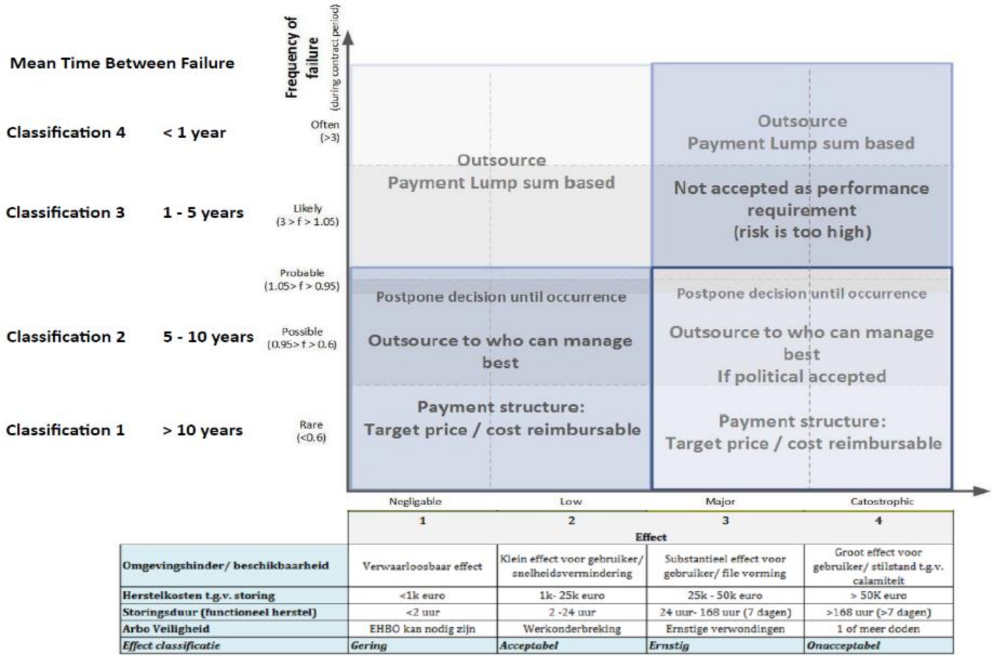


Standtijd (MTBF)						
Vaak	≤1 jaar	4	PRV	PRV	diepere analyse	diepere analyse
Af en toe	1- 5 jaar	3	PRV	PRV	PRV	diepere analyse
Gering	5- 10 jaar	2	SAO	PRV	PRV	PRV
Nauwelijks	≥10 jaar	1	SAO	SAO	PRV	PRV
			1	2	3	4
			Effect			
Omgevingshinder/ beschikbaarheid			Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing			<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)			<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid			EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie			***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure 23: Risk matrix (Imtech, 2013)

For this example, the frequency of failure is given in four classifications. Where failures occur at least once a year are rated as more than 3 times during the contract period, which is plausible given the shorter contract periods that are used when choosing for PBMC. The same routine is used for the remaining classifications. The same process was used to change the original effect (average repair time) to the new criteria: availability, costs of repair, downtime and safety. This can be seen in figure 25. In this new model, the original risk allocation matrix and the new risk matrix are combined to create a new risk allocation matrix that is able to interpret the data from the FMECA of the current object.

The risk allocation matrix can now be used in the specific case where the risk matrix and FMECA was designed for. It is important to note that this change needs to be made for every individual case where the risk allocation matrix is used, but this modification provides the option to use a risk allocation matrix on nearly every individual case imaginable.



	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)	<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure 24: Altered risk allocation matrix by Brommet (2015), now applicable to tunnels

4.4.4 Defining instructions for steps of the decision-support method

In the conceptual design of the decision-support method, a brief explanation of each step was included in the design. During the case study it was found that these explanation where covering the base, but in some cases didn't go deep enough to help the user of the decision-support method. A more clear definition of instructions for steps 1 to 5 are aimed on introducing improvements to it. Step 1 needs new instructions, because this step is new. The remaining steps just receive an update based on the results that were found during the first run of the case study. Steps 6 and 7 remain unchanged.

Step 1: Case analysis

An FMECA is performed to gain insight in the failure modes of an asset/system/object. During the FMECA, information about the predictability, plannability and criticality can be found and used in the remainder of the steps. The guidelines on how to perform an FMECA can be found in section 3.5.1 of the main report and appendix 4. The performance of this FMECA should at least result in the creation of a risk matrix and a risk register. Those parts are used to redesign the risk allocation matrix and contain most of the information that is needed during the remaining steps of the process.
Visual representation of this step can be found in appendix 6 figure A6.1.

Step 2: Determining a suitable size/scope

During this step one of the main parameters is set. This is not final, but creates a starting point to continue on to step three. This step is used to find the biggest single element that can be outsourced as one piece. This is done by using FME(C)A to obtain information about the criticality of certain systems, sub-systems or components within the total scope. The level where the criticality originates might help determine what size/scope should be used. The size/scope that is used to start with is the lowest size/scope where a system critical component can be found. After this size/scope is chosen, the remaining steps are performed. If the decision appears to be wrong during the performance of the remaining steps (it was too big of too small) the user is left with the possibility to adjust the size/scope along the way (both up and down) in accordance to the situation that is found.
Visual representation of this step can be found in appendix 6 figure A6.2.

Step 3: Risk allocation matrix

The next step is to use the risk allocation matrix by Brommet. The matrix however, needs to be adjusted to the object that is being evaluated. This is done in accordance with the instructions that were introduced in section 4.4.3. Following these instructions, the risk allocation matrix can be redesigned to fit the current case which can be used in the decision-support method.

By using the risk allocation matrix, a first suggestion is done about the method of outsourcing that can be used based on predictability and plannability of maintenance of an object. Besides the two already mentioned decision criteria, risk division is also evaluated as part of using this matrix. This says something about where the responsibility for certain decision should be.

First the MTBF and the average downtime of that component need to be found in the FMECA. This is standard data and should be available. The answers can be plugged into the risk allocation matrix and give a suggested answer to the question on how to outsource a certain part.

Secondly, the results need to be looked at in further detail. The first suggestion is based on the average that could be found by combining all individual parts into one big pile of data. Now it is key to take a closer look and try to find the extremes. These could be the parts with the highest frequency of failure (short MTBF and high probability) and the highest downtime. The possibility remains that on closer investigation it turns out to be wise to exclude the extremes from the bigger picture to increase the reliability of the results. This means that the size/scope for that part is then adjusted and an individual conclusion needs to be drawn for that specific part at the last step of the decision-support method. The outcome of this step will then be carried on to the next step.
Visual representation of this step can be found in appendix 6 figure A6.3 & A6.4.

Step 4: Determine a suitable contribution of the contractor

The following step takes the decision criteria predictability and plannability a step further. This is where the amount of contribution of the contractor is decided. The information that is used to decide this can also be extracted from the FMECA. The results of the use of the risk allocations matrix are also taken into account when making the suggestion here.

From the risk allocation matrix an overall judgement can be derived concerning the predictability of the failures that occur. Besides the information that is provided from this matrix, the results from the FMECA can be used to define the predictability of failures. The MTBF gives an indication on the failure rate of a component. Interpretation of these results depend on the strategy that the CA is willing to choose. Shorter MTBF equals higher failure rates, but countered with a good maintenance strategy will be very plannable. Longer MTBF equals lower failure rates are less predictable thus harder to plan. This results to lower predictability and plannability. Eventually, the decision is highly dependent on the strategy of the CA and the expert judgement that is given during the execution of the decision-support method.

Note that the size/scope can be changed during this step due to the information that becomes available during this step. (Strongly, this also happened during the first run of the case study where two different approaches where suggested for different parts of the system)

Based on that information, the expert judgement and the strategy of the CA, a suggestion is made for high or low contribution of the contractor.
Visual representation of this step can be found in appendix 6 figure A6.5 & A6.6.

Step 5: Determine suitable performance requirements

In this step, the performance requirements are chosen. These are based on the measurability of performances. If performance is easily measured, a higher level of performance requirements can be chosen. If performances are hard to measure, simple performance requirements might be more suitable.

The choices made here also heavily depend on the ambition and strategy that the organization wants to follow. If the organization has sufficient information about the behavior of an object, and is satisfied with keeping the risk and control within the organization, they can easily use work instructions to outsource the work. If the ambition is to give the contractor more freedom and challenge them to come up with innovative and progressive solutions, outsourcing on a higher level, for instance using performance levels or output-based might be a better solution.

So also at this step, the outcome is dependent on the data that is available, but also on the expert judgement and strategy of the CA.
Visual representation of this step can be found in appendix 6 figure A6.7.

Step 6: Cross-check

This step is aimed at checking whether the suggested level of performance requirements work in combination with the proposed level of contribution of the contractor. If a certain performance level is requested, a certain level of freedom for the contractor might be needed. This way the allocation of responsibility is checked in order to make sure that the request is realistic. If either one of the variables is too high, and therefore not compatible with the other, an adjustment needs to be made to either one of them.
Visual representation of this step can be found in appendix 6 figure A6.8.

Step 7: Proposed solution and expected outcome

This last step of the process summarizes the eventual proposed solution that is the result of the process. The proposed solution will be the chosen parameters for the size/scope, contribution for the contractor and the performance requirements.
Visual representation of this step can be found in appendix 6 figure A6.9.

4.4.5 Conclusion

At this point, the first run of the case study is finished and the results are analyzed. Based on these results a few recommended changes to the conceptual design of the decision-support method have been made. These changes have been introduced and explained at the start of section 4.4. All these changes have now been implemented in the redesign of the decision-support method. This improved version is shown and explained in section 4.4.4 and its corresponding tables and graphs are found in appendix 6. The biggest changes and the schematic representation of the improved design are shown below.

The conclude and summarize, the biggest changes are as follows:

- Including FMECA as an official first step (resulting in a 7 step method)
- Including a method to redesign the risk allocation matrix to suit the current case
- Defining more elaborate instructions on some of the steps

This results to the following schematic representation the decision-support method.

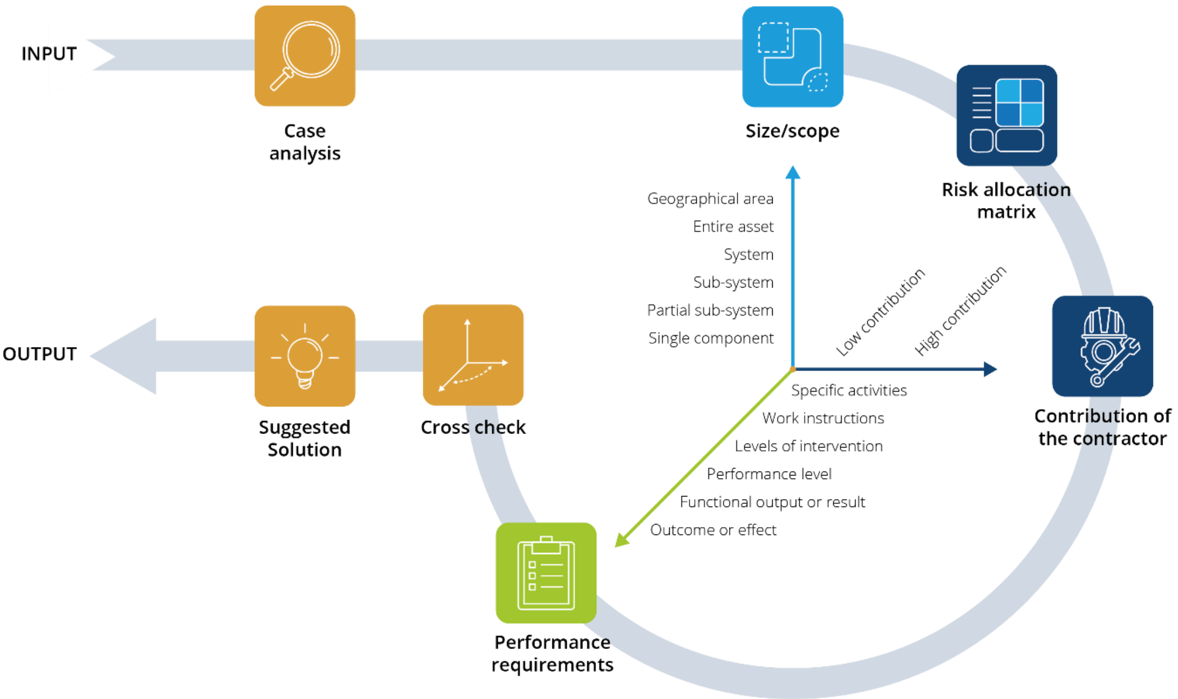


Figure 25: Schematic representation of the redesign of the decision-support method (as found in appendix 6)

This method can now be used during the second run of the case study. During this second attempt, the new steps will be followed and the procedure of the first case study is repeated in order to compare the results and find new data. Based on these results another redesign might be possible in order to improve the design of the decision-support method even further.

4.5 Case study (Run 2)

During this second run of the case study the steps of the redesign of the decision-support method are tested to see if they work as expected. The design that is tested here is a result of the findings in chapter 3 and improved with the help of the results of the first run of the case study. During this second run, many of the steps and results will look similar to the first run. The big difference lies with the steps that were improved during the redesign. The instructions that were clarified in the process won't change much of the outcome, for the instructions are the result of the outcome of the first run of the case study.

The redesign of the decision-support method that will be used during this case study is shown in the figure below and is explained in section 4.4.5 and Appendix 6.

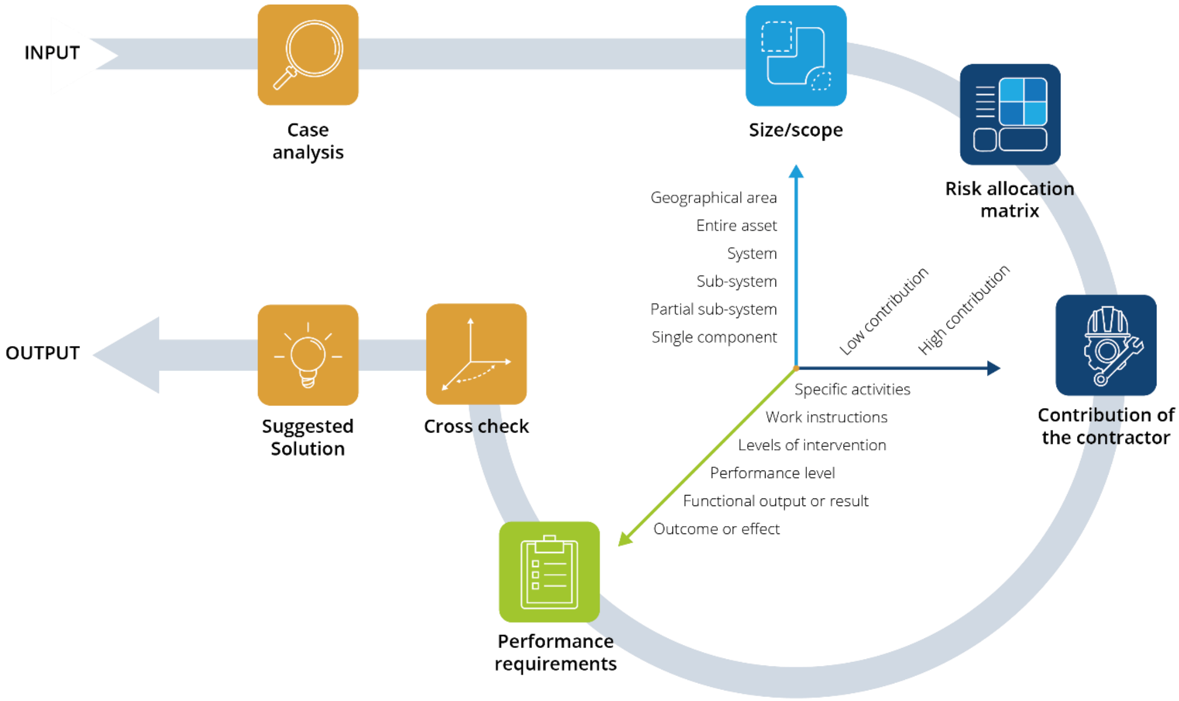


Figure 26: Decision-support method visualized (as found in appendix 6)

The results of the second run of the case study are split into two parts. In appendix 7, the process description and the results of the case study found. The steps that have been taken and the data that was used along with its interpretation leading to the final results for three different systems are stated in this appendix. In this appendix, the flaws of the conceptual design are already found and visible, but are not yet discussed or solved. This is done in the other part about the case study that is found in this chapter.

In section 4.5.1, every individual step that is performed during the application of the decision-support method is reviewed based on the results that were found in appendix 7. This review mainly focuses on the functionality and practicality of the individual steps. During this second case study, the value of outcome is being judged.

In section 4.5.2, a general discussion about the first run of the case study is presented. Rather than discussing the individual steps, as is already done in the previous section, the bigger picture is reviewed here. This is also the part where the outcome is placed within the bigger picture.

Based on the outcome of the discussions in sections 4.5.1 and 4.5.2, recommended improvements are presented in section 4.5.3. These improvements can be for individual steps, but might as well cover a bigger range of multiple steps or significant changes in the design of the decision-support method.

The last part of this case study is the conclusion in section 4.5.4. The conclusion is a review of the findings of the second run of the case study and a list of recommended improvements that should be implemented to make the final version of the decision-support method before the validation.

The suggested improvements will be researched and worked out in section 4.6 and a redesign will be made. Which will then be used for the validation of the method during the expert meeting.

4.5.1 Review of the functionality of steps of the improved decision-support method

This section covers the review of the individual steps of the redesigned decision-support method during the second run of the case study. This review focuses on the functionality and practicality of the steps that are performed during the case study. The outcome of each step in relation to the case and a description of the actual process can be found in appendix 8.

The first section covers the gathering of information and the performance of FMECA. In this particular case, the FMECA had already been done and the results are presented. After that, every section reviews an individual step. In every section the functionality and practicality of that specific step is reviewed and the findings on that are presented. These findings can be used as input for recommended improvements, but might also be a confirmation that the steps are technically working and achieve the goals for which they are added to the decision-support method. No hard decision are taken in this section yet. This is postponed until after the general discussion about the results.

step 1: Case analysis

Before the first step the information about the tunnel was collected and an FMECA was found. Although this FMECA was from 2013, the information could still be used to perform the rest of the steps and be used as a proof of concept. If this was encountered in real cases, the FMECA might need some adjustments to be more accurate. That is why step 1 of the redesigned decision-support method features the possibility to perform, adjust or complete the FMECA. During this case study, this was not done because the results were sufficient enough to perform the case study.

Along with this FMECA came the criticality analysis. This criticality analysis was used to decide which systems and sub-systems are critical to the overall function of the tunnel and/or have a direct impact on the safety of the tunnel. From this criticality analysis a list of systems came forth that are critical to the functioning of the tunnel. From this list, 3 systems were selected to apply the remaining steps of the decision-support method on. These systems are: the emergency power supply, main pump basement and video and CCTV system. Two of the three systems were central systems, having impact on the entire tunnel (emergency power supply and main pump basement), and the last system was a tube bound (video and CCTV System). During this phase, a general assessment of the tunnel was made to map out what systems were present and what should be included in the eventual contract. In a real case, all systems should be evaluated this way, but for the goal of proving the concept, these three systems will be enough.

The procedure of using the decision-support method starts off with collecting more information about the individual system, like the functional requirements and the reason of existence of the system. This information is necessary to understand the importance of the system and make informed decisions in the remainder of the process. Without knowing the importance of certain functions of a system, decisions that need to be made further along the decision-making method might be underestimated. This information was found in the previous contract and supplemented with information from the documents holding all generally required system specifications for the RWS Tunnels.

Step 2: Determining a suitable size/scope

Because of the way the case was introduced and the information that was gathered through the FMECA, the second step of the process was already done for the most part. This step was to determine a suitable size/scope to use as a starting point for the next steps. In all three cases it has been chosen to start on the level of sub-systems. The reason for this was the fact that a bigger level would create more problems than it would solve (at this stage). The entire tunnel was not an option, first and foremost because that is too complex and there are too many risks involved. Secondly because it would not fit the goal of this case study. The reason for not choosing the level of systems was the fact that different critical sub-systems were present within one system and evaluating them individually would be more efficient. The decision then was made to use the sub-systems as a starting point, keeping in mind that this could change due to the outcome of the other steps of the decision-support method.

Step 3: Risk allocation matrix

The third step was the use of the risk allocation matrix by Brommet (2015). In earlier stages of the development and testing of the decision-support method problems arose from the use of this model because it wasn't suitable for tunnels (it was originally designed for Sluices). This problem has since been solved by adding an adaptation method to the decision-support method. This adaptation was originally planned as part of step three, but was already performed as part of step 1 and the data gathering phase. This was done because this will only have to be done once at the start of the method. It resulted to an increase of suitability for use on the Noordtunnel specifically during this step (and the remaining steps) of the decision-support method.

During this case study two approaches were used to interpret the data from the FMECA within the risk allocation matrix as has been described in the new instructions during the redesign. First the overall scores of all failure modes were combined and an average score was given. Secondly the individual failure modes were evaluated to see whether another approach was possible. The MTBF and downtime were normative in most cases, but also repair costs and hindrance were of high impact in some cases. Interpretation of the numbers is really hard, because there is no hard proof and the numbers are mostly obtained from expert judgement. The risk allocation matrix was therefore used to get a general perception of what would be wise to do, but the real decision was made during the next step.

Step 4: Determining a suitable contribution of the contractor

The next step is to find a suitable contribution of the contractor by evaluating the predictability and the plannability of the maintenance work. The FMECA is a very suitable source of information during this part of the decision-support method. Information about the expected failure modes, the chances of that failure, options for maintenance solutions and a suggested maintenance strategy can be used to define the predictability and plannability of a system. Preventive maintenance for instance can make things plannable, and therefore also predictable. An unpredictable system can therefore be made predictable for the contractor and more reliable for the client. Whether this is a viable option depends on the amount of resources and capacity that is available within the organization of the CA. The goals and ambition, and the corresponding strategy that is chosen will be of major impact on the eventual decision that will be made. This has not yet been taken into account during this version of the decision-support method. The risk dossier was eventually used to get insight of the life expectancy of certain systems as a whole, impacting the decision to include or exclude the renewal of that particular system in the contract. This information was very helpful. The only thing that lacked was solid information of MTTF (mean time till failure) of certain systems measured from a certain point in time. This could help improve the predictability and make the decision even more clear.

Step 5: Determining suitable performance requirements

The next step was deciding the suitable level of performance requirements that will be used for every sub-scope. During this step, the measurability of the performances was the leading factor. In the risk dossier some information could be found whether or not measurable performance requirements were set, but this information was scarce. Eventually it was possible to make an informed decision about the level of performance requirements that could be used and was suitable for the situation it was meant for. There were however a few instances where multiple solutions were possible, depending on the interpretation of the information.

The outcome is therefore highly dependent on the expert judgement of the evaluator and the goals & wishes of the CA. What really missed here was an overview of all measurable data of the last few years to predict a level of performance that could then be used to set new performance requirements. This only feasible when measurable data can be acquired and this data can be used to judge the delivered performance. Keep in mind that this is only interesting if the level of performance requirements is at least higher than levels of intervention. Similarly, the eventual choice is highly dependent of the chosen ambition, goals and strategy of the CA. This could be improved in a future version of the decision-support method.

Step 6: Cross-check

The sixth step of the process is a cross-check of the interfaces to see whether the chosen solutions can be used together. The goal of this step is to see whether the different chosen parameter can collaborate in good way. This is an important step to prevent impossible contracting solutions where the contractor is burdened with an unfair share of risk. A striking example is a situation where the contractor can be punished when not delivering a certain performance, but at the same time is not allowed to do everything in its power to deliver that performance. This situation can occur when a Low contribution of the contractor is expected, but a high performance level is required. This check is important and helps fine-tuning the proposed solution in the advantage of both parties.

Step 7: Proposed solution

After this step the proposed solution is presented, this is the last step of the decision-support method. It presents an overview of the decisions that were taken in terms of scope/size, contribution of the contractor and the level of performance requirements is proposed. This is a summary of the decision that come from the model, backed up with a short explanation on why this was the proposed solution. This provides a good overview of the outcome.

4.5.2 General discussion

The second run of the case study is used to test the new implementations and see if more improvements are required to increase the effectiveness of the decision-support method. The gathering of information and the execution of an FMECA is now the official first step of the process. By making an explicit distinction between the information gathering & FMECA (step 1) and the choosing a suitable starting point with regard to size/scope (step 2), the second step becomes way more clear and it forces the users to motivate this decision even more.

Another step that was introduced, was the redesign of the risk allocation matrix to suit the current case. The redesign worked as expected and gave more clear results that were achieved in the previous case study. The redesign was placed at step 3, where the use of the risk allocation matrix is also placed. This seemed like a logical choice at the time. However during this run of the case study, it became clear that this might not have been the best choice since. All the information to perform the redesign is found whilst the FMECA is performed. Moreover, the redesign only has to be performed once and will then be used throughout the entire run of the decision-support method. It therefore seems more logical to place the redesign of the risk allocation matrix in step one, where the preparations for the remaining steps is done. That was also how it has been performed during this case study and with positive results.

This coincides with the next discovery. The decision-support method has been seen as a linear process of six or seven steps until now. When looking more closely at what is actually happening, the process isn't linear, but more circular. Step 1 is the initiator of the entire method. All the information is gathered, the FMECA is performed and if the previous note about the redesign risk allocation matrix is implemented, this is done once during step 1. After that, the remaining 6 steps are done over and over for every individual part, hence the circular motion of steps 2 to 7.

The instructions that were added during the last redesign of the decision-support method were reverse-engineered from the results from the first case study and performed as expected during this second run of the case study. It didn't result to changes in the outcome, but increased the speed in which this run could be performed. An increase of efficiency has therefore been achieved.

Another aspect that came up during both the first and second run of the case study was the effect that the expert judgement and the willingness of the CA have on the decision that are made during the decision-support method. The willingness of the company plays a huge role at the determination of the performance requirements that are used. This has not yet happened to the decision-support method, so a different solution should be found to tackle that problem and generate a way to come up with that information. The fact that expert judgement remains important is just part of the method.

4.5.3 Recommended improvements

Based on the results, review and general discussion of this second run of the case study, a few recommended improvements are given. These improvements could affect the method as a whole, or be specified to adjust specific steps. The improvements themselves are made and explained in section 4.6. This will result in a final design of the decision-support method that will be used as input for the validation of the method during the expert meeting.

Redesign of the risk allocation matrix

The redesign of the risk allocation matrix worked as expected and was correctly implemented in the latest design of the decision-support method. However the placement of the actual execution of the redesign didn't fit the process in its entirety. It was therefore recommended to change the position of the redesign from step 3 to step 1.

Circular characteristic of the decision-support method

Besides the changes to the location of the risk allocation matrix's redesign, the linear characteristic of the method is subject to change. Instead of one linear model, the model will be more of a circular nature. This coincides with the actual way the method was used during the execution of the case study. By changing the flow of the method, it will be easier to understand what happens during every step.

Decision-making process

In order to deal with the issues that were found in both case studies concerning the importance of the willingness of the CA on the respected outcome of the decision-support method, it is suggested to put the decision-support method in a bigger perspective. Therefore a process is developed where the company can use a guideline to set boundary conditions and determine what they want to achieve and what they are willing to do for it in return. This data can then be used as input during the execution of the decision-support method.

4.5.4 Conclusion of case study run 2

During this second run of the case study, the redesign of the decision-support method has been tested. Technically, the method worked as designed. The remarks that were made originated mainly in the way the method is set up, the influence of expert judgement on the decision-making and the lack of data that was available from the CA's perspective on the decision-making. In order to improve the current version of the decision-support method, three recommendation are done:

- Change the location of the redesign of the risk allocation matrix
- Introduce a circular character to the steps of the decision-support method
- Introduce a decision-making process that includes the view of the CA before starting the decision-support method

The first recommendation fits the redesign process of the risk allocation matrix in a more logical position and makes it easier to refer to during the course of using the steps of the decision-support method. The location will be during step one, which is the entire gathering of information, doing FMECA and preparing for the remaining steps of the decision-support method.

The second improvement is mainly a visual one, which will make understanding the decision-support method a lot easier. By introducing this circular design, a clear distinction can be made between the set-up of the method and the continuous and repeating execution of the remaining steps of the method.

The last recommendation will try to fulfill the wishes and demands of the CA into the process. This type of information lacked during the two runs of the case study but will have a great influence on the eventual outcome of the decision-support method in practice.

These recommendations will be explored and implemented in section 4.6. This will result in a final version of the decision-support method that was based on the two case studies. This final version will be used as input for the validation during the expert meeting.

4.6 Redesign of the decision-support method

This section of the report focusses on redesigning the decision-support method based on the findings in the second run of the case study. In this section, the recommended improvements from the second run are evaluated, researched, designed, explained and implemented. The improvements that were recommended during the second run read as follows:

- Relocating the redesign of the risk allocation matrix
- Visualize the circular character of the steps of the decision-support method
- Design and introduce a decision-making process that highlights the CA viewpoint

This section is concluded with the improved version of the decision-support method. This improved version is the final version after the two runs of the case study and will be presented during the expert meeting. The final result will also be shown in appendix 9.

4.6.1 Relocating the redesign of the risk allocation matrix

Following the findings during the first run of the case study, the decision was made to add a structured way to redesign the risk allocation matrix for a particular case. The redesign worked fine and was also successfully used during this second run of the case study. The chronological order of performing the steps was however concluded to be illogical. During the execution of the case study, this step was relocated to the start of the method, during or right after step one. This made way more sense because the data required to perform the redesign is found and processed beforehand. The second reason why this felt right was the fact that the redesign is only performed once during the entire method, so having it come into view every time step three (risk allocation matrix) is executed, does not help the usability of the method. Locating it at step one, where all the actions are aimed at getting the right information and making sure everything is prepared for a smooth start of the decision-support method makes sense.

In practice, the prerequisites for redesigning the risk allocation matrix are:

- the matrix itself, which is known and present
- the risk matrix, which is made during the execution of the FMECA
- the risk dossier in order to use the risk allocation matrix after the redesign

It is therefore decided that the step of redesigning the risk allocation matrix is placed as the last part within step one. By doing so, the redesign is still part of the preparation phase of the decision-support method and all prerequisites are met before the redesign is executed. This is similar to the way the redesign is done during the second run of the case study and it worked. This means that this change is already case-study tested and was received with a positive result.

4.6.2 Circular character of the decision-support method

The second change that is made to the decision-support method has to do with the structure that is built around it. This isn’t so much of a change, but more as a way to visualize the method in such a way that it represents what is actually happening. During the previous runs of the case study, the method that was proposed to be used, was a linear model. But the method that was followed wasn’t. The first step of FMECA and information gathering is a step that is done once for the whole method. After that an endless loop existed of steps 2-7 to complete the method for every individual part that is evaluated. Thus the visual representation that was used up until now doesn't show what is actually happening. The new visual representation should give the user a good impression of what is actually happening during the execution of the decision-support method.

In this design, step 1 is seen as a separate step that is performed before anything else is done. After this first step, the first system that will be evaluated is chosen during step 2 (size/scope). For this particular part, all remaining steps are executed until a suggested solution for that part is found. This results is set aside. Then step 2 (size/scope) is started again for a new part. For this part, again all the remaining steps are executed until a suggested solution is found. This cycle will continue until the entire object is evaluated. This new cycle is visualized in figure 27.

4.6.3 Introducing a decision-making process

During the first run of the case study, the main goal was to see if the steps function as they supposed to. The outcome of the decision-support method wasn't really the goal. This was done because a lot of information and knowledge is missing, which would otherwise be present by means of the experts executing the decision-support method. During the second run, the focus was more on that issue, and the following was noticed. It became clear during both runs that expert judgement is not the only item that influences the decision-making. The most obvious data, although not yet considered, was the viewpoint of the contracting authority, the organization behind the contract.

It was found that during step 4 and step 5 of the decision-support method, the influence of the CA could actually play a major role in the decision-making and could majorly influence the outcome. When the CA wants to put in as little effort as possible, in some cases that would mean that a lot of responsibility is given to the contractor, influencing the contribution of the contractor significantly. Consequently, the contractor needs to get a lot of freedom within the performance requirements that are chosen. But this could also work the other way around. If the CA wants to keep control of certain aspects, the performance requirements need to be clear and demarcated, leaving little room for own interpretation for the contractor and a low contribution of the contractor. These questions need to be answered by the CA before the decision-support method is started. It concerns the ambition and the goals that the CA has for the asset and the contract. But this also has to do with the state of the asset and the state of the organization at the moment. These factors tell something about the possibilities that are there. Based on that information, the CA can determine a strategy which can be used as guideline whilst executing the decision-support method. This ensures that the goals, whishes, demands and limitations of the CA and the organization are taken into account when designing a PBMC.

Although this was actually outside the scope of this thesis, an introduction is made on a method that could help fill this gap of information. This method is built around the current decision-support method. It contains steps that gather the organizational and market information that is needed to start with the decision-support method and picks up again when the decision-support method is performed.

The method and corresponding structure to make this happen is called the decision-making process. It covers a longer period of time containing different steps leading up to the design of a PBMC. The decision-support method is just a step in this longer process.

The structure of the decision-making process is an important factor in reaching the required outcome. If the process is not structured properly, the advantage of using this process is nullified. To create this structure, the process is divided into several steps. Every step contributes to the final result in its own way. Some are meant to establish a starting point, some are included to acquire data or information and others are used to value or evaluate certain decisions. But all are necessary to reach the eventual goal of providing the user with insight on the possible decisions that can be taken when making a PBMC.

In this section, the only an introduction is made on the steps that are used within this process. The explanation and instructions for this process are covered in appendix 8. It is shown that the process consists of 5 steps, covering everything that was mentioned up until this section so far. First the organization has to determine which ambition it has for this particular asset and contract. Then the organization needs to set realistic goals that coincide with these ambitions. During the second step, the an exploration needs to be performed to see what the total scope of the contract will be, what the current state of the object is, and what possibilities the organization and the market have to offer. The combined information of the previous steps should make it possible to determine a strategy that the organization wishes to use to reach the set goals. Armed with an ambition, a set of goals, knowledge about the asset, organization & market and a sound strategy, the contract design team can start using the decision-support method. The support method delivers a set of solutions for the individual parts of the asset. During the fifth and last step of the decision-making process, these solutions are combined in total solution and a final decision concerning the entire asset will be presented.

In short, the five steps of the decision-making process are designed as follows:

1. Determination of ambition and goals
   At the start of the process, the organizational ambition and goals they want reach with the new contract need to be expressed and have to be clear. They will determine the direction that is taken during the decision process.
2. Exploration
   During the exploration phase the total scope of the contract is determined, the current state of the assets (and asset information) is established. As well as the current state of the organization and the market. This is set out against the ambition and goals that were set.
3. Determination of strategies
   During the exploration, opportunities and problems are found. A strategy needs to be determined to show which opportunities should be taken, intentions to solve certain problems, and decide which problems are left as is.
4. Decision-support method
   The decision-support method is used to guide every individual part of the asset through the solution space in order to give a suggestion about the way of outsourcing that might work best for that particular part of the contract.
5. Concept decision and conclusions
   A list of conclusions and concept decisions comes from the decision-support method and need to be evaluated through expert judgement and converted to final decisions that can be used in the contract.

As mentioned before, the design itself is part of appendix 9. This also includes the introduction, exploration and the explanation of the process. The process itself is not tested because it doesn’t fall within the scope of this thesis. It is however important enough to be mentioned because it can affect the outcome in a significant way. The proposal for this process was therefore taken into account when discussing the decision-support method during the expert meeting as part of the validation process.

The inclusion of the decision-making process doesn’t change the way the actual decision-support method works, it just places it in a bigger perspective. The final version will therefore mention the existence of this decision-making process and the part the decision-support method plays within this process, but the real focus will be on the decision-support method itself.

4.6.4 Final version of the decision support method

Now that the two runs of the case study are done, the final design of the decision-support method that is based on the results of the entire case study can be made. The designs started as a conceptual design and has been improved over the course of two redesigns in section 4.4 and 4.6. This final design is the result of the changes that have been made in this section. All the changes have now been implemented in the final design. The final design of the decision-support method is shown and explained in appendix 10. The biggest changes that were implemented during this last redesign are shown below, as well as a schematic representation of the final design.

The biggest changes are as follows:

- The location of the redesign of the risk allocation matrix is moved to step 1
- The method has gotten a circular character, as can be seen in the figure below
- The steps decision-making process have been introduced, putting the decision-support method in a bigger perspective without changing the decision-support method itself

Resulting in the following schematic representation of the decision-support method.

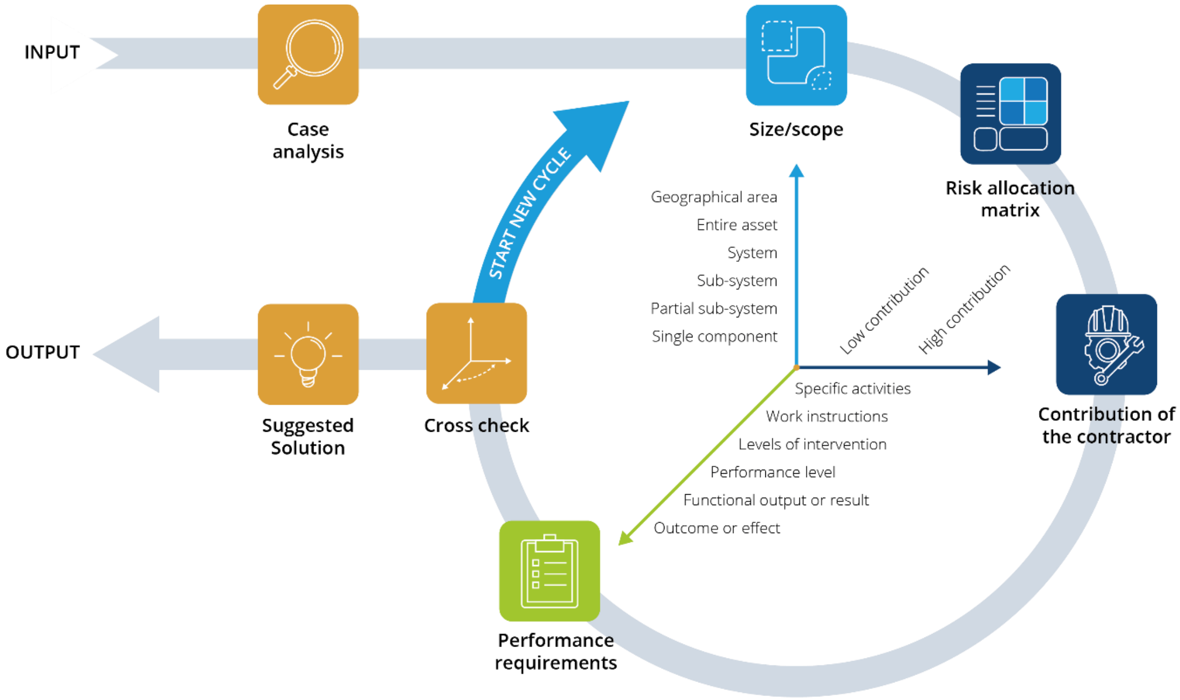


Figure 27: Schematic representation of the final decision-support method (as found in appendix 9)

This method can now be used as input for validation. During this validation, the final design is presented during an expert meeting to show what the decision-support method can do and how it can help with future design of new PBMC.

4.7 Conclusion

One sub-research question was set to be answered at the start of this chapter. The goal of this entire chapter was aimed at finding the answers to that research questions, continuing the work that was done during the literature study and eventually contribute on answering the main research question. The main research question of this thesis reads as follows:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

During this chapter, the results of chapter 3, the conceptual design of the decision-support method, was put to the test during two runs of the case study. The sub-research question that has been explored during these case studies reads as follows:

'What are the results of the technical application of the support method to real case examples?'

During these case studies, the technical application of the decision-support method was tested and the results were analyzed. Based on the outcome of these analysis, the conceptual design is improved twice by redesigning it based on the new knowledge that was found during the case studies.

Section 4.1 was used to give a small and clear introduction of the asset that was chosen to perform the case study on. The actual decision for this asset was already made in section 2.3. After the introduction of the asset, the available information that could be used during the case study was collected and presented in section 4.2. The list of sources that is shown there is used during the actual execution of the case studies.

Section 4.3 was the first actual run of the case study using the conceptual design of the decision-support method that was created in chapter 3. The focus during this first run was on the technical applicability of the method. Appendix 5 was used to show a description of the process of following the steps of the decision-support method. Section 4.3.1 was used to review the way the decision-support method worked on a technical level. A general discussion was written about the results of that first run of the case study was written in section 4.3.2 and the a list of improvements was generated in section 4.3.3. These improvements were then researched and implemented in section 4.4. After the implementation a redesign of the original method was created and shown in 4.4.5 and appendix 6.

Four major changes were made based on the first run of the case study:

- Include the FMECA as separate step to the decision-support method
- Consequently determining a suitable size/scope becomes step 2
- Formulate a structured approach to the redesign of the risk allocation matrix
- Define more specific instructions for the original steps 1 to 4

FMECA was added to the decision-support method as an official first step and brought the total number of steps to 7. Step 1 became step 2 and was made more elaborate with a clearer explanation. Increasing the importance of that step. More specific instruction were also defined for steps 2, 3 and 4 of the original model. These became 3, 4 and 5 during the eventual redesign.

Another big, but important change was the introduction of a structured method to change the risk allocation matrix from a sluice based system to a tunnel based system that could specifically be used for this case. The structured way that was created was added to the step where the risk allocation matrix was used and was created in such a way that the matrix could be altered based on any form of asset.

With these changes the conceptual design of the decision-support method was now changed for the first redesign based on the results of the case study. This transformation is visualized by the following figure.

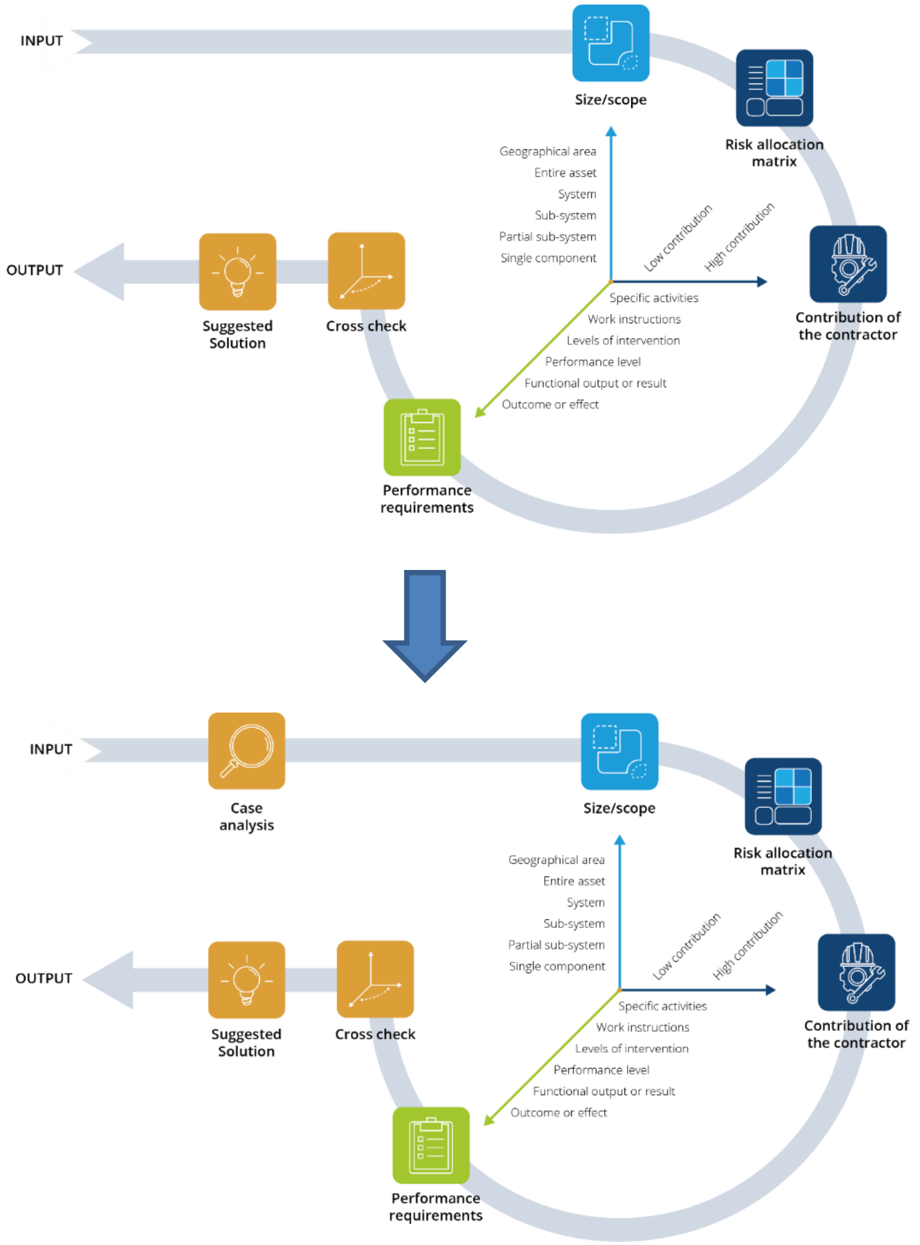


Figure 28: Transition from conceptual design to redesign of the decision-support method visualized after case study run 1

The second run of the case study follows the same structure as the first one, starting at section 4.5. During this second run of the case study, the redesigned model of the decision-support method was used. During this second run, the focus was still on the practical application of the method, but also on the outcome and the influencing factors on that result.

More improvements were found during the second run of the case study. Based on the results that were reviewed in section 4.5.1 and the discussion in section 4.5.2, a list of improvements was generated in section 4.5.3. These improvements where then researched and implemented in section 4.6. After the implementation a redesign of the original method was created and shown in appendix 9.

Three major changes were made based on the second run of the case study:

- Relocating the redesign of the risk allocation matrix
- Visualize the circular character of the steps of the decision-support method
- Design and introduce a decision-making process that highlights the CA viewpoint

The relocation of the new risk allocation matrix was already done during the second run of the case study. The new location of the redesign was during step one right after the FMECA. This made more sense because it is a once per asset transition, which is the same for the FMECA and it is based on the information that is found during the FMECA.

The circular character of the decision-support method is locked up in the way it works, but wasn't yet visualized in that manner. Therefore the decision was made to visualize the method in such a way that it looks the way it actually works to avoid confusion.

The last big change was the introduction of the decision-making process. This puts the decision-support method in a bigger perspective and gives it a place within the process of creating a PBMC. The decision-support method itself is no changed by this improvement. The information that is available for the users however could be improved significantly by this change. But it has to be noted that this is only an introduction of the decision-making process and more research need to be done on this topic.

With these changes the first redesign of the decision-support method is changed into the final design based on the results of the two case studies. This transformation is visualized by the following figure.

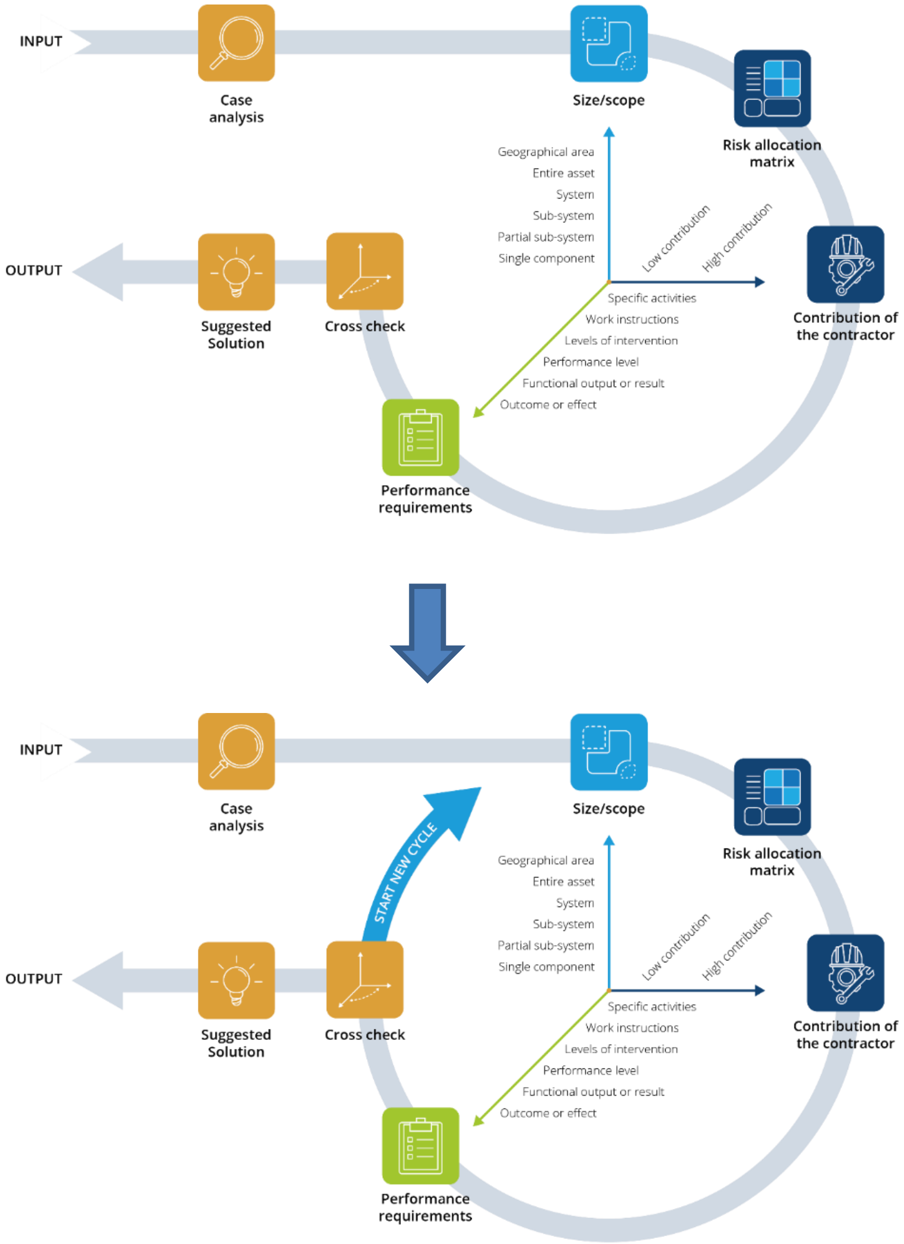


Figure 29: Transition from redesign to final design of the decision-support method visualized after case study run 2

The final design is explained in appendix 9 and will be used as input for the validation during the expert meeting. During this meeting the experts will be confronted with the methodology and the results of the case studies. Based on this presentation, the experts can give their opinions on the way the method works, the value it might have in the future and the improvements that might be needed to use the method in practice.

When looking back at the research questions that were set at the beginning of this chapter, the following can be said. The chapter continues where chapter three left off in finding an answer to the main research question. The structured way that has been created in chapter three is tested, analyzed and improved. The various versions of the decision-support method were tested on their technical application during real cases and improved based on the results that were found during these case studies. This resulted to the final version of the decision-support method that is ready to be presented for validation during the expert meeting. This will be covered in chapter 5.

Chapter 5

Validation

This chapter is used to validate the final design of the decision-support method that was found during the case study using an expert meeting within Rijkswaterstaat. The comments that were made during this meeting are used to make final improvements to the design.

5

5. Validation

The validation marks the end of the development of the decision-support method during this thesis. During this validation, the goal is to let the experts give their opinion on the way the decision-support method works in practice and whether they think it can add something to the quality of the design of the PBMC. The validation is also used to help strengthen the answer to the main research question:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

The validation is done by discussing the results of the case study with experts in the field. Some of these discussions were one on one but the biggest discussion was organized during an expert meeting. During this chapter the expert meeting is explained and the discussion with all the experts is presented step by step. The discussion is based around the following sub-research question that was set at the beginning of this thesis:

'What are the expert opinions on the practical application of the decision-support method on real case examples?'

Based on these discussions, a conclusion is formulated that captures the general opinion of the experts about the practical application of the decision-support method in its current state. Based on this conclusion, further improvements can be suggested. These will be presented at the end of this chapter. These can be in the form of an immediate change of the method, creating a redesign of the final design shown in appendix 9, or merely a suggestion for future research into this topic.

5.1 Expert meeting

The expert meeting is an important part of the validation of this thesis. During the expert meeting the decision-support method that has been developed during this thesis is presented. Every step of the method is introduced and explained during a presentation and then discussed afterword by the experts. During the discussion, the experts are asked to comment on the technical use of the steps and the practical application of the steps of the decision-support method on real cases. The goal of the expert meeting is to learn whether they think that the decision-support method can help them while designing a PBMC in the future. Which steps are promising, and which steps might need further research? Eventually the case study and the expert meeting will be the base for the conclusions and recommendations that will be given about this thesis.

5.1.1 Expert validation

The validation is an important part of this thesis. To validate the proposed design of the decision-support method and the entire work of this thesis, experts were asked for a review. The experts were invited to a meeting that was held within Rijkswaterstaat. During this meeting, people working at contract design teams, technical advisors and the managers were consulted to review the work. The meeting started with a presentation about the work, followed by a discussion with the present experts. During the presentation and especially during the discussion, valuable information is gained that still can be implemented in the final version. After the presentation, some of the experts read the report in its entirety and generously reported helpful feedback. This feedback was also taken into account when writing the discussion and the expert conclusions. Not all invited experts were able to join the meeting, however, their input was delivered through a phone call, email or on a separate meeting. This input is added to the discussion and therefore taken into account in the conclusion. The next table (Table 3) shows the experts that have delivered their input to this thesis.

Experts from Rijkswaterstaat that were part of the validation process (direct and indirect)	
Name	Function
Peter Jansen	Technical manager Tunnelteam II *Technisch manager Tunnelteam II*
Martijn van Gils	Contract advisor tunnel maintenance procurement *Contractadviseur Landelijke inkoop tunnelonderhoud*
Hans Kievits	Procurement advisor tunnel maintenance procurement *Inkoopadviseur Landelijke inkoop tunnelonderhoud*
Matthijs Neuhaus	Technical advisor Tunnelteam II *Technisch adviseur Tunnelteam II*
Hans Bruinsma	Advisor tunnel maintenance procurement *Adviseur Landelijke inkoop tunnelonderhoud*
Marco Dreschler	Supervisor *Stagebegeleider*

Table 5: Experts from Rijkswaterstaat that were part of the validation process

5.2 Review results

During the meeting, all comments and suggestions are categorized per step in order to trace back all changes that are made to reach the final version of the method. The feedback that was delivered by the experts in other ways has been used in these step descriptions as well.

Presentation

The presentation was used to introduce the research to the experts and give them an understanding of why and how this research was conducted. The main ingredients of the decision-support method where introduced before getting into the method itself. As a start, the literature study was explained including the considerations, decision criteria and the parameters. Based on that info, the solution space was introduced to explain the options that are explored by the decision-support method. Then the decision-support method itself was introduced, briefly explaining all seven steps and their purpose. After that, all steps where explained again in detail with the help of schemes, figures and examples that were found during the case study, all in order to explain how the final design was created and how it should be used in practice. During the presentation itself, a few questions were asked, but most questions were saved for the discussion afterwards and in the personal feedback.

Expert discussion

During the discussion, the entire process of this thesis was on the agenda, but the focus was on the individual steps of the decision-support method. The experts that commented on the design of the decision-support method, during the expert meeting of afterward, were positive about the way it was set-up, the way it was presented and could follow the individual steps as they were shown. During the discussion, the individual steps were again analyzed and valuable feedback was given.

General comments about the method and step 1: Case analysis

The experts were positive about the way the main decision criteria were found and formulated. This gives a good starting point for the process and validates the use of the RCM and FMECA methodology to gain necessary information.

During the discussion a comment was given about a ‘what if’ scenario: ‘’What if an FMECA is not available or not even optional?’’ The decision-support method provides for this scenario by explaining that step one is about gaining information about predictability, plannability and criticality, not about doing an FMECA or using RCM. FMECA remains the preferred solutions because it is a known, understandable, and relatively easy to use method which provides valuable information that can be used during the decision-support method. Another advantage is the possibility to adjust the level of depth of the FMECA to a case. It is however possible to use another risk evaluation tool which provides similar information regarding predictability, plannability and criticality. This is however not tested during this thesis and will be recommended for future research.

Eventually it was concluded that step one is about finding information regarding predictability, plannability and criticality in order to proceed to the next step. FMECA is found to be the preferred tool to provide that information.

The group was really satisfied with this answer and positive about the this first step. It was brought up that Rijkswaterstaat uses a similar kind of system called P-IHP (*Prestatiegestuurd Instandhoudingsplan*) or performance-driven conservation plan. This method falls within the RCM category and follows the same structure as FMECA, but is more focused on critical components and often leads to a decision (leaving Rijkswaterstaat in control) solely based on the criticality of an object. This decision is made without looking at other aspects or options. This is another reason why the experts were enthusiastic about the presented methodology.

Step 2: Determine a suitable size/scope

The idea of the three parameters that could be used to create a custom made solution for every individual item was received well. The idea behind the solutions space was easy to understand and makes it easy to navigate through all the available options. The second step was therefore a logical conclusion. The relationship of all three parameters have been clearly established proving that one parameter must be defined in order to precision the other two parameters accordingly. The decision to start with the size/scope based on the criticality and the other results from the FMECA was seen positive, mainly because it opened the ability to search for different solutions within one system. Another advantage was said to be the fact that it creates the ability to choose different solutions, where the current situation almost dictates that critical components are kept under control of Rijkswaterstaat, whilst this is not always the best option.

Step 3: Risk allocation matrix

The risk allocation matrix from Brommet was an interesting part of the discussion, mainly because many connections to real cases were established. The method to adjust the matrix to a specific case or work field was not really clear during the presentation, but after some examples and further explanation about the meaning and the goal of the matrix within the bigger picture, the matrix was seen as a good addition to the method. The matrix helps understand why certain choices should be made with respect to responsibility and payment regimes based on the frequency of occurrence and the effect that an occurrence might have.

Clear examples of real cases might improve the usability and clarity of the matrix. It was also fun to see how the experts where immediately trying to come up with case examples and started discussing how to put them into the model and whether this was working or not. This is exactly the way it is meant to be used: start discussing why something should be in a certain corner of the matrix. This is not something a model can generically tell for every situation; the experts themselves need to adjust and use the matrix according to the situation. Therefore, their expert judgement and experience are still a very important factor when using the decision-support method.

The experts were very pleased with this model because, it both serves as an individual tool as well as part of the decision-support method. It will help create clarity on certain decisions that need to be taken. It can also help to classify re-occurring matters and help prevent unnecessary repetition of certain discussions that occur nowadays. The experts hint to the situation where similar events are dealt with in different ways, because they are all discussed as individual events. With the help of the risk allocation matrix the same solution will be suggested for similar events, thus avoiding unnecessary discussions, which saves time and provide better solutions. This doesn't just apply for this model, but for the entire methodology of the decision-support method as well.

When certain repetitive discussions about certain problems can be prevented through the use of these tools, which clearly classifies certain events or problems and are easy to use, the design time of a contract can definitely be reduced and the quality of the contracts can be increased.

Step 4: Determine a suitable contribution of the contractor

The next step of the process is deciding an appropriate level of contribution of the contractor. When this was first mentioned and explained during the presentation the focus was on the decision criteria and tools that were used to decide the level of contribution. These criteria were predictability & plannability and the tools that were used to get the information were the FMECA & the risk allocation matrix. But the first remark that was given by the experts during the discussion was that the contribution of the contractor is actually representing the amount of responsibility that they will have and that is in fact true. This criteria wasn't yet linked to this parameter, but is exactly what happens during this step. Thus this adds another decision criteria to the decision making during this step.

The decision between the two available choices was clear, especially when realizing that these given options are basic. Every other possibility or combination of tasks can be outsourced in such a way that it is appropriate for the specific situation. But because of the many variables, the proposed amount options are limited to two. The other options can be pursued based on expert judgement, experience or specific individual circumstances. The group liked the fact that the basic options are given based on important aspects to consider, but not limiting the freedom to act differently as a certain situation might require.

Step 5: Determine suitable performance requirements

The next step is about the determination of suitable levels of performance requirements. Although the figure during the presentation showed some examples of the different levels, the group was keen to have more examples that clearly defined the different levels of performance requirements. During the discussion, some examples were found and contributed more insight in the different levels and how to differentiate them.

Another remark was the connection between measurability and the chosen level. That connection should be clearly explained and defined in order to make it even more useful. One of the members of a contract design team of Rijkswaterstaat expected them to use the scale from specific activities up until performance levels, but he could not imagine them using output or outcome, for it is open for too much discussion.

During the following discussion, the importance of the interests and commitment of the contractor became clear. If the CA wishes to use output/result based or outcome/effect-based performance requirements, the contractor should at least have the same interests as the CA. An example that was found during the discussion was for instance the maintenance of a roundabout, including the middle section. If the CA (municipality) wishes that the appearance roundabout is positive, safe, inviting and so on, this can only be achieved (using outcome/effect as a performance requirement) when the contractor has an interest in achieving that. This can for instance be achieved by connecting the name of the company to the roundabout. They have an interest in keeping it clean, safe and inviting because they are associated with it, and although this is hard to measure, they will do the best they can to achieve that result.

Step 6: Cross-check

The following step was the cross-check that is performed when all the parameters are chosen. There was not much comment on the step itself, because it was a logical consequence of the previous steps in the process.

Step 7: Suggested solution for the parameters

There was however one comment that did have so much to do with the method itself, but more on how this would work in real cases. This had to do with the last step, where all the decisions are final and a proposed solution is presented for all systems individually. Especially the fact that all systems are evaluated individually lead to a discussion about the behavior of the contractor.

During the use of the decision-support method, all systems/sub-systems/components are evaluated individually and a proposed solution is presented based on those assumptions. This means that every part is separately checked for the possible risks. Based on that 'individual' assessment, a statement is made about the amount of responsibility that a contractor can/will bear and how to deal with that risk. In practice however, as spoken by the experts, the contractor will never include all the risks in their calculations. Individual assessments and an assessment as a whole could mean a big difference. The probability of all the risks happening at the same time is close to zero and the contractor knows that. That is their domain, their expertise, that is what they do all the time. In most cases its a financial issue, where the contactor decides which risks to price and which to accept, hoping to have a realistic bid, with an acceptable amount of risk.

Using the decision-support method, it should be clear that every risk is individually evaluated. In the end, the overview of all individual risks should be combined and seen as a whole. Only then they know how a contractor will approach those risks in his bidding. The important lesson for the CA is to focus on the risks that are unacceptable and put them in the contract in such a way that the contractor can't ignore them.

The main issue here is that the decision-support method doesn't include a step where all the individual outcomes are brought together to create a whole. The bigger picture is missing and needs to be addressed either in a separate step of the decision-support method or the decision-making process.

5.3 Expert conclusions

There was a positive attitude from the experts about the methodology and a good discussion about some of the topics that were presented. During the discussion, the remarks are very useful for improving, refining and finalizing this thesis. Some of the comments can (or were) already included in the final version, while some of the comments will be included as future research or improvement topics. The overall impression of the presented methodology was very good. The experts were very interested and saw many opportunities for it to be used in practice. Both when using individual steps and the decision-support method as a whole. The main advantages that were pointed out were the clear distinctions and definitions of the parameters (variables) and the decision criteria that were used. This helps them to create a baseline to fall back on. This can for instance help them avoid unnecessary and repetitive discussions about decisions that need to be made for every contract. Using this method they can easily show why and how certain decisions have been established.

Although some variables, like the performance requirements and the matrix by Brommet, could use some more examples to clarify the different options, the variety of presented tools and techniques are definitely helping the contract design team in making their decision is a structured way. At this stage, there is a need for trustworthy and constant amount of data to base the PBMC on. The use of the decision-support method will pressure the CA to find this data which tells exactly what information is needed, when it is needed. This could really help make the decisions, but also to convince the higher management that certain information is needed and why it is important to gather that specific information. Although the current model of the decision-support method is clear, some visual improvements could be made to explain the process by showing the steps and corresponding actions. This can also help clarifying which kind of information is needed during each step.

For Rijkswaterstaat specifically, they are starting to use a method called P-IHP (*prestatiegestuurd instandhoudingsplan*) or performance-driven conservation plan. But the experts themselves say that although it is roughly the same as FMECA, the outcome is interpreted in a different way. The information contains the failure modes and actions to prevent those failures, which is also done within FMECA, but now Rijkswaterstaat is using that information to keep all responsibility for critical systems/components for themselves almost automatically. By using the decision-support method, the outcome can still be the same, but not before other options and opportunities are explored. That is another positive feature of this method.

The biggest downside is the fact that the individual evaluation of the different systems, and therefore the individual evaluation of the risks, is not realistic when looking at the way the contractor deals with the risks. Therefore, the last step becomes very important to focus on looking at the bigger picture and not just at the individual outcomes of the decision-support method. This is perhaps the hardest part to capture within the method, but definitely one worth looking into.

One of the findings during the presentation and the discussion was the fact that although the method itself could be followed with the instructions and information that was provided, some steps in the process needed further explanation. This is not so much on how to approach the individual steps, but more on how the steps of the decision-support method interact amongst each other. A solution to this problem could be a visual representation of the procedure as a whole, explaining the steps that are taken to move along the decision-support method. It should be similar to the way it is presented in appendix 9, but just more practical and focused on the procedure of moving along the method.

The overall impression of the presentation and the produced results were good. The experts were very interested to see how things work and what that could mean for them in their specific areas of expertise. All of them are keen to see the final results when it is finished to see how they can use, implement or use parts of the decision-support method because this should definitely be possible and can be useful in future projects.

5.4 Further improvements

During the discussion with the experts of Rijkswaterstaat an overall positive opinion was received about the steps of the decision-support method. There weren't many suggestions given about improvements that could be made within the steps themselves. It was however advised that some steps might be clearer with a few examples. These examples could especially be helpful while using the risk allocation matrix of Brommet. But also the use of the performance requirements and the size/scope could be improved with addition of some examples according to the experts. During the expert meeting, only the basics of the decision-support method was presented. Therefore, much of the in-depth information that is present in the report was not visible at the time. One of the experts commented after reading the report concluding that a lot of the background information and the requested examples were in fact already present in appendix 2,3 and 4.

A bigger issue that was brought up during the meeting was the last step of the decision-support method. The last step of the decision support method gives an overview of all individually suggested solutions for the outsourcing of individual parts of an asset. It is however not realistic to see all these parts as individual contract pieces, because a contractor won't see it that way either. Therefore the outcome of the decision-support method has to be put in the bigger picture of making a PBMC. This subject is further discussed in section 5.4.1.

The last point that was brought up during the discussion with the experts of Rijkswaterstaat was the suggestion to make a better visual representation of the procedure that needs to be followed when using the decision-support method. This could have two advantages: the method will be easier to follow and users know when a certain step is done, how it should be done and when the step is finished. Secondly it will become more clear to the CA what information is necessary during which step and why. Therefore it will become easier for the contract design team to justify their request for information. This subject is further discussed in section 5.4.2.

In short, the recommendations that were given during discussion between the experts of Rijkswaterstaat were as follows:

➢ More in-depth information and examples for the various steps	(Appendices 2,3 & 4)
➢ The bigger picture explained	(section 5.4.1)
➢ Clear visualization of the procedure of the decision-support method	(section 5.4.2)

5.4.1 The bigger picture

The result of the final step of the decision-support method is an overview of the proposal. This is however an evaluation of all the individual parts. The combination of all individual results will be seen as a concept solution which can be used as a starting point for the final solution. The final solution has to put all the individual parts back in the context of the entire outsourceable object and use expert judgement to see how the final solution can work.

An important factor that needs to be taken into account is the way the contractor looks at a contract. Using the decision-support method, all risks are for instance measured individually and put next to each other. This shows a somewhat dramatic picture of reality because the probability of all these risks happening at the same time is close to zero. The contractor looks at all the risks that can happen, but knows that not all of them will happen all together. Based on that thought, the contractor will decide how much risk they are willing to take and how much risk will need to be paid for by the CA.

The contract design team needs to take this into consideration when drawing a final design of the PBMC, but have to keep in mind that the decision-support method doesn't help with this final step of bringing all these individual suggestions for a solution back together in the bigger picture.

This step however is not treated in this thesis, but is an important step to a final solution. This will be a recommendation for further research on how to use the results of the decision-support method in practice to come up with a final solution for a PBMC.

5.4.2 Clear visualization of the procedure of the decision-support method

During the discussion with the experts of Rijkswaterstaat an issue came up with the visual design of the decision-support method as a whole. The 6-page final design gives a clear overview of what should be done and provides the necessary information to execute the steps, but it lacks a one view explanation of the entire procedure.

The improvement that is suggested here by the experts is a more clear visual representation of the decision-support method. The reason for this is the fact that it should be easier to see which information is needed when during the method. But not only is it interesting to see when the information is needed, but also why. This could make it easier for the contract design teams to request their superiors for the required information.

Besides the advantages it could have for acquiring the necessary information, it could also prove easier to follow if the entire procedure of the decision-support method is captured on one page. The procedure should include the required input, the required output and the actual actions that need to be taken in between. It should also contain the flow of steps. As was explained in chapter 4, it is also possible to go back a few steps if it was found that an earlier decision conflicts with a later decision. By visualizing these options the use of the decision-support method becomes easier.

The outcome of this improvement should be a flowchart containing an input (this could be information or the output of the previous step), an activity (what should be done during this step) and an output what should the result of this step be). Furthermore it is important to clarify the relation between the input, activities and output. Besides the visual representation, an explanation of each of the activities should be added to the flowchart. Most of the information that should be included in this flowchart is already available in appendix 9. It is however not brought together yet in a clear procedure.

This flowchart should be constructed and will be added as an appendix (appendix 10). The actual flowchart will be introduced in the previously mentioned appendix and discussed during the conclusion of this thesis.

5.5 Conclusion

One sub-research question was set to be answered at the start of this chapter. The goal of this entire chapter was aimed at finding the answers to the research questions, continuing the work that was done during the case study and eventually contribute on answering the main research question. The main research question of this thesis reads as follows:

'Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?'

During this chapter, the results of chapter 4 are discussed during an expert meeting. The sub-research question that has been explored during the validation reads as follows:

'What are the expert opinions on the practical application of the decision-support method on real case examples?'

This chapter used the results of the case studies in chapter 4 to draw a realistic view on the practical application of the decision-support method on real case examples. This view is presented during an expert meeting and during individual conversations with the experts to get their opinions on the performance of the individual steps of the decision-support method.

After a short introduction on section 5.1, stating the sub-research question for this chapter as stated above, the six experts involved during the validation were introduced in section 5.1.1. The six experts that were stated here were either present during the actual expert meeting or were individually approached to discuss the results of the case studies and the design of the decision-support method with. To make the results more readable, the results are clustered per step during the expert discussion.

Section 5.2 covers the actual expert meeting and the review of the results. The part reviews the functioning of the decision-support method in practice and the view of the experts on how certain steps could still be improved.

The meeting was started with a presentation covering the most important findings of the literature study based on which the first conceptual design of the decision-support method was created. Eventually the final design of the decision-support method was presented as a starting point for the discussion. The road to this final design by means of the case study was briefly explained to show how the method worked in practice.

After the presentation, a discussion was held about all the individual steps of the decision-support method. The results were also processed in a step-wise fashion in order to make it easier to create a link between certain improvements to certain steps of the process.

Section 5.3 gives the actual conclusions of the experts after the expert meeting. During these expert conclusions, the first actual suggestions for improvements are found. But also that there were a lot of positive aspects to the work that has been done so far. The experts were very positive about the methodology that was used in the literature study to bring all the components together from different literature works, especially the finding of the main decision criteria and the parameters of PBMC were seen as very positive points. Another positive point, which also did raise some questions, was the use of FMECA. During the discussion a 'what if' scenario was presented where FMECA could not be used. The resulting answer of not prescribing but just suggesting this method was satisfying. The information that can be used as input eventually results to an outcome which ended up being positive. The FMECA practically ensures a good input of information and therefore a positive outcome. The experts also praised this method opposed to the P-IHP that Rijkswaterstaat is currently trying to use because of the amount of extra information and therefore options that FMECA has to offer.

Improvements were suggested for the final step of the decision-support method. This improvement had to do with the fact that the outcome of the decision-support method has individual solutions for every part and not an integral solution for the entire asset. This is true and is in fact an issue, but it is not seen as a part of this thesis but will definitely be taken as recommendation for future research into this topic.

Another improvement that was suggested during the expert discussion was the use of examples during the steps where size/scope is decided, the risk allocation matrix is used and the use of performance requirements. It was however concluded that in-depth information was in fact given, including examples in the appendices that are written about these steps. However this information was verbally brought across during this meeting, which was helpful, but was not presented in writing. The information is now captured in appendices 2,3 & 4 and therefore no further action was taken on this suggestion.

The last suggestion that was made concerned the visual representation of the decision-support method. They suggested that a procedural approach of the method would increase the effect of the method to the outside world, by briefly explaining what input (information) is required, in which the contract design team can probably get that information more easily from the CA. Furthermore, it will be easier to follow the steps of the decision-support method. The suggested solution was a flowchart containing the input, activity and output of each step, the description of the activities and the relation between the input, activities and out for the entire method. This flowchart will be constructed based on the information in appendix 9 (and the main report of thesis if necessary) and presented in appendix 10. The content of the method will not be changed thus the final result will only be introduced during the final conclusion of this thesis.

As a final answer to the sub-research question that was asked in the beginning of this chapter the following can be said. The overall opinions of the experts about the use of the decision-support method were positive. The individual steps show promising results and some of the experts are even considering to start using parts of the method during the actual design process of their PBMC. A lot of positive remarks were also given regarding the way the method was constructed using bit and pieces of information that was scattered in different literary works. Examples of this were the decision criteria and the way the parameters of PBMC were found and explained. Besides the positive points, some suggestions for improvements were given. Of the three major suggestions for improvements, one was already part of the appendices of this thesis (in-depth information and examples), one was judged to be important but not part of the scope of this thesis (the bigger picture) and one is actually worked out and implemented in the final conclusions and added as appendix 10 of this thesis (procedural approach to the decision-support method).

Chapter 6

Conclusion

This chapter is used to review the most important conclusions that were found during this research. The main research question is answered and a final conclusion is given about the design and use of the decision-support method. The chapter is concluded with recommendations to further improve the design and use of the decision-support method.

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6. Conclusion

The problem that was addressed during this thesis was the absence of a standardized method in literature that helps finding, combining and interpreting information and using available tools and techniques. The standardized method should help determine suitable parameters as a base in which a performance-based maintenance contract (PBMC) can be drafted. The objective that was found solve the problem has been determined as follows:

''The objective is to find a structured way for the contracting team to find suitable parameters in an early stage of the process in drafting the Performance-Based Maintenance Contract.''

The main problem and the objective have been used to create a specific main research question. This question has been guiding this thesis from start to finish. Throughout the execution process of this thesis, the answer to this main problem and objective have been formulated piece by piece to finally draw a final conclusion which resolves the following main research question:

''Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?''

Further, in order to answer the research question thoroughly, 5 sub-research questions have been formulated and solved. The answers to these questions are found during the three main chapters of this thesis. First, the parameters based on which PBMC can be drafted are found, evaluated and explained. Then the necessary tools, techniques and sources of information are found to make it possible to tune the parameters according to the needs of the object that is being outsourced. After that, the goal was to find a way to bring all that information together in a structured method that is easy to understand and usable by contract design teams during their contract design process. The last step was to validate the results that have been found in the previous chapters.

In this thesis the work of Schoenmaker is used as a starting point to approach the problem that is being stated in the main research question. In the various chapters, different elements of his work are used and brought together to build the eventual decision-support method. The different elements where mainly found in *De Ingeslagen Weg* (Schoenmaker, 2011), Analysing Outsourcing Policies In An Asset Management Context (Schoenmaker & Verlaan, 2013), The Dynamics Of Outsourcing Maintenance Of Civil Infrastructure In Performance Based Contracts (Schoenmaker, de Bruijn, & Herder, 2013) and a lecture/presentation about performance based outsourcing of maintenance (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017).

The elements that were used during this thesis were mainly loose elements. In *De Ingeslagen Weg* the dynamics of outsourcing through performance-based contracting was highlighted. In this work, the way performance requirements work and could be used in this context was explained. Also, the connection between the level of performance requirements and the size of system was shown for the first time. These elements were used and combined with other findings to create the decision-support method. In the 2013 works of Schoenmaker, the six-stage model was introduced and explained. This cyclic approach to the maintenance process was used to get more insight in the way outsourcing could be done. This model helps with deciding the way outsourcing can be done in various ways, with different levels of responsibility and control for both the contractor and the contracting authority (CA). The last work of Schoenmaker that had a major impact on the outcome of this thesis is a presentation about performance-based outsourcing of maintenance. During this presentation, the different elements of size/scope, six-stage model (thus contribution of the contractor) and the performance requirements are introduced on a basic level. During this thesis, this knowledge is expanded with new insights, more background information and brought together in a methodology that can be used in practice.

This approach lead to, with the addition of other literature and practical research, the design and use of the decision-support method where all the different elements for creating performance-based contracts for maintenance are brought together in one clear methodology. Through literature research a list of considerations that are important when outsourcing using PBMC was made. Those considerations where then categorized and evaluated. The result of this process was a list of decision criteria. Among these criteria there were lesser and more important ones. The most important criteria where chosen to be the main decision criteria when outsourcing using PBMC. The decision criteria were:

- Predictability
- Plannability
- Measurability
- Responsibility
- Criticality

Using these main decision criteria and general knowledge about the use of PBMC, parameters were found that describe the variety of options that are available for the contract design team when outsourcing. The parameters define three axes which can be categorized by answering the following questions: 'what is being outsourced, who is going to do it, what requirements are set for the job?'

These parameters are based on the earlier work by Schoenmaker and confirmed in other literature about performance-based contracting by van Rhee, Stankevic66666h and Sultana (van Rhee, Kaelen, & van de Voort, Performance Based Contracting - Waarom, wanneer, wat, hoe?, 2009) (Stankevich, Qureshi, & Queiroz, 2005) (Sultana, Rahman, & Chowdhury, An Overview of Issues to Consider Before Introducing Performance-Based Road Maintenance Contracting, 2012). Every parameter comes with a range of possibilities and the sum of all those possible combinations is known as the 'solution space' of the PBMC. The parameters that were found are:

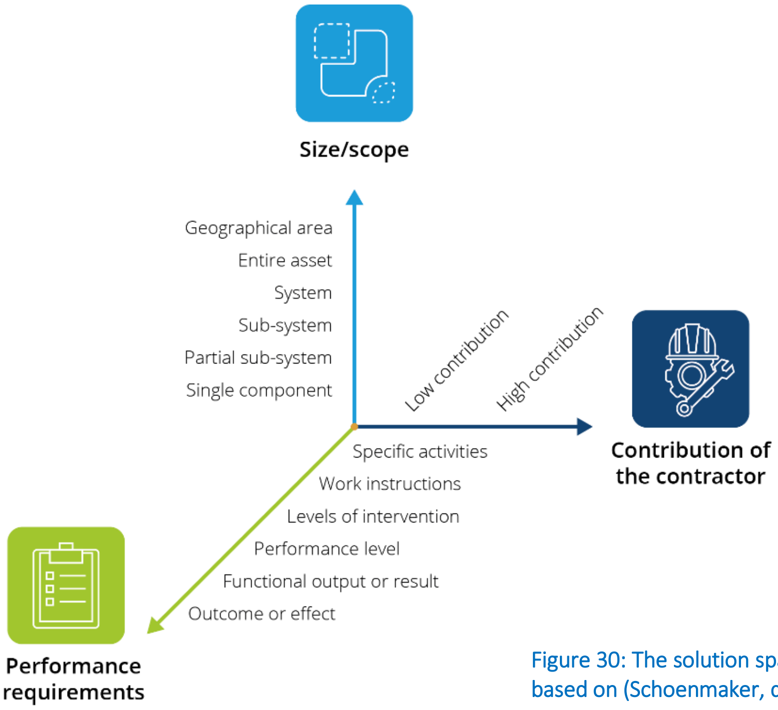

Figure 30: The solution space of the decision-support method based on (Schoenmaker, de Bruijn, & Herder, 2013)

Using these parameters, decisions can be made on three critical points of the contract design process and result in an informed decision about a suitable way of outsourcing. But in order to make decisions, information is needed to describe these parameters, information linked to the main decision criteria that were mentioned before.

Different tools and techniques such as RCM by Moubray (Reliability Centered Maintenance II, 1998), FMECA and the risk allocation matrix by Brommet (Managing the Dutch Waterworks using long-term Maintenance Contracts, 2015) are brought in to help the contract design teams in finding useful information to base their decisions on. The introduction of these known tools proved very useful in acquiring information that was used during the eventual case study and was received positively during the expert meeting. Some techniques, like RCM and FMECA were already known by most of the experts, but also the introduction of the risk allocation matrix (which is not so known) was something they wanted to know more about. At this stage, all the necessary components were present, but there was no structure yet. Another main issue was the lack of structure and a methodology that could bring all those separate elements of information together in one overview.
The main structure that was designed during this thesis to ensure that overview was the decision-support method. This method purely focuses on the decision that need to be made about the parameters when it comes to outsourcing using PBMC.

6.1 Decision-support method

The main focus of this thesis was on the introduction, design and explanation of the decision-support method: the actual structure that could help the contract design teams to base their decisions on when outsourcing maintenance using a PBMC. The main research question has therefore been built around that issue. Following the case study and the expert meeting it can be concluded that the decision-support method is indeed a structured way that can help the contract design teams in performing their job of designing a PBMC.

The steps of the decision-support method help guide the contract design team through the process of acquiring, analyzing and interpreting the information. Through this, informed decisions about the three critical parameters can be established on the basis of which they can make a suggestion about the way of outsourcing using the PBMC. The method, as the name already suggests, does not provide clear answers, but merely supports the process of decision making that is performed by the contract design team. The experts judgement of the team still remains an important part of the process.

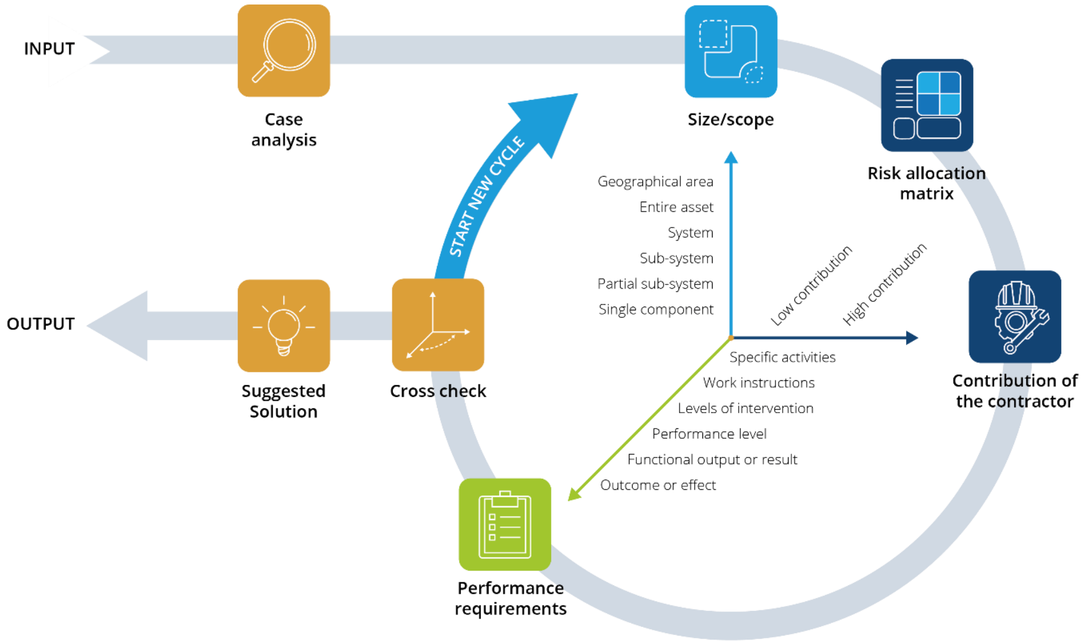

Figure 31: Cyclic design of the decision-support method

The biggest advantage of the decision-support method is the introduction of structure. The current ways that are used lack structure and make the job of the design teams way harder. It also results in discussions that are being started about the same problems multiple times. Using this structure, clear answers can be formulated based on reliable data time after time, making these repetitive discussions obsolete. Apart from that, when the same data is used in multiple occasions for different assets, it gives the CA motive to keep collecting that data and keep it up to date. At this point in time, finding reliable information is hard for the contract design teams.

A downside of the proposed methodology is the fact that the assets are automatically broken into smaller parts and evaluated as single and loose elements. Within the method the asset as a whole is not evaluated. This means that an extra step has to be performed afterwards, considering everything again as being part of the entire asset, and not just as a system, sub-system of separate element. Another issue is the fact that the method is only tested on a tunnel with the availability of enough usable information. The case hasn't been tested on other assets or used with less available information. Therefore there is no data on the behavior of the methodology in those scenarios. During the design of the method, this scenario was taken into account but it hasn't been put to the test. During the expert meeting however, positive remarks were made about the way this problem was tackled, also from other departments (highway maintenance). The method was designed within Rijkswaterstaat and the case study was performed there as well. The design of the method however was done in such way that it should be usable in other companies, even with fewer resources. Although, this is still yet to be tested.

6.2 Decision-making process

During the course of developing the decision-support method, it was noticed that a viewpoint of the CA had an essential impact on the decisions that could be made during the decision-support method. It is therefore important to have that information available when the decision-support method is used. It was decided that a second structure was needed to provide that information. This new structure was called the decision-making process. This process contains a few steps that precede the decision-support method. The decision-making process was the general structure that was introduced to describe the entire process of decision-making that the contract design team would go through when designing a PBMC. This process has been introduced and is based on questions that arose whilst using the decision-support method. Many of the questions could be answered using technical data of an object or using the expected behavior of certain parts. Some things however are influenced by the way the CA wishes to carry out certain interventions or the opinion that they have on certain processes and are not covered within decision-support method. To make sure that these considerations are also covered during the design process, these considerations are to explored during the steps of the decision-making process. During this thesis, only the outline of this process has been described without going into detail on how these steps should be performed in a real case. It was however interesting to find that the case study at some points of the decision making really could have used the information that would have been obtained through these steps, proving the importance of including those steps to the process. This part was not part of the original scope, but is mentioned due to its importance within the scope of PBMC.

6.3 The bigger picture

The biggest realization about the use of the decision-support method is the fact that it is only a small part in a bigger process. When looking at the bigger picture it can be concluded that the decision-support method is preceded by a process, which is covered by the steps that were introduced in the decision-making process, but also lacks some subsequent steps before the PBMC can actually be written. The steps that need to be taken after the decision-support method has been executed are mentioned, but not researched because they were not within the scope of this thesis. It is however important to mention that even though the steps of the decision-making process are as promising as they are, more research will be needed to complete the entire process of writing a PBMC. Especially when concerning the steps that come right after completion of the decision-support method. The result is a number of individually evaluated decisions about the way certain elements of the asset could be outsourced, but the last step that puts these individual decisions back into one perspective, the bigger picture, is still missing. For now this depends on the skill of the contract design teams to come up with an eventual proposal for a PBMC.

6.4 Answering the research question

Eventually, the thesis is there to provide a suitable answer to the research question that was set at the beginning. This main research question was as follows:

‘’Which structured way can assist contract design teams in making informed decisions when drafting Performance-Based Maintenance Contracts?’’

During the course of this thesis, the aim has been use literature and scientific data to come up with a methodology that could fulfil this question. The structure way that has become an important part of the answer to the main research question was the decision-support method.

The steps of the decision-support method that were introduced in chapter 3 and have been improved over the course of chapters 4 and 5 proving the fact that this indeed assists the contract design teams in their jobs. Based on the results of the case study and the opinions during the expert meeting it can be concluded that this methodology can be used on real cases and will in fact be helpful during the decision-making of the contract design team whilst drafting PBMC. It is however important to realize that it is merely a support tool and still needs the expert opinions of the people working with this method to function properly.

6.5 The final result

The final result of this thesis is a 7 step methodology that is tested and improved during two runs of the case study and evaluation by several experts. This leads to the decision-support method in its final form as can be seen in appendix 9. During the case study, it has been apparent that the methodology works with the information that is available and functions as it is supposed to. It was found that the impact of the expert knowledge still plays an important role, but has not been seen as problem per se. During the validation the experts were positive about the different steps that were presented, even though some improvements were still to be made. Based on the comments that were given during the expert meeting about the clarity of the method, a procedural approach to the decision-support method has been made and is presented in appendix 10.

With this final result a new methodology structure is created, both tested in practice and valued by experts, that can help contract design teams in making informed decisions when drafting PBMC.

6.6 Recommendations

Besides the introduction of the method itself, some recommendations can be given concerning the use of steps that were introduced in the decision-support method and the use of the decision-making process in general.

Clear starting point from the contracting authority is needed

During the case study and the development of the decision-support method it became clear that the opinion and the capabilities of the CA are very influential on the available options in the contract design. It is therefore important to create a clear base-line with the needs and wishes of the CA before starting the contract design. Questions about the capability and capacity of the own organization is very important in weighing the decision that need to be made during the contract design. The steps of the decision-making process are provided to stimulate the contract design team to think about these considerations. Whether the decision-support method or another design methodology is used, the gathering of this base-line information remains important in the decision-making process for PBMC.

Gathering of technical information about the asset

During the design of the decision-support method, the use of FMECA was recommended because of the usability and great source of crucial information. During the case study, this choice proved to be very valuable. The FMECA provides the contract design team with loads of data that can be used in their decision making. The recommendation to use FMECA, or another risk model, remains an important one. The biggest flaw in the current working methodology, according to the experts, is the fact that the search for information is slow and unreliable. The use of FMECA and the information that it provides, given that it is accurate and up-to-date, proves to be very valuable. This was seen during the case study and confirmed by the experts during the expert meeting.

Structure the way PBMC are drafted

The thesis was initiated with the idea of structuring the drafting of PBMC. This will be and remains to be the recommendation to the CA. Start using the decision-support method, or an adaptation of it, to perform the contract design process in a structured way in order to make all important and necessary considerations to make an informed decision about the outsourcing of the maintenance of an asset. Implementing this process into the current working method will be challenging, because of the extra information that needs to be gathered and getting it up-to-date. But in the end it can help increase the efficiency with which the contracts can be written, increase the effectiveness of the contracts that are written and increase the reliability of the maintenance interventions that will be planned.

Chapter 7

Discussion

Although the research was performed with the greatest care and dedication, there are always limitation to what can be done. This chapter is there to discuss the limitations of this research and highlight the areas where future research is needed to bring the results of this research to a higher level.

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7. Discussion

This chapter provides the limitations which must be taken into account for the reliability if this research. Further recommendations are made for further research that can help improve the reliability and usability of this concept in a broader context.

7.1 Limitations

Limitations of the research are areas that are not yet optimal or could have been improved. This does not necessarily mean that these are to be disregarded, but it definitely means that there is room for improvement.

Limited testing and usage under different circumstances

The decision-support method has been tested under good or even ideal circumstances with an abundance of information to use. The method has not been tested under circumstance where for instance, little to no information is available. How will the method perform when FMECA is not an option? This is the question that remains unanswered at this stage. Although the method was designed to deal with these circumstances and the fact that there is always the option to fall back to the original way of working, this has not been tested during this thesis.

Furthermore, the methodology has only been tested on a tunnel case. Although expert opinions have faith in the fact that it will probably function the same with different forms of infrastructure (because tunnels are very complex due to the many systems they have, a simpler systems should work as well), this has not been tested and therefore not proven.

Outcome of the decision-support method still dependent on the expert opinion

The decision-support method provides the handles to be used during the design process of a PBMC. It was not designed to give a specific answer for every specific situation. This means that there is a lot of interpretation and expert opinion in the outcome of the process. This was intentionally done because it was impossible to take every possible outcome into account and provide suitable considerations for every one of them. It is however possible to add more guidelines to help steer the design teams into a general direction when confronted with an issue where interpretations of opinion are required.

Limited depth of the decision-making process

During the writing of the thesis it became clear that the input from the decision-making process on the outcome of the decision-support method was bigger than expected. During the thesis there was a limited focus on the decision-making process, and was therefore added just as an appendix to this thesis. When the decision-support method is going to be used in practice, it must be an integral part of the entire decision-making process, not just a separate methodology. This includes the steps that precede the decision-support method, but also steps that follow as described in the following part.

Outcome of the decision-support method focused on individual parts instead of the whole asset

An important aspect to keep in mind while using the decision-support method (and a positive side as well) is the fact that all parts are individually examined. These result to thorough and detailed analyses of the part and can help tailor a solution for that particular part. The downside however is the fact that a single part never functions as a single entity within a contract. The contract will open the doors to opportunities and threats. This means that the individual value of a part will be strengthened or weakened by another part of the contract. The sum of all risks is not the risk that the contractor is willing to take, but the chance of all the risks actually happening altogether is also close to zero. The contractor will therefore take the contract as a whole and evaluate the risk that they are willing to take.

The step of going back from separate parts to the whole contract again is not included in the decision-support method. Although it is taken into account in the totality of the idea of using the steps of the decision-making process, how this is supposed to be done in a real case is still yet to be worked out.

7.2 Future research

This thesis is a good start to improve the way PBMC are drafted by introducing a structured methodology, but the work is not done yet. Future research can help improve the developed method and work on counteracting the current limitations.

Improving the structure of the overall decision-making process

In order to make the decision-support method function properly, the entire decision-making process needs to be worked out in detail. During this thesis the outline of a possible decision-making process have been given, including the basic requirements that it should fulfill. Further research will be necessary to complete that part of the methodology in order to let the decision-support method function as a part of a bigger whole.

Finding a structured way to bring the results of the decision-support method back in the bigger picture

One of the limitations is the fact that the decision-support method approaches the problem by downsizing it into little pieces that eventually form the contract. The contract on the other hand is not seen as a bunch of little pieces, but as one whole. The outcome of the decision-support method should therefore be interpreted, evaluated and be brought back together in order to make it fit the bigger picture. At this point the methodology does not support the ability to bring the pieces back together. This now depends on expert opinions and interpretations of the user. Further research should be performed to find a structure way to guide this process.

Setting clearer guidelines to exclude different interpretations of results and opinions from the method

During the case study, it was found that some decisions are still open to interpretations and opinions. This is not inherently negative, but needs to be limited as much as possible. Future research could be used to increase the amount of guidelines that could be used during the decision-making process, leading to independent decision-making throughout the company or sector as a whole. It must however be said that the outcome of the decision-support method is merely a suggestion and is also based on the knowledge of the local circumstances and some room for expert interpretations needs to be in place in order to take those considerations into account.

Further testing of the method under different circumstances

The case study has been performed under the watchful eye of Rijkswaterstaat and was focused on the use of the decision-support method on a tunnel. In order to get more accurate results and to prove that the methodology as it was presented will work under different circumstances, more case studies and tests need to be performed. A test with a different CA is needed to prove that the method is useful for different organizations. A pilot with a different kind of infrastructure is advised to prove that it will work in different maintenance sectors. The last test that can prove useful is a case study where limited information is available and/or the use of FMECA proves to be difficult.

Chapter 8

Appendices

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8. Appendices

- *Appendix 1: Full list of considerations*
- *Appendix 2: Decision criteria*
- *Appendix 3: Parameters explained*
- *Appendix 4: Reliability centered maintenance & FMECA explained*
- *Appendix 5: Case study – Run 1 –*
- *Appendix 6: Figures corresponding to the improved decision-support method after run 1*
- *Appendix 7: Case study – Run 2 –*
- *Appendix 8: Introduction of the decision-making process*
- *Appendix 9: Final design of the decision-support method*
- *Appendix 10: Procedural approach to the decision-support method*

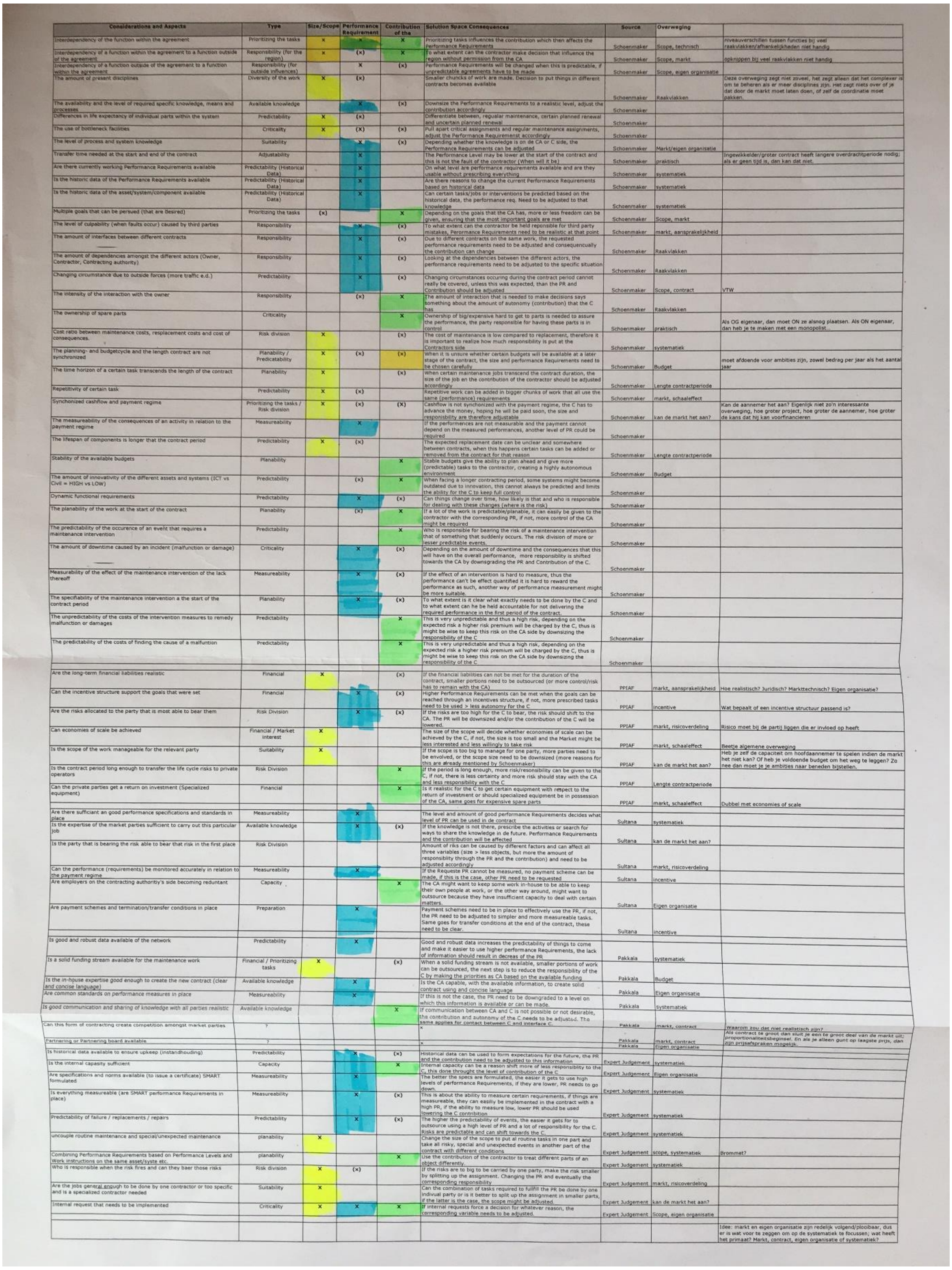
Appendix 1

Full list of considerations

Appendix 1: Full list of considerations

Considerations and Aspects	Type	Size/Scope	Performance Requirements	Contribution of the Contractor	Solution Space Consequences
Interdependency of the function within the agreement	Prioritizing the tasks	x	x	X	Prioritizing tasks influences the contribution which then affects the Performance Requirements
Interdependency of a function within the agreement to a function outside of the agreement	Responsibility (for the region)	x	(x)	X	To what extent can the contractor make decision that influence the region without permission from the CA
Interdependency of a function outside of the agreement to a function within the agreement	Responsibility (for outside influences)		X	(x)	Performance Requirements will be changed when this is predictable, if unpredictable agreements have to be made
The amount of present disciplines	Diversity of the work	X	(x)		Smaller chuncks of work are made. Decision to put things in different contracts becomes available
The availability and the level of required specific knowledge, means and processes	Available knowledge		X	(x)	Downsize the Performance Requirements to a realistic level, adjust the contribution accordingly
Differences in life expectancy of individual parts within the system	Predictability	X	(x)		Differentiate between, regualar maintenance, certain planned renewal and uncertain planned renewal
The use of bottleneck facilities	Criticality	X	(X)	(x)	Pull apart critical assignments and regular maintenance assignments, adjust the Performance Requiremenst accordingly
The level of process and system knowledge	Suitability		X	(x)	Depending whether the knowledge is on de CA or C side, the Performance Requirements can be adjusted
Transfer time needed at the start and end of the contract	Adjustability		X		The Performance Level may be lower at the start of the contract and this is not the fault of the contractor (When will it be)
Are there currently working Performance Requirements available	Predictability (Historical Data)		X		On what level are performance requirements available and are they usable without prescribing everything
Is the historic data of the Performance Requirements available	Predictability (Historical Data)		X		Are there reasons to change the current Performance Requirements based on historical data
Is the historic data of the asset/system/component available	Predictability (Historical Data)		X		Can certain tasks/jobs or interventions be predicted based on the historical data, the performance req. Need to be adjusted to that knowledge
Multiple goals that can be persued (that are desired)	Prioritizing the tasks	(x)		X	Depending on the goals that the CA has, more or less freedom can be given, ensuring that the most important goals are met
The level of culpability (when faults occur) caused by third parties	Responsibility		X	(x)	To what extent can the contractor be held reponsible for third party mistakes, Perormance Requirements need to be realistic at that point
The amount of interfaces between different contracts	Responsibility		X	(x)	Due to different contracts on the same work, the requested performance requirements need to be adjusted and consequencually the contribution can change
The amount of dependencies amongst the different actors (Owner, Contractor, Contracting authority)	Responsibility		X	(x)	Looking at the dependencies between the different actors, the performance requirements need to be adjusted to the specific situation
Changing circumstance due to outside forces (more traffic e.d.)	Predictability		X	(x)	Changing circumstances occuring during the contract period cannot really be covered, unless this was expected, than the PR and Contribution should be adjusted
The intensity of the interaction with the owner	Responsibility		(x)	X	The amount of interaction that is needed to make decisions says something about the amount of autonomy (contribution) that the C has
The ownership of spare parts	Criticality			X	Ownership of big/expensive hard to get to parts is needed to assure the performance, the party responsible for having these parts is in control
Cost ratio between maintenance costs, resplacement costs and cost of consequences.	Risk division	X		(x)	The cost of maintenance is low compared to replacement, therefore it is important to realize how much responsibility is put at the Contractors side
The planning- and budgetcycle and the length contract are not synchronized	Planability / Predicatability	X	(x)	(x)	When it is unsure whether certain budgets will be available at a later stage of the contract, the size and performance Requirements need to be chosen carefully
The time horizon of a certain task transcends the length of the contract	Planability	X		(x)	When certain maintenance jobs transcend the contract duration, the size of the job en the contribution of the contractor should be adjusted accordingly
Repetitivity of certain task	Predictability	X	(x)		Repetitive work can be added in bigger chunks of work that all use the same (performance) requirements
Synchonized cashflow and payment regime	Prioritizing the tasks / Risk division	X	(x)	(X)	Cashflow is not synchonized with the payment regime, the C has to advance the money, hoping he will be paid soon, the size and responsibility are therefore adjustable
The measureability of the consequences of an activity in relation to the payment regime	Measureability		X		If the performences are not measurable and the payment cannot depend on the measured performances, another level of PR could be required
The lifespan of components is longer that the contract period	Predictability	X	(x)		The expected replacement date can be unclear and somewhere between contracts, when this happens certain tasks can be added or removed from the contract for that reason
Stability of the available budgets	Planability			X	Stable budgets give the ability to plan ahead and give more (predictable) tasks to the contractor, creating a highly autonomous environment
The amount of innovativity of the different assets and systems (ICT vs Civil = HIGH vs LOW)	Predictability		(x)	X	When facing a longer contracting period, some systems might become outdated due to innovation, this cannot always be predicted and limits the ability for the C to keep full control
Dynamic functional requirements	Predictability		X	(x)	Can things change over time, how likely is that and who is responsible for dealing with these changes (where is the risk)
The planability of the work at the start of the contract	Planability		(x)	X	If a lot of the work is predictable/planable, it can easily be given to the contractor with the corresponding PR, if not, more control of the CA might be required
The predictability of the occurence of an event that requires a maintenance intervention	Predictability			X	Who is responsible for bearing the risk of a maintenance intervention that of something that suddenly occurs. The risk division of more or lesser predictable events.
The amount of downtime caused by an incident (malfunction or damage)	Criticality		X	(x)	Depending on the amount of downtime and the consequences that this will have on the overall performance, more responsibility is shifted towards the CA by downsgrading the PR and Contribution of the C.
Measurability of the effect of the maintenance intervention of the lack thereoff	Measureability		X	(x)	If the effect of an intervention is hard to measure, thus the performance can't be effect quantified it is hard to reward the performance as such, another way of performance measurement might be more suitable.
The specifiability of the maintenance intervention a the start of the contract period	Planability		X	(x)	To what extent is it clear what exactly needs to be done by the C and to what extent can he be held accountable for not delivering the required performance in the first period of the contract.
The unpredictability of the costs of the intervention measures to remedy malfunction or damages	Predictability			X	This is very unpredictable and thus a high risk, depending on the expected risk a higher risk premium will be charged by the C, thus is might be wise to keep this risk on the CA side by downsizing the responsibility of the C
The predictability of the costs of finding the cause of a malfuntion	Predictability			X	This is very unpredictable and thus a high risk, depending on the expected risk a higher risk premium will be charged by the C, thus is might be wise to keep this risk on the CA side by downsizing the responsibility of the C

Are the long-term financial liabilities realistic	Financial	X		(x)	If the financial liabilities can not be met for the duration of the contract, smaller portions need to be outsourced (or more control/risk has to remain with the CA)
Can the incentive structure support the goals that were set	Financial		X	(x)	Higher Performance Requirements can be met when the goals can be reached through an incentives structure, if not, more prescribed tasks need to be used > less autonomy for the C
Are the risks allocated to the party that is most able to bear them	Risk Division		X	(x)	If the risks are too high for the C to bear, the risk should shift to the CA. The PR will be downsized and/or the contribution of the C will be lowered.
Can economies of scale be achieved	Financial / Market interest	X			The size of the scope will decide whether economies of scale can be achieved by the C, if not, the size is too small and the Market might be less interested and less willingly to take risk
Is the scope of the work manageable for the relevant party	Suitability	X			If the scope is too big to manage for one party, more parties need to be envolved, or the scope size need to be downsized (more reasons for this are already mentioned by Schoenmaker)
Is the contract period long enough to transfer the life cycle risks to private operators	Risk Division			X	If the period is long enough, more risk/resonsibility can be given to the C, if not, there is less certainty and more risk should stay with the CA and less responsibility with the C
Can the private parties get a return on investment (Specialized equipment)	Financial			X	Is it realistic for the C to get certain equipment with respect to the return of investment or should specialized equipment be in possession of the CA, same goes for expensive spare parts
Are there sufficiant an good performance specifications and standards in place	Measureability		X		The level and amount of good performance Requirements decides what level of PR can be used in de contract
Is the expertise of the market parties sufficient to carry out this particular job	Available knowledge		X	(x)	If the knowledge is not there, prescribe the activities or search for ways to share the knowledge in de future. Performance Requirements and the contribution will be affected
Is the party that is bearing the risk able to bear that risk in the first place	Risk Division				Amount of riks can be caused by different factors and can affect all three variables (size > less objects, but more the amount of responsiblity through the PR and the contribution) and need to be adjusted accordingly
Can the performance (requirements) be monitored accurately in relation to the payment regime	Measureability		X		If the Requeste PR cannot be measured, no payment scheme can be made, if this is the case, other PR need to be requested
Are employers on the contracting authoritiy's side becoming reduntant	Capacity			X	The CA might want to keep some work in-house to be able to keep their own people at work, or the other way around, might want to outsource because they have insufficient capacity to deal with certain matters.
Are payment schemes and termination/transfer conditions in place	Preparation		X		Payment schemes need to be in place to effectively use the PR, if not, the PR need to be adjusted to simpler and more measureable tasks. Same goes for transfer conditions at the end of the contract, these need to be clear.
Is good and robust data available of the network	Predictability		X		Good and robust data increases the predictability of things to come and make it easier to use higher performance Requirements, the lack of information should result in decreas of the PR
Is a solid funding stream available for the maintenance work	Financial / Prioritizing tasks	X		(x)	When a solid funding stream is not available, smaller portions of work can be outsourced, the next step is to reduce the responsibility of the C by making the priorities as CA based on the available funding
Is the in-house expertise good enough to create the new contract (clear and concise language)	Available knowledge		X		Is the CA capable, with the available information, to create solid contract using and concise language
Are common standards on performance measures in place	Measureability		X		If this is not the case, the PR need to be downgraded to a level on which this information is available or can be made.
Is good communication and sharing of knowledge with all parties realistic	Available knowledge			X	If communication between CA and C is not possible or not desirable, the contribution and autonomy of the C needs to be adjusted. The same applies for contact between C and interface C.
Can this form of contracting create competition amongst market parties	?				x
Partnering or Partnering board available	?				x
Is historical data available to ensure upkeep (instandhouding)	Predictability		X	(x)	Historical data can be used to form expectations for the future, the PR and the contribution need to be adjusted to this information
Is the internal capasity sufficient	Capacity			X	Internal capacity can be a reason shift more of less responsiblity to the C, this done throught the level of contribution of the C
Are specifications and norms available (to issue a certificate) SMART formulated	Measureability		X		The better the specs are formulated, the easier it gets to use high levels of performance Requirements, if they are lower, PR needs to go down.
Is everything measureable (are SMART performance Requirements in place)	Measureability		X	(x)	This is about the ability to measure certain requirements, if things are measureable, they can easilly be implemented in the contract with a high PR, if the ability to measure low, lower PR should be used lowering the C contribition
Predictability of failure / replacements / repairs	Predictability		X	(x)	The higher the predictability of events, the easier it gets for to outsource using a high level of PR and a lot of responsibility for the C. Risks are predictable and can shift towards the C.
uncouple routine maintenance and special/unexpected maintenance	planability	X			Change the size of the scope to put al routine tasks in one part and take all risky, special and unexpected events in another part of the contract with different conditions
Combining Performance Requirements based on Performance Levels and Work instructions on the same asset/syste etc.	planability			X	Use the contribution of the contractor to treat different parts of an object differently.
Who is responsible when the risk fires and can they baer those risks	Risk division	X	(x)		If the risks are to big to be carried by one party, make the risk smaller by splitting up the assignment. Changing the PR and eventually the corresponding responsibility
Are the jobs general enough to be done by one contractor or too specific and is a specialized contractor needed	Suitability	X			Can the combination of tasks required to fulfill the PR be done by one indivual party or is it better to split up the assignment in smaller parts, if the latter is the case, the scope might be adjusted.
Internal request that needs to be implemented	Criticality	X	X	X	If internal requests force a decision for whatever reason, the corresponding variable needs to be adjusted.



Considerations and Aspects	Type	Size/Scope	Performance Requirement	Contribution of the	Solution Space Consequences	Source	Overweging	
Interdependency of the function within the agreement	Prioritizing the tasks	x	x	x	Prioritizing tasks influences the contribution which then affects the Performance Requirements	Schoenmaker	Scope, technisch	niveauverschillen tussen functies bij veel raakvlakken/afhankelijkheden niet handig
Interdependency of a function within the agreement to a function outside of the agreement	Responsibility (for the region)	x	(x)	x	To what extent can the contractor make decision that influence the region without permission from the CA	Schoenmaker	Scope, markt	opknippen bij veel raakvlakken niet handig
Interdependency of a function outside of the agreement to a function within the agreement	Responsibility (for outside influences)		x	(x)	Performance Requirements will be changed when this is predictable, if unpredictable agreements have to be made	Schoenmaker	Scope, eigen organisatie	
The amount of present disciplines	Diversity of the work	x	(x)		Smaller chuncks of work are made. Decision to put things in different contracts becomes available	Schoenmaker	Raakvlakken	Deze overweging zegt niet zoveel, het zegt alleen dat het complexer is om te beheren als er meer disciplines zijn. Het zegt niets over of je dat door de markt moet laten doen, of zelf de coordinatie moet pakken.
The availability and the level of required specific knowledge, means and processes	Available knowledge		x	(x)	Downsize the Performance Requirements to a realistic level, adjust the contribution accordingly	Schoenmaker		
Differences in life expectancy of individual parts within the system	Predictability	x	(x)		Differentiate between, regualar maintenance, certain planned renewal and uncertain planned renewal	Schoenmaker		
The use of bottleneck facilities	Criticality	x	(X)	(x)	Pull apart critical assignments and regular maintenance assignments, adjust the Performance Requiremenst accordingly	Schoenmaker		
The level of process and system knowledge	Suitability		x	(x)	Depending whether the knowledge is on de CA or C side, the Performance Requirements can be adjusted	Schoenmaker	Markt/eigen organisatie	
Transfer time needed at the start and end of the contract	Adjustability		x		The Performance Level may be lower at the start of the contract and this is not the fault of the contractor (When will it be)	Schoenmaker	praktisch	Ingewikkelder/groter contract heeft langere overdrachtperiode nodig; als er geen tijd is, dan kan dat niet.
Are there currently working Performance Requirements available	Predictability (Historical Data)		x		On what level are performance requirements available and are they usable without prescribing everything	Schoenmaker	systematiek	
Is the historic data of the Performance Requirements available	Predictability (Historical Data)		x		Are there reasons to change the current Performance Requirements based on historical data	Schoenmaker	systematiek	
Is the historic data of the asset/system/component available	Predictability (Historical Data)		x		Can certain tasks/jobs or interventions be predicted based on the historical data, the performance req. Need to be adjusted to that knowledge	Schoenmaker	systematiek	
Multiple goals that can be persued (that are desired)	Prioritizing the tasks	(x)		x	Depending on the goals that the CA has, more or less freedom can be given, ensuring that the most important goals are met	Schoenmaker	Scope, markt	
The level of culpability (when faults occur) caused by third parties	Responsibility		x	(x)	To what extent can the contractor be held reponsible for third party mistakes, Perormance Requirements need to be realistic at that point	Schoenmaker	markt, aansprakelijkheid	
The amount of interfaces between different contracts	Responsibility		x	(x)	Due to different contracts on the same work, the requested performance requirements need to be adjusted and consequencually the contribution can change	Schoenmaker	Raakvlakken	
The amount of dependencies amongst the different actors (Owner, Contractor, Contracting authority)	Responsibility		x	(x)	Looking at the dependencies between the different actors, the performance requirements need to be adjusted to the specific situation	Schoenmaker	Raakvlakken	
Changing circumstance due to outside forces (more traffic e.d.)	Predictability		x	(x)	Changing circumstances occuring during the contract period cannot really be covered, unless this was expected, than the PR and Contribution should be adjusted	Schoenmaker	Scope, contract	VTW
The intensity of the interaction with the owner	Responsibility		(x)	x	The amount of interaction that is needed to make decisions says something about the amount of autonomy (contribution) that the C has	Schoenmaker	Raakvlakken	
The ownership of spare parts	Criticality			x	Ownership of big/expensive hard to get to parts is needed to assure the performance, the party responsible for having these parts is in control	Schoenmaker	praktisch	Als OG eigenaar, dan moet ON ze alsnog plaatsen. Als ON eigenaar, dan heb je te maken met een monopolist...
Cost ratio between maintenance costs, resplacement costs and cost of consequences.	Risk division	x		(x)	The cost of maintenance is low compared to replacement, therefore it is important to realize how much responsibility is put at the Contractors side	Schoenmaker	systematiek	
The planning- and budgetcycle and the length contract are not synchronized	Planability / Predicatability	x	(x)	(x)	When it is unsure whether certain budgets will be available at a later stage of the contract, the size and performance Requirements need to be chosen carefully	Schoenmaker	Budget	moet afdoende voor ambities zijn, zowel bedrag per jaar als het aantal jaar
The time horizon of a certain task transcends the length of the contract	Planability	x		(x)	When certain maintenance jobs transcend the contract duration, the size of the job en the contribution of the contractor should be adjusted accordingly	Schoenmaker	Lengte contractperiode	
Repetitivity of certain task	Predictability	x	(x)		Repetitive work can be added in bigger chunks of work that all use the same (performance) requirements	Schoenmaker	markt, schaaleffect	
Synchonized cashflow and payment regime	Prioritizing the tasks / Risk division	x	(x)	(X)	Cashflow is not synchonized with the payment regime, the C has to advance the money, hoping he will be paid soon, the size and responisbility are therefore adjustable	Schoenmaker	kan de markt het aan?	Kan de aannemer het aan? Eigenlijk niet zo'n interessante overweging, hoe groter project, hoe groter de aannemer, hoe groter de kans dat hij kan voorfinancieren
The measureability of the consequences of an activity in relation to the payment regime	Measureability		x		If the performences are not measurable and the payment cannot depend on the measured performances, another level of PR could be required	Schoenmaker		
The lifespan of components is longer that the contract period	Predictability	x	(x)		The expected replacement date can be unclear and somewhere between contracts, when this happens certain tasks can be added or removed from the contract for that reason	Schoenmaker	Lengte contractperiode	
Stability of the available budgets	Planability			x	Stable budgets give the ability to plan ahead and give more (predictable) tasks to the contractor, creating a highly autonomous environment	Schoenmaker	Budget	
The amount of innovativity of the different assets and systems (ICT vs Civil = HIGH vs LOW)	Predictability		(x)	x	When facing a longer contracting period, some systems might become outdated due to innovation, this cannot always be predicted and limits the ability for the C to keep full control	Schoenmaker		
Dynamic functional requirements	Predictability		x	(x)	Can things change over time, how likely is that and who is responsible for dealing with these changes (where is the risk)	Schoenmaker		
The planability of the work at the start of the contract	Planability		(x)	x	If a lot of the work is predictable/planable, it can easily be given to the contractor with the corresponding PR, if not, more control of the CA might be required	Schoenmaker		
The predictability of the occurence of an event that requires a maintenance intervention	Predictability			x	Who is responsible for bearing the risk of a maintenance intervention that of something that suddenly occurs. The risk division of more or lesser predictable events.	Schoenmaker		
The amount of downtime caused by an incident (malfunction or damage)	Criticality		x	(x)	Depending on the amount of downtime and the consequences that this will have on the overall performance, more responsiblity is shifted towards the CA by downsgrading the PR and Contribution of the C.	Schoenmaker		
Measurability of the effect of the maintenance intervention of the lack thereoff	Measureability		x	(x)	If the effect of an intervention is hard to measure, thus the performance can't be effect quantified it is hard to reward the performance as such, another way of performance measurement might be more suitable.	Schoenmaker		
The specifiability of the maintenance intervention a the start of the contract period	Planability		x	(x)	To what extent is it clear what exactly needs to be done by the C and to what extent can he be held accountable for not delivering the required performance in the first period of the contract.	Schoenmaker		
The unpredictability of the costs of the intervention measures to remedy malfunction or damages	Predictability			x	This is very unpredictable and thus a high risk, depending on the expected risk a higher risk premium will be charged by the C, thus is might be wise to keep this risk on the CA side by downsizing the responsibility of the C	Schoenmaker		
The predictability of the costs of finding the cause of a malfuntion	Predictability			x	This is very unpredictable and thus a high risk, depending on the expected risk a higher risk premium will be charged by the C, thus is might be wise to keep this risk on the CA side by downsizing the responsibility of the C	Schoenmaker		
Are the long-term financial liabilities realistic	Financial	x		(x)	If the financial liabilities can not be met for the duration of the contract, smaller portions need to be outsourced (or more control/risk has to remain with the CA)	PPIAF	markt, aansprakelijkheid	Hoe realistisch? Juridisch? Markttechnisch? Eigen organisatie?
Can the incentive structure support the goals that were set	Financial		x	(x)	Higher Performance Requirements can be met when the goals can be reached through an incentives structure, if not, more prescribed tasks need to be used > less autonomy for the C	PPIAF	incentive	Wat bepaalt of een incentive structuur passend is?
Are the risks allocated to the party that is most able to bear them	Risk Division		x	(x)	If the risks are too high for the C to bear, the risk should shift to the CA. The PR will be downsized and/or the contribution of the C will be lowered.	PPIAF	markt, risicoverdeling	Risico moet bij de partij liggen die er invloed op heeft
Can economies of scale be achieved	Financial / Market interest	x			The size of the scope will decide whether economies of scale can be achieved by the C, if not, the size is too small and the Market might be less interested and less willingly to take risk	PPIAF	markt, schaaleffect	Beetje algemene overweging
Is the scope of the work manageable for the relevant party	Suitability	x			If the scope is too big to manage for one party, more parties need to be envolved, or the scope size need to be downsized (more reasons for this are already mentioned by Schoenmaker)	PPIAF	kan de markt het aan?	Heb je zelf de capaciteit om hoofdaannemer te spelen indien de markt het niet kan? Of heb je voldoende budget om het weg te leggen? Zo nee dan moet je je ambities naar beneden bijstellen.
Is the contract period long enough to transfer the life cycle risks to private operators	Risk Division			x	If the period is long enough, more risk/resonsibility can be given to the C, if not, there is less certainty and more risk should stay with the CA and less responsibility with the C	PPIAF	Lengte contractperiode	
Can the private parties get a return on investment (Specialized equipment)	Financial			x	Is it realistic for the C to get certain equipment with respect to the return of investment or should specialized equipment be in possession of the CA, same goes for expensive spare parts	PPIAF	markt, schaaleffect	Dubbel met economies of scale
Are there sufficiant an good performance specifications and standards in place	Measureability		x		The level and amount of good performance Requirements decides what level of PR can be used in de contract	Sultana	systematiek	
Is the expertise of the market parties sufficient to carry out this particular job	Available knowledge		x	(x)	If the knowledge is not there, prescribe the activities or search for ways to share the knowledge in de future. Performance Requirements and the contribution will be affected	Sultana	kan de markt het aan?	
Is the party that is bearing the risk able to bear that risk in the first place	Risk Division				Amount of riks can be caused by different factors and can affect all three variables (size > less objects, but more the amount of responsiblity through the PR and the contribution) and need to be adjusted accordingly	Sultana	markt, risicoverdeling	
Can the performance (requirements) be monitored accurately in relation to the payment regime	Measureability		x		If the Requeste PR cannot be measured, no payment scheme can be made, if this is the case, other PR need to be requested	Sultana	incentive	
Are employers on the contracting authoritiy's side becoming reduntant	Capacity			x	The CA might want to keep some work in-house to be able to keep their own people at work, or the other way around, might want to outsource because they have insufficient capacity to deal with certain matters.	Sultana	Eigen organisatie	
Are payment schemes and termination/transfer conditions in place	Preparation		x		Payment schemes need to be in place to effectively use the PR, if not, the PR need to be adjusted to simpler and more measureable tasks. Same goes for transfer conditions at the end of the contract, these need to be clear.	Sultana	incentive	
Is good and robust data available of the network	Predictability		x		Good and robust data increases the predictability of things to come and make it easier to use higher performance Requirements, the lack of information should result in decreas of the PR	Pakkala	systematiek	
Is a solid funding stream available for the maintenance work	Financial / Prioritizing tasks	x		(x)	When a solid funding stream is not available, smaller portions of work can be outsourced, the next step is to reduce the responsibility of the C by making the priorities as CA based on the available funding	Pakkala	Budget	
Is the in-house expertise good enough to create the new contract (clear and concise language)	Available knowledge		x		Is the CA capable, with the available information, to create solid contract using and concise language	Pakkala	Eigen organisatie	
Are common standards on performance measures in place	Measureability		x		If this is not the case, the PR need to be downgraded to a level on which this information is available or can be made.	Pakkala	systematiek	
Is good communication and sharing of knowledge with all parties realistic	Available knowledge			x	If communication between CA and C is not possible or not desirable, the contribution and autonomy of the C needs to be adjusted. The same applies for contact between C and interface C.	Pakkala	markt, contract	Waarom zou dat niet realistisch zijn?
Can this form of contracting create competition amongst market parties	?				x	Pakkala	markt, contract	Als contract te groot dan sluit je een te groot deel van de markt uit; proportionaliteitsbeginsel. En als je alleen gunt op laagste prijs, dan zijn prijsafspraken mogelijk.
Partnering or Partnering board available	?				x	Pakkala	Eigen organisatie	
Is historical data available to ensure upkeep (instandhouding)	Predictability		x	(x)	Historical data can be used to form expectations for the future, the PR and the contribution need to be adjusted to this information	Expert Judgement	systematiek	
Is the internal capasity sufficient	Capacity			x	Internal capacity can be a reason shift more of less responsiblity to the C, this done throught the level of contribution of the C	Expert Judgement	Eigen organisatie	
Are specifications and norms available (to issue a certificate) SMART formulated	Measureability		x		The better the specs are formulated, the easier it gets to use high levels of performance Requirements, if they are lower, PR needs to go down.	Expert Judgement	systematiek	
Is everything measureable (are SMART performance Requirements in place)	Measureability		x	(x)	This is about the ability to measure certain requirements, if things are measureable, they can easilly be implemented in the contract with a high PR, if the ability to measure low, lower PR should be used lowering the C contribition	Expert Judgement	systematiek	
Predictability of failure / replacements / repairs	Predictability		x	(x)	The higher the predictability of events, the easier it gets for to outsource using a high level of PR and a lot of responsibility for the C. Risks are predictable and can shift towards the C.	Expert Judgement	systematiek	
uncouple routine maintenance and special/unexpected maintenance	planability	x			Change the size of the scope to put al routine tasks in one part and take all risky, special and unexpected events in another part of the contract with different conditions	Expert Judgement	scope, systematiek	Brommet?
Combining Performance Requirements based on Performance Levels and Work instructions on the same asset/syste etc.	planability			x	Use the contribution of the contractor to treat different parts of an object differently.	Expert Judgement	systematiek	
Who is responsible when the risk fires and can they baer those risks	Risk division	x	(x)		If the risks are to big to be carried by one party, make the risk smaller by splitting up the assignment. Changing the PR and eventually the corresponding responsibility	Expert Judgement	markt, risicoverdeling	
Are the jobs general enough to be done by one contractor or too specific and is a specialized contractor needed	Suitability	x			Can the combination of tasks required to fullfill the PR be done by one indivual party or is it better to split up the assignment in smaller parts, if the latter is the case, the scope might be adjusted.	Expert Judgement	kan de markt het aan?	
Internal request that needs to be implemented	Criticality	x	x	x	If internal requests force a decision for whatever reason, the corresponding variable needs to be adjusted.	Expert Judgement	Scope, eigen organisatie	
								Idee: markt en eigen organisatie zijn redelijk volgend/plooibaar, dus er is wat voor te zeggen om op de systematiek te focussen; wat heeft het primaat? Markt, contract, eigen organisatie of systematiek?

Appendix 2

Decision criteria

Appendix 2: Decision criteria

Based on the literature of Pakkala (2005), Schoenmaker (2011) , Sultana (2012) and the PPIAF (2014) more than 60 different considerations were found that are important when outsourcing using PBMC. These considerations are first mentioned in chapter 3.3 where they were categorized into 14 different types. Based on the amount of times every type occurs, a top 5 is found. These five main considerations will be used as the most important decision criteria while using the decision-support method.

The five main criteria are: Predictability, Plannability, Measurability, Responsibility and Criticality.

It is however important to notice that these criteria are made up of several individual considerations and therefore represent a group of aspects. It is hard to cover all the individual considerations in just one criterion. The next part is used to explain how interpret these criteria and what considerations they are based on. This is done to ensure that it is clear what they mean and how to use them correctly. The explanations are based on information of the 4 sources mentioned before: (Pakkala, 2005), (Schoenmaker, 2011), (Sultana, Rahman, & Chowdhury, 2012) and (PPIAF, 2014). Because the different considerations per category are from individual sources, the sources are not mentioned with every occurrence in this appendix.

Predictability

Predictability is: ‘the ability to be predicted’ (Oxford Dictionaries, 2018). This may seem obvious, but what does this have to do with maintenance contracts. When analyzing the considerations, 16 of them were linked to this criterion. Predictability is used and explained in many different ways and contexts throughout the different considerations. Examples of these are the predictability of the behavior of outside forces, predictability of the behavior of the asset through time (based on historical data or expert judgement), predictability of the life expectancy and corresponding replacement dates, predictability of the maintenance that is required to keep the asset running, predictability of the effects of using different/known performance requirements and the predictability of costs.

Because the considerations originate from different sources, they overlap in some cases. Some even have a cause-effect relationship. When taking all considerations together they are in fact out to answer the same question. Therefore the following explanation is used to describe predictability.

To what extent is the behavior of an asset (technical and/or influenced by outside forces) predictable enough to know what maintenance work needs to be done during the contract period, what replacement work can be expected and can count as a base for a cost estimate?

Plannability

In the oxford dictionaries (2018), and in the entire English language for that matter, the word plannability is not literally found. The closest is the word planning, which is explained as: ‘the process of making plans for something’ (Oxford Dictionaries, 2018). Plannability is a contraction of planning and ability, loosely translated to: ‘the ability to plan something’. Plannability based on 7 considerations that were found in the literature. As with predictability, plannability is also explained in different ways and contexts. Plannability can be argued financially, when there is doubt about the stability of the available budgets or dissimilarity in the planning- and budget cycle & the contract length. As with the last argument, the length of the contract can be shorter that the time horizon of a certain task, which makes plannability harder to do. On a more technical level, the extent to which the maintenance work is specifiable at the start of the contract has influence on the work that can already be planned.

Plannability and Predictability are connected and dependent on many levels. But they’re definitely not the same thing. Things can be predictable, but not yet plannable. They can be plannable, but do not necessarily have to be predictable. In many cases however, one might find that predictable maintenance work is often plannable and unpredictable work will obviously be harder to plan, hence the connections and dependency that is mentioned earlier. The big difference lies in the question that this consideration is trying to answer. The amount of plannability depends on the amount of information that is present at the start of the contract about the maintenance interventions that will take place during the contract, the amount of money that is available for those interventions and the certainty that those interventions will or will not happen during the contract period. This is very important if for instance the cost estimates for certain interventions are already made and agreed upon before the contract is even started. This can be beneficial for the CA because they know beforehand what the costs will be and the solution is probably cheaper than an ad hoc solution, but they want to be certain that the intervention is necessary. Based on that, the following explanation is used to describe plannability.

To what extent is enough specific technical information and enough financial certainty present to be able to plan maintenance interventions, of which they are confident that will be necessary, throughout the entire length of the contract?

Measurability

The same as with plannability, measurability is simplified to: 'The ability to be measured', where measurable is defined is almost the same way: 'Able to be measured' (Oxford Dictionaries, 2018). Measurability is based on 7 considerations found in several scientific articles and literature. Measurability has three main arguments that influence this criterion. The first one resembles the definition and is about the ability to measure the consequences of an activity in relations to the payment regime, ability to measure the effects of an intervention or lack thereof and eventually if the requirements that are set are even measurable.

The second consideration is whether there is a good way to monitor the requirements with respect to the payment regime. There is a crucial difference between the ability to measure (ability to put a ruler next to an object to see how long it is) and monitoring (having a person actually putting that ruler in place on a regularly basis). One is more technical and describes the ability to measure, monitoring is about the regime and availability of taking those measurements regularly.

The third and last consideration addresses the ability to use common standards on performance measure and the availability of SMART formulated specifications and norms to issue a certificate. This is about the way the performance requirements are written and whether they are already available and proven. Based on these three different approaches of measurability, the following explanation is given to use this criterion unambiguously during this thesis.

To what extent are common standards, specifications and norms on performance measuring available to base measurable performance requirements on and is the CA able to monitor those performance requirements sufficiently in relation to the payment regime?

Responsibility

Responsibility is a very broad concept. The Oxford Dictionaries (2018) allocates the following definitions to responsibility: 'the state or fact of having a duty to deal with something or of having control over someone', 'The state or fact of being accountable or to blame for something', 'the opportunity or ability to act independently and take decision without authorization.' The considerations that are found certainly have interfaces with these definitions, and therefore the final explanation of responsibility will be based on those definitions.

The first group of considerations is based on interdependency within or outside of the agreement. This has to do with whether the contractor can make decisions about certain aspects of the work without permission of the CA, thus the amount of responsibility that the Contractor has. Interdependency can also mean to what extent a contractor is responsible for things that happen outside of the agreement but have a direct impact on the work of the Contractor. This is also mentioned in another consideration as the level culpability when faults occur caused by third parties of the Contractor or CA.

The second group of considerations is a different kind, more focused on the levels of interactions and dependencies amongst the different actors. The main question here is to what extent a certain party can make decision without consulting or even receiving permission to do so. The first group is focused on the 'what if' scenarios, who bears the responsibilities then. The second group is focused on the freedom the different parties have in their decision-making during the contract period. Given that freedom of decision comes with more responsibilities as defined by the Oxford Dictionaries (2018). Based on these findings, the final explanation of the concept responsibility will be as follows.

To what extent is a party accountable or to blame for things that happen (negative effects) during the contract period, considering whether these effects were to be expected, are part of the agreement (or not) & therefore the duty of that particular party and whether this party had decision-making authority to prevent the negative effect from happening?

Criticality

Criticality is defined as: 'crucial importance' (Oxford Dictionaries, 2018). Translated to the maintenance issues that are being discussed here, it is about parts of the system that are of crucial importance. If those parts fail, the entire system will fail, also known as the use of a bottleneck. When looking at the other considerations, the amount of downtime caused by a malfunction of damage is paramount to the severity of the criticality. Ownership of spare parts is also put under criticality. This is also traced back at reducing the amount of downtime for critical components. Another consideration mentions internal requests. These are requests/orders from the CA that are already made before the contract is written. Deviation from these decisions is often not possible. Based on these considerations the following explanation for criticality is given.

To what extent is a part (of a system) crucial importance for the functioning of a system or even the entire asset based on the effects it has on downtime, malfunctions, safety issues, costs and nuisance for the users?

Appendix 3

Parameters explained

Appendix 3: Parameters explained

Size and scope

In chapter 3, this parameter has already been explained. First the parameter itself, and then the range that the parameter covers. In this chapter the parameter size and scope is again being treated, this time focusing on how the range and the different options should be used and interpreted within the decision-support method. In the previous chapter, the range of the parameter has been decided to be as follows:

- Geographical area
- Asset
- System
- Sub-system
- Partial sub-system
- Component

This breakdown will be used within the decision-support method to act as a starting point to adjust the other parameters. In order to work with this parameter, it is important to get an understanding of the different choices that can be made, why they are being made and what these choices actually mean.

Geographical area

If a geographical area is chosen in this step, the scope is confined by a boundary (visible or invisible) and includes all assets (not excluding systems, sub-systems, partial sub-systems and components unless stated otherwise) that fall within this boundary. When a geographical area is chosen, that will be the starting position during use of the decision-support method. If this turns out to be a wrong choice, a new Size and Scope is chosen and the process is started over.

An example of a geographical area could be the area around a highway bridge. This area consists of a few individual assets, the bridge itself including the movable bridge deck and the on/off ramp, the control tower, the stretch of highway surrounding the bridge and the nature surrounding the bridge.

Asset

If an asset is chosen, the scope (during the use of the decision-support method) only includes that particular asset. If an asset is chosen, the other parameters should be adjusted to fit that particular asset, especially the contribution of the contractor is an interesting one because the contractor either gets full responsibility of the entire asset, or not. Also finding a fitting performance requirement that covers the entire asset might prove difficult. When the it contains a simple asset (small pedestrian bridge) this option might be an easier choice than the movable bridge with far more systems and sub-systems within the asset that was mentioned before.

An example of an asset could be a part of the previous example, for instance the control tower. This includes all the systems, sub-systems, partial sub-systems and components that are part of the control tower.

System

If a system is chosen as a scope, this includes all sub-systems that fall within this system. The parameters are adjusted accordingly in such a way that the same contribution of the contractor and overall performance requirement can be chosen for the entire system. If this does not work out, smaller size/scope can be chosen and the decision-support method will commence again with the new size/scope.

Example of systems within the control tower are the technical installations, IT-infrastructure, civil engineering etc. Everything that falls within one of these classifications is included. All the sub-systems that are present within the systems are includes once one is chosen.

Sub-systems

Sub-systems are the next level that can be descended to. At this level it often becomes easier to adjust the contribution of the contractor and the performance requirements because with every step the total size is being decreased. Even now it can be the case that no fitting parameters can be found to match this level of size and scope, in that case the size must be decreased once more and the method started again with the new variables.

An example of a sub-system within the area of technical installation (system) is for instance the lighting. This includes everything that has to do with the lighting within the control tower. The lights themselves, the wiring, the controls etc. Other examples are drainage installations, ventilation systems, traffic control management installations, fire safety installations, communications etc.

Partial sub-systems

The partial sub-systems are smaller groups of components that are there for a certain task. If the previous example is taken, the partial sub-systems are the lights, the controls and the wiring. Don't mistake this level with the level of components, for a set of components results in a partial sub-system.

An example for instance might be all the outside lighting on the control tower. This does only includes the light, fittings and housing. The rest of the components will fall under a different partial sub-system.

Components

The Components are the smallest scope that can be chosen. This will only be done in special cases where all other levels of Scope are inadequate. The reason why this is not chosen that often is because the scale is so small that there will be too many components to individually evaluate and process. On bigger scale assignments this will only be chosen if there is absolutely no other option or with very special/critical components.

An example of a single component within the precious line of examples is the simple light bulb. Within the other examples of partial sub-systems, components might be a single wire or a switch.

The examples that are used in this explanation are merely to illustrate and show how the parameter can be used. The fact that 6 levels were chosen was done to create the options that can used during the decision-making process. This does not exclude the freedom of users to use different levels that suit a certain case more than the predetermined levels. As well as the examples that were given to illustrate the different levels. As longs as the users and the companies using the method agree on the terms and boundaries that are chosen at the beginning so that no misunderstanding will occur along the way about terminology and use of the different levels of the parameter(s).

Six-stage model

The six-stage model (Figure A3.1) was also introduced in chapter 3 of this thesis. In that chapter the focus was on the entire model, the meaning of the different steps, the overall goal of the model and eventually briefly about the range that will be used in the decision-support method. In this chapter, a more detailed explanation is given about the range and the use of the range within the decision-support method in order to make it easy to use in practice.

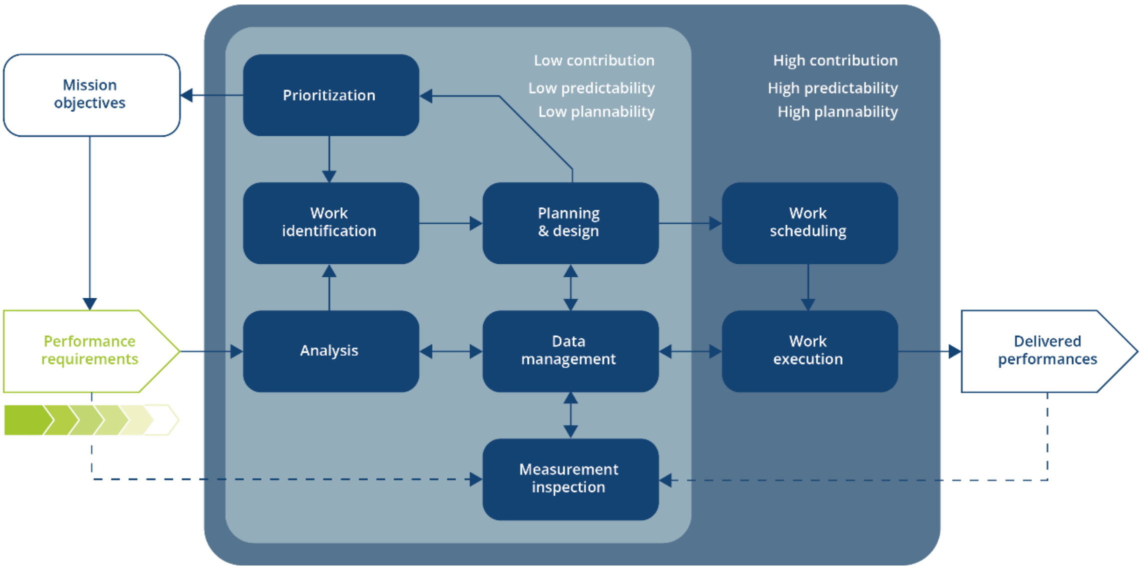


Figure A3.1: Six-stage model based on (Schoenmaker, de Bruijn, & Herder, The dynamics of outsourcing maintenance of civil infrastructure in performance based contracts, 2013)

The six-stage model is an important tool within the decision-support method and is there to help decide about the level of contribution of the contractor. Using decision-criteria like predictability and plannability, the model will suggest a preferred option. The contribution of the contractor is in fact the amount of responsibility that the contractor will have during the contract period. The suggested range, and therefore the available options are limited to a high and a low contribution of the contractor, hence giving the contractor a high or low level of responsibility. During the introduction in chapter 3, it was stated that all blocks within the Six-stage model can individually be assigned to certain parties. Although this is still true, the decision was made to simplify the model for use within the methodology and limit the decision freedom to two option. If expert judgement however should suggest that another (not yet given) option is preferable, this can always be done. For now, the explanation will focus on the two given options.

Low contribution of the contractor

The contractor is only responsible for the tasks that are mentioned on the left side of the low line. This means that the contractor is assigned tasks that are meant to monitor a certain part and keep the CA informed about developments that occur. This can be expected breakdowns, wear and tear, necessary maintenance interventions to ensure the function of that part etc. The contractor is however not allowed to take decision about initiating those proposals, that responsibility remains with the CA. This does not mean that the contractor is not assigned any maintenance tasks, the standard life-preserving maintenance can still be part of the tasks of the contractor.

The payment mechanism that is suggested for this option is as follows. The contractor receives a pre-set fee to be able to monitor the condition of certain parts through the entire length of the contract. In the case that no interventions, repairs of replacements are done, the CA only pays for the monitoring. In the case that interventions are necessary, repairs are executed and parts are replaced, the Contractor will be paid accordingly. This will be for the work that is actually delivered either cost reimbursable (all costs are directly passed on to the CA) or through a target price (a fixed price is agreed upon for certain repairs or replacements).

The payment regimes that are used for this option allow the CA to postpone the decision to intervene until the moment it truly occurs. That is why this option is suggested for work that is not predictable and not plannable. Variable maintenance work is something that will often fall within this category. When major replacements are coming up, but the time and necessity of the replacements are still unclear, is it worth the risk to put in the contract (lump sum up front) and eventually ending up replacing it when it was not necessary. This particular option leaves the decision-making option open for the CA during the contract period.

The expected moment of occurrence is a very important factor in the decision-making process on this topic. If a replacement (which is absolutely necessary) is expected in year 1 of a 5-year contract. This is a certain event which can be planned upon and it will pose no risk to give the decision-making authority of the replacement to the contractor. It is even possible to add a bonus fee if the contractor can postpone the replacement to a later stage of the contract. But if the same event is expected in year 5 of a 5-year contract, the object might be able to survive the contract period and replacement can be postponed till the next contract. In that case it might be wise to keep the decision-making authority in the contracting authorities' hands. In that case the contractor is not allowed to start replacing the object at its own initiative. In order to prevent the contractor from letting the maintenance of the object go, in order to earn extra money by getting the replacement order, the contractor should be rewarded if the expected life-time of the object is extended and the contractor should not have the certainty of having the replacement order when it has to be executed.

An important fact to keep in mind is the division of responsibility. The contractor can only be held responsible for things that they could have prevented. If the contractor failed to report imminent failure of a component (which they reasonably could have done), they are responsible for the consequences of that failure. If the contractor report the imminent failure and the CA neglected to act upon that warning, the contractor is not liable for any consequences as a result of that failure.

High contribution of the contractor

The contractor is responsible for the tasks that are mentioned on the left side of the high line. This means that the contractor is responsible for all the tasks within the maintenance cycle. With this option, the contactor still has the monitoring function and will performance standard life-preserving maintenance, but on top of that the contractor will be responsible for the entire functioning of an object. Replacement of components, repairs and major maintenance interventions have to be carried out in order to preserve the functional state of an object. Different from the other option, the contactor now has the responsibility for making the go no-go decision on commencing these interventions.

The payment mechanism is also different in this case. This option encourages the contractor to plan every intervention that will be necessary during the contract period up front, thus also being able to calculate the costs up front. For this option lump sum payments and fixed price are appropriate mechanisms. By using this method, the CA has knowledge of the expected costs during the contract period and will not be surprised by budget changes. The contractor has to calculate all costs and risks and has to make bid accordingly. By using this method, the contractor can take and leave risks (by covering them) as they think is wise and competition amongst contractors can be expected.

The use of these payment regimes requires the parties to have information about the behavior of the assets. The maintenance interventions that are required must be at least predictable and if possible also plannable. The difference between the two criteria are already explained in chapter 4.1. Routine maintenance work can easily be put in the hands of the contractor. It is routine (plannable and predictable) work that has low risk for either party. Think of work that is repeated at regular intervals (plannable) and work that occurs often (predictable) and has a low impact on the overall performance of the asset.

It becomes interesting when the maintenance work, repairs or replacements are of a questionable nature, meaning that they are somewhat predictable but still uncertain. Or that the work is not yet plannable for either party. In those cases, two options are available and need to be evaluated based on expert judgement. The first option is to conclude that the work is too unpredictable and due to the high impact consequences is too risky to put in the hands of the contractor. In that case the decision is postponed until occurrence. The other option is to put that risk with the contractor and let them come up with a competitive bid and solution to the problem. Criteria that play a role in this decision can for instance be the impact of failure of the component, the amount of certainty of failure (in time), the expected costs to solve of prevent the failure and the amount of responsibility that the contractor and the CA already have and what they can bear.

An important aspect of this last option is the fact the entire responsibility of the function of the asset/object lies in the hands of the contractor. If there is a functional failure, the costs and effects are for the contractor, but in many cases the CA is also hurt by these failures and there is still a shared responsibility. The same applies when the Contractor is not able bear the consequences of a risk happening. In that case the CA is the responsible party again. It therefore takes experience, careful evaluation and expert judgement to make the right decision about this topic. The methodology is therefore not providing the exact answers, helps by providing the important steps of the process in order to come to an informed decision. This is very important to keep in mind when using this model and the rest of this methodology. (Schoenmaker & Verlaan, Analysing Outsourcing Policies in an Asset Magement Context: A Six-Stage Model, 2013)

Performance requirements

In chapter 3, the different levels of performance requirements have been briefly explained. To help use the different levels that were presented, some extra information is given about these different levels. About what they mean, when they are useful and how they relate to the other parameters. This chapter is also used to show some examples to get a feeling with the concept of the different levels that are available. The chosen level eventually determines how a certain task, intervention or outcome is requested to the contractor. The contractor can then deliver the performance as is was requested by the contractor authority. Bear in mind here that a performance can be as simple as 'executing a written instruction' and as difficult as 'bringing a sense of security back to the public'. The levels that are chosen are highly dependent on numerous variable that will be discussed and explained in this chapter. Instead of treating all the variable independently, it was decided to treat the different levels of performance requirements based on examples and bring up the decision variables as they come along. In order to do so, the different levels are given in the figure below.

Figure A3.2: Levels of performance requirements based on (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017)

Before all levels are treated individually, one main criterion that is crucial to this decision must be mentioned. The chosen level of performance requirements is dependent on many variables, but mainly on the measurability that a task, job or request has. This decision criteria will be used on any individual level to decide whether it can be used. Another important thing that has to be mentioned is the relation between the risk for the contractor (responsibility) and the increased difficulty in performance measuring. With a specific activity, the measuring will either be: 'Yes, the task has been performed' or 'No, the task has not been performed.' The freedom and risk for the contractor are both very low in this case, because all responsibility lies with the CA. The outcome or effect however are way harder to measure. When is the effect as it was requested, whether it be safety or happiness, it is really hard to measure. The freedom of the contractor and the risk however are way bigger, because all the decisions are made by the contractor himself. This is an interesting consideration for the CA that needs careful evaluation before taking a final decision. Every level is now explained whilst taken the appropriate variables into consideration.

Specific activities

The use of specific activities is focused on 'what' exactly should be done, 'when' it should be done and 'how' it should be done. This means that it is aimed and controlling the execution in detail. The CA can choose this form of performance requirements when they want to keep total control. In this case the contractor has no freedom at all. The contractor will perform as requested and is not liable for any failures in design, technical problems or problems that are consequential to the timing of the intervention. The contractor however is liable when mistakes are made during the execution of the work, the specific activities are not performed as requested or serious flaws in the designs should have been noticed during the execution. Payment here is mostly done for each individual input. This means that every activity is charged independently and based on the amount of work that must be done (Porter, 2005). This type of performance requirement is ideal when performances are hard to measure, or historical data shows that this type of intervention at a certain interval is the only way to keep the asset functional. The responsibility and the risk for the contractor are very low in this case.

An example of a specific activity is for instance the replacement of an entire pump engine for a tunnel. These are expensive and important interventions where the CA wants full control about the what, when and how the work is done during the replacement. By framing it as a specific activity, the CA can stay in control and get their desired result.

Work instructions

The work instructions are in many respects similar to the specific activities. The biggest difference with the previous level is the fact that work instructions are only focused on What and How, not so much on When. Where the specific activity describes one activity at a certain moment in time, the work instruction can describe a general activity that will occur numerous times within the contract period but needs to be executed in a way that is exactly described by the CA. Again, keeping control about how the intervention will be executed. The moment of intervention is independent of the work instructions and can be based on the condition of the asset, the suggestions of the contractor, scheduled beforehand or ordered by the CA for any number of reasons. This level of performance requirement is usable when performance measurement is difficult because the timing of interventions is independent of the activity. Also, the performance itself is easy to check because it is working in accordance to the written instruction. The payment mechanism can vary per situation. Because the activity is already described in detail, the contractor can make a target price for which every intervention of that kind will be solved. When there is more certainty about the work, for instance a monthly reoccurring event, the payment can be done through a monthly lump sum payment. Same as with the specific activities, the risk and responsibility of the contractor is low. The contractor is settled on input (AustRoads, 2003).

An example of a situation where a work instruction can prove a useful outcome is replacement of the big fans at the entrance of road tunnels. These fans are occasionally damaged by truck hitting them. In that case they need to be replaced, following a strict set of instructions by the CA. Because this intervention has great impact on the functioning and availability of the entire tunnel and surrounding road system, the CA wants to stay in charge here. Besides the intervention itself, the functioning of the fans is crucial to the function of the entire tunnel and needs to be done with the greatest care, giving the CA even more reason to make sure it is done in accordance with the desired specifications.

Level of intervention

The level of intervention is meant to given meaning to when an intervention must take place. The contractor must monitor the condition of the asset up till a point where an intervention must take place. This condition is called the intervention level. When this level is reached the intervention by means of maintenance, repairs, replacement or any other kind of intervention must be performed to put the condition back to a position which is far above the intervention level. The interventions that take place when the level of intervention is reached can be predetermined or can be open for discussion when occurring, depending on the agreement that is made between the contractor and CA. the contribution of the contractor (responsibility) is very important here. The payment is dependent on the work that is agreed upon and the predictability of the work. But payments are generally only received when actual work has been done. In order to prevent contractors to perform less Life-extending maintenance in order to increase aging and provoke a situation where the level of intervention is reached earlier than necessary, bonusses can be introduced if the level of intervention is only reached after a certain period of time. This makes the job of the contractor more challenging but can also result in more rewards. More initiative is expected from the contractor than with the input-based performance requirements. The contractor is accountable for failing to keep up to the standards up till the moment the contractor reported the issue. Depending on the agreement the responsibility then stays with the contractor or will shift towards the CA. The contractor is settled on output in this case (Porter, 2005).

An example of the use of levels of intervention is as follows. The contractor must perform simple life extending maintenance to a certain system. Whilst doing that they have to monitor the condition of that system and report the outcome of the monitoring to the CA. When the level of intervention is going to be (or is already) crossed, the contractor will in accordance with the agreement start the intervention or suggest an intervention whilst waiting on approval of the CA. A case example is the maintenance of streetlights. When a contractor is responsible for the lights alongside a road or within a tunnel, the CA may require the contractor to maintain a certain performance level. This could for instance be that at least 90% if the lights should work and that no more than 4 consecutive lights may fail at the same time. When this point is reached, the contractor must intervene.

Performance level

Using performance levels as a performance requirement can only be done when there is some form of measurability in place. The payment regime is now dependent of the performances that a system delivers and the contractor is paid accordingly. When a performance level is requested, the contractor must do whatever is necessary to keep a system at or above that level for the duration of the contract. The contractor gets a monthly or annual fee to do so. If the performance level drops below the required performance level, the contractor can receive a penalty. The other way around is also possible, when the performance level is way better than required a bonus can be awarded. The used method and timing of the repairs is the responsibility of the contractor. This means that the contractor has more risk and higher responsibility than with the previous levels. The big difference with a Level of Intervention is the way the request is formulated. In the first case, the threshold is the bear minimum that is required before an intervention is needed (allowed). In the case of performance levels, it must perform at a certain level to be functional and the Contractor had to make sure that is does. Systems or components that are more critical to the functioning of the asset can be put on this level (given that performances are in fact measurable). The contractor is settled on output in this case (AustRoads, 2003).

An example of the use of performance levels is the capacity of the pumps that drain water from the tunnels or the fans that are used to remove smoke in case of a tunnel fire. That capacity is important to guarantee the safety and with that the availability and consequently the function of a tunnel. It is measurable, and it always needs to be kept at a certain level. If the contractor is given such a requirement, they must do everything in their power to keep that performance at the right level. Another example of performance level is the luminance of the lighting in a tunnel. The CA can always require a certain amount of light in the tunnel. In case of tunnel lighting this even comes with an upper and lower boundary. The contractor must make sure, by means of repairs, maintenance (cleaning), replacements and adjustments that this requirement is achieved during the entire contract period.

Output or result

With these last two levels over performance requirements, the boundaries get less clear. The transition between the performance levels, which is an output-based requirement, to output or result based requirements, which lean more to outcome-based requirements, is very gradually. The difference here is the fact that the requirement is based on the result that is requested and not the method through which it is achieved. Therefore, the output that is delivered by the contractor is his choice, but the eventual outcome should be matching the expectations of the CA. This means that the requirements that are set by the CA need to leave room for the contractor to come up with their own solution. The CA merely describes the result that they want to achieve and the contractor has to convince the CA that they can accomplish that for a certain amount of money. This means that the contactor has to make an offer beforehand and will be receive a lump sum payment on either completion of the task, or performance according to the request (monthly, yearly) depending on the requirements. The CA again has the possibility to award bonusses if the results exceed the expectations and use penalties if the result is below the required standards. This however becomes increasingly difficult when moving towards outcome-based performance requirements because they are more open to interpretations and hard to measure in a fair way. The risk for the contractor is increasing as well, because more responsibility for the result (function) is put at the contractor. The ideal situation is where the contractor is directly impacted by the success of the performance of the asset. In that case the CA is assured of 100% commitment and the contractor is likely to have the same goals. This becomes increasingly important when the performances become less measurable, the required results less detailed and the outcome vaguely described. Another important aspect of this type of requirement is the fact that the contractor needs to have enough freedom to make certain decisions about the methodology they like to use in order to achieve a certain result. This is in terms of time and money, but also in term of interventions (besides routine maintenance) they're allowed to perform (Porter, 2005).

An example of result-based requirements is the request for optimal lighting. The problem with this requirement is the fact that we all have a different understanding of optimal. For one party optimal might be as much light as possible, whilst another party might feel more for lights that only illuminate when there are cars driving by. Therefore, there have to be certain boundaries in place that illustrate what optimal means and how this will be measured. The solution however stays in the hands of the Contractor.

Outcome or effect

This last level of performance requirements is quite like the previous one. But here the outcome is based on the desired effect that the interventions, repairs or replacements have. These performance requirements are the hardest to measure and can be very hard to interpret. This makes the last one very hard to use in practice, especially when there is no previous experience of working together with a contractor. Because effect-based requirements, even more that result based requirements, are open for one's interpretation, the eventual outcome can vary a lot from what was expected, but not necessarily wrong. The payment mechanism that is connected to this type of performance requirements is often a lump sum, but adding bonusses or issuing penalties (the bonusses less than the penalties) can become problematic because there is only an opinion to back any claims. The same as mentioned before, is the importance of the commitment of the contractor to achieve the same goals as the CA to achieve the desired effect. When this is not the case, what motivation does a contractor have to prefer the best solution over the cheap solution. Where the last option leaves him the most money (Porter, 2005).

An example of effect based requirements is the request for a sense of safety/security. This can be a request for a tunnel or a parking garage concerning the lighting. The first problem that should be tackled is who should feel safe and secure? The users, the contractor or the CA, and how is this going to be measured. These are all problems that can be encountered when using the effect-based requirements. Therefore it is important to realize what goals are to be achieved, are they aligned with the goals of the contractor and what do they have to gain to make sure that those goals are in fact achieved. If for instance, the name of the contractor is connected to the work, it is also a matter of reputation and the willingness to perform will probably increase. So these outcome-based requirements are definitely useful, but need to be put in the right context to make them work properly.

Hybrid

It is important to point out that these 6 options that were explained before are not cornered in by clear and solid boundaries. They act as reference to explain certain options in combination with the available information and the goals that were set. This means in practice that it is not of too much importance which of the 6 levels of performance requirements is chosen, but all the more important what goal the requirement should achieve and how it was formulated. This could well mean that in same cases a form will be chosen that picks the best proporties of two different levels and combines them into a form that helps achieving the goals that were set. This is especially the case with the levels that fall within the same catergorie. Specific activities and work instructions, which both focus on what should be done. Levels of intervention and performance levels, which are focussed on when to do it. And in the end the result and effect based requirements which are focussed on why things should be done. Although many ideas and possible considerations were introduced here, the expert judgement and evaluation of the specific situation remains very important for these decisions.

Appendix 4

Reliability centered maintenance
&
FMECA explained

Appendix 4: Reliability centered maintenance & FMECA explained

Reliability centered maintenance (RCM)

When the parameters are being tuned, information is needed to make the right considerations when dealing with the decision criteria. Tools and techniques are being used to provide that information. One of the ways to gain information about the decision criteria is the RCM method. This method is defined by Moubray (1997) as 'A process used to determine the maintenance requirements of any physical asset in its operating context' and 'A process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context'. A third definition is given by Buckland (2003) based on the IEC60300-3-11 (1999) which reads: 'A systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks.'

A more recent explanation was given by Hastings (2015) and said that RCM is a systematic method for establishing maintenance policy. The technique is able to give an in-depth analysis of the asset and provide information about the maintenance work that is required (suggested) for the coming period. This technique is therefore extremely helpful in providing information about the predictability, plannability and criticality of the maintenance work. This method is therefore applied in an early stage of the Decision-Support Method to assist the contract design team in making decision about the Size/Scope and lay the base for the decision about the contribution of the contractor. 'The applications of RCM must involve an appropriate level of engineering authority, consistent with the technology if the application for which the maintenance policy is being developed. At the same time, the value of this technique lies in combining knowledge of maintenance, engineering, and management staff in a structure process, providing benefits from the in-depth communication involved' (Hastings, 2015).

The concept of RCM is described as a number of steps that need to be taken. Hastings (2015) identified the five steps that are shown in the figure on the right. In the following section the essentials of the RCM methodology are explained in order to reproduce this concept in cases where this method is not yet used. If the RCM methodology is already in place at the start of the Decision-Making Process it should provide the necessary information about Predictability, Plannability and Criticality.

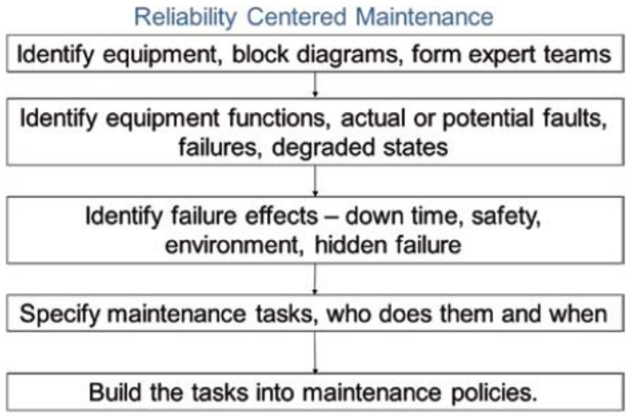


Figure A4.1: Reliability-centered maintenance concept (Hastings, 2015)

Outcome of the RCM methodology

The goal of using the RCM methodology is getting more information about the Predictability, Plannability and Criticality of the maintenance measures of an asset. The RCM methodology should at least identify the expected maintenance measure in the foreseeable future that are needed to keep the asset operational. The value of RCM increases when suggestions about the type of maintenance (Preventive, Predictive, Failure Finding Maintenance, Modifications, Run-To-Failure) is given. This way the contract design team can base decisions on that information.

But since the RCM methodology is not implemented everywhere, and the information might not be available, the methodology is explained in the next section in order to either use the method, compare it to the existing method (information might be equally useful) or skip this step altogether and find another way to gain information about Predictability, Plannability and Criticality. The following sections are not meant to show what a perfect RCM application is, but merely to show what information should be there and how RCM can aid in accomplishing that.

The RCM cycle

The RCM methodology is a cycle containing numerous steps. The following steps are being used in the RCM Cycle: decomposition of the asset, risk determination, risk analysis, maintenance strategies, maintenance measures, implementations, monitoring, reviewing and adjusting (van den Boomen, 2015) (Colibri Advies BV, 2018). This cycle is visualized in the following Figure.

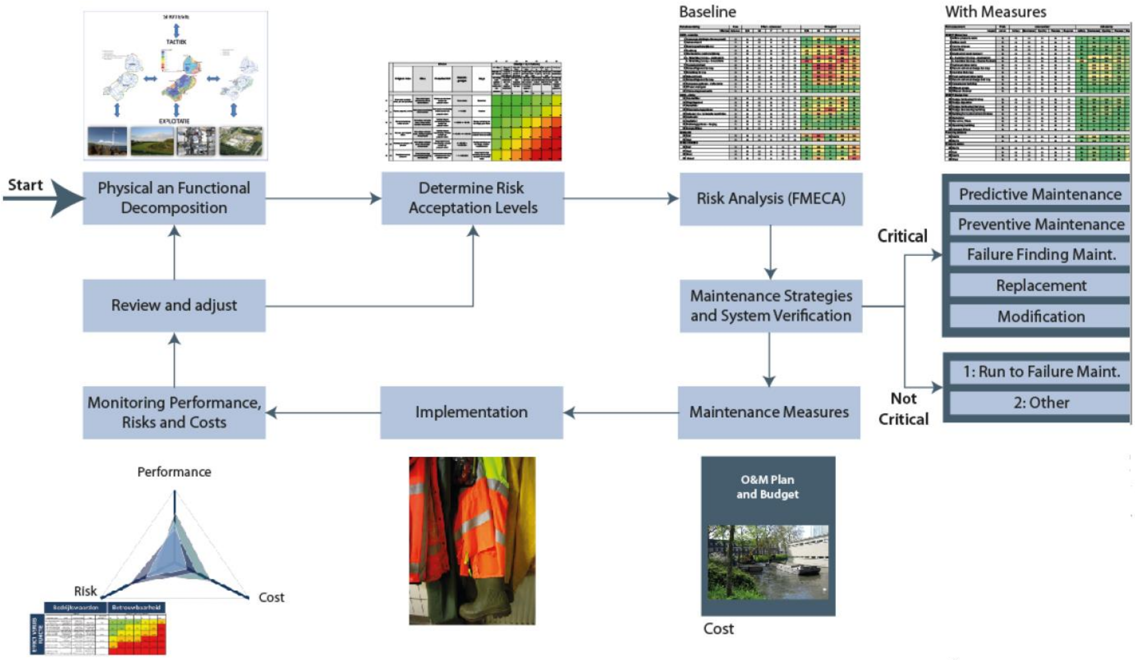


Figure A4.2: The RCM cycle (van den Boomen, 2015)

For the use within the Decision-Support Method, steps 1 to 5 are the most interesting because there the necessary information will be provided. These steps will be further explained.

Physical and functional decomposition

The first step is to make a physical decomposition of the asset or the geographical area for which the contract will be written. This is important to gain insight in the separate assets that might be part of the contract. This is especially important when a larger area is part of the scope of the contract. But the physical decomposition goes into much more detail than just the assets. The assets themselves are also decomposed into systems and components. The levels that were mentioned at the Size or Scope section in chapter 3.4.1 can be helpful here. Eventually every physical part of the area of asset should be known and put into an object register of object tree (Colibri Advies BV, 2018).

Then there is the functional decomposition. The functional decomposition is a breakdown of all the functions that the asset must perform. The goal is to break down the overall function of the asset or system into smaller parts. This should provide information on the different functions that different systems of the asset fulfil and what their importance is in the overall performance of the asset. The importance of certain functions tells something about the criticality of certain components. A fault tree analysis is good way to gain insight in how the mutual relations between different systems work (van den Boomen, 2015).

Eventually the two decompositions are combined and should deliver the following information. For every part of the system should be known what its function is, and when it fails. A very simple example is lighting. The system consists of lightbulbs, switches, power supply, wiring etc. The light fails when

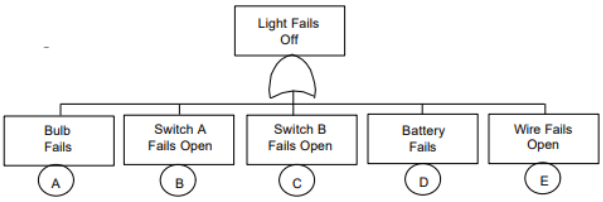
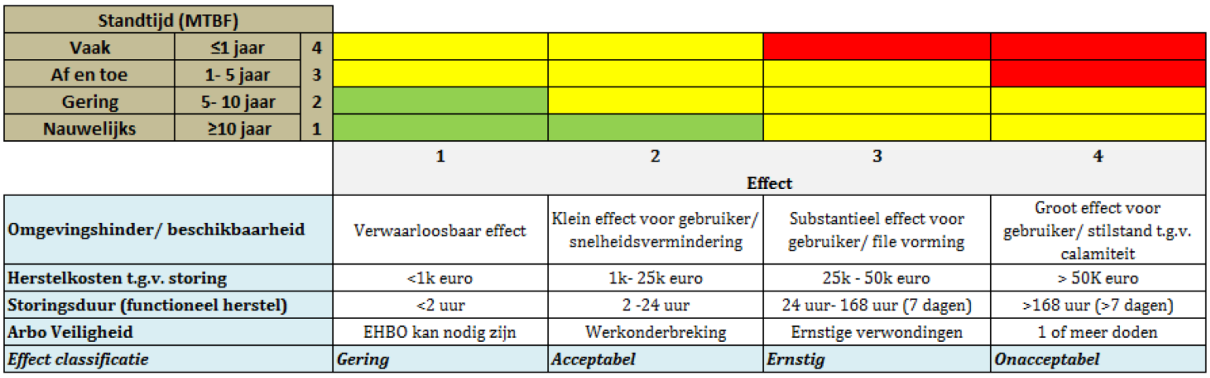


Figure A4.3: FTA example (Ericson, 1999) there is no light. But the absence of light can be caused by either a broken light bulb, a broken switch, no power supply or faulty wiring (Ericson, 1999). The results of this Fault Tree Analysis (FTA) is stored in a risk register and taken to the next step in the Cycle.

Risk matrix

The risk matrix is an important part of the RCM cycle. The risk matrix makes a connection between the Mean Time Between Failure (MTBF) and the impact that an event will have. Depending on the wishes of the Contacting Authority this can be scaled in 4,5 or 6 levels. For the MTBF this can vary from days to months and years. The MBTF predicts the probability of the occurrence of an event. For the impact the range is from negligible to catastrophic. What this exactly means differs from situation to situation. When the matrix is done, it will show events that are inherently good, events that have an acceptable risk level and events that are unacceptable. The focus on the maintenance strategies will often be on the last two groups (van den Boomen, 2015).

The following figure (figure A4.4) shows an example of a Risk Matrix used by Rijkswaterstaat (Imtech, 2013). This figure shows a scale of 4 levels. For the impact 4 different categories were chosen. Nuisance & availability, Repair costs, Downtime and Safety. The categories can differ per project and to the desire of the CA. It is important that the MTBF and the categories are clearly specified in order to work efficiently with this matrix.



Standtijd (MTBF)						
Vaak	**≤1 jaar**	**4**	🟨	🟨	🟥	🟥
Af en toe	**1- 5 jaar**	**3**	🟨	🟨	🟨	🟥
Gering	**5- 10 jaar**	**2**	🟩	🟨	🟨	🟨
Nauwelijks	**≥10 jaar**	**1**	🟩	🟩	🟨	🟨
			1	**2**	**3**	**4**
			Effect			
Omgevingshinder/ beschikbaarheid			Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing			<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)			<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid			EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie			***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A4.4: Risk matrix example (Imtech, 2015)

In this matrix, the green zone is acceptable and doesn't need much extra attention. It is often a predictable low impact risk. The yellow zone is bearing a higher risk that needs extra attention. These risks need to be contained and reduces by using mitigating measures. The red zone is unacceptable and needs to be investigated to see whether this risk can be reduced to yellow or other technical solutions need to be implemented to reduce the risk.

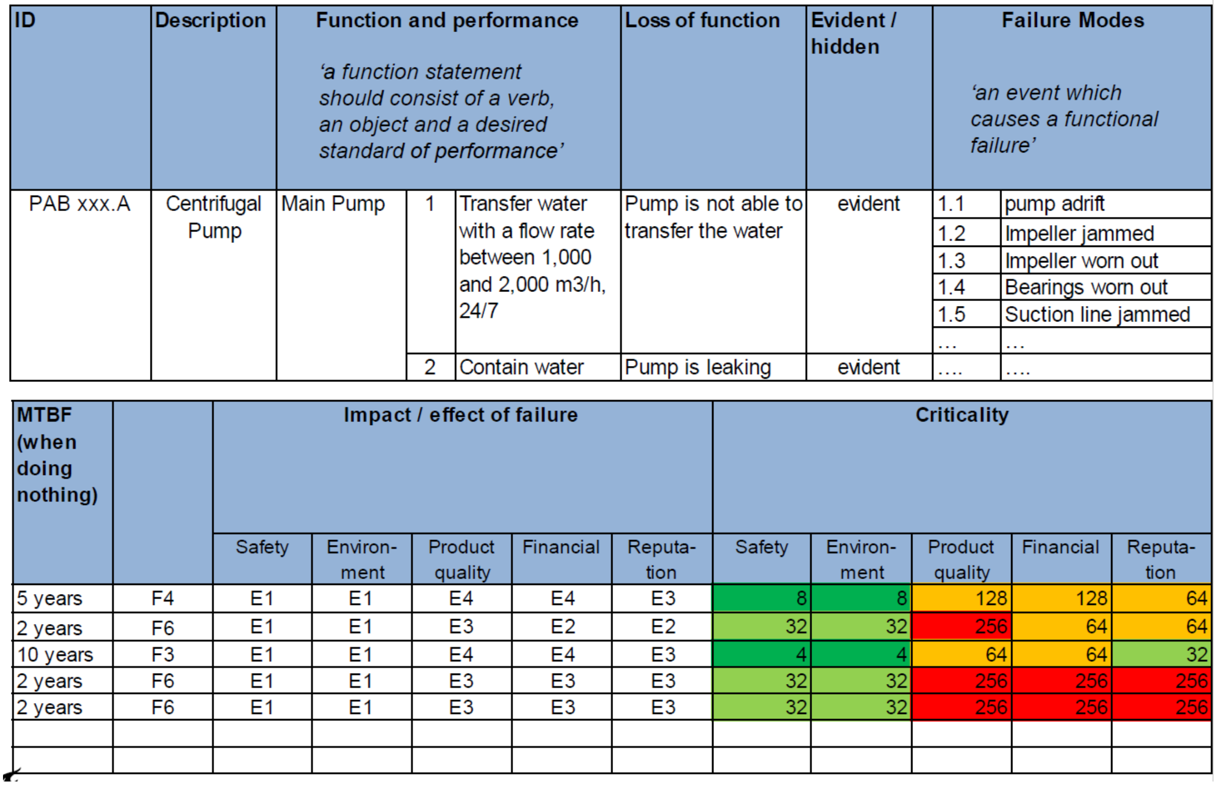
Risk analysis (FMECA)

The next step is to perform a risk analysis on the objects within the system. A structured way to approach this is by performing a Failure Mode Effect & Criticality Analysis (FMECA). The goal of the FMECA is to assess what the effects are if an object within the system loses its function. Every object that was found during the segmentation of the asset (physical decomposition) gets a risk classification using the Risk Matrix from the previous paragraph. These classifications are based on expert judgement and available information about the objects, the current state of the object and the historical data that is available of an object. During that process the Failure modes (all possible ways of failure of a component/system that were found during the functional decomposition) are assessed and the Failure probabilities are determined. The consequences and the severity of the various failure modes are determined at put together. This results in the following conclusions. The Failure probability x Effect = Risk. The risk number is put into the risk matrix and results in a pass, risk or unacceptable risk. By doing it this way, the critical components are found and the Criticality can be determined. Everything is put together in the Risk Register. This is a combined list of all available and verified information on all the risks of an object (van den Boomen, 2015).

This risk register should at least contain the following information at this point.

- A description of the system/object
- The function of that system/object/part and the performance (if possible stated as a desired standard of performance that could be used as a performance requirement)
- Technical description of when we speak about loss of function
- Whether loss of function occurs as Complete Failure, Partial Failure, Intermittent Failure or Hidden Failure.
- All failure modes that can lead to that loss of function (FTA example)
- MTBF (when doing nothing)
- Impact / Effect of failure on the different categories
- Criticality of a certain failure mode (MTBF x Effect = Criticality)

An example of this is shown in the figure below. For this example the range of the MTBF is 1 to 6 (F1 to F6) and the effects are also scale 1 to 6 (E1 to E6) (van den Boomen, 2015) (Colibri Advies BV, 2018).



ID	**Description**	**Function and performance** *'a function statement should consist of a verb, an object and a desired standard of performance'*			**Loss of function**	**Evident / hidden**	**Failure Modes** *'an event which causes a functional failure'*	
PAB xxx.A	Centrifugal Pump	Main Pump	1	Transfer water with a flow rate between 1,000 and 2,000 m3/h, 24/7	Pump is not able to transfer the water	evident	1.1	pump adrift
							1.2	Impeller jammed
							1.3	Impeller worn out
							1.4	Bearings worn out
							1.5	Suction line jammed
							…	…
			2	Contain water	Pump is leaking	evident	….	….

MTBF (when doing nothing)		**Impact / effect of failure**					**Criticality**				
		Safety	Environ-ment	Product quality	Financial	Reputa-tion	Safety	Environ-ment	Product quality	Financial	Reputa-tion
5 years	F4	E1	E1	E4	E4	E3	8	8	128	128	64
2 years	F6	E1	E1	E3	E2	E2	32	32	256	64	64
10 years	F3	E1	E1	E4	E4	E3	4	4	64	64	32
2 years	F6	E1	E1	E3	E3	E3	32	32	256	256	256
2 years	F6	E1	E1	E3	E3	E3	32	32	256	256	256

Figure A4.5: FMECA example of a centrifugal Pump (van den Boomen, 2015)

At this stage, a lot of information that is useful for the Decision-Support Method is already found. The critical components are identified and some prediction can already be done about the breakdown of certain parts of the system. But a next step can be used to dig deeper in the maintenance regimes and proposed strategies to make the maintenance interventions even more predictable and in some cases even plannable. This is done in the two following steps.

Maintenance strategy

As was mentioned before, the risks can't be unacceptable (be in the red zone). Mitigating measures need to be taken in order to bring back the risk to an acceptable level. This can for instance be done by adjusting the maintenance strategy. There is an added advantage of using this method with regards to the Decision-Support Method. Because recommended maintenance interventions are already decided, the work becomes more predictable and plannable for a contractor whilst at the same time significantly reducing the risks for the parties involved.

In order to do this, suggestions are made on the kind of maintenance strategy that is used. For unacceptable risks, Predictive Maintenance, Preventive Maintenance, Scheduled Replacement, Failure Finding Maintenance (especially with Hidden Failures) and Modifications might be suggested to reduce the risk to an acceptable level. Given that it is technically feasible, and the suggested option is economically worth doing. For acceptable risks and components that pose no risk at all, Run to Failure Maintenance can be used, but any other kind of maintenance that was earlier mentioned is acceptable as well. Given that it is technically feasible and economically worth doing (van den Boomen, 2015).

The next figure shows a flow chart to help choose an appropriate maintenance strategy. This flow chart was made by van den Boomen (2015) adapted from the work of Moubray (Reliability-Centered Maintenance II, 1997).

Abbreviations used in the flow chart:

H:	Hidden	PdM:	Predictive Maintenance
S:	Safety	CBM:	Condition Based Maintenance
E:	Environment	PM:	Preventive Maintenance
O:	Operation	FFM:	Failure Finding Maintenance
		RtF:	Run to Failure

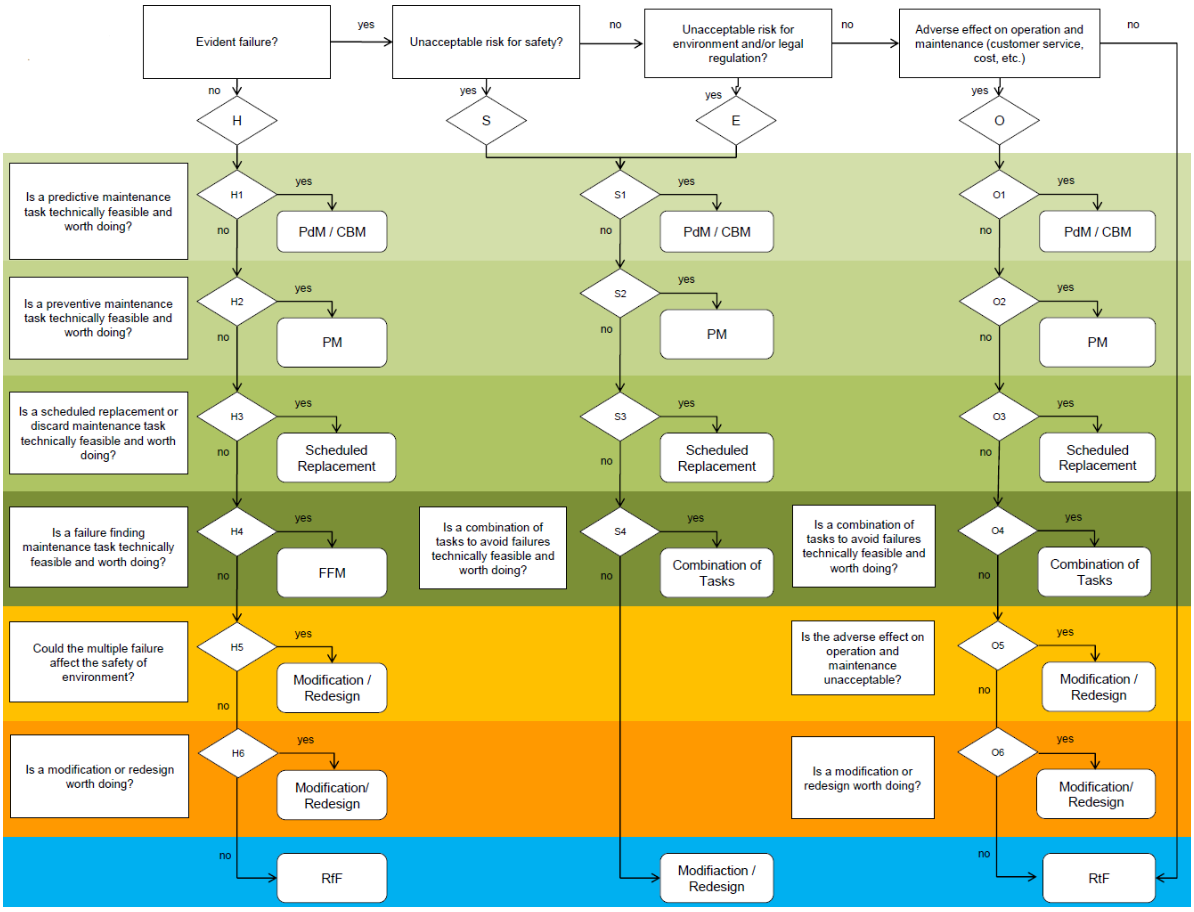


Figure A4.6: Maintenance strategy flow chart adapted from Moubray (RCM II, 1997)

Maintenance measures

In this last step, the maintenance strategies are being used to develop concrete plans for the maintenance regimes. Based on the information that is available and the requirements that came out of the flow chart of the previous paragraph, a suggestion for maintenance measures is made. These maintenance strategies and suggested maintenance measures are also added to the risk register.

The kind of maintenance measure is depending on the information that is available about the object. For predictive or condition-based maintenance, there has to be some information about the condition status of the object and about the prediction of when functional failure will occur. Preventive maintenance and scheduled replacements use the predicted lifetime to plan maintenance interventions. This can either be running time or calendar hours. Known failure patterns will be used to increase the accuracy of these predictions. Failure Finding Maintenance is done with systems that are known to have Hidden Failures. This is mainly equipment that is not used on a regular basis like emergency lighting or smoke detectors. This equipment needs to undergo regular testing to ensure functionality (van den Boomen, 2015).

Based on these considerations, maintenance measures can be assigned to the different objects and systems. If possible already provided with a suggested maintenance schedule. By doing so, the risk is reduced to an acceptable level and the work becomes more predictable, plannable and critical issues are already dealt with in an early stage of the process

Unavailability of RCM

RCM and the FMECA were chosen for their ability to meet the need for information about Predictability, Plannability and Criticality. The RCM method aims at improving the reliability of the maintenance work by finding the Critical components, Predicting the maintenance that will be required and make the work Plannable for the Contractors. The choice for RMC was made because it can be implemented rather easy and can be applied on various levels of depth. Therefore the method is fit for almost every situation. It is however imaginable that a smaller organization has more trouble engaging in a new method like RCM (if they are not used to do so) than for instance Prorail, Rijkswaterstaat or any other government driven organization. The government driven organizations often have more resources and experience in trying new methods (given that they’re not already using RCM).

An important factor to point out here is that the RCM (and FMECA) are suggested solutions for finding the necessary information. But every other method that is able to point out Criticality and is if able to Predict maintenance work will suffice. An added bonus will be if the method is also able to give some level of Plannability about the predicted maintenance work. The more information is provided as input during the use of the Decision-Support Method, the more accurate the results will be.

Another important factor is that the use of the FMECA, and especially the depth of the FMECA can vary from case to case. In some cases, it is wise to get everything right, down to every bolt and screw. However, in many cases a more overall view of the asset is more than enough to do the Predictions that you need. By just using and analyzing the first steps of the FMECA process, a lot of important information is already gain.

It is not so much the RCM methodology that is important for the process, it is the information that it provides. If RCM is used in a correct, high quality input can be used during the entire Decision-Making Process, but the RCM method is not crucial. If another methodology, or a simplified version of the RCM method is used, this will still work. If they’re able to gain reliable information about Criticality of systems, Predictability of maintenance work and Plannability of maintenance interventions. But it is important that the quality of the information input is crucial for the level of the eventual outcome.

Appendix 5

Case study — Run 1 —

Appendix 5: Case study - Run 1 -

Case study: Noordtunnel - Run 1 -

Figure A5.1: Noordertunnel (Zuid-Holland), Patrick van Dam (2017)

Figure A5.2: Google maps view of the Noordtunnel (07-11-2018)

1. *Goal of the first run of the case study*

The goal of the first run of this case study is to test the performance of the conceptual design of the decision-support method. Because this is the first conceptual design, flaws and room for improvement is very much expected. At the end of this first test, the results will be evaluated and the suggested improvements will be discussed. Improvements that are expected are the further improvements of the steps, expanding or reducing the number of steps or making changes in the way the method works. During this first run, the most important thing to see is whether the steps work in practice, the outcome and the results are not the main focus. This is more important during the second run of the case study.

2. *Execution of the case study*

For this case study, an actual case is selected to act as subject during this test. This is done in accordance with the boundary conditions and decisions that were already made in chapter 2.3 of the main report. This means that the case study will be performed on the Noordtunnel.

Before the decision-support method can be used, basic information about the tunnel is needed. This part is used to introduce the case/subject, provide basic information and already start with the collection of data that will be useful during the remainder of the process.

After the case introduction, the use of the decision-support method starts. During this first run of the case study, the method as explained in the end of chapter 3 of the main report are used. This is the conceptual design of the decision-support method. The method is visualized in the figure below (Figure A5.3).

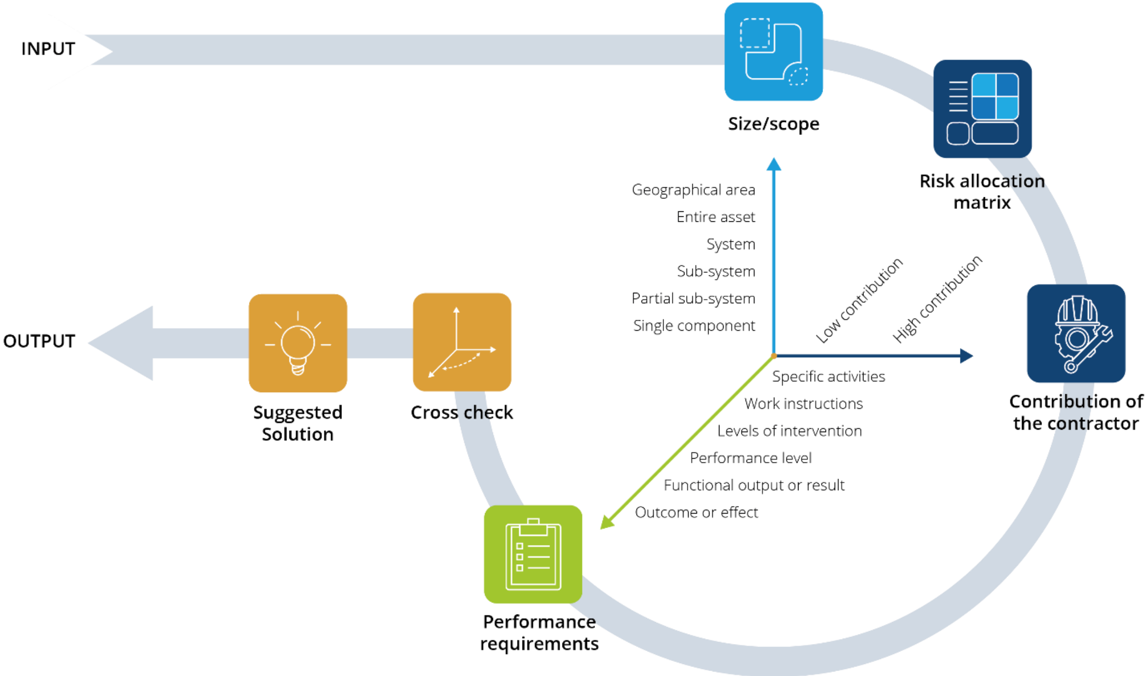


Figure A5.3: Schematic representation of the conceptual design of the decision-support method (as found in Appendix 5)

Using the method as described above means that after the initial introduction of the case and the collection of data using the RCM and/or FMECA methodology is done, the steps of the conceptual design of the decision-support method can be used. The cycle of 6 steps will be repeated a number of times for individual systems of the tunnel. The different systems will be evaluated systematically using these 6 steps before continuing to a next part of the tunnel.

For this case study, three parts of the tunnel will be evaluated through the use of the conceptual design of the decision-support method. The focus will be on the usability of the method, not on the outcome of the process itself.

3. Information gathering and step 1 of the conceptual design of the decision-support method

Before a start can be made on using the steps of the decision-support method, information is needed. This information will function as input for the decision-support method. Within Rijkswaterstaat, the reliability of the tunnels is an important aspect. During the information gathering, it was found that for the Noordtunnel, RCM was already used. That is the reason that a function FMECA was already present. Normally, it would have been recommended to use RCM and perform the FMECA in order to gain the necessary information for the use of the decision-support method. But as mentioned before, this had already been done in 2012/2013 for the Noordtunnel. This information is used during this first run of the case study.

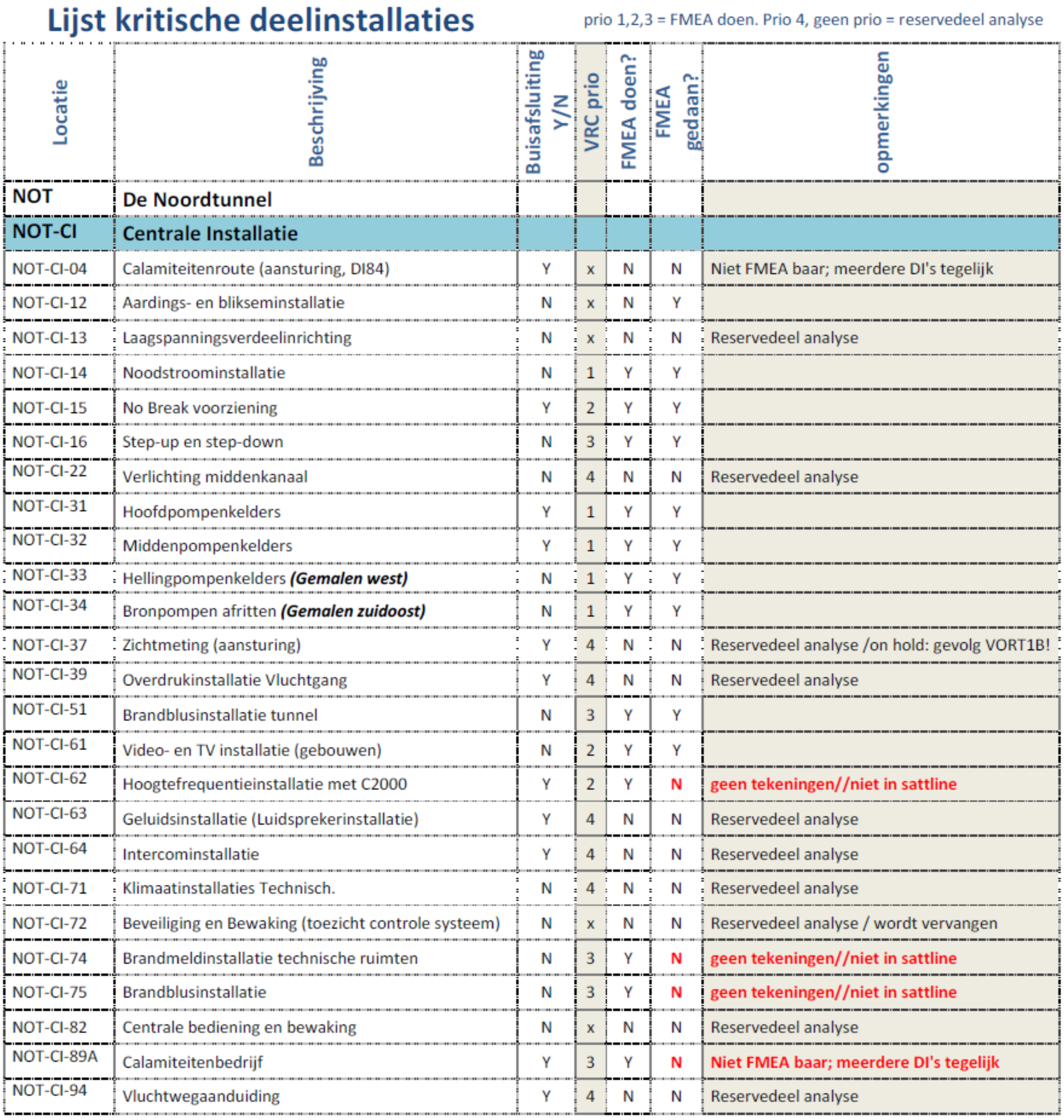
The FMECA was performed by Imtech Asset Solutions and led to results that can be found in the References (*Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel & Verbeterd onderhoudsconcept VOT2 NOORDTUNNEL*).

From the report of Imtech, a criticality analysis is used to determine the critical systems. These critical systems were determined by doing a quick FMECA where the main criteria was: 'if the system is directly related to traffic safety or fulfilling another safety feature, then the system is marked as critical.' The results from this criticality analysis were three lists of critical systems (general tunnel systems and tunnel tube specific systems - north & south -). Those lists are shown in the following figures A5.4 & A5.5: List of critical sub-systems (central/North tube). (Imtech, *Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel* p.16/17, 2013)

Based on the safety norms (VRC21 – *Veiligheidsrichtlijn deel C Hstk.21*) a recovery priority (1-4) is given to each critical system. A recovery priority of 1 means immediate intervention and 4 means that an intervention at the next routine maintenance moment will be sufficient. For this case study, recovery priorities of at least 1-3 are chosen.

From this data, 3 separate systems are chosen to be used during this first run of the case study to test the conceptual design of the decision-support method. Two of them are general tunnel sub-systems and the last one is a tube specific tunnel sub-system. The systems that were chosen are systems that are critical to either traffic safety or fulfilling a safety feature. The systems that are chosen for this first run of the case study are the following:

•	NOT-CI-14	Noodstroominstallatie	(Emergency Power Supply)	General
•	NOT-CI-31	Hoofdpompenkelders	(Main Pump Basements)	General
•	NOT-N-61	Video- en TV-installatie	(video and CCTV system)	North/South

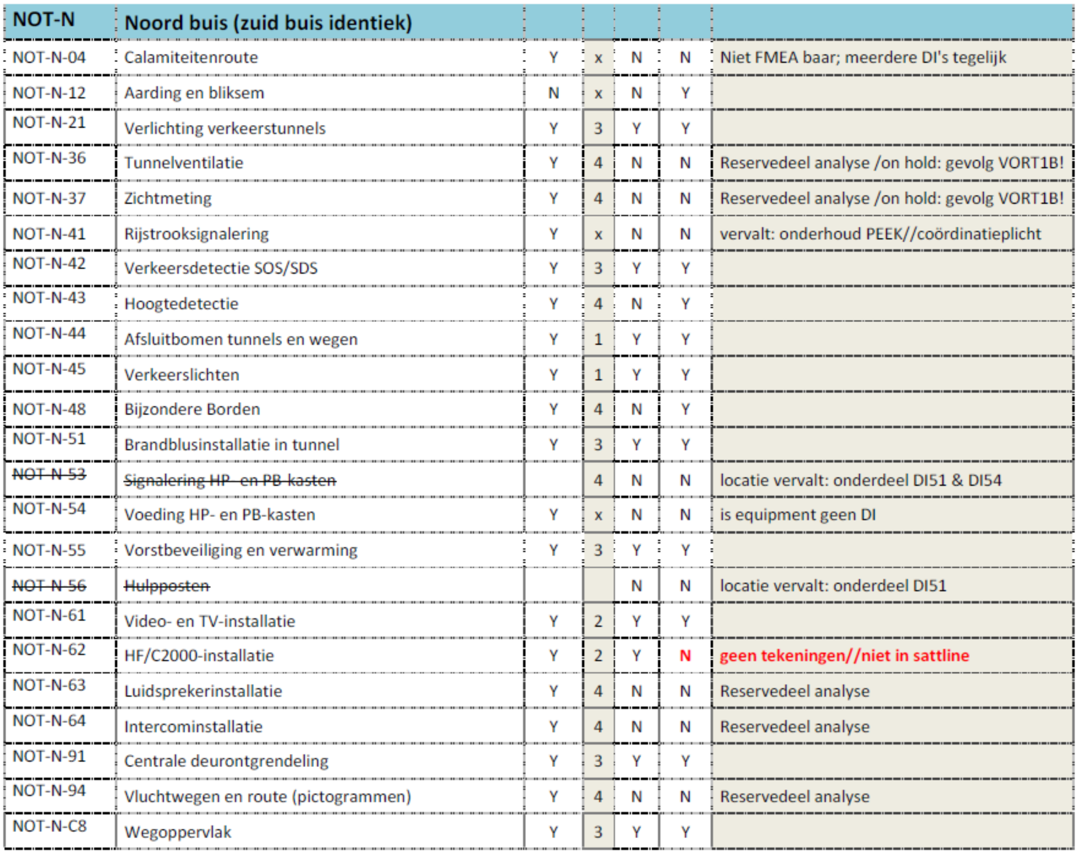


Lijst kritische deelinstallaties

prio 1,2,3 = FMEA doen. Prio 4, geen prio = reservedeel analyse

Locatie	Beschrijving	Buisafsluiting Y/N	VRC prio	FMEA doen?	FMEA gedaan?	opmerkingen
NOT	**De Noordtunnel**					
NOT-CI	**Centrale Installatie**					
NOT-CI-04	Calamiteitenroute (aansturing, DI84)	Y	x	N	N	Niet FMEA baar; meerdere DI's tegelijk
NOT-CI-12	Aardings- en bliksеminstallatie	N	x	N	Y	
NOT-CI-13	Laagspanningsverdeelinrichting	N	x	N	N	Reservedeel analyse
NOT-CI-14	Noodstroominstallatie	N	1	Y	Y	
NOT-CI-15	No Break voorziening	Y	2	Y	Y	
NOT-CI-16	Step-up en step-down	N	3	Y	Y	
NOT-CI-22	Verlichting middenkanaal	N	4	N	N	Reservedeel analyse
NOT-CI-31	Hoofdpompenkelders	Y	1	Y	Y	
NOT-CI-32	Middenpompenkelders	Y	1	Y	Y	
NOT-CI-33	Hellingpompenkelders ***(Gemalen west)***	N	1	Y	Y	
NOT-CI-34	Bronpompen afritten ***(Gemalen zuidoost)***	N	1	Y	Y	
NOT-CI-37	Zichtmeting (aansturing)	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-CI-39	Overdrukinstallatie Vluchtgang	Y	4	N	N	Reservedeel analyse
NOT-CI-51	Brandblusinstallatie tunnel	N	3	Y	Y	
NOT-CI-61	Video- en TV installatie (gebouwen)	N	2	Y	Y	
NOT-CI-62	Hoogtefrequentieinstallatie met C2000	Y	2	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-63	Geluidsinstallatie (Luidsprekerinstallatie)	Y	4	N	N	Reservedeel analyse
NOT-CI-64	Intercominstallatie	Y	4	N	N	Reservedeel analyse
NOT-CI-71	Klimaatinstallaties Technisch.	N	4	N	N	Reservedeel analyse
NOT-CI-72	Beveiliging en Bewaking (toezicht controle systeem)	N	x	N	N	Reservedeel analyse / wordt vervangen
NOT-CI-74	Brandmeldinstallatie technische ruimten	N	3	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-75	Brandblusinstallatie	N	3	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-82	Centrale bediening en bewaking	N	x	N	N	Reservedeel analyse
NOT-CI-89A	Calamiteitenbedrijf	Y	3	Y	**N**	**Niet FMEA baar; meerdere DI's tegelijk**
NOT-CI-94	Vluchtwegaanduiding	Y	4	N	N	Reservedeel analyse

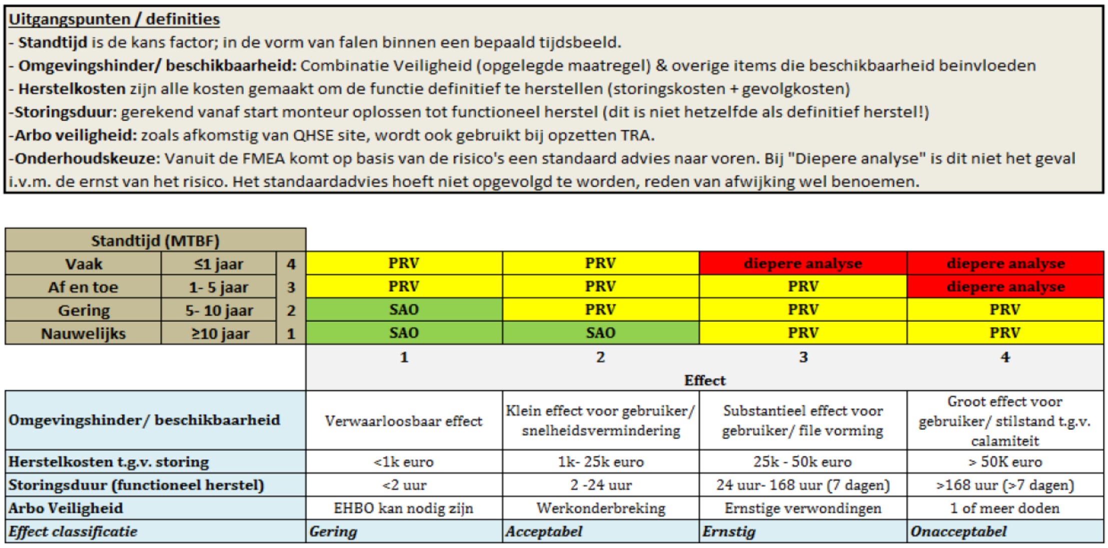
Figure A5.4: List of critical sub-systems (central tunnel systems) (Imtech, 2013)



NOT-N	Noord buis (zuid buis identiek)					
NOT-N-04	Calamiteitenroute	Y	x	N	N	Niet FMEA baar; meerdere DI's tegelijk
NOT-N-12	Aarding en bliksem	N	x	N	Y	
NOT-N-21	Verlichting verkeerstunnels	Y	3	Y	Y	
NOT-N-36	Tunnelventilatie	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-N-37	Zichtmeting	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-N-41	Rijstrooksignalering	Y	x	N	N	vervalt: onderhoud PEEK//coördinatieplicht
NOT-N-42	Verkeersdetectie SOS/SDS	Y	3	Y	Y	
NOT-N-43	Hoogtedetectie	Y	4	N	Y	
NOT-N-44	Afsluitbomen tunnels en wegen	Y	1	Y	Y	
NOT-N-45	Verkeerslichten	Y	1	Y	Y	
NOT-N-48	Bijzondere Borden	Y	4	N	Y	
NOT-N-51	Brandblusinstallatie in tunnel	Y	3	Y	Y	
~~NOT-N-53~~	~~Signalering HP- en PB-kasten~~		4	N	N	locatie vervalt: onderdeel DI51 & DI54
NOT-N-54	Voeding HP- en PB-kasten	Y	x	N	N	is equipment geen DI
NOT-N-55	Vorstbeveiliging en verwarming	Y	3	Y	Y	
~~NOT-N-56~~	~~Hulpposten~~			N	N	locatie vervalt: onderdeel DI51
NOT-N-61	Video- en TV-installatie	Y	2	Y	Y	
NOT-N-62	HF/C2000-installatie	Y	2	Y	N	geen tekeningen//niet in sattline
NOT-N-63	Luidsprekerinstallatie	Y	4	N	N	Reservedeel analyse
NOT-N-64	Intercominstallatie	Y	4	N	N	Reservedeel analyse
NOT-N-91	Centrale deurontgrendeling	Y	3	Y	Y	
NOT-N-94	Vluchtwegen en route (pictogrammen)	Y	4	N	N	Reservedeel analyse
NOT-N-C8	Wegoppervlak	Y	3	Y	Y	

Figure A5.5: List of critical sub-systems (North tube tunnels systems) (Imtech, 2013)

For correct and efficient use of the FMEA, the risk matrix is needed to interpret the different numbers that are used in the FMEA. The risk matrix can be found in the figure below (Figure A5.6) and is also originated from the document Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel p.18 (Imtech, 2013).



Uitgangspunten / definities
- **Standtijd** is de kans factor; in de vorm van falen binnen een bepaald tijdsbeeld.
- **Omgevingshinder/ beschikbaarheid:** Combinatie Veiligheid (opgelegde maatregel) & overige items die beschikbaarheid beinvloeden
- **Herstelkosten** zijn alle kosten gemaakt om de functie definitief te herstellen (storingskosten + gevolgkosten)
-**Storingsduur:** gerekend vanaf start monteur oplossen tot functioneel herstel (dit is niet hetzelfde als definitief herstel!)
-**Arbo veiligheid:** zoals afkomstig van QHSE site, wordt ook gebruikt bij opzetten TRA.
-**Onderhoudskeuze:** Vanuit de FMEA komt op basis van de risico's een standaard advies naar voren. Bij "Diepere analyse" is dit niet het geval i.v.m. de ernst van het risico. Het standaardadvies hoeft niet opgevolgd te worden, reden van afwijking wel benoemen.

Standtijd (MTBF)						
Vaak	**≤1 jaar**	**4**	**PRV**	**PRV**	**diepere analyse**	**diepere analyse**
Af en toe	**1- 5 jaar**	**3**	**PRV**	**PRV**	**PRV**	**diepere analyse**
Gering	**5- 10 jaar**	**2**	**SAO**	**PRV**	**PRV**	**PRV**
Nauwelijks	**≥10 jaar**	**1**	**SAO**	**SAO**	**PRV**	**PRV**
			1	**2**	**3**	**4**
			Effect			
Omgevingshinder/ beschikbaarheid			Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing			<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)			<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid			EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie			***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A5.6: Risk matrix (Imtech, 2013)

4. Remaining steps of the decision-support method per system

For the three (sub)-systems that were chosen to be evaluated during the first run of the case study, the remaining steps of the decision-support method will be executed. By choosing the three sub-systems during the previous section, step 1: determining a suitable size/scope is already been done. This will act as a starting point for the remaining steps 2 to 6. These are the 5 steps (2-6) as shown in chapter 3 of the main report and figure A5.3 of this case study document. The order of steps and layout will be the same for each of the three (Sub)-Systems.

4.1 Sub-system NOT-CI-14: Noodstroominstallatie (emergency power supply)

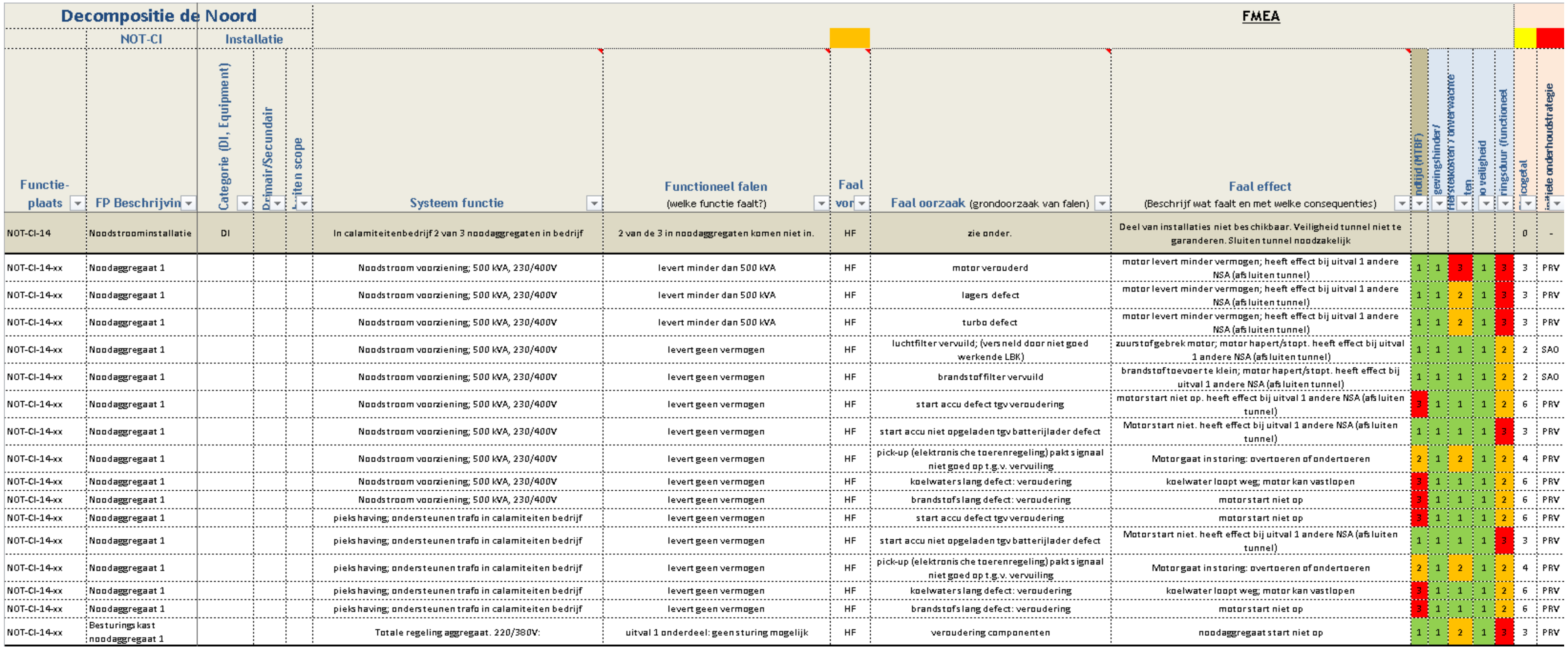
The emergency power supply is a sub-system of the main category power supply group. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the power supply can be found below.

Functional requirements:

- *(FE1301)* Both primary, redundant power grid connections and emergency power supplies need to be capable of delivering the required power supply under all operational circumstances.
- *(FE1502)* The no-break has to continue the power supply to system critical components automatically in case of failure of the primary power source. Functioning of the systems cannot stop during the transition.
- *(FE1403)* When the primary power supply fails, alternative power supplies need to take over automatically. Alternate power supplies can be redundant grid connections, emergency power supplies and no-breaks.
- *(FE1504)* The power supply for critical power users has to be able to be maintained for at least >60 minutes through the use of no-breaks after failure of the main power supply.
- *(FE1405)* Changing back from alternate power supplies to the main power supply has to happen in a controlled way and without loss of power.

Goal: Delivering electrical power supply for the tunnel systems when the primary source of power fails. The emergency power supply takes over from the main power supply with an intervention of the no-breaks to prevent loss of power during the transition.

The emergency power supply of the Noordtunnel consists of 3 separate emergency power generators of which at least 2 need to be active during an emergency. The generators engage when the other power supplies fail. The FMEA for all 3 generators are identical and can be found on the next page (figure A5.7).



Decompositie de Noord					FMEA											
	NOT-CI	Installatie														
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder/	Herstelkosten / onverwachte ten	o veiligheid	ringsduur (functioneel	icogetal	itiele onderhoudstrategie
NOT-CI-14	Noodstroominstallatie	DI			In calamiteitenbedrijf 2 van 3 noodaggregaten in bedrijf	2 van de 3 in noodaggregaten komen niet in.	HF	zie onder.	Deel van installaties niet beschikbaar. Veiligheid tunnel niet te garanderen. Sluiten tunnel noodzakelijk						0	-
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	motor verouderd	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	3	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	lagers defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	turbo defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	luchtfilter vervuild; (versneld door niet goed werkende LBK)	zuurstofgebrek motor; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstoffilter vervuild	brandstoftoevoer te klein; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Besturingskast noodaggregaat 1				Totale regeling aggregaat. 220/380V:	uitval 1 onderdeel: geen sturing mogelijk	HF	veroudering componenten	noodaggregaat start niet op	1	1	2	1	3	3	PRV

Figure A5.7: FMEA of the emergency power supply (Imtech, 2013)

Step 2: Risk allocation matrix

The next step is to use the risk allocation matrix of Brommet to get a first insight of the way of outsourcing that can be used. For the emergency power supply an FMECA was performed and using a risk matrix, the mean time between failure (MTBF) and the effects (hindrance/ repair costs/ downtime until functional repair/ safety) can be seen. The input of the risk matrix is translated to the model of Brommet and used to decide where individual components should be placed. The information comes from the performed FMECA and can be seen in the previously shown figure (figure A5.7).

The translations were done very basically by linking the corresponding number of severity of the risk matrix (figure A5.6) to certain points in the risk allocation matrix by Brommet. This delivered the following result (figure A5.8) and was used accordingly.

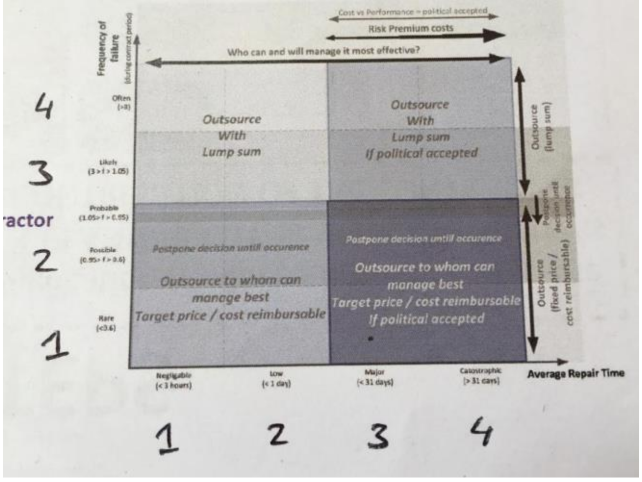


Figure A5.8: Altered risk allocation matrix for case study run 1 based on Brommet (2015)

The first approach uses the average MTBF of all components and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF:	1,86	(once every 5-10 years)
Average Downtime:	2,33	(< 1 day)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence.

When analyzing in further detail, it can be concluded that there is almost always a combination of high probability and low downtime, or low probability and high downtime. No extremes can be found (highest probability or highest downtime). This explains the averages that were found earlier. When decided to outsource the sub-system as a whole, the advice would be to go with the averages and choose to outsource in a cost reimbursable way and postpone the decision until occurrence. If the decision is made to outsource the components individually, the advice would be to outsource the components with an MTBF of 1 and 2 in a cost reimbursable way and postpone the decision until occurrence and outsource the components with an MTBF of 3 with lump sum and let the contractor decide when to replace certain components. The reasoning behind this is that it is that in the first case, the probability of something happening is relatively low, though still possible. Thus it is unrealistic to let the contractor take those costs into account at the start of the contract. In the latter case the probability is higher and it is more realistic that the contractor is able to deal with these occurrences themselves.

Step 3: Determine a suitable contribution of the contractor

The six-stage model continues where Brommet left off and gives even more insight on how to deal with predictability and plannability to provide an advice concerning the contribution of the contractor. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. Given that the MTBF intervals are relatively large, the predictability is not that good. 9/15 failure modes have a MTBF of 5-10 years or > 10 years, thus chances of it occurring within the contract period are not significant, but can still happen. The other 6 failure modes have a MTBF of 1-5 years and are likely to at least happen once or more during the contract period. The repairs and preventive measures however are somehow cost-efficient and can easily be integrated in the contract.

The advice here would be to make a cut and divide the contribution of the contractor (responsibility) for failure modes in two groups. The first group consists of 4 items of which the exact moment of failure are hard to predict, but have a high impact due to downtime and costs. For this group of failure modes, the contractor should solely perform tests, routine maintenance and report their findings to the contracting authority. Responsibility for repairs, revisions and replacements lies with the contracting authority. Specific items that are meant here are the revision of the engine, replacement of the bearings and the replacement of the turbo. The fourth item is the replacement of the emergency power supply in general, but given the remaining lifespan of 19 years, this is completely out of the question at this time. The contractor can only be held responsible for the effects of a failure (within this group) when they could reasonably have been expecting failure but neglected to report this to the contracting authority. If the upcoming failure was reported and the client didn’t act on it, the contractor is no longer responsible for the effects of that failure.

The second group consists of routine maintenance of the emergency power supply, the replacement of components and small repairs to ensure the functioning of the system. The measures are reasonably predictable and can, due to low costs, can also be planned. The contractor is responsible for the functioning of the system and is therefore accountable for the effects that occur when the system fails and the reason is traced back to a failure mode within this group of possible failures (not being the failures mentioned in the previous paragraph).

Step 4: Determine suitable performance requirements

For the emergency power supply are no measurable performance requirements available/set at this time. The system either works, or it doesn’t. When looking at the description of functional failure, the emergency power supply can fail in two ways: it doesn’t deliver the supposed 500kVa or it doesn’t deliver any power at all. This could be used as a performance requirement (the performance level).

An important aspect to consider here is that the emergency power supply is a passive system which is only active when called upon. This means that all failures are hidden until the system is active and the failure is revealed, by which time it is too late. The system should therefore be tested regularly and when tested, a certain threshold must at least be met to ensure adequate fulfillment of the function when called upon. This is especially important for the 500kVa requirement. The suggestion here is to keep the 500kVa as a top-requirement for the emergency power supply, but to use a different performance requirement for the contract(or) specifically.

At this time, the emergency power supply is maintained with a preventive maintenance strategy, using a pre-set amount of test-moments to inspect and test the functionality of the system. Historic data (RWS: Historisch overzicht storingen 2009-2014) shows that the reasons for malfunctioning of the system are non-related to the failure modes that were mentioned in the FMECA. The test-intervals are therefore adequate and the routine maintenance (including small repairs and regular replacement of weaker components) are sufficient to maintain the functioning of the system.

The suggestion for the level of outsourcing is as follows:

The top-requirement is that the emergency power supply needs to deliver at least 500 kVa when called upon. This is the minimum performance level. This requirement however is not the requirement that is solely the responsibility of the contractor. The contractor has to notify the CA when they expect the performance level to be under the threshold before the next test. Therefore there is a shared responsibility for this requirement.

For the routine maintenance tasks RWS can, based on the historic data and the positive results about the current maintenance strategy and test intervals, prescribe the amount of test moments and the maximum time between the intervals (based on the lowest MTBF of the components). When RWS wishes to continue this trend, they can prescribe the test intervals, but also at which interval certain components need to be replaced. Then this is a work instruction.

The other option is to leave the responsibility with the contractor and ask for a level of intervention. In that case it is still possible to prescribe a minimum amount of test moments and even prescribe a maximum interval between those test moments, but the contractor decides when they perform the tests. Hence, the performance requirement is the functionality of the emergency power supply. When the emergency power supply is turned on, it should deliver power and none of the failure modes which result in a situation where no power is delivered can happen. This is a *level of intervention*. More responsibility lies with the contractor, but they also get more freedom in when and how to replace the worn-out parts of the system. The eventual choice depends on the ambition/strategy of the contracting authority.

Step 5 Cross-check

The compatibility check is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

Given that the cut is made between the 3 unpredictable components and the more predictable routine maintenance components, the following can be said. The less predictable components have low contribution from the contractor and therefore share responsibility with the contractor. The top-requirement is a performance level, but essentially the actual requirement for the contractor is a work instruction, instructing the contractor when to check, what to check and a request to inform the contracting authority when the performance level is not going to be achieved before the next test.

The components for which was decided are more predictable were set to have a high contribution of the contractor. This is correct when the performance requirements are based on the level of intervention and the contractor has the authority to decide when and how to intervene, as long as the system functions. When the decision is made to prescribe the test intervals and when certain components need to be replaced, the performance requirement is a work instruction and the contribution of the contractor should be changed to low. In that case, more responsibility will stay with contracting authority and less risk will remain for the contractor.

Step 6: Proposed solution

<table>
<tr><td>Size/Scope</td><td>Entire system divided in two parts based on predictability of failure modes</td></tr>
<tr><td colspan="2">Based on the predictability and the effects of certain failure modes that can be derived from the FMEA made for the emergency power supply, the advice would be to divide the scope in two groups and approach these groups separately. The first group consists of unpredictable failure modes with high impact. The second group consists of reasonably predictable failure modes with low impact.</td></tr>
<tr><td>Contribution of the contractor</td><td>Low (Unpredictable) & High (Predictable)</td></tr>
<tr><td colspan="2">For the unpredictable failure modes, the contribution of the contractor will be low. The contractor is responsible for simple routine maintenance and responsible for testing the system and informing the contracting authority about the current status of the system. When the system performance fall beneath a certain threshold, the contractor should inform the contracting authority that an intervention is advised, but the ultimate decision is for the contracting authority.

For the predictable failure modes, the contribution of the contractor will be high. The contractor is responsible for testing the system and performing all necessary interventions (repairs) to ensure that the system works. The contractor gets the freedom to decide (within the set maximums intervals) when the tests are performed and what interventions are done. The responsibility for the effects of failure caused by these predictable failure modes is for the contractor.</td></tr>
<tr><td>Performance Requirement</td><td>Work Instructions (Unpredictable) & Level of Intervention (Predictable)</td></tr>
<tr><td colspan="2">For the unpredictable failure modes for which a low contribution for the contractor is suggested, the performance requirements should be formulated as a work instruction. This is in line with the low contribution for the contractor that is chosen. Furthermore, the contracting authority can prescribe the maintenance which has proven successful during the last couple of years and keeps the possibility to steer things when the current maintenance regime proves to be insufficient.

For the predictable failure modes for which a high contribution for the contractor is suggested, the performance requirements should be formulated as a level of intervention. This is in line with the high contribution for the contractor that is chosen. The contractor has the responsibility to keep the performance of the system at a certain level (the system has to function when requested) and have the freedom to decide how, when and what maintenance interventions are necessary to comply to that requirement.</td></tr>
</table>

4.2 Sub-system NOT-Cl-31: Hoofdpompkelder (main pump basement)

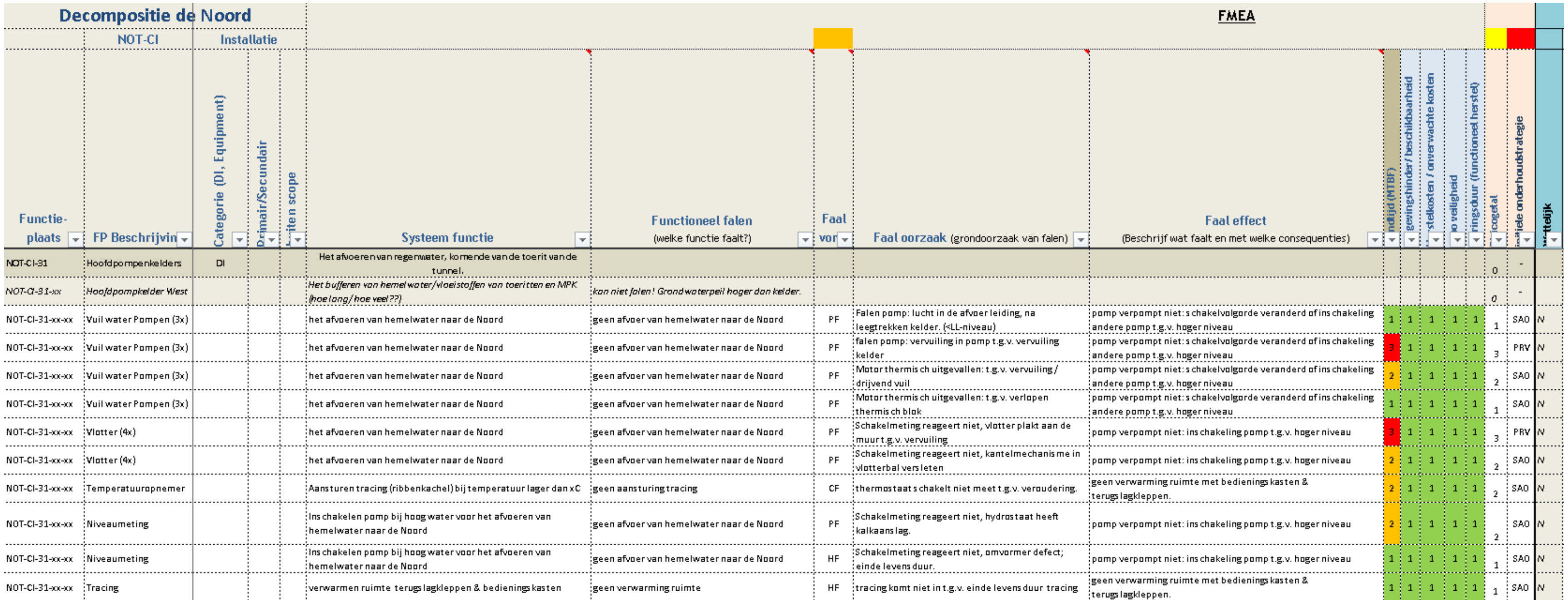
The main pump basement is a sub-system of the main category water drainage and ventilation systems group. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the power supply can be found below.

Functional requirements:

- *(FE3101)* There has to be a pump capacity of 2m^3 per minute.
- *(FE3102)* Water should be able to flow into the liquid basement
- *(FE3103)* The middle basement should have a minimal net capacity of 30m^3.
- *(FE3104)* In case of an Emergency state in the tunnel, the pump system should automatically start to stow away the water.

Goal: The main pump basement, including the pumps have to keep the water from accumulating op the road in the tunnel and in the basement. The basement is in place to collect the water that is drained from the tunnel road surface. The pumps eliminate the water out of the (storage) basements.

The main pump basement consists of two basements, one on the south west and one on the east side. Both basements have 3 pumps. Because both basements are identical and the failure modes are the same, for this example only one basement is checked. The FMEA for the west main pump basement can be found on the next page (Figure A5.9).



Decompositie de Noord					FMEA												
	NOT-CI	Installatie															
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder/ beschikbaarheid	stelkosten / onverwachte kosten	o veiligheid	ringsduur (functioneel herstel)	icogetal	iele onderhoudstrategie	ttelijk
NOT-CI-31	Hoofdpompenkelders	DI			Het afvoeren van regenwater, komende van de toerit van de tunnel.										0	-	
NOT-CI-31-xx	*Hoofdpompkelder West*				*Het bufferen van hemelwater/vloeistoffen van toeritten en MPK (hoe lang/ hoe veel??)*	*kan niet falen! Grondwaterpeil hoger dan kelder.*									*0*	-	
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Falen pomp: lucht in de afvoer leiding, na leegtrekken kelder. (<LL-niveau)	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	N
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	falen pomp: vervuiling in pomp t.g.v. vervuiling kelder	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	3	1	1	1	1	3	PRV	N
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Motor thermisch uitgevallen: t.g.v. vervuiling / drijvend vuil	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	N
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Motor thermisch uitgevallen: t.g.v. verlopen thermisch blok	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	N
NOT-CI-31-xx-xx	Vlotter (4x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, vlotter plakt aan de muur t.g.v. vervuiling	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	3	1	1	1	1	3	PRV	N
NOT-CI-31-xx-xx	Vlotter (4x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, kantelmechanisme in vlotterbal versleten	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	N
NOT-CI-31-xx-xx	Temperatuuropnemer				Aansturen tracing (ribbenkachel) bij temperatuur lager dan xC	geen aansturing tracing	CF	thermostaat schakelt niet meet t.g.v. veroudering.	geen verwarming ruimte met bedieningskasten & terugslagkleppen.	2	1	1	1	1	2	SAO	N
NOT-CI-31-xx-xx	Niveaumeting				Inschakelen pomp bij hoog water voor het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, hydrostaat heeft kalkaanslag.	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	N
NOT-CI-31-xx-xx	Niveaumeting				Inschakelen pomp bij hoog water voor het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	HF	Schakelmeting reageert niet, omvormer defect; einde levensduur.	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	N
NOT-CI-31-xx-xx	Tracing				verwarmen ruimte terugslagkleppen & bedieningskasten	geen verwarming ruimte	HF	tracing komt niet in t.g.v. einde levensduur tracing	geen verwarming ruimte met bedieningskasten & terugslagkleppen.	1	1	1	1	1	1	SAO	N

Figure A5.9: FMEA of the main pump basement (Imtech, 2013)

Step 2: Risk Allocation matrix

The next step is to use the risk allocation matrix of Brommet to get a first insight of the way of outsourcing that can be used. For the main pump basement an FMECA was performed and by using a risk matrix, the mean time between failure (MTBF) and the effects (hindrance/ repair costs/ downtime until functional repair/ safety) can be seen. The input of the risk matrix is translated to the matrix of Brommet and used to decide where individual components should be placed within the matrix (see figure A5.8). The information comes from the performed FMECA and can be seen in the previously shown figure (figure A5.9). For this analysis, the simplified transition of the matrix by Brommet is used again. This has to be improved for the second run of the case study to improve the results that this step provides to the decision-support method.

The first approach uses the average MTBF of all components and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF: 1,8 (once every 5-10 years)
Average Downtime: 1 (< 2 hours)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence.

When analyzing in further detail, it can be concluded that the effect of failure is always low, therefore all failure can be found on the left side of the model. Downtime is low, costs of repairs are low and the hindrance for the users is negligible. Because of uncertainty about the MTBF however, most are failures can be found in the lower left corner with the advice to postpone the decision about repairs until occurrence. Two failure modes are found in the upper left corner, with an MTBF of 1-5 years, and a higher likelihood of happening during the contract period (5 years). For these failure modes it is advised to put them in the contract on a lump sum based way.

It should be noted that based on the data in the risk dossier, all failures have low impact, can be prevented or solved at low cost and no hindrance for the users of the tunnel. Thus, although failure modes are unpredictable, the preventive maintenance measures can be planned to prevent the failures altogether. And if in the worst case a failure might occur, the effects are very limited, thus low risk for the contractor.

Step 3: Determine a suitable contribution of the contractor

The six-stage model continues where Brommet left off and gives even more insight on how to deal with predictability and plannability and will provide and advice concerning the contribution of the contractor. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. The MTBF intervals are quite clear for this system. There are 8 failure modes that are not so likely to occur during the contract period (MTBF 5-10 years and >10 years) and 2 failure modes that are likely to occur at least once during the contract period (MTBF of 1-5 years). The effects when occurring are really low and have no direct impact on the functioning of the tunnel. The problems can be solved fast and at low costs.

With that being said, the failures are reasonably predictable and the maintenance measures (routine maintenance) can be planned in such a way that the chances of failure can be kept relatively low at low costs. Backed by the fact that the effects of failure are also not significant, it is safe enough to give the contract high contribution for the maintenance of this system. They will have the freedom to plan the maintenance moments and are free to perform the necessary repairs and replacements that seem fit to ensure the functioning of the main pump basement.

The only thing that is left out here is the replacement of the pumps. The risk dossier states that the expected lifetime of the pumps reaches at least 2028 and it is therefore not necessary to include this in the contract. If the contractor, for any reason thinks that the pumps need to be replaced earlier, they are obliged to report this to the contracting authority who will then take a final decision.

Step 4: Determine suitable performance requirements

For the main pump basement performance requirements are in place. The system functions when 2m^3 of water can be pumped out of the basement. If this requirement is not met, the main pump basement fails its requirements. Furthermore, no puddles should form in the tunnel (due to insufficient storage or lack of pump capacity). The last requirement is the ability to store at least 30m^3 of water. The last one in combined with the in-ability to pump away the water is also a failure of the system.

The main pump basement is an active system with measurable performance requirements. The puddles can be seen and the cause can be traced. The pump capacity can be tested and measured in order to see if the contractor is in compliance with the set requirements.

The suggested level of the performance requirements is a performance level. The contractor should make sure that the required amount of water can be pumped away at all times and should do everything within their ability to make sure no puddles arise in the tunnel due to failures within the main pump basement.

Step 5: Cross-check

The compatibility check is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

For the contribution of the contractor is chosen for a full responsibility for the contractor. The contractor is free in deciding about the maintenance regime the desired maintenance interventions. The contractor is able to do everything in its power to achieve the requested performance requirements. This is in line with the suggestion to use performance levels as a performance requirement for the contractor. The contractor can receive punishment when the performance levels are not met because they are free take every measure to prevent that from happening without interference from the contracting authority. The proposed solution is therefore seen realistic from a compatibility standpoint.

Step 6: Proposed solution

Size/Scope	The main pump basement as one system
Because both the effects of failure and the risk of them happening are relatively low, and the maintenance regime can be planned in a predictable way, the choice was made to outsource the main pump basement as a whole.	
Contribution of the Contractor	High Contribution of the Contractor
Most of the failure modes will not occur during the contact period and the failure that have a higher probability of occurring can be mitigated with small (cheap) routine maintenance measures. The effects when a risk fires are almost negligible, thus a low risk job for the contractor where full responsibility and thus high contribution of the contractor can be expected.	
Performance Requirement	Performance Level
For the main pump basement, measurable performance requirements are available and the requesting the contractor to achieve these performance requirements is seen as acceptable with the amount of contribution of the contactor that was decided before. Therefore, the performance requirements are formulated as performance levels of which the contractor bears the responsibility of upholding those performance levels.	

4.3 Sub-system NOT-N-61: Video and CCTV system (north and south identical)

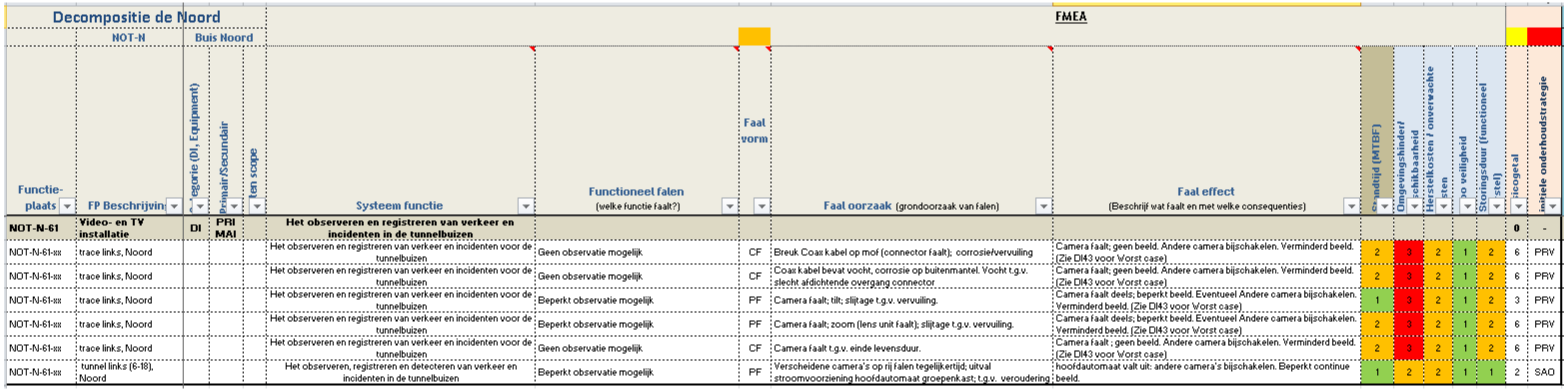
The video and CCTV system is a sub-system of the main category general communication system. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the general communications systems can be found below.

Functional requirements:

- *(FE6101)* A vehicle needs to be visible on overlapping CCTV footage for the entire length of the tunnel.
- *(FE6102)* When opening an emergency box, taking a fire extinguisher or using an emergency telephone should automatically open a visual camera feed of that event on the operators screen.
- *(FE6103)* Vehicles driving too slow or against the flow of traffic should be detected and should automatically open a visual camera feed of that event on the operators screen.
- *(FE6104)* The PTZ cameras should react to the input given by the operator in the control room (movement).

Goal: The CCTV system provides the operators in the control room with a live feed of the situation in the tunnel. The feed provides information that can be used by the operators to monitor and steer the flow of traffic or take preventive or mitigating measures in case of an incident in the tunnel.

The CCTV system consists of moving and non-moving cameras throughout both tunnel tubes. The cameras are connected to the control room, from which the entire tunnel can be monitored. The system fails when the identification of a vehicle throughout the entire length of the tunnel is no longer possible without interruption. The FMECA for both the northern and the southern tube are the same, thus only one will be taken into account during the decision process and will be the same for the other. The FMECA for the northern tube CCTV system can be found on the next page (Figure A5.10).



Decompositie de Noord									FMEA							
	NOT-N	Buis Noord														
Functie-plaats	FP Beschrijvin	egorie (DI, Equipment)	Primair/Secundair	ten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vorm	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	Omgevingshinder/ schikbaarheid	Herstelkosten / onverwachte sten	o veiligheid	Storingsduur (functioneel stel)	icogetal	initiele onderhoudstrategie
NOT-N-61	**Video- en TV installatie**	**DI**	**PRI MAI**		**Het observeren en registreren van verkeer en incidenten in de tunnelbuizen**										**0**	-
NOT-N-61-xx	trace links, Noord				Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen	Geen observatie mogelijk	CF	Breuk Coax kabel op mof (connector faalt); corrosie/vervuiling	Camera faalt; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)	2	3	2	1	2	6	PRV
NOT-N-61-xx	trace links, Noord				Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen	Geen observatie mogelijk	CF	Coax kabel bevat vocht, corrosie op buitenmantel. Vocht t.g.v. slecht afdichtende overgang connector	Camera faalt; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)	2	3	2	1	2	6	PRV
NOT-N-61-xx	trace links, Noord				Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen	Beperkt observatie mogelijk	PF	Camera faalt; tilt; slijtage t.g.v. vervuiling.	Camera faalt deels; beperkt beeld. Eventueel Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)	1	3	2	1	2	3	PRV
NOT-N-61-xx	trace links, Noord				Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen	Beperkt observatie mogelijk	PF	Camera faalt; zoom (lens unit faalt); slijtage t.g.v. vervuiling.	Camera faalt deels; beperkt beeld. Eventueel Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)	2	3	2	1	2	6	PRV
NOT-N-61-xx	trace links, Noord				Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen	Geen observatie mogelijk	CF	Camera faalt t.g.v. einde levensduur.	Camera faalt ; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)	2	3	2	1	2	6	PRV
NOT-N-61-xx	tunnel links (6-18), Noord				Het observeren, registreren en detecteren van verkeer en incidenten in de tunnelbuizen	Beperkt observatie mogelijk	PF	Verscheidene camera's op rij falen tegelijkertijd; uitval stroomvoorziening hoofdautomaat groepenkast; t.g.v. veroudering	hoofdautomaat valt uit: andere camera's bijschakelen. Beperkt continue beeld.	1	2	2	1	1	2	SAO

Figure A5.10: FMEA of the video and CCTV system (Imtech, 2013)

Step 2: Risk allocation matrix

The next step is to use the risk allocation matrix of Brommet to get a first insight of the way of outsourcing that can be used. For the video and CCTV system an FMECA was performed and by using a risk matrix, the mean time between failure (MTBF) and the effects (hindrance/ repair costs/ downtime till functional repair/ safety) can be seen. The input of the risk matrix is translated to the model of Brommet and used to decide where individual components should be placed within the model (see figure A5.8). The information comes from the performed FMECA and can be seen in the previously shown figure (figure A5.10). For this analysis, the simplified transition of the matrix by Brommet is used again. This has to be improved for the second run of the case study to improve the results that this step provides to the decision-support method.

The first approach uses the average MTBF of all components and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF: 1,667 (once every 5-10 years)
Average Downtime: 1,833 (2-24 hours)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence. But this is only when just MTBF and downtime are taken into consideration. The hindrance averages around 2.83, which is a significant effect for the user and high probability of traffic jams. This will influence the maintenance regime, because this has to prevented if possible. This will also be further discussed within the six-stage model and the performance requirements.

Based on Brommet, the advice is to postpone the decision to intervene until more certainty can be provided. This can be done in a cost-reimbursable way. Whether this will hold depends on the outcomes of the six-stage model and the performance requirements.

Step 3: Determine a suitable contribution of the contractor

The six-stage model continues where Brommet left off and gives even more insight on how to deal with predictability and plannability and will provide and advice concerning the contribution of the contractor. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. The MTBF intervals are quite clear for this system. All of the 6 failure modes that are not so likely to occur during the contract period (MTBF 5-10 years and >10 years).

The effects that failure modes have when occurring however need to be looked at in some more detail. The costs and the downtime are manageable and can be found in de lower left corner of Brommet, meaning that effects are acceptable. The hindrance however has a severe impact on the functioning of the tunnel and needs to be avoided if possible.

Given that the impact is very unwanted, the FMEA suggests preventive maintenance on all but one of the possible failure modes. This makes the maintenance of this system both predictable and plannable, given the MTBFs that are available and the routine maintenance jobs that are proposed to prevent the failures from happening. With this in mind it becomes easy for the contractor to predict what to expect for the duration of the contract period and will therefore be able to provide a high contribution to the maintenance work.

Final decisions concerning replacements of whole cameras with new ones stays within the contracting authority due to rapid developments in techniques. Given that most of the cameras have already been replaced in 2011, this is not an issue for this contracting period. If cameras should fail during the current contract period and can't be repaired, they are replaced with available spare cameras of the same type. This is not seen as the kind of replacement as mentioned above, therefore the contractor is free to do so. If the spare camera is not available, the contractor should ask the contracting authority whether a new replacement camera should be acquired and what kind of camera that should be.

The advice therefore is high contribution for the contractor with the exception of the replacement decision.

Step 4: Determine suitable performance requirements

For the video and CCTV systems are general functional requirements available. The most crucial being that a vehicle needs to be visible on overlapping CCTV footage for the entire length of the tunnel. This is however not a performance requirement that is given to the contractor. According to the risk dossier, the performance requirements for this system are not yet available. When looking at the system there is no clear and measurable data, other than the system fulfilling its functional requirement or not. Essentially, the minimum requirement is whether the camera provides feed to the control room or fails to do so.

Because this system is paramount for monitoring events in the tunnel and therefore ensuring the safety in the tunnel, failure of the entire system or a part of the system should be prevented. The performance requirements should therefore be high enough to ensure that the system works properly all the time. The main requirement should therefore be that the cameras work. The exact way that this requirement is formulated should be dependent on the situation. If redundant cameras are in place a requirement could state that certain cameras may not fail simultaneously, and in case of failure state a maximum repair time.

The suggestion is to use levels of intervention as a performance requirement. The requirement should be a minimum amount of working cameras with a list of cameras that cannot fail simultaneously and a maximum downtime in case of failure.

Step 5: Cross-check

The compatibility check is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

For the contribution of the contractor is chosen for a full responsibility for the contractor. The contractor is free in the choices about the maintenance regime the desired maintenance interventions. The contractor is able to do everything in its power to achieve the requested performance requirements. This is in line with the suggestion to use levels of intervention as a performance requirement for the contractor. The contractor has no control over replacements of cameras with newer cameras unless this is cleared with the contracting authority first. This however does not affect the ability of the contractor to achieve the requirements. If the contractor thinks that the requirements cannot be met with the current system (due to age or a technical malfunction) this can be brought to the attention of the contracting authority. The CA can then decide how to proceed. The contractor is then no longer responsible for failure caused by problems he warned them for. The contractor can receive punishment when the performance levels are not met because they are free to take every measure to prevent that from happening without interference from the contracting authority (with the exception of replacement with newer models).

The proposed solution is therefore seen realistic from a compatibility standpoint.

Step 6: Proposed solution

<table>
<tr><td>Size/Scope</td><td>Video and CCTV as one system</td></tr>
<tr><td colspan="2">Because the system can be maintained with a very predictable maintenance plan, the regime can be planned in advance and most of the components can be approached in the same way the suggestion is to outsource the video and CCTV system as one piece.</td></tr>
<tr><td>Contribution of the Contractor</td><td>High Contribution of the Contractor</td></tr>
<tr><td colspan="2">The failure modes of the video and CCTV system have a high MTBF, meaning that the chances of failure during the contract period are relatively low. The average downtime and the cost for repairs are also not really high. The only thing that scores badly is the hindrance for the end users (both operators and traffic in the tunnel) in case of failure. This is why preventive maintenance for most of the components is advised. This makes the maintenance regime plannable and the work of the maintenance contractor predictable and the risks are relatively low. This is why a high contribution of the contractor is suggested.</td></tr>
<tr><td>Performance Requirement</td><td>Levels of intervention</td></tr>
<tr><td colspan="2">For the video and CCTV system, no clear measurable performance requirements are available. Therefore, performance levels are hard to use. That’s why one level down, the levels of intervention are chosen as the suggested form of outsourcing. These performance requirements can be formulated in a more general way and still stay in line with the high contribution of the contractor that was suggested.</td></tr>
</table>

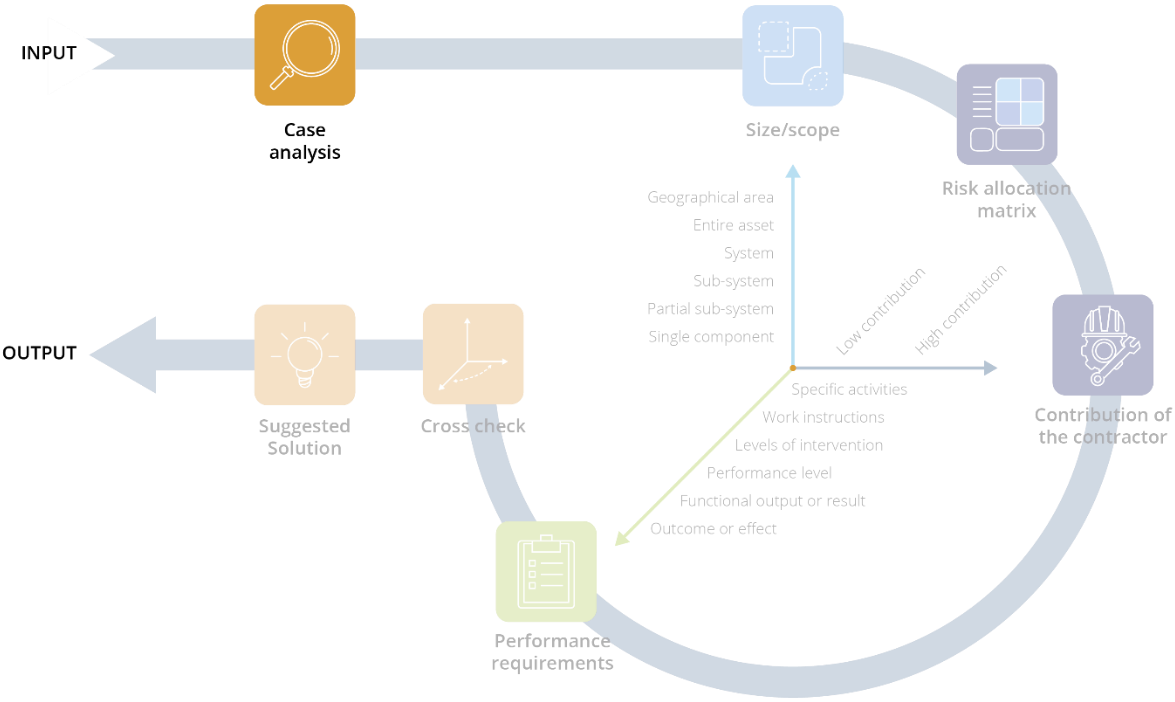
Appendix 6

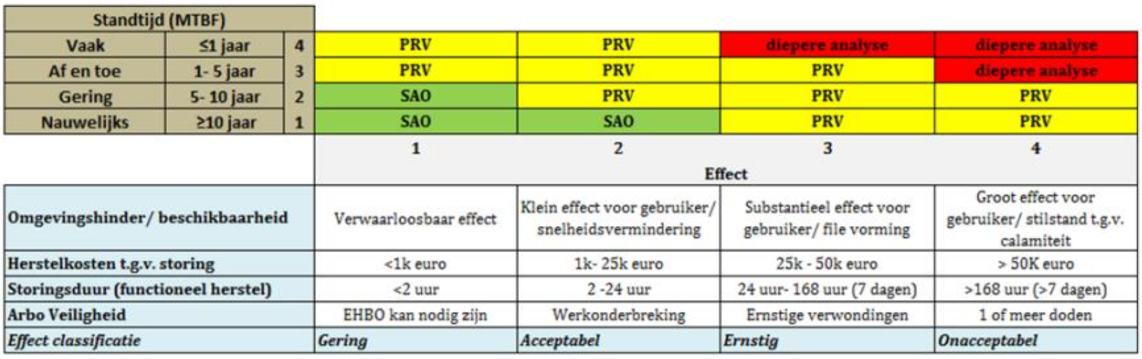
Figures corresponding to the improved decision-support method after run 1

Appendix 6: Figures corresponding to the improved decision-support method after run 1

After the first run of the case study a few improvements have been made to the original design of the decision-support method. In this appendix the tables and graphs corresponding to the improved steps of the decision-support method are presented.

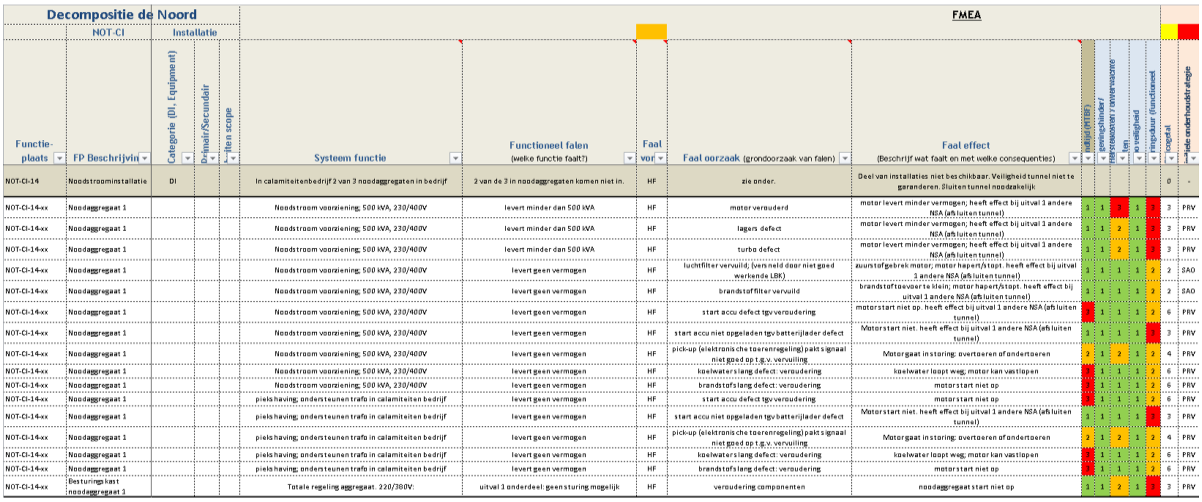
Step1: Case analysis





Standtijd (MTBF)						
Vaak	≤1 jaar	4	PRV	PRV	diepere analyse	diepere analyse
Af en toe	1- 5 jaar	3	PRV	PRV	PRV	diepere analyse
Gering	5- 10 jaar	2	SAO	PRV	PRV	PRV
Nauwelijks	≥10 jaar	1	SAO	SAO	PRV	PRV
			1	2	3	4
			Effect			

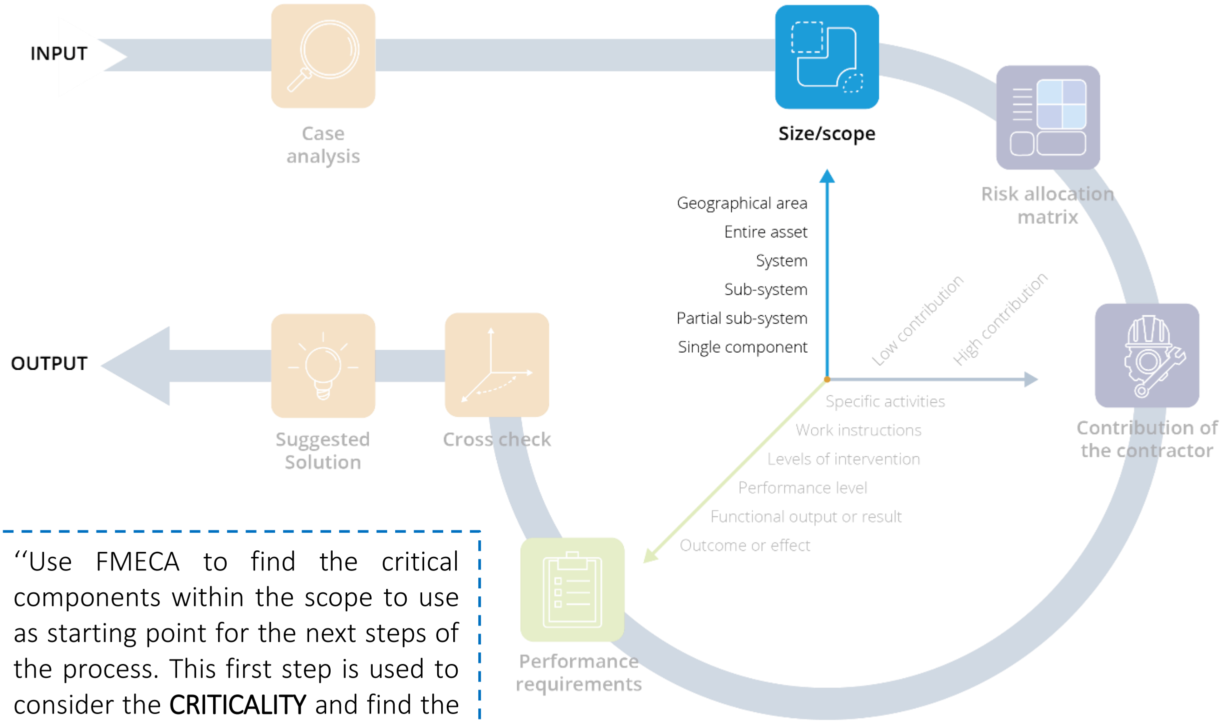
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)	<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***



Decompositie de Noord					FMEA												
	NOT-CI	Installatie															
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	rimair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder/	Herstelkosten / onverwachte	ten	o veiligheid	ringsduur (functioneel	icogetal	iele onderhoudstrategie
NOT-CI-14	Noodstroominstallatie	DI			In calamiteitenbedrijf 2 van 3 noodaggregaten in bedrijf	2 van de 3 in noodaggregaten komen niet in.	HF	zie onder.	Deel van installaties niet beschikbaar. Veiligheid tunnel niet te garanderen. Sluiten tunnel noodzakelijk							0	-
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	motor verouderd	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	3	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	lagers defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	turbo defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	luchtfilter vervuild; (versneld door niet goed werkende LBK)	zuurstofgebrek motor; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstoffilter vervuild	brandstoftoevoer te klein; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Besturingskast noodaggregaat 1				Totale regeling aggregaat. 220/380V:	uitval 1 onderdeel: geen sturing mogelijk	HF	veroudering componenten	noodaggregaat start niet op	1	1	2	1	3	3	PRV

Figure A6.1: Conceptual design of the decision-support method: step 1 (risk matrix + risk register) (Imtech, 2013)

Step 2: Size and scope



''Use FMECA to find the critical components within the scope to use as starting point for the next steps of the process. This first step is used to consider the **CRITICALITY** and find the right **SIZE/SCOPE** for each part to continue.''

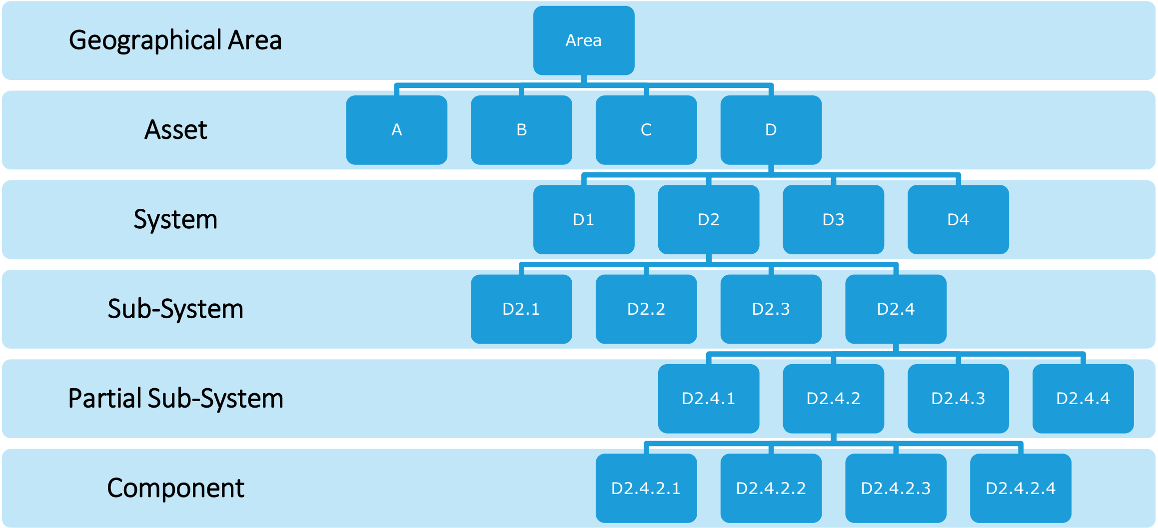
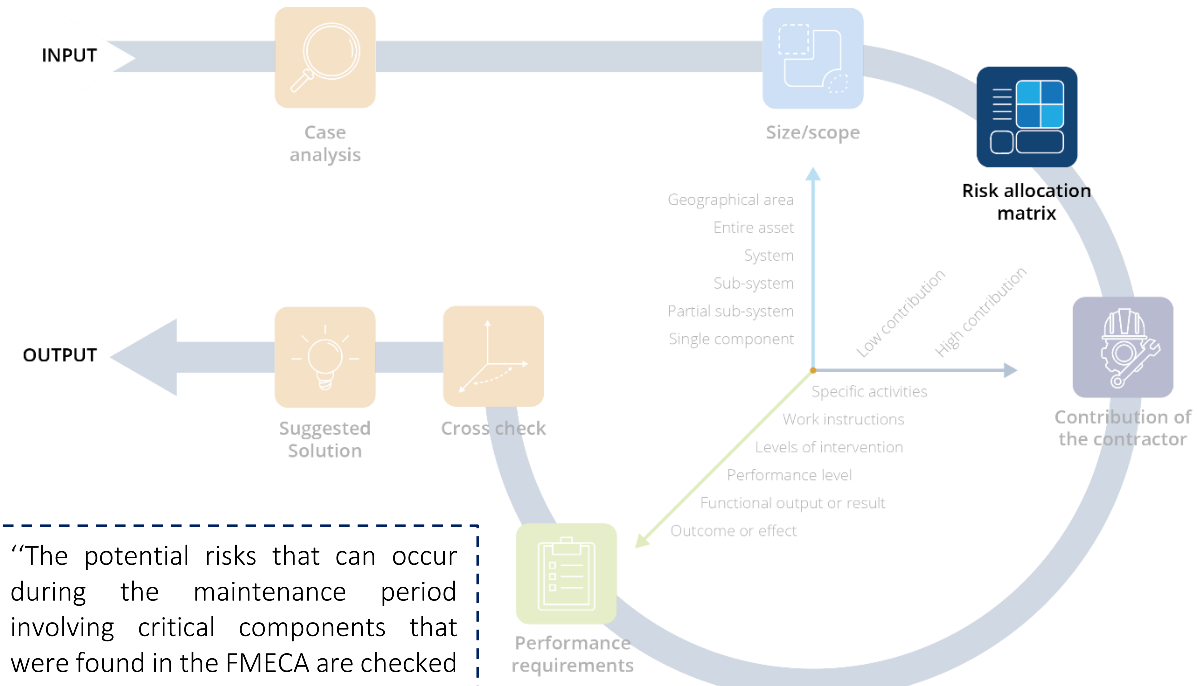


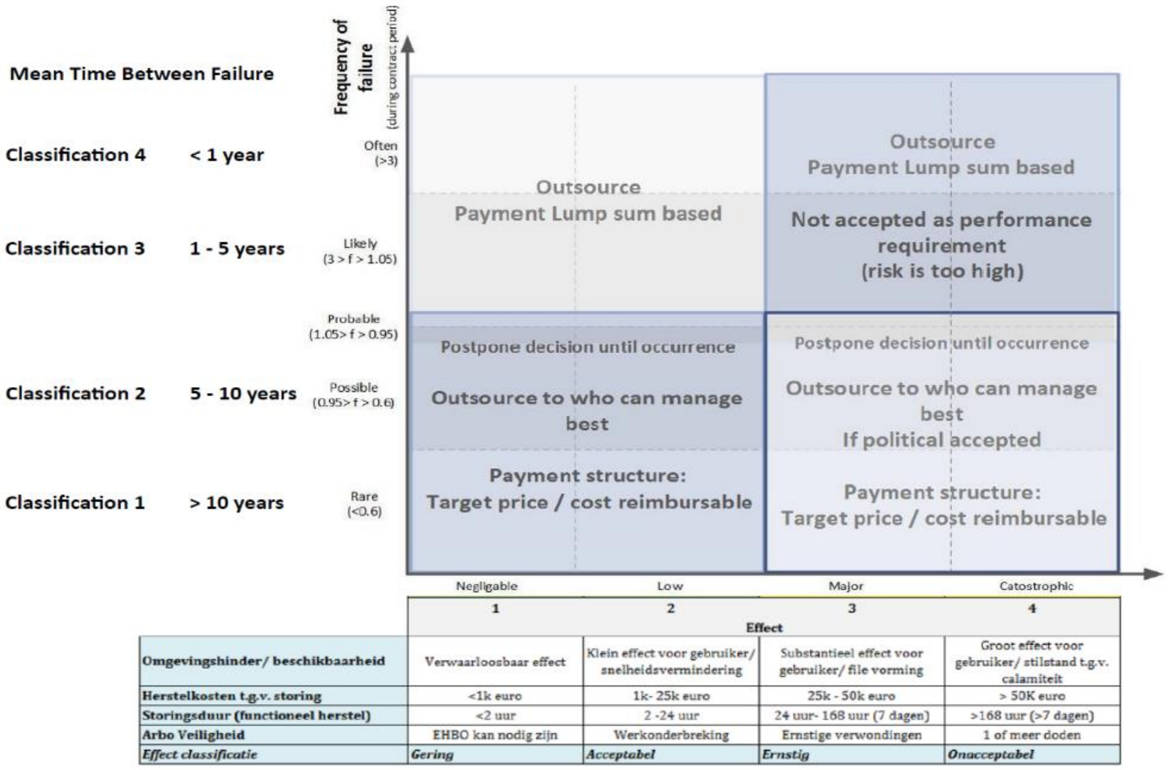
Figure A6.2: Conceptual design of the decision-support method: step 2

Step 3: Risk allocation matrix



> ‘‘The potential risks that can occur during the maintenance period involving critical components that were found in the FMECA are checked for their PREDICTABILITY & PLANNABILITY using the model by Brommet.’’

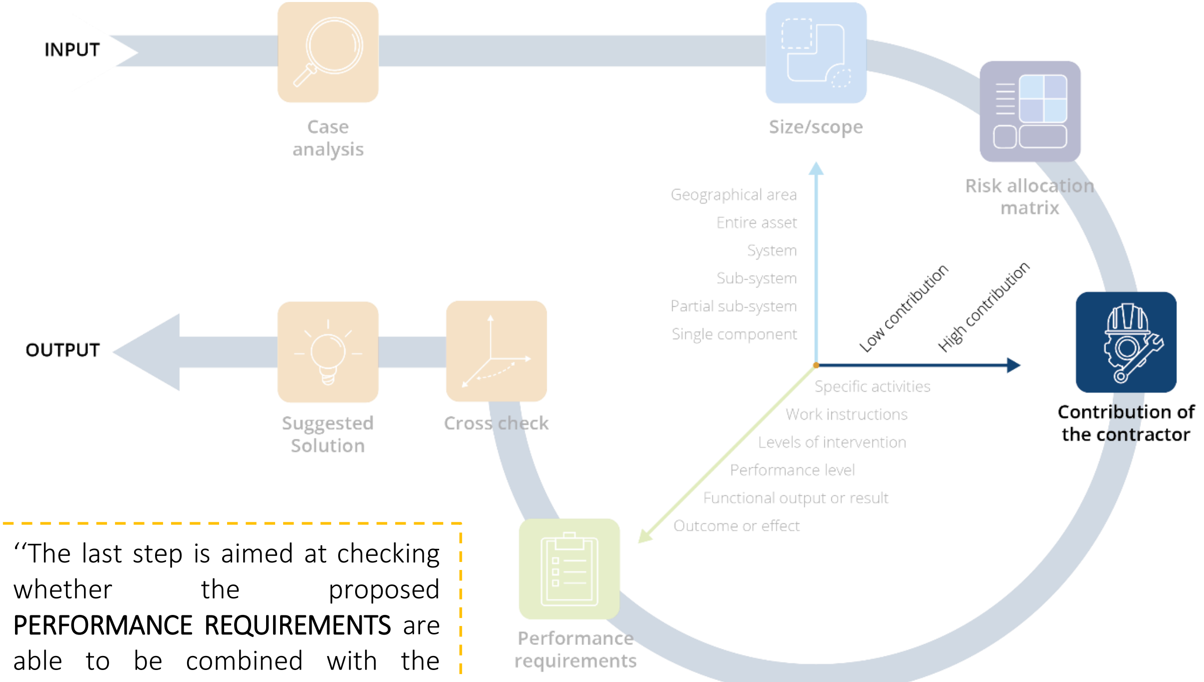
Figure A6.3: Conceptual design of the decision-support method: step 3



	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)	<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A6.4: Altered risk allocation matrix based on Brommet (2015)

Step 4: Contribution of the contractor



> ‘’The last step is aimed at checking whether the proposed **PERFORMANCE REQUIREMENTS** are able to be combined with the proposed **CONTRIBUTION OF THE CONTRACTOR**. The acceptable **RESPONSIBILITY** is checked here.’’

Figure A6.5: Conceptual design of the decision-support method: step 4

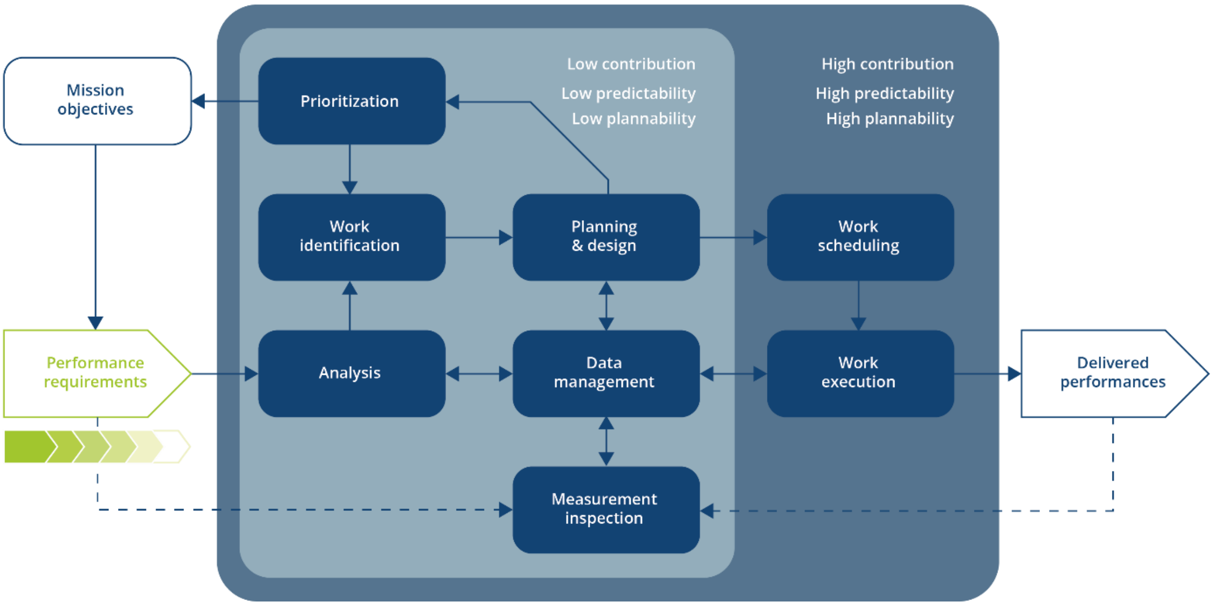
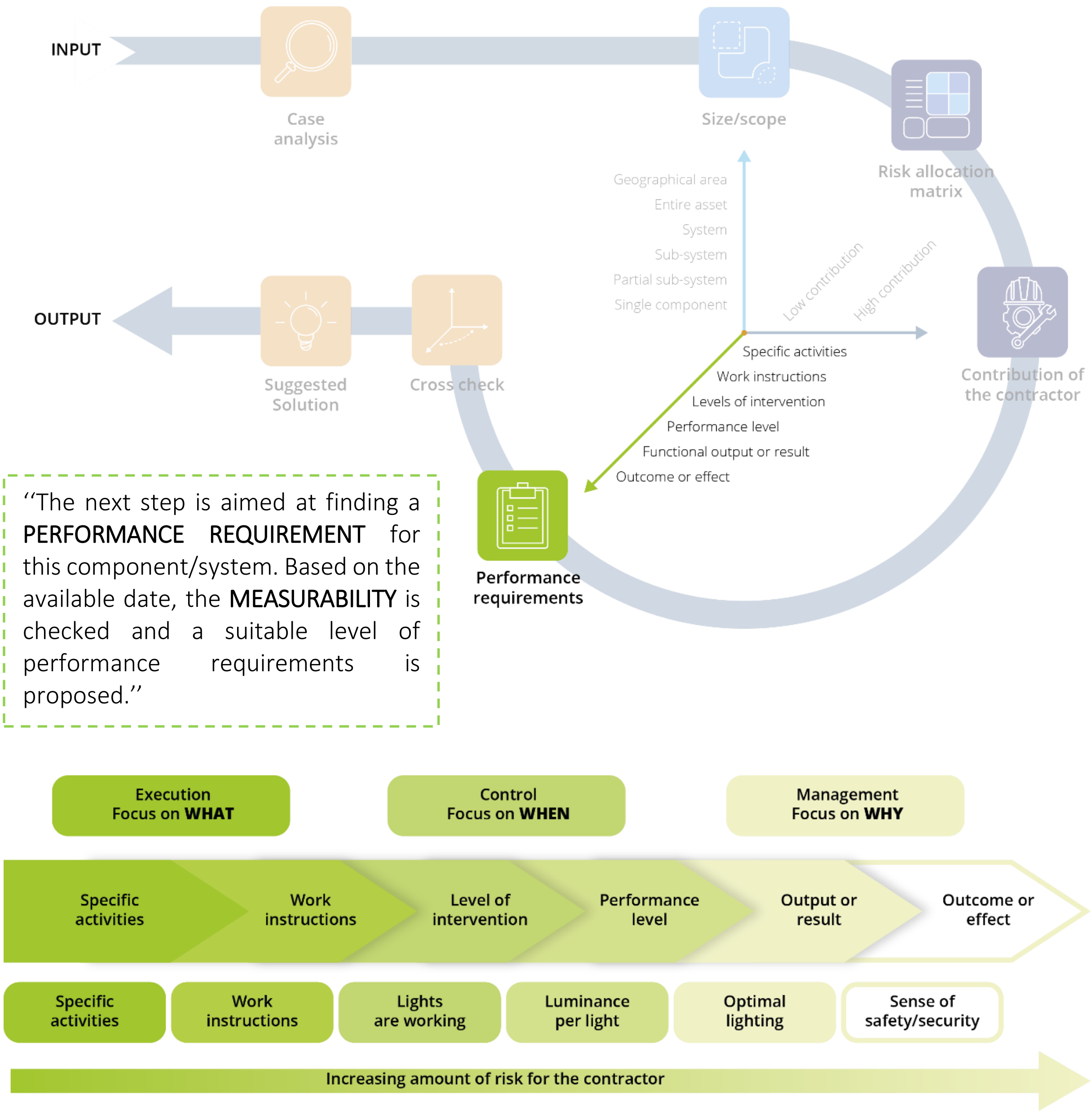


Figure A6.6: Six Stage Model based on Schoenmaker, de Bruijn & Herder (2013)

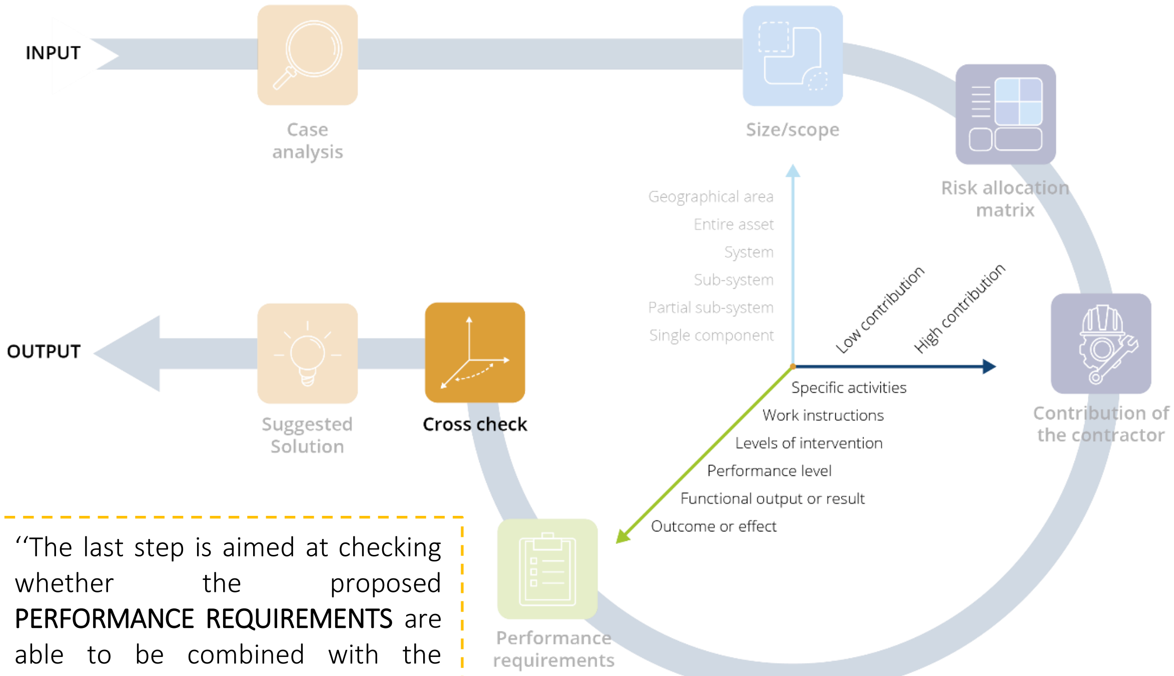
Step 5: Performance requirements



''The next step is aimed at finding a PERFORMANCE REQUIREMENT for this component/system. Based on the available date, the MEASURABILITY is checked and a suitable level of performance requirements is proposed.''

Figure A6.7: Conceptual design of the decision-support method: step 5 partly based on Schoenmaken & Verlaan (2013)

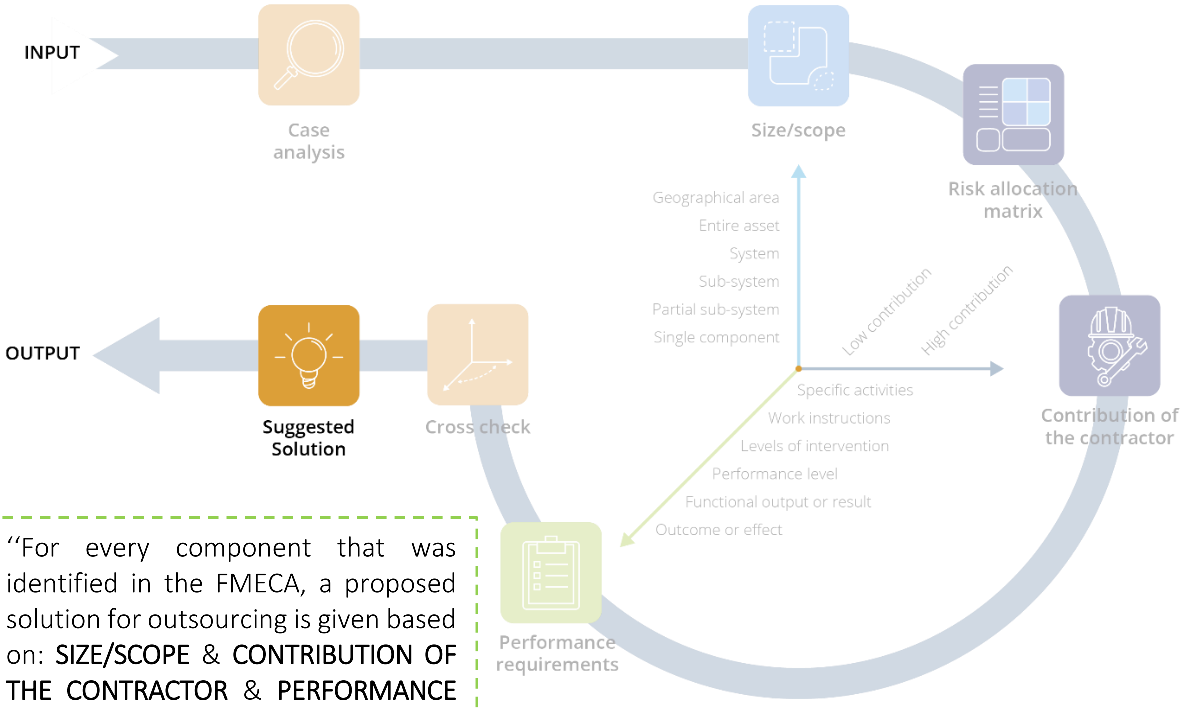
Step 6: Cross-check



''The last step is aimed at checking whether the proposed **PERFORMANCE REQUIREMENTS** are able to be combined with the proposed **CONTRIBUTION OF THE CONTRACTOR**. The acceptable **RESPONSIBILITY** is checked here.''

Figure A6.8:Conceptual design of the decision-support method: step 6

Step 7: Proposed solution and expected outcome



''For every component that was identified in the FMECA, a proposed solution for outsourcing is given based on: SIZE/SCOPE & CONTRIBUTION OF THE CONTRACTOR & PERFORMANCE REQUIREMENTS.''

Figure A6.9: Conceptual design of the decision-support method: step 7

Concept decision

The last step delivers a concept decision about the way outsourcing can be done. The model can however only take so many considerations into account and things can and probably will be missed. This concept decision is a starting point for experts to reach a final conclusion. The concept results will be discussed and tested for feasibility within the context of the contract. The final decision will be made outside of the decision-support method.

Schematic representation of the redesign of the decision-support method

The redesign of the decision-support method that was created after the first run of the case study consists of 7 steps and is executed for every individual component or system. This way a repetitive sequence of steps is created as represented in the figure below. By following these steps for every element, a systematical breakdown of the entire system is achieved and a proposed solution for the outsourcing of the individual part is found with every round of using the method.

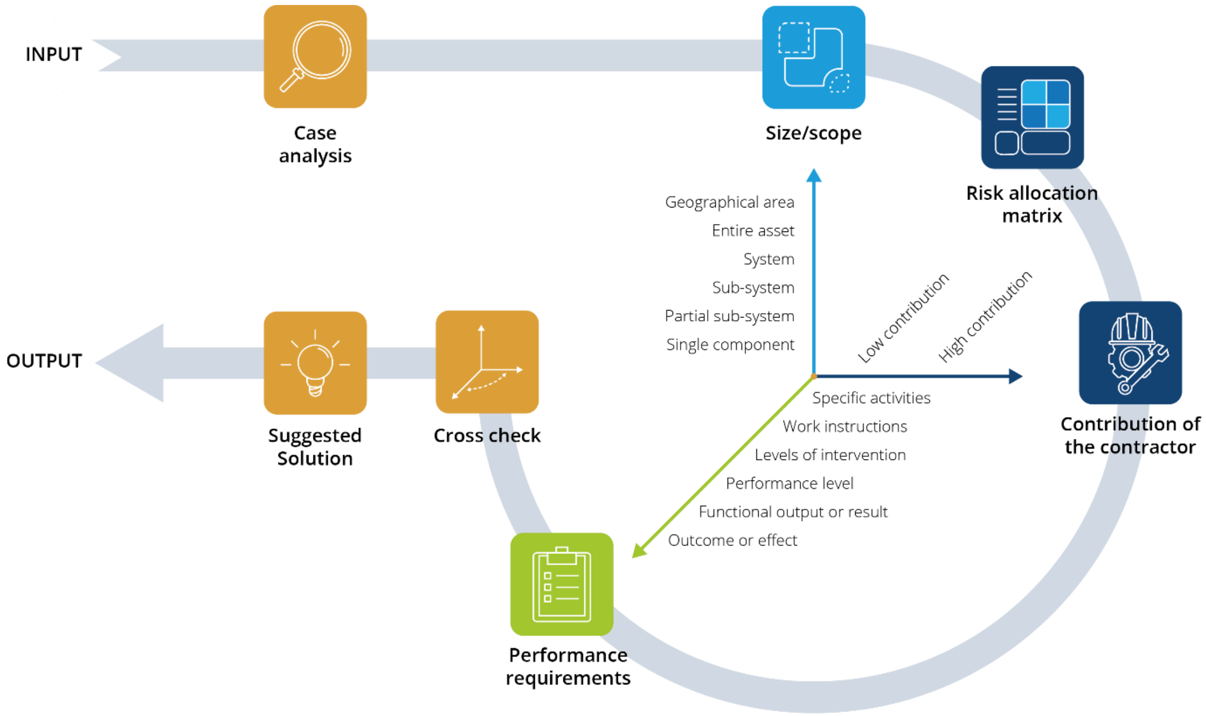


Figure A6.10: Schematic representation of the redesign of the decision-support method

Appendix 7

Case study – Run 2 –

Appendix 7: Case study - Run 2 -

Case study: Noordtunnel - Run 2 -

Figure A7.1: Noordertunnel (Zuid-Holland), Patrick van Dam (2017)

Figure A7.2: Google maps view of the Noordtunnel (07-11-2018)

1. Goal of the second run of the case study

The goal of the second run of the case study is to test of the improved design of the decision-support method, whether it will perform as expected. During this case study, the some of the steps might be similar to the steps that were already taken during the first run of the case study. The goal is to improve these similar steps and make them even more valuable, whilst at the same time, test the steps that were added or altered in this improve version of the decision-support method. Even though this is an improved design, room for improvement is still present. At the end of this second test, the results will be evaluated and the suggested improvements will be discussed. During this second run, the focus is on the steps that were altered during the redesign and the process of decision making.

2. Execution of the case study

At the start of the case study, an actual case will be selected to act as subject during this test. This is done in accordance with the boundary conditions and decisions that were already made in section 2.3 of the main report. This means that the case study will be performed on the Noordtunnel.

Before any further steps from the decision-support method can be taken, basic information about the tunnel is needed. This part of used to introduce the case/subject, provide basic information and already start with the collection of data that will be useful during the remainder of the process.

After the case introduction, the steps of the decision-support method are used for the second time. During the case study, the method as explained in chapters 3 and 4 of the main report is used. Those chapters will be used as a guideline throughout the entire case study. The method is visualized in the figure below (Figure A7.3).

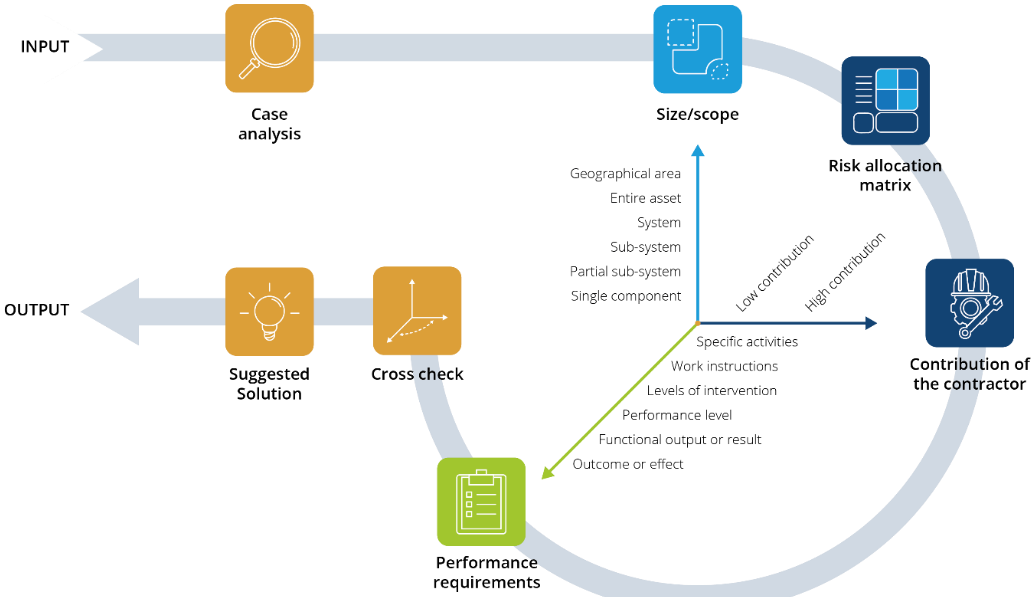


Figure A7.3: Decision-support method visualized

Using the method as described above means that after the initial introduction of the Case, an FMECA will be used to gain a lot of useful data about the entire tunnel. After that initial step, the cycle of steps 2-7 will be repeated a couple of times for different parts of the tunnel. The different parts will be evaluated systematically using these 6 steps before continuing to a next part of the tunnel.

For this case study, three parts of the tunnel will be evaluated through the use of the decision-support method. The focus will be on the usability of the Method, not on the outcome of the process itself.

When the case study is completed, the results will be added to the main report and integrated in section 4.7 about the practical application of the decision-support method.

3. *Introducing the decision-support method*

Within Rijkswaterstaat, the reliability of the tunnels is an important aspect (Rijkswaterstaat Steunpunt ProBO, 2016) (Rijkswaterstaat, 2010). Different than in the conceptual design of the decision-support method, the use of the RCM (reliability centered maintenance) tool FMECA (Failure Mode Effect and Criticality Analysis) is now the official first step of the method. This tool is used to map the risks and come up with a reliable maintenance plan. During the use of this method, the tool is mainly used as a source of information to base further decisions on.

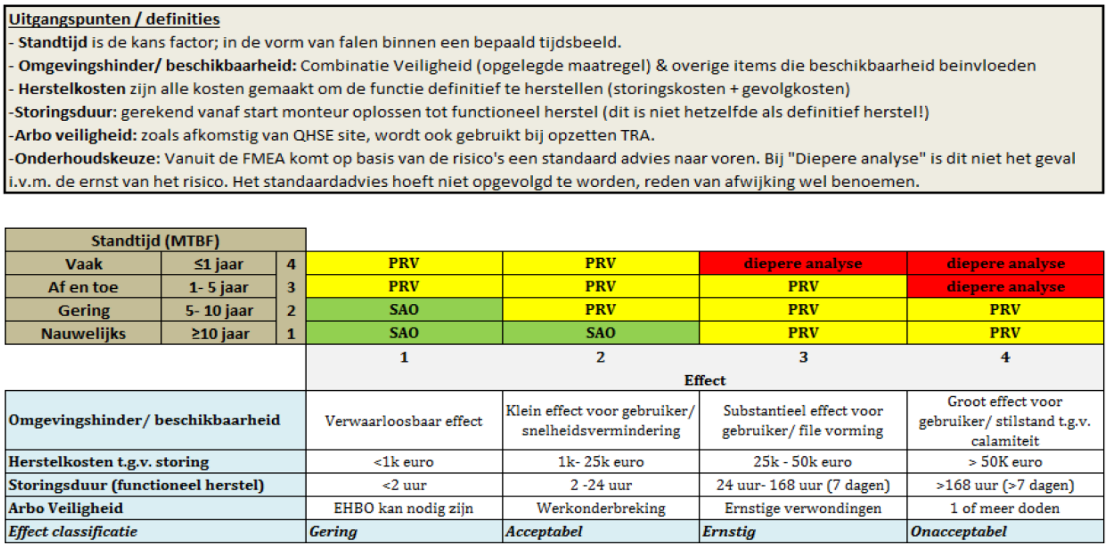
Step 1: Case analysis

The most important part of this step is the execution of an FME(C)A. For the Noordtunnel, this was already done in 2012/2013 (Imtech, 2013). The FME(C)A was performed by Imtech Asset Solutions and will be used throughout this run of the case study as source of information (Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel, 2013) (Verbeterd Onderhoudsconcept VOT2 NOORDTUNNEL, 2013).

The report from Imtech contains a huge amount of information that could be used for decision making during the use of the decision-support method. This information was also used during the first run of the case study and proved to be very useful. The big difference between the first run and the second run is the fact that the use of FMECA is now the official first step of the decision-support method. The big downside of using the version from Imtech of the FMECA is the fact that it dates back from 2013. When this scenario happens in a real case, the FMECA should be re-evaluated and updated with current information and knowledge about the asset. In this case however, the usefulness of the information is more important than the accuracy of the information and the 2013 version suffice. Additionally, it should be noted that the actual FMECA is only performed for the critical systems of the Noordtunnel. The options of choosing systems to use for this test are therefore somewhat limited, but this shouldn't be an issue because the goal of the case study is to test the functioning of the method, not to see if the results are completely accurate.

Risk matrix

For correct and efficient use of the FMECA, the risk matrix is needed to interpret the numbers and color codes that are used in the risk register. The risk matrix can be found in the figure below (Figure A7.4) and also originates from the document from Imtech (Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel, 2013, p. 18).



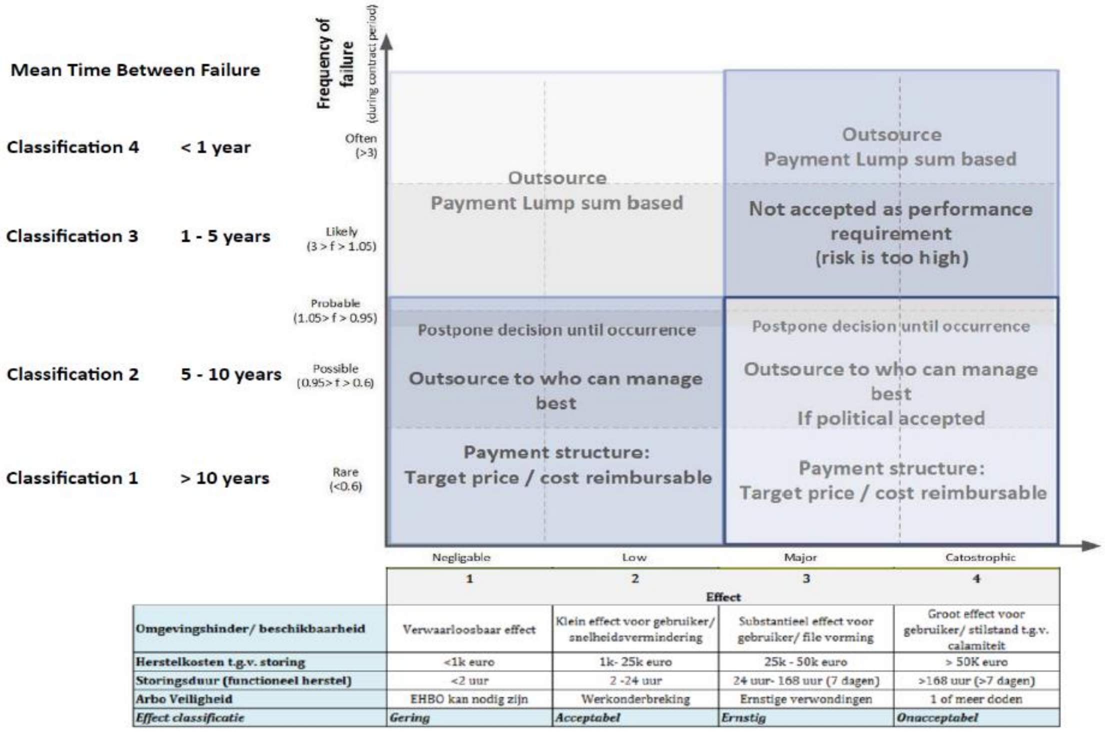
Uitgangspunten / definities
- **Standtijd** is de kans factor; in de vorm van falen binnen een bepaald tijdsbeeld.
- **Omgevingshinder/ beschikbaarheid:** Combinatie Veiligheid (opgelegde maatregel) & overige items die beschikbaarheid beinvloeden
- **Herstelkosten** zijn alle kosten gemaakt om de functie definitief te herstellen (storingskosten + gevolgkosten)
-**Storingsduur:** gerekend vanaf start monteur oplossen tot functioneel herstel (dit is niet hetzelfde als definitief herstel!)
-**Arbo veiligheid:** zoals afkomstig van QHSE site, wordt ook gebruikt bij opzetten TRA.
-**Onderhoudskeuze:** Vanuit de FMEA komt op basis van de risico's een standaard advies naar voren. Bij "Diepere analyse" is dit niet het geval i.v.m. de ernst van het risico. Het standaardadvies hoeft niet opgevolgd te worden, reden van afwijking wel benoemen.

Standtijd (MTBF)						
Vaak	**≤1 jaar**	**4**	**PRV**	**PRV**	**diepere analyse**	**diepere analyse**
Af en toe	**1- 5 jaar**	**3**	**PRV**	**PRV**	**PRV**	**diepere analyse**
Gering	**5- 10 jaar**	**2**	**SAO**	**PRV**	**PRV**	**PRV**
Nauwelijks	**≥10 jaar**	**1**	**SAO**	**SAO**	**PRV**	**PRV**
			1	**2**	**3**	**4**
			Effect			
Omgevingshinder/ beschikbaarheid			Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing			<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)			<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid			EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie			***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A7.4: Risk matrix (Imtech, 2013)

Adaptation of the risk allocation matrix

At a later step of the decision-support method, the risk allocation matrix will be used. Before this matrix can be used for this case, it needs to be adapted to the current situation. This is done as part of this chapter because the risk matrix that was just made, is used to transform the standard risk allocation matrix to the one shown below. This risk allocation matrix is adapted to the Noordtunnel (figure A7.5) using the MTBF and the effects that are used in the risk matrix and will be used in the risk register. This was introduced during the redesign of the decision-support method after case study run 1.

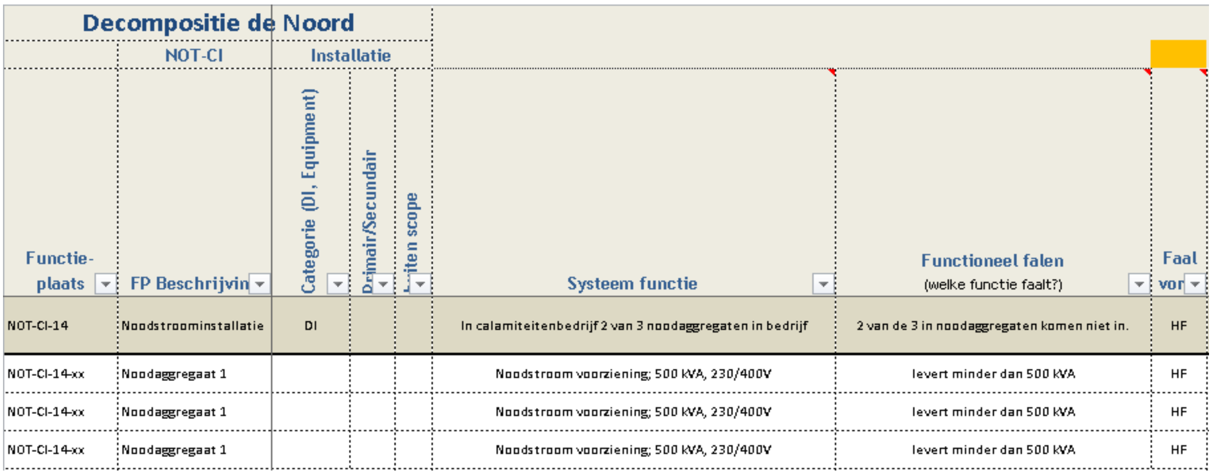


	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)	<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A7.5: Altered risk allocation matrix based on the matrix by Brommet (2015), now applicable for the Noordtunnel

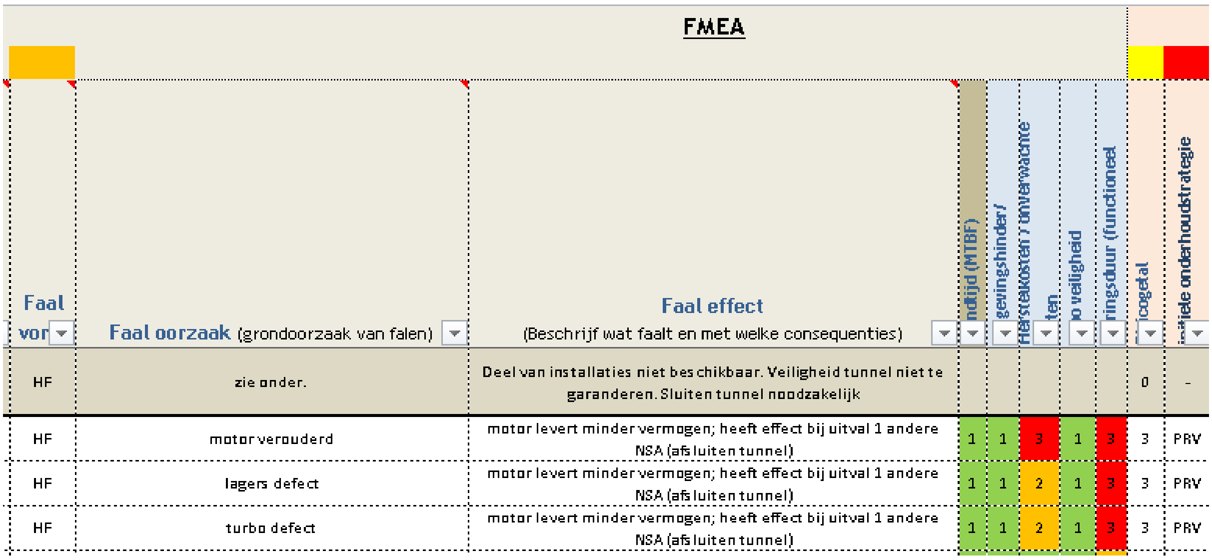
Risk register

All the information that is gathered through the FMECA is captured in the risk register. This is the list that is used to find all the necessary information. The risk register was part of the report from Imtech (Verbeterd Onderhoudsconcept VOT2 NOORDTUNNEL, 2013). The two figures (A7.6 & A7.7) below show the left and right side of the risk register, showing 3 lines of information. The original list contains all systems that are part of the asset.



Decompositie de Noord								
	NOT-CI	Installatie						
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor
NOT-CI-14	Noodstroominstallatie	DI			In calamiteitenbedrijf 2 van 3 noodaggregaten in bedrijf	2 van de 3 in noodaggregaten komen niet in.	HF
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF

Figure A7.6: Risk register left side (Imtech,2013)



FMEA

Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder /	Herstelkosten / onverwachte ten	o veiligheid	ringsduur (functioneel	icogetal	iele onderhoudstrategie
HF	zie onder.	Deel van installaties niet beschikbaar. Veiligheid tunnel niet te garanderen. Sluiten tunnel noodzakelijk						0	-
HF	motor verouderd	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	3	1	3	3	PRV
HF	lagers defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
HF	turbo defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV

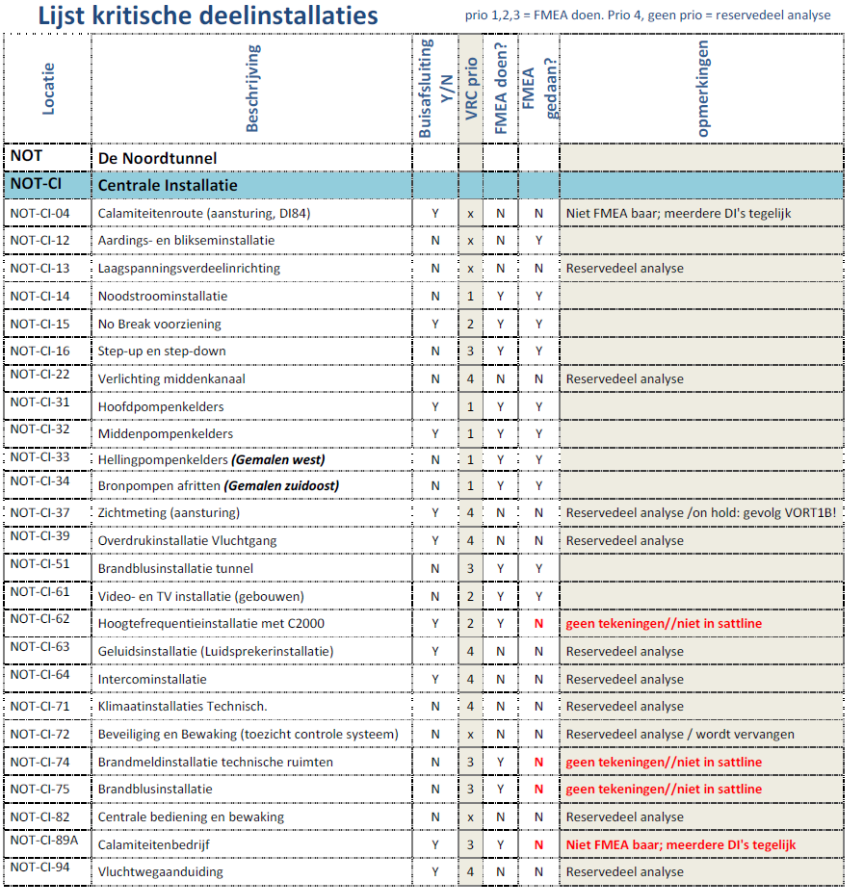
Figure A7.7: Risk register right side (Imtech, 2013)

Criticality analysis

From the report of Imtech, a criticality analysis is used to determine the critical systems. These critical systems were determined by doing a quick FMECA where the main criteria was: 'if the system is directly related to traffic safety or fulfilling another safety feature, then the system is marked as critical.' The results from this criticality analysis were two lists of critical systems (general tunnel sub-systems and tunnel tube specific sub-systems North + South). Those lists are shown in the following figures A7.8 & A7.9: List of critical sub-systems (General/North tube) and part of the report from Imtech (Begeleidend schrijven verbeterd onderhoudsconcept Noord tunnel, 2013, p. 16/17).

Based on the safety norms (VRC21 – Veiligheidsrichtlijn deel C Hstk.21) a recovery priority (1-4) is given to each critical system. A recovery priority of 1 means immediate intervention and 4 means that an intervention at the next routine maintenance moment will be sufficient. From this data, 3 separate systems are chosen to test the remaining steps of the decision-support method (2-7). Two of them are general tunnel systems and the last one is a tube specific tunnel system. The (sub)-systems that were chosen are systems that are critical to either traffic safety or fulfilling a general safety feature.
The (Sub)-Systems that are chosen for this case study are the following:

•	NOT-CI-14	Noodstroominstallatie	(Emergency Power Supply)	General
•	NOT-CI-31	Hoofdpompenkelders	(Main Pump Basements)	General
•	NOT-N-61	Video- en TV-installatie	(video and CCTV system)	North/South

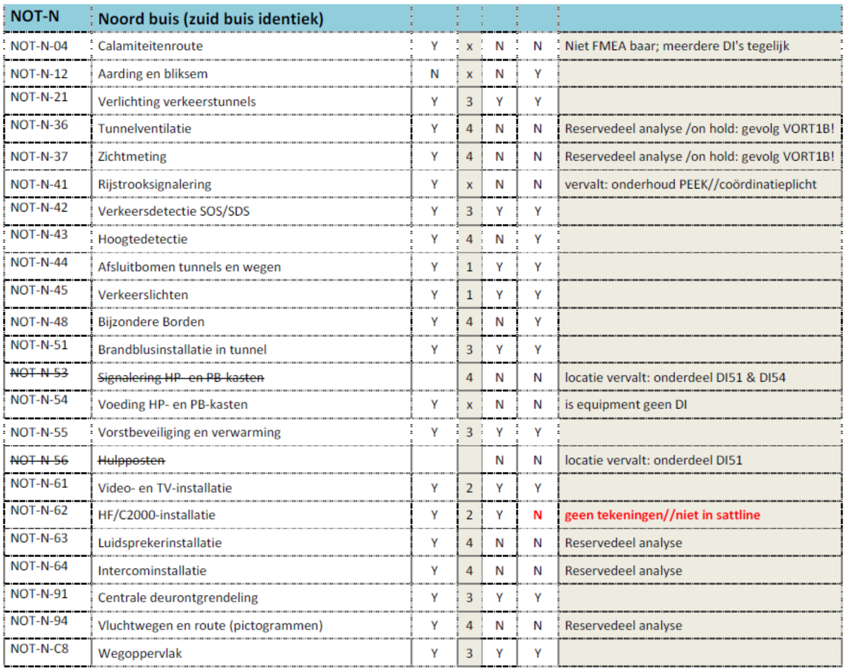


Lijst kritische deelinstallaties

prio 1,2,3 = FMEA doen. Prio 4, geen prio = reservedeel analyse

Locatie	Beschrijving	Buisafsluiting Y/N	VRC prio	FMEA doen?	FMEA gedaan?	opmerkingen
NOT	**De Noordtunnel**					
NOT-CI	**Centrale Installatie**					
NOT-CI-04	Calamiteitenroute (aansturing, DI84)	Y	x	N	N	Niet FMEA baar; meerdere DI's tegelijk
NOT-CI-12	Aardings- en blikseminstallatie	N	x	N	Y	
NOT-CI-13	Laagspanningsverdeelinrichting	N	x	N	N	Reservedeel analyse
NOT-CI-14	Noodstroominstallatie	N	1	Y	Y	
NOT-CI-15	No Break voorziening	Y	2	Y	Y	
NOT-CI-16	Step-up en step-down	N	3	Y	Y	
NOT-CI-22	Verlichting middenkanaal	N	4	N	N	Reservedeel analyse
NOT-CI-31	Hoofdpompenkelders	Y	1	Y	Y	
NOT-CI-32	Middenpompenkelders	Y	1	Y	Y	
NOT-CI-33	Hellingpompenkelders ***(Gemalen west)***	N	1	Y	Y	
NOT-CI-34	Bronpompen afritten ***(Gemalen zuidoost)***	N	1	Y	Y	
NOT-CI-37	Zichtmeting (aansturing)	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-CI-39	Overdrukinstallatie Vluchtgang	Y	4	N	N	Reservedeel analyse
NOT-CI-51	Brandblusinstallatie tunnel	N	3	Y	Y	
NOT-CI-61	Video- en TV installatie (gebouwen)	N	2	Y	Y	
NOT-CI-62	Hoogtefrequentieinstallatie met C2000	Y	2	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-63	Geluidsinstallatie (Luidsprekerinstallatie)	Y	4	N	N	Reservedeel analyse
NOT-CI-64	Intercominstallatie	Y	4	N	N	Reservedeel analyse
NOT-CI-71	Klimaatinstallaties Technisch.	N	4	N	N	Reservedeel analyse
NOT-CI-72	Beveiliging en Bewaking (toezicht controle systeem)	N	x	N	N	Reservedeel analyse / wordt vervangen
NOT-CI-74	Brandmeldinstallatie technische ruimten	N	3	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-75	Brandblusinstallatie	N	3	Y	**N**	**geen tekeningen//niet in sattline**
NOT-CI-82	Centrale bediening en bewaking	N	x	N	N	Reservedeel analyse
NOT-CI-89A	Calamiteitenbedrijf	Y	3	Y	**N**	**Niet FMEA baar; meerdere DI's tegelijk**
NOT-CI-94	Vluchtwegaanduiding	Y	4	N	N	Reservedeel analyse

Figure A7.8: List of critical sub-systems (General)



NOT-N	**Noord buis (zuid buis identiek)**					
NOT-N-04	Calamiteitenroute	Y	x	N	N	Niet FMEA baar; meerdere DI's tegelijk
NOT-N-12	Aarding en bliksem	N	x	N	Y	
NOT-N-21	Verlichting verkeerstunnels	Y	3	Y	Y	
NOT-N-36	Tunnelventilatie	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-N-37	Zichtmeting	Y	4	N	N	Reservedeel analyse /on hold: gevolg VORT1B!
NOT-N-41	Rijstrooksignalering	Y	x	N	N	vervalt: onderhoud PEEK//coördinatieplicht
NOT-N-42	Verkeersdetectie SOS/SDS	Y	3	Y	Y	
NOT-N-43	Hoogtedetectie	Y	4	N	Y	
NOT-N-44	Afsluitbomen tunnels en wegen	Y	1	Y	Y	
NOT-N-45	Verkeerslichten	Y	1	Y	Y	
NOT-N-48	Bijzondere Borden	Y	4	N	Y	
NOT-N-51	Brandblusinstallatie in tunnel	Y	3	Y	Y	
~~NOT-N-53~~	~~Signalering HP- en PB-kasten~~		4	N	N	locatie vervalt: onderdeel DI51 & DI54
NOT-N-54	Voeding HP- en PB-kasten	Y	x	N	N	is equipment geen DI
NOT-N-55	Vorstbeveiliging en verwarming	Y	3	Y	Y	
~~NOT-N-56~~	~~Hulpposten~~			N	N	locatie vervalt: onderdeel DI51
NOT-N-61	Video- en TV-installatie	Y	2	Y	Y	
NOT-N-62	HF/C2000-installatie	Y	2	Y	**N**	**geen tekeningen//niet in sattline**
NOT-N-63	Luidsprekerinstallatie	Y	4	N	N	Reservedeel analyse
NOT-N-64	Intercominstallatie	Y	4	N	N	Reservedeel analyse
NOT-N-91	Centrale deurontgrendeling	Y	3	Y	Y	
NOT-N-94	Vluchtwegen en route (pictogrammen)	Y	4	N	N	Reservedeel analyse
NOT-N-C8	Wegoppervlak	Y	3	Y	Y	

Figure A7.9: List of critical sub-systems (North tube)

4. Remaining steps of the decision-support method per system

For all of the three (sub)-systems that were chosen to evaluate during this case study, the remaining steps of the improved decision-support method will be executed. Step 1 has already been performed by using the FMECA and transforming the risk allocation matrix. Step 2 has been started already but will be concluded within a separate step. This means that there are the 6 steps (2-7) as shown in section 4.4 of the main report and figure A7.3 of this case study document that still need to be done. The order of steps and layout will be the same for each of the three (sub)-systems.

4.1 Sub-system NOT-Cl-14: Noodstroominstallatie (emergency power supply)

The emergency power supply is a sub-system of the main category power supply group. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the power supply can be found below.

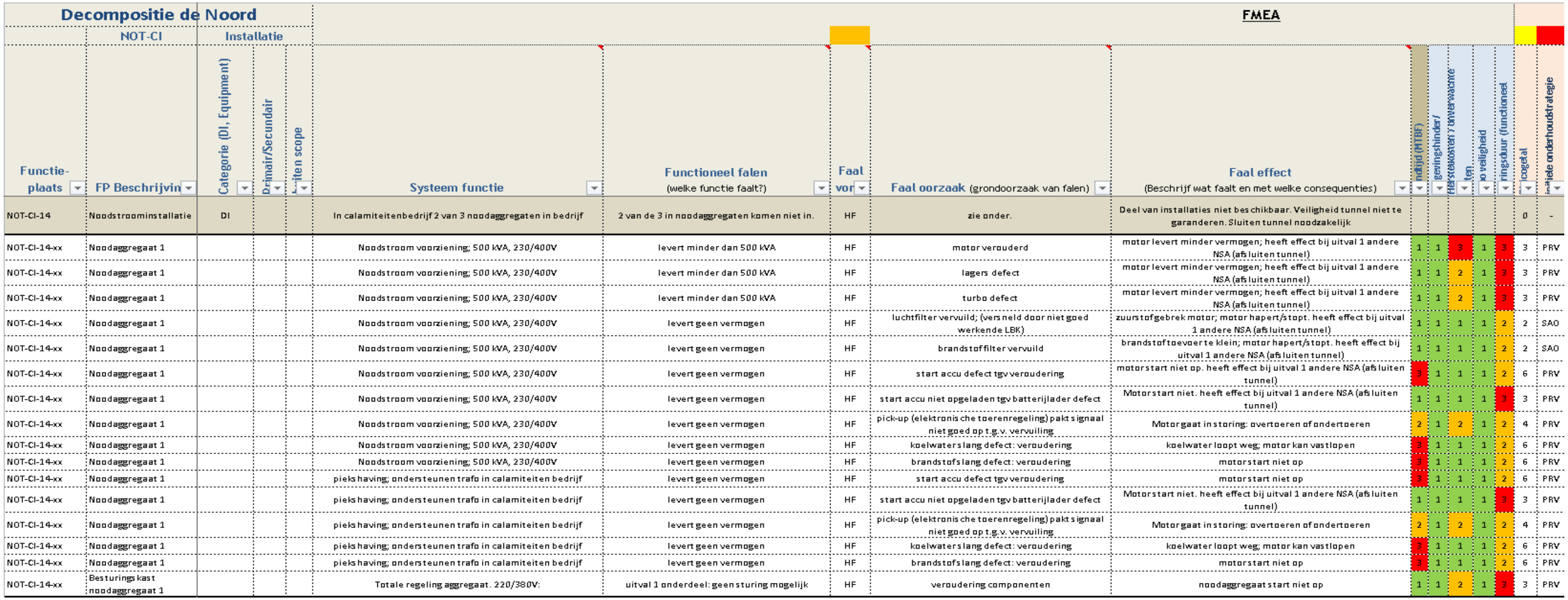
Functional requirements:

- *(FE1301)* Both primary, redundant power grid connections and emergency power supplies need to be capable of delivering the required power supply under all operational circumstances.
- *(FE1502)* The no-break has to continue the power supply to system critical components automatically in case of failure of the primary power source. Functioning of the systems cannot stop during the transition.
- *(FE1403)* When the primary power supply fails, alternative power supplies need to take over automatically. Alternate power supplies can be redundant grid connections, emergency power supplies and no-breaks.
- *(FE1504)* The power supply for critical power users has to be able to be maintained for at least >60 minutes through the use of no-breaks after failure of the main power supply.
- *(FE1405)* Changing back from alternate power supplies to the main power supply has to happen in a controlled way and without loss of power.

Besides the functional requirements for the system group, the sub-system has a purpose to fulfill. The purpose or goal of the sub-system is explained below.

Goal: Delivering electrical power supply for the tunnel systems when the primary source of power fails. The emergency power supply takes over from the main power supply with an intervention of the no-breaks to prevent loss of power during the transition.

The emergency power supply of the Noordtunnel consists of 3 separate emergency power generators of which at least 2 need to be active during an emergency situation. The generators engages when the other power supplies fail. The FMECA for all 3 generators are identical and can be found on the next page (figure A7.10) and the report from Imtech (Verbeterd Onderhoudsconcept VOT2 NOORDTUNNEL, 2013).



Decompositie de Noord						FMEA											
	NOT-CI	Installatie															
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder/	Herstelkosten / onverwachte ten	o veiligheid	ringsduur (functioneel	icogetal	iële onderhoudstrategie
NOT-CI-14	Noodstroominstallatie	DI			In calamiteitenbedrijf 2 van 3 noodaggregaten in bedrijf	2 van de 3 in noodaggregaten komen niet in.	HF	zie onder.	Deel van installaties niet beschikbaar. Veiligheid tunnel niet te garanderen. Sluiten tunnel noodzakelijk						0	-
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	motor verouderd	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	3	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	lagers defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	turbo defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	luchtfilter vervuild; (versneld door niet goed werkende LBK)	zuurstofgebrek motor; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstoffilter vervuild	brandstoftoevoer te klein; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				pieks having; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Besturingskast noodaggregaat 1				Totale regeling aggregaat. 220/380V:	uitval 1 onderdeel: geen sturing mogelijk	HF	veroudering componenten	noodaggregaat start niet op	1	1	2	1	3	3	PRV

Figure A7.10: FMEA of the emergency power supply (Imtech, 2013)

Step 2: Determine a Suitable size/scope

Most of the work has already been done by choosing the emergency power supply in the previous section as a subject for the first evaluation. There are a few reasons that strengthen this decision. The emergency power supply is a critical sub-system within the entire tunnel system. Using the entire power supply group as starting point means that several critical sub-systems are combined and is not desirable. The choice to take the sub-system as a starting point, with the possibility to be adjusted along the way (both up and down) was therefore made.

Step 3: Risk allocation matrix

The next step is to use the risk allocation matrix by Brommet to get a first insight in the way of outsourcing that can be used. The emergency power supply was evaluated through FMECA. The information that was captured in the risk register (Figure A7.10) is interpreted with the help of the risk matrix (Figure A7.4) into usable data. This data contains the mean time between failure (MTBF) and the effects (hindrance/ repair costs/ downtime till functional repair/ safety) of the different failure modes that the sub-system can have. This data will be used as input for the risk allocation matrix. For this to work, the altered risk allocation matrix (Figure A7.5) is used.

The first approach uses the average MTBF of all failure modes and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF:	1,86	(once every 5-10 years)
Average Downtime:	2,33	(< 1 day)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence.

When analyzing in further detail, it can be concluded that a combination of high probability and low downtime, or low probability and high downtime is found in most cases. No extremes can be found (highest probability combined with highest downtime). This explains the averages that were found earlier. When decided to outsource the sub-system as a whole, the advice would be to go with the averages and choose to outsource in a cost reimbursable way and postpone the decision until occurrence. If the decision is made to outsource the different parts of the sub-system (based on the failure modes) individually, the advice would be to outsource the parts with an MTBF of 1 and 2 in a cost reimbursable way and postpone the decision until occurrence and outsource the parts with an MTBF of 3 with lump sum and let the contractor decide when to replace certain components. The reasoning behind this is that it is that in the first case, the probability of something happening is relatively low, though still possible. Thus it is unrealistic to let the contractor take those costs into account at the start of the contract. In the latter case the probability is higher and it is more realistic that the contractor is able to deal with these occurrences themselves.

Step 4: Determine a suitable contribution of the contractor

The next step is there to determine the contribution of the contractor, or the responsibility of the contractor. That is where the six-stage model is used to continue where Brommet stopped and provides even more insight on how to deal with predictability and plannability of the maintenance work. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. Given that the MTBF intervals are relatively large, the predictability is not that good. 9/15 failure modes have a MTBF of 5-10 years or > 10 years, thus chances of it occurring within the contract period are not significant, but can still happen. The other 6 failure modes have an MTBF of 1-5 years and are likely to at least happen once or more during the contract period. The repairs and preventive measures however are somehow cost efficient and can easily be integrated in the contract.

The advice here would be to make a cut and divide the contribution of the contractor (responsibility) for failure modes in two groups. The first group consists of 4 items of which the exact moment of failure are hard to predict, but have a high impact due to downtime and costs. For this group of failure modes, the contractor should solely perform tests, routine maintenance and report their findings to the CA. Responsibility for repairs, revisions and replacements lies with the CA. Specific items that are meant here are the revision of the engine, replacement of the bearings and the replacement of the turbo. The fourth item is the replacement of the emergency power supply in general, but given the remaining lifespan of 19 years, this is completely out of the question at this time. The contractor can only be held responsible for the effects of a failure (within this group) when they could reasonably have been expecting failure but neglected to report this to the CA. If the upcoming failure was reported and the client didn't act on it, the contractor is no longer responsible for the effects of that failure.

The second group consists of routine maintenance of the emergency power supply, the replacement of components and small repairs to ensure the functioning of the system. The measures are reasonably predictable and can, due to low costs, also be planned. The contractor is responsible for the functioning of the system and is therefore accountable for the effects that occur when the system fails and the reason is traced back to a failure mode within this group of possible failures (not being the failures mentioned in the previous paragraph).

Step 5: Determine suitable performance requirements

For the emergency power supply are no measurable performance requirements available/set at this time. The system either works, or it doesn't. When looking at the description of functional failure, the emergency power supply can fail in two ways: it doesn't deliver the supposed 500kVa or it doesn't deliver any power at all. This could be used as a performance requirement (the performance level).

An important aspect to consider here is that the emergency power supply is a passive system which is only active when called upon. This means that all failures are hidden until the system is active and the failure is revealed, by which time it is too late. The system should therefore be tested regularly and when tested, a certain threshold must at least be met to ensure adequate fulfillment of the function when called upon. This is especially important for the 500kVa requirement. The suggestion here is to keep the 500kVa as a top-requirement for the emergency power supply, but to use a different performance requirement for the contract(or) specifically.

At this time, the emergency power supply is maintained with a preventive maintenance strategy, using a pre-set amount of test-moments to inspect and test the functionality of the system. Historic data (RWS: Historisch overzicht storingen 2009-2014) shows that the reasons for malfunctioning of the system are non-related to the failure modes that were mentioned in the FMECA. The test-intervals are therefore adequate and the routine maintenance (including small repairs and regular replacement of weaker components) are sufficient to maintain the functioning of the system.

The suggestion for the level of outsourcing is as follows:
The top-requirement is that the emergency power supply needs to deliver at least 500 kVa when called upon. This is the minimum performance level. This requirement however is not the requirement that is solely the responsibility of the contractor. The contractor has to notify the CA when they expect the performance level to be under the threshold before the next test. Therefore there is a shared responsibility for this requirement.

For the routine maintenance tasks RWS can, based on the historic data and the positive results about the current maintenance strategy and test intervals, prescribe the amount of test moments and the maximum time between the intervals (based on the lowest MTBF of the components). When RWS wishes to continue this trend, they can prescribe the test intervals, but also at which interval certain components need to be replaced. Then this is a work instruction.

The other option is to leave the responsibility with the contractor and ask for a level of intervention. In that case it is still possible to prescribe a minimum amount of test moments and even prescribe a maximum interval between those test moments, but the contractor decides when he performs the tests. Hence, the performance requirement is the functionality of the emergency power supply. When the emergency power supply is turned on, it should deliver power and none of the failure modes which result in a situation where no power is delivered can happen. This is a *level of intervention*. More responsibility lies with the contractor, but they also get more freedom in when and how to replace the worn-out parts of the system. The eventual choice here depends on the ambition/strategy of the CA.

Step 6: Cross-check the interfaces

The cross-check of the interfaces is a compatibility check which is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

Given that the cut is made between the 3 unpredictable parts and the more predictable routine maintenance parts, the following can be said. The less predictable parts have low contribution from the contractor and therefore share responsibility with the CA. The top-requirement is a performance level, but essentially the actual requirement for the contractor is a work instruction, instructing the contractor when to check, what to check and a request to inform the CA when the performance level is not going to be achieved before the next test.

The parts for which was decided that are more predictable were set to have a high contribution of the contractor. This is correct when the performance requirements are based on the level of intervention and the contractor has the authority to decide when and how to intervene, as long as the system functions. When the decision is made to prescribe the test intervals and when certain components need to be replaced, the performance requirement is a work instruction and the contribution of the contractor should be changed to low. In that case, more responsibility will stay with CA and less risk will remain for the contractor.

Step 7: Suggest a solution for the parameters

<table>
<tr><td>Size/Scope</td><td>Sub-System divided in two partial sub-systems based on Predictability of failure modes</td></tr>
<tr><td colspan="2">Based on the predictability and the effects of certain failure modes that can be derived from the FMECA made for the emergency power supply, the advice would be to divide the scope in two groups and approach these groups separately. The first group consists of unpredictable failure modes with high impact. The second group consists of reasonably predictable failure modes with low impact.</td></tr>
<tr><td>Contribution of the contractor</td><td>Low (Unpredictable) & High (Predictable)</td></tr>
<tr><td colspan="2">For the unpredictable failure modes, the contribution of the contractor will be low. The contractor is responsible for simple routine maintenance and responsible for testing the system and informing the contracting authority about the current status of the system. When the system performance falls beneath a certain threshold, the contractor should inform the contracting authority that an intervention is advised, but the ultimate decision is for the contracting authority.

For the predictable failure modes, the contribution of the contractor will be high. The contractor is responsible for testing the system and performing all necessary interventions (repairs) to ensure that the system works. The contractor gets the freedom to decide (within the set maximums intervals) when the tests are performed and what interventions are done. The responsibility for the effects of failure caused by these predictable failure modes is for the contractor.</td></tr>
<tr><td>Performance Requirement</td><td>Work Instructions (Unpredictable) & Level of Intervention (Predictable)</td></tr>
<tr><td colspan="2">For the unpredictable failure modes for which a low contribution for the contractor is suggested, the performance requirements should be formulated as a work instruction. This is in line with the low contribution for the contractor that is chosen. Furthermore, the contracting authority can prescribe the maintenance which has proven successful during the last couple of years and keeps the possibility to steer things when the current maintenance regime proves to be insufficient.

For the predictable failure modes for which a high contribution for the contractor is suggested, the performance requirements should be formulated as a level of intervention. This is in line with the high contribution for the contractor that is chosen. The contractor has the responsibility to keep the performance of the system at a certain level (the system has to function when requested) and have the freedom to decide how, when and what maintenance interventions are necessary to comply to that requirement.</td></tr>
</table>

4.2 Sub-system NOT-CI-31: Hoofdpompkelder (main pump basement)

The main pump basement is a sub-system of the main category water drainage and ventilation systems group. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the power supply can be found below.

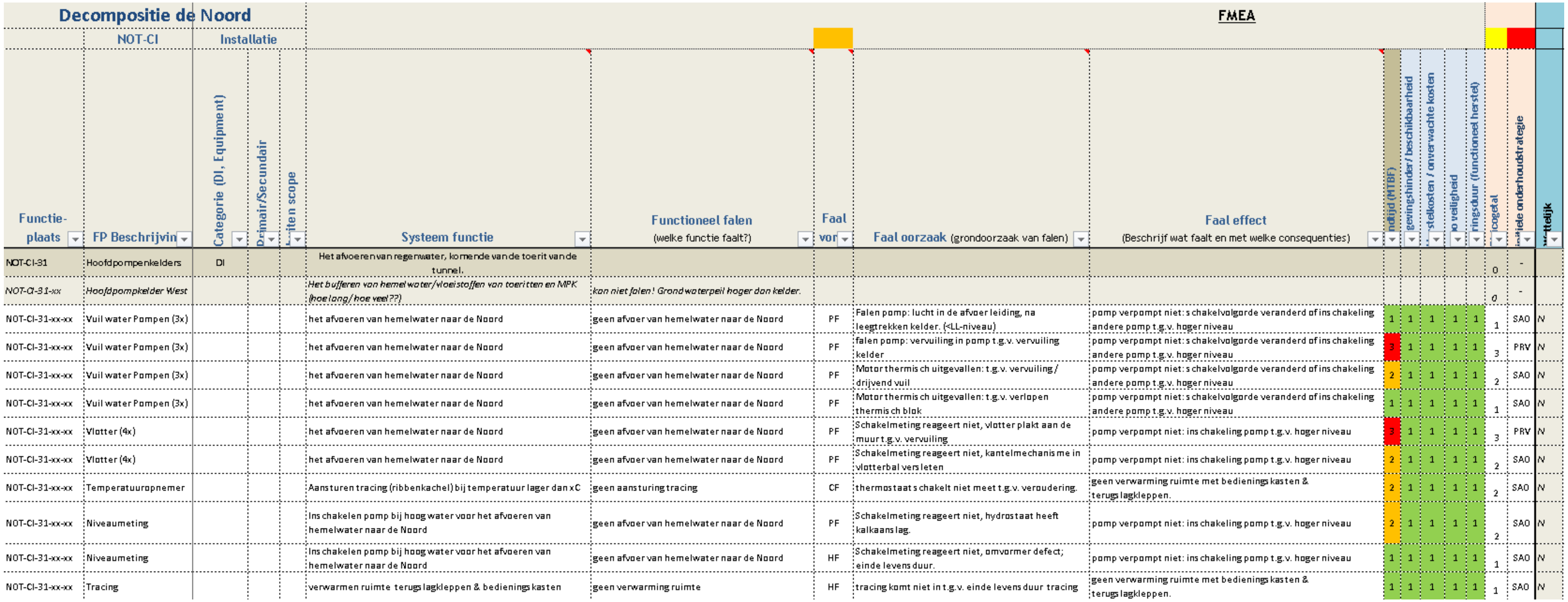
Functional requirements:

- *(FE3101)* There has to be a pump capacity of $2m^3$ per minute.
- *(FE3102)* Water should be able to flow into the liquid basement
- *(FE3103)* The middle basement should have a minimal net capacity of $30m^3$.
- *(FE3104)* In case of an Emergency state in the tunnel, the pump system should automatically start to stow away the water.

Besides the functional requirements for the system group, the sub-system has a purpose to fulfill. The purpose or goal of the sub-system is explained below.

Goal: The main pump basement, including the pumps has to keep the water from accumulating on the road in the tunnel and in the basement. The basement is in place to collect the water that is drained from the tunnel road surface. The pumps eliminate the water out of the (storage) basements.

The main pump basement consists of two basements, one on the south west and one on the east side. Both basements have 3 pumps. Because both basements are identical and the failure modes are the same, for this example only one basement is checked. The FMECA for the west main pump basement can be found on the next page (Figure A7.11).



Decompositie de Noord					FMEA												
NOT-CI		Installatie															
Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	ndtijd (MTBF)	gevingshinder/ beschikbaarheid	stelkosten / onverwachte kosten	o veiligheid	ringsduur (functioneel herstel)	icogetal	iele onderhoudstrategie	ttelijk
NOT-CI-31	Hoofdpompenkelders	DI			Het afvoeren van regenwater, komende van de toerit van de tunnel.										0	-	
NOT-CI-31-xx	*Hoofdpompkelder West*				*Het bufferen van hemelwater/vloeistoffen van toeritten en MPK (hoe lang/hoe veel??)*	*kan niet falen! Grondwaterpeil hoger dan kelder.*									*0*	-	
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Falen pomp: lucht in de afvoer leiding, na leegtrekken kelder. (<LL-niveau)	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	*N*
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	falen pomp: vervuiling in pomp t.g.v. vervuiling kelder	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	3	1	1	1	1	3	PRV	*N*
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Motor thermisch uitgevallen: t.g.v. vervuiling / drijvend vuil	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	*N*
NOT-CI-31-xx-xx	Vuil water Pompen (3x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Motor thermisch uitgevallen: t.g.v. verlopen thermisch blok	pomp verpompt niet: schakelvolgorde veranderd of inschakeling andere pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	*N*
NOT-CI-31-xx-xx	Vlotter (4x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, vlotter plakt aan de muur t.g.v. vervuiling	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	3	1	1	1	1	3	PRV	*N*
NOT-CI-31-xx-xx	Vlotter (4x)				het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, kantelmechanisme in vlotterbal versleten	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	*N*
NOT-CI-31-xx-xx	Temperatuuropnemer				Aansturen tracing (ribbenkachel) bij temperatuur lager dan xC	geen aansturing tracing	CF	thermostaat schakelt niet meet t.g.v. veroudering.	geen verwarming ruimte met bedieningskasten & terugslagkleppen.	2	1	1	1	1	2	SAO	*N*
NOT-CI-31-xx-xx	Niveaumeting				Inschakelen pomp bij hoog water voor het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	PF	Schakelmeting reageert niet, hydrostaat heeft kalkaanslag.	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	2	1	1	1	1	2	SAO	*N*
NOT-CI-31-xx-xx	Niveaumeting				Inschakelen pomp bij hoog water voor het afvoeren van hemelwater naar de Noord	geen afvoer van hemelwater naar de Noord	HF	Schakelmeting reageert niet, omvormer defect; einde levensduur.	pomp verpompt niet: inschakeling pomp t.g.v. hoger niveau	1	1	1	1	1	1	SAO	*N*
NOT-CI-31-xx-xx	Tracing				verwarmen ruimte terugslagkleppen & bedieningskasten	geen verwarming ruimte	HF	tracing komt niet in t.g.v. einde levensduur tracing	geen verwarming ruimte met bedieningskasten & terugslagkleppen.	1	1	1	1	1	1	SAO	*N*

Figure A7.11 : FMEA of the main pump basement (Imtech, 2013)

Step 2: Determine a suitable size/scope

Most of the work has already been done by choosing the main pump basement as a subject for the second evaluation. There are a few reasons that strengthen this decision. The main pump basement is a critical sub-system within the entire tunnel system. Using the entire water drainage and ventilations systems group as starting point means that several critical sub-systems are combined and is not desirable. The choice to take the sub-system as a starting point, with the possibility to be adjusted along the way (both up and down) was therefore made.

Step 3: Risk allocation matrix

The next step is to use the risk allocation matrix by Brommet to get a first insight in the way of outsourcing that can be used. The main pump basement was evaluated through FMECA and the acquired data will be evaluated using the risk register (Figure A7.11) and the risk matrix (Figure A7.4). For the risk allocation matrix the altered version shown in figure A7.5 is used.

The first approach uses the average MTBF of all components and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF:	1,8	(once every 5-10 years)
Average Downtime:	1	(< 2 hours)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence.

When analyzing in further detail, it can be concluded that the effect of failure is always low, therefore all failures can be found on the left side of the model. Downtime is low, costs of repairs are low and the hindrance for the users is negligible. Because of uncertainty about the MTBF however, most of the failures can be found in the lower left corner with the advice to postpone the decision about repairs until occurrence. Two failure modes are found in the upper left corner, with an MTBF of 1-5 years, and a higher likelihood of happening during the contract period (5 years). For these failure modes is advised to put them in the contract in a lump sum based way.

It should be noted that based on the data in the risk dossier, all failures have low impact and can be prevented or solved at low cost and no hindrance for the users of the tunnel. Thus, although failure modes are unpredictable, the preventive maintenance measures can be planned to help prevent the failures altogether. If in the worst case a failure might occur, the effects are very limited, thus low risk for the contractor.

Step 4: Determine a suitable contribution of the contractor

The next step is there to determine the contribution of the contractor, or the responsibility of the contractor. That is where the six-stage model is used to continue where Brommet stopped and provides even more insight on how to deal with predictability and plannability of the maintenance work. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. The MTBF intervals are quite clear for this system. There are 8 failure modes that are not so likely to occur during the contract period (MTBF 5-10 years and >10 years) and 2 failure modes that are likely to occur at least once during the contract period (MTBF of 1-5 years). The effects when occurring are really low and have no direct impact on the functioning of the tunnel. The problems can be solved fast and at low costs.

With that being said, the failures are reasonably predictable and the maintenance measures (routine maintenance) can be planned in such a way that the chances of failure can be kept relatively low at low costs. Backed by the fact that the effects of failure are also not significant, it is safe enough to give the contractor high contribution for the maintenance of this system. They will have the freedom to plan the maintenance moments and free to perform the necessary repairs and replacements that they see fit to ensure the functioning of the main pump basement. The only thing that is left out here is the replacement of the pumps. The risk dossier states that the expected lifetime of the pumps reaches at least 2028 and it is therefore not necessary to include this in the contract. If the contractor, for any reason thinks that the pumps need to be replaced earlier, they are obliged to report this to the CA who will then take a final decision.

Step 5: Determine suitable performance requirements

For the main pump basement performance requirements are in place. The system functions when $2m^3$ of water can be pumped out of the basement. If this requirement is not met, the main pump basement fails its requirements. Furthermore, no puddles should form in the tunnel (due to insufficient storage or lack of pump capacity). The last requirement is the ability to store at least $30m^3$ of water. The last one in combined with the in-ability to pump away the water is also a failure of the system.

The main pump basement is an active system with measurable performance requirements. The puddles can be seen and the causes can be traced. The pump capacity can be tested and measured in order to see if the contractor is in compliance with the set requirements.

The suggested level of the performance requirements is a performance level. The contractor should make sure that the required amount of water can be pumped away at all times and should do everything within their ability to make sure no puddles arise in the tunnel due to failures within the main pump basement.

Step 6: Cross-check the interfaces

The cross-check of the interfaces is a compatibility check which is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

For the contribution of the contractor is chosen for a full responsibility for the contractor. The contractor is free in deciding about the maintenance regime the desired maintenance interventions. The contractor is able to do everything in its power to achieve the requested performance requirements. This is in line with the suggestion to use performance levels as a performance requirement for the contractor. The contractor can receive punishment when the performance levels are not met because they are free to take every measure to prevent that from happening without interference from the CA.

The proposed solution is therefore seen realistic from a compatibility standpoint.

Step 7: Suggest a solution for the parameters

<table>
<tr><td>Size/Scope</td><td>The Main Pump Basement as one system</td></tr>
<tr><td colspan="2">Because both the effects of failure and the risk of them happening are relatively low, and the maintenance regime can be planned in a predictable way, the choice was made to outsource the main pump basement as a whole.</td></tr>
<tr><td>Contribution of the contractor</td><td>High Contribution of the Contractor</td></tr>
<tr><td colspan="2">Most of the failure modes will not occur during the contract period and the failure that have a higher probability of occurring can be mitigated with small (cheap) routine maintenance measures. The effects when a risk fires are almost negligible, thus a low risk job for the contractor where full responsibility and thus high contribution of the contractor can be expected.</td></tr>
<tr><td>Performance Requirement</td><td>Performance Level</td></tr>
<tr><td colspan="2">For the main pump basement, measurable performance requirements are available and the requesting the contractor to achieve these performance requirements is seen as acceptable with the amount of contribution of the contactor that was decided before. Therefore, the performance requirements are formulated as performance levels of which the contractor bears the responsibility of upholding those performance levels.</td></tr>
</table>

4.3 Sub-system NOT-N-61: Video and CCTV system (north and south are identical)

The video and CCTV System is a sub-system of the main category general communication system. First the functional requirements of the system group are evaluated, as well as the goal of the sub-system within the asset. This is done to provide same extra information about the part that is being evaluated. The functional requirements for the general communications systems can be found below.

Functional requirements:

- *(FE6101)* A vehicle needs to be visible on overlapping CCTV footage for the entire length of the tunnel.
- *(FE6102)* When opening an emergency box, taking a fire extinguisher or using an emergency telephone should automatically open a visual camera feed of that event on the operators screen.
- *(FE6103)* Vehicles driving too slow or against the flow of traffic should be detected and should automatically open a visual camera feed of that event on the operators screen.
- *(FE6104)* The PTZ cameras should react to the input given by the operator in the control room (movement).

Besides the functional requirements for the system group, the sub-system has a purpose to fulfill. The purpose or goal of the sub-system is explained below.

Goal: The CCTV system provides the operators in the control room with a live feed of the situation in the tunnel. The feed provides information that can be used by the operators to monitor and steer the flow of traffic or take preventive or mitigating measures in case of an incident in the tunnel.

The CCTV system consists of moving and non-moving cameras throughout both tunnel tubes. The cameras are connected to the control room, from which the entire tunnel can be monitored. The system fails when the identification of a vehicle throughout the entire length of the tunnel without interruption is no longer possible. The FMECA for both the northern and the southern tube are the same, thus only one will be taken into account during the decision process and will be the same for the other. The FMECA for the northern tube CCTV system can be found below (Figure A7.12).

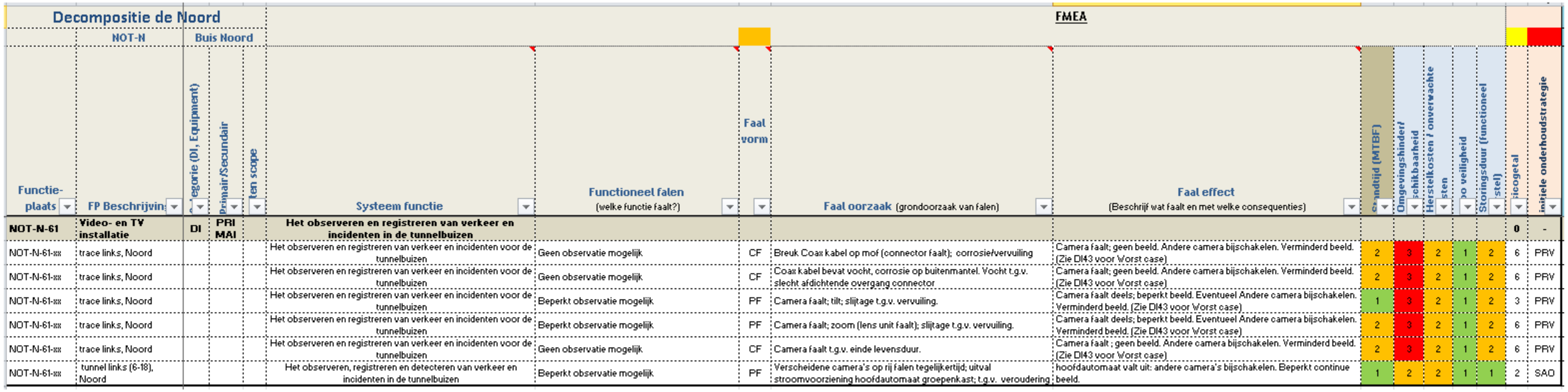
<table>
<tr><th colspan="5">Decompositie de Noord</th><th colspan="12">FMEA</th></tr>
<tr><th></th><th>NOT-N</th><th colspan="3">Buis Noord</th><th colspan="12"></th></tr>
<tr><th>Functie-plaats</th><th>FP Beschrijvin</th><th>tegorie (DI, Equipment)</th><th>Primair/Secundair</th><th>ten scope</th><th>Systeem functie</th><th>Functioneel falen (welke functie faalt?)</th><th>Faal vorm</th><th>Faal oorzaak (grondoorzaak van falen)</th><th>Faal effect (Beschrijf wat faalt en met welke consequenties)</th><th>ndtijd (MTBF)</th><th>Omgevingshinder/ schikbaarheid</th><th>Herstelkosten / onverwachte sten</th><th>o veiligheid</th><th>Storingsduur (functioneel stel)</th><th>icogetal</th><th>initiele onderhoudstrategie</th></tr>
<tr><td>NOT-N-61</td><td>Video- en TV installatie</td><td>DI</td><td>PRI MAI</td><td></td><td>Het observeren en registreren van verkeer en incidenten in de tunnelbuizen</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0</td><td>-</td></tr>
<tr><td>NOT-N-61-xx</td><td>trace links, Noord</td><td></td><td></td><td></td><td>Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen</td><td>Geen observatie mogelijk</td><td>CF</td><td>Breuk Coax kabel op mof (connector faalt); corrosie/vervuiling</td><td>Camera faalt; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)</td><td>2</td><td>3</td><td>2</td><td>1</td><td>2</td><td>6</td><td>PRV</td></tr>
<tr><td>NOT-N-61-xx</td><td>trace links, Noord</td><td></td><td></td><td></td><td>Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen</td><td>Geen observatie mogelijk</td><td>CF</td><td>Coax kabel bevat vocht, corrosie op buitenmantel. Vocht t.g.v. slecht afdichtende overgang connector</td><td>Camera faalt; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)</td><td>2</td><td>3</td><td>2</td><td>1</td><td>2</td><td>6</td><td>PRV</td></tr>
<tr><td>NOT-N-61-xx</td><td>trace links, Noord</td><td></td><td></td><td></td><td>Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen</td><td>Beperkt observatie mogelijk</td><td>PF</td><td>Camera faalt; tilt; slijtage t.g.v. vervuiling.</td><td>Camera faalt deels; beperkt beeld. Eventueel Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)</td><td>1</td><td>3</td><td>2</td><td>1</td><td>2</td><td>3</td><td>PRV</td></tr>
<tr><td>NOT-N-61-xx</td><td>trace links, Noord</td><td></td><td></td><td></td><td>Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen</td><td>Beperkt observatie mogelijk</td><td>PF</td><td>Camera faalt; zoom (lens unit faalt); slijtage t.g.v. vervuiling.</td><td>Camera faalt deels; beperkt beeld. Eventueel Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)</td><td>2</td><td>3</td><td>2</td><td>1</td><td>2</td><td>6</td><td>PRV</td></tr>
<tr><td>NOT-N-61-xx</td><td>trace links, Noord</td><td></td><td></td><td></td><td>Het observeren en registreren van verkeer en incidenten voor de tunnelbuizen</td><td>Geen observatie mogelijk</td><td>CF</td><td>Camera faalt t.g.v. einde levensduur.</td><td>Camera faalt ; geen beeld. Andere camera bijschakelen. Verminderd beeld. (Zie DI43 voor Worst case)</td><td>2</td><td>3</td><td>2</td><td>1</td><td>2</td><td>6</td><td>PRV</td></tr>
<tr><td>NOT-N-61-xx</td><td>tunnel links (6-18), Noord</td><td></td><td></td><td></td><td>Het observeren, registreren en detecteren van verkeer en incidenten in de tunnelbuizen</td><td>Beperkt observatie mogelijk</td><td>PF</td><td>Verscheidene camera's op rij falen tegelijkertijd; uitval stroomvoorziening hoofdautomaat groepenkast; t.g.v. veroudering</td><td>hoofdautomaat valt uit: andere camera's bijschakelen. Beperkt continue beeld.</td><td>1</td><td>2</td><td>2</td><td>1</td><td>1</td><td>2</td><td>SAO</td></tr>
</table>

Figure A7.12: FMEA of the video and CCTV system (Imtech, 2013)

Step 2: Determine a suitable size/scope

Most of the work has already been done by choosing the video and CCTV system as a subject for the second evaluation. There are a few reasons that strengthen this decision. The video and CCTV system is a critical sub-system within the entire tunnel system. Using the entire general communications systems group as starting point means that several critical sub-systems are combined and is not desirable. The choice to take the sub-system as a starting point, with the possibility to be adjusted along the way (both up and down) was therefore made.

Step 3: Risk allocation matrix

The next step is to use the risk allocation matrix by Brommet to get a first insight in the way of outsourcing that can be used. The video and CCTV system was evaluated through FMECA and the acquired data will be evaluated using the risk register (Figure A7.12) and the risk matrix (Figure A7.4). For the risk allocation matrix the altered version shown in Figure A7.5 is used.

The first approach uses the average MTBF of all components and the average of the effects (in this case downtime). This will deliver the following outcome:

Average MTBF: 1,667 (once every 5-10 years)
Average Downtime: 1,833 (2-24 hours)

This means that most of the work will probably fall within the lower left corner of the model, proposing to outsource the work via target price/cost reimbursable by a party that can manage the work best, and most important, to postpone the decision for the work until occurrence. But this is only when just MTBF and downtime are taken into consideration. The hindrance averages around 2.83, which is a significant effect for the user and high probability of traffic jams. This will influence the maintenance regime, because this has to prevented if possible. This will also be further discussed within the six-stage model and the performance requirements.

Based on Brommet, the decision should be to postpone the decision to intervene until more certainty can be provided. This can be done in a cost-reimbursable way. Whether this will hold depends on the outcomes of the six-stage model and the performance requirements.

Step 4: Determine a suitable contribution of the contractor

The next step is there to determine the contribution of the contractor, or the responsibility of the contractor. That is where the six-stage model is used to continue where Brommet stopped and provides even more insight on how to deal with predictability and plannability of the maintenance work. The six-stage model uses predictability and plannability to decide whether the contractor will be able to be responsible for certain tasks. The MTBF intervals are quite clear for this system. All of the 6 failure modes that are not so likely to occur during the contract period (MTBF 5-10 years and >10 years).

The effects that failure modes have when occurring however need to be looked at in some more detail. The costs and the downtime are manageable and can be found in de lower left corner of Brommet, meaning that effects are acceptable. The hindrance however has a severe impact on the functioning of the tunnel and needs to be avoided if possible.

Given that the impact is very unwanted, the FMECA suggests preventive maintenance on all but one of the possible failure modes. This makes the maintenance of this system both predictable and plannable, given the MTBFs that are available and the routine maintenance jobs that are proposed to prevent the failures from happening. With this in mind it becomes easy for the contractor to predict what to expect for the duration of the contract period and will therefore be able to provide a high contribution to the maintenance work.

Final decisions concerning replacements of all cameras with new ones stays within the CA due to rapid developments in techniques. Given that most of the cameras have already been replaced in 2011, this is not an issue for this contracting period. If cameras should fail during the current contract period and can't be repaired, they are replaced with available spare cameras of the same type. This is not seen as the kind of replacement as mentioned above and the contractor is free to do so. If the spare camera is not available, the contractor should ask the CA whether a new replacement camera should be acquired and what kind of camera that should be. The advice therefore is high contribution for the contractor with the exception of the replacement decision.

Step 5: Determine suitable performance requirements

For the video and CCTV systems are general functional requirements available. The most crucial being that a vehicle needs to be visible on overlapping CCTV footage for the entire length of the tunnel. This is however not a performance requirement that is given to the contractor. According to the risk dossier, the performance requirements for this system are not yet available. When looking at the system there is no clear and measurable data, other than the system fulfilling its functional requirement or not. Essentially, the minimum requirement is whether the camera provides feed to the control room or fails to do so.

Because this system is paramount for monitoring events in the tunnel and therefore ensuring the safety in the tunnel, failure of the entire system or a part of the system should be prevented. The performance requirements should therefore be high enough to ensure that the system works properly all the time. The main requirement should therefore be that the cameras work. The exact way that this requirement is formulated should be dependent on the situation. If redundant cameras are in place a requirement could state that certain cameras may not fail simultaneously, and in case of failure state a maximum repair time.

The suggestion is to use levels of intervention as a performance requirement. The requirement should be a minimum amount of working cameras with a list of cameras that cannot fail simultaneously and a maximum downtime in case of failure.

Step 6: Cross-check the interfaces

The cross-check of the interfaces is a compatibility check which is meant to find discrepancies between the different variables. Depending on the choice that is made for the level of performance requirements, the contribution of the contractor and with that the amount of responsibility/risk for the contractor needs to be adjusted.

For the contribution of the contractor is chosen for a full responsibility for the contractor. The contractor is free in the choices about the maintenance regime the desired maintenance interventions. The contractor is able to do everything in its power to achieve the requested performance requirements. This is in line with the suggestion to use levels of intervention as a performance requirement for the contractor. The contractor has no control over replacements of cameras with newer cameras unless this is cleared with the CA first. This however does not affect the ability of the contractor to achieve the requirements. If the contractor thinks that the requirements cannot be met with the current system (due to age or a technical malfunction) this can be brought to the attention of the CA. The CA can then decide how to proceed. The contractor is then no longer responsible for failure caused by problems he warned them for. The contractor can receive punishment when the performance levels are not met because they are free to take every measure to prevent that from happening without interference from the CA (with the exception of replacement with newer models).

The proposed solution is therefore seen realistic from a compatibility standpoint.

Step 7: Suggest a solution for the parameters

<table>
<tr><td>Size/Scope</td><td>Video and CCTV as one system</td></tr>
<tr><td colspan="2">Because the system can be maintained with a very predictable maintenance plan, the regime can be planned in advanced and most of the components can be approached in the same way the suggestion is to outsource the video and CCTV system as a whole.</td></tr>
<tr><td>Contribution of the contractor</td><td>High Contribution of the Contractor</td></tr>
<tr><td colspan="2">The failure modes of the video and CCTV system have a high MTBF, meaning that the chances of failure during the contract period are relatively low. The average downtime and the cost for repairs are also not really high. The only thing that scores badly is the hindrance for the end users (both operators and traffic in the tunnel) in case of failure. This is why preventive maintenance for most of the components is advised. This makes the maintenance regime plannable and the work of the maintenance contractor predictable and the risks are relatively low. This is why a high contribution of the contractor is suggested.</td></tr>
<tr><td>Performance Requirement</td><td>Levels of intervention</td></tr>
<tr><td colspan="2">For the video and CCTV system, no clear measurable performance requirements are available. Therefore, performance levels are hard to use. That’s why one level down, the levels of intervention are chosen as the suggested form of outsourcing. These performance requirements can be formulated in a more general way and still stay in line with the high contribution of the contractor that was suggested.</td></tr>
</table>

Appendix 8

Introduction of the decision-making process

Appendix 8: Introduction of the decision-making process

During the case study was found that certain information from the perspective of the CA, the organization and the market was missing. For optimal decision-making this information should actually be available. That is why this decision-making process was introduced. The decision-making process takes a look at the bigger picture that surrounds the decision-support method and deals with the questions regarding the viewpoint of the CA, the state of the organization and the capabilities of the market. Although the decision-support method is the most important part of this thesis, the process in its entirety is important for well-informed decision making. The considerations and aspects that are not included in the decision-support method are treated in other steps of the decision-making process.

In this appendix, the current decision-making process is briefly explained to create an 'as is' situation to compared to this newly developed methodology. The entire process, which consists of 5 steps, will be introduced and explained. The actual process that is introduced here which is outside the scope of the thesis, is meant to purely lay out the opportunities to fill the absence of information when working with the decision-support method. This newly introduced process will therefore not be tested on a real case.

Current decision-making process

The use of PBMC is increasing rapidly. Since the introduction of this new type of contract it has experienced a rapid growth. Systems, or at least the information about the systems, was not ready for this type of contracts. Although that has improved over the years, it is not yet integrated in the contract design methodology. Because of this, many PBMC do not reach their full potential. There is no clear indication of the possibilities and choices that are available within the performance contracts. The information is only gathered when necessary and provided only if it is already available because there is no clear need for that information in the first place. Literature that describes the decision process in current contract design teams is from van Rhee (van Rhee, Kaelen, & van de Voort, 2009) and Stankevich (Stankevich, Qureshi, & Queiroz, 2005). In literature, an attempt is being made to give some tools that can be used when writing a PBMC, but are more focused on the process after the necessary information that is needed found.

Through interviews, conversations and discussions with employees from Rijkswaterstaat about the current contracting process, a lot of information was gained about the current practices with regards to designing PBMC. Although this is only the view from Rijkswaterstaat's perspective, it is a big, growing and progressive organization and this view will give a good insight in how these contracts are written at this time. Especially the processes that are being used, the ways information is gained, the kind of information that is gained and the way everything is evaluated and used to base the decisions within the contracts on is very interesting for the writing of this thesis.

The current process of designing PBMC poses great challenges for the contract design team. Necessary information is hard to find, the process of gathering the information is slow, and there is no clear guideline about what information should be available. The structure that can help them find the right information and which gives assurance that the information is available and ready to use is simply not present. Even though Rijkswaterstaat is developing and trying to improve that by gathering more and more data, the results are not yet there. The lack of structure in the approach might be a cause of this. Another point that was addressed by the contract design team was the use of a P-IHP (*Prestatiegestuurd Instandhoudingsplan*) or performance-driven conservation plan. The use of this technique from the RCM-family is developed to help the contract design team in their contract design, focusing on the necessary actions to ensure that the performances are being met. The big disadvantage of this method is the depth that is used (in most cases only the critical components are evaluated), the lack of diversity in the solution space and reasoning behind this method that is used. The problem here is not necessarily the methodology, but also the way the results are interpreted and used. This results, according to the experts, to a situation where the most suitable option is not always an available option. As an example, all critical components that are found with this methodology are almost automatically being assigned as RWS responsibility, without further reasoning. Whilst this is not always the most suitable option.

Another issue that is addressed by the experts is the lack of structured reasoning. This results to repetitive discussions of the same problems all the time, even within the same projects. With a clear structure and line of reasoning (method or model) this might be prevented, leaving more room for discussions that really matter. The lack of structure also results to a lack of good numbers that can be used whilst designing the contract. Acquiring accurate figures at this stage is really challenging, because the current methodology does not inspire to get the figures up to standard. This makes the job of the contract design team though and results in a lot of time wasted in search for information that can be used to design the contracts.

The fact that information is hard to be obtained results to the fact that the contracts are being kept as safe as possible and are roughly based on the previous contracts. Due to this, many tasks are written instructions and the performance requirements are kept as simple as possible, often because there is no data to do otherwise.

The contract design team must dig up information of every individual system one by one in order to base the outsourcing decisions on. Because there is no clear guideline and standardized information is not yet available, designing the contracts is a hunt for good intel. The experts regret this, because valuable time is lost finding information, that otherwise could be used to explore new solutions and options. They are eager to have a solid structure and clear methodology that simplifies and supports their request for certain information in such a way that the supply of this information becomes natural. The methodology should be able to substantiate the decisions that are taken during the decision-making process in other to avoid unnecessary discussions in the future.

In order to meet those needs, the decision-making process has been introduced to cut the process into a set of easy to follow steps. By using these steps, the need for information is justified and can become part of the methodology. It will also justify the eventual decision that are made by the contract design teams in the future and makes repetitive discussions obsolete. The following sections describe the outline of the decision-making process.

Introducing steps of the decision-making process

The structure of the decision-making process is an important factor in reaching the required outcome. If the process is not structured properly, the advantage of using this process is nullified. To create this structure, the process is divided into several steps. Every step contributes to the final result in its own way. Some are meant to establish a starting point, some are included to acquire data or information and others are used to value or evaluate certain decisions. But all are necessary to reach the eventual goal of providing the user with insight on the possible decisions that can be taken when making the PBMC.

The process is therefore cut into the following 5 steps:

- Determination of ambition and goals
  At the start of the process, the organizational ambition and goals they want reach with the new contract need to be expressed and have to be clear. They will determine the direction that is taken during the decision process.
- Exploration
  During the exploration phase the total scope of the contract is determined, the current state of the assets (and asset information) is established. As well as the current state of the organization and the market. This is set out against the ambition and goals that were set.
- Determination of strategies
  During the exploration, opportunities and problems are found. A strategy needs to be determined to show which opportunities should be taken, intentions to solve certain problems, and decide which problems are left as is.
- Decision-support method
  The decision-support method is used to guide every individual part of the asset through the solution space in order to give a suggestion about the way of outsourcing that might work best for that particular part of the contract.
- Concept decision and conclusions
  A list of conclusions and concept decisions comes from the decision-support method and need to be evaluated through expert judgement and converted to final decisions that can be used in the contract.

The decision-making process

This chapter is dedicated to development and the explanation of all the different steps of the decision process. Every step has a purpose in the eventual process and will be executed the same way, independent of the company or specific job or assignment that it is used for. By implementing one general approach the decision process can be used for PBMC throughout the entire infrastructure maintenance sector. This will especially be true for the determining the ambition and goals, exploration and determining strategies and the concept decisions and conclusions part. The decision-support method itself might differ a little bit from user to user. Although the aspects and considerations are chosen to be as general as possible, some are specifically used in a certain sector and are necessary to be kept in (or in-/excluded from) the method to make it work. This is due to the fact that some aspects might be extremely important in a certain sector, whilst others might not even be a consideration at all.

The next sections are used to explain the process and will be used as a guide through all the steps.

Determination of goals and ambition

This first step is important because it will test whether this process fits within the ambition and the goals of the organization. The process is aimed at getting the most out of PBMCs. When there is no ambition within the organization to use PBMCs, it is just a waste of time to continue with this process. When it is clear that there is at least the ambition, or it is even a goal for the organization to use PBMCs, continuing with this process will be meaningful.

When starting the process, the organization needs to have a clear ambition and have set SMART goals in order to reach the most effective outcome of these steps. The reason this is important is because it will determine the direction that the company likes to pursue for this particular job. Different ambitions and goals will deliver different results when following these steps.

The ambition describes the desire to do or achieve something and will decide the amount of determination of the company to achieve a success. The goals are the objects of the company's ambition; 'an aim or desired result'. (Oxford Dictionaries, 2018) In short this means that the company first comes up with an ambition, 'what is it that we want to achieve', an ultimate goal so to speak. And in the next step realistic goals are formulated that need to be achieved in order to realize that ambition.

For coming up with an ambition, no strict rules apply. The ambition can be an ultimate goal or a deep desire to achieve something. The only thing that is important is that the company stands by that ambition and is determined to pursue it. The company will have to pursue the ambition by setting goals in such a way that they work towards achieving the ambition. In order to do that, the goals need to be formulated very carefully. One of the most common mistakes made when setting goals is making them too vague or open-ended. At that point they can be compared with wishes, good intentions or even like an ambition, rather than actual goals. In order to prevent the use of weaker goals, the goals will have to formulated in a SMART way. SMART is a principle that is frequently used within project management work, where the method helps to clarify the actual goal and desired results, making it more manageable and increasing the success rate. SMART is an acronym that can be used to guide your goal setting and when using it, most managers will understand what you mean. It was first introduced by George T. Doran in a 1981 issue of Management Review (Doran, 1981).Throughout the years, SMART goals have been developed and changed, depending on the situation they were applied to. Professor Robert S. Rubin (Saint Louis University) even stated (The society for Industrial and Organizational Psychology) that SMART has come to mean different things to different people. So, the SMART principle doesn't have one particular meaning anymore. The next example shows the original meaning by George T. Doran and the alternative meanings that were thought up over time as state by Robert S. Rubin (between brackets). So the acronym SMART means that the goals should at least be:

- Specific (Simple, Sensible, Significant)
- Measurable (Meaningful, Motivating)
- Attainable (Agreed, Acceptable, Achievable)
- Relevant (Reasonable, Realistic, Resourced, Result-Based)
- Time bound (Time-based, Time-Limited, Time/cost-limited, Timely, Time-sensitive)

A **SPECIFIC** goal should clearly define what you are going to accomplish. The main questions that should be answered are what the goal is and why it is important to achieve.

A **MEASURABLE** goal is needed to see how the goal will be achieved. How will you know the result has been achieved and how will you verify the achievement or performance of the goal. It is therefore important to identify criteria for measuring the progress towards the achievement of each goal.

An **ATTAINABLE** goal means that it should be possible to achieve a certain goal. Is it possible to see the path that leads to the accomplishment of the goal? Furthermore it is important to state who is going to be able to reach that goal.

A **RELEVANT** goal is important to keep the willingness to achieve that goal. It must be a realistic goal and represent an objective the organization is willing to work for to achieve. It should be clear where the goal will take the organization, which progress will be made and what future possibilities will this particular goal/achievement create.

A **TIME BOUND** goal will create a sense of urgency. By setting times for each step along the way people stay motivated and know when certain tasks should be accomplished to reach the goal. Besides that, it creates the possibility to keep track of and account for all the steps needed to accomplish the goal.

By focusing the attention on these five areas while setting the goals, the chances of successfully achieving the goals get increased. When an organization gets familiar with the use of SMART, it can opt for the use of two more areas, which are aimed at reviewing and improving the use of SMART goals. The acronym is then extended into SMARTER by including the following areas:

- Evaluated
- Reviewed

By **EVALUATING** the SMART goal setting process by measuring to what extent the set goals have been achieved, improvements can be made in the use of SMART goals when using them the next time. The goals can also be changed in order to reduce the time needed to achieve the goals.

By **REVIEWING** the approach or behavior to reach the goal through reflection, adjustments can be made to increase the effectivity of the SMART goals making it easier to accomplish the goals that were set.

By determining the ambition and the goals help the creators of the new contract to make their decisions in line with the view that the company has for the foreseeable future. This should be done for every job where this decision process is used. Although the ambition that the company has will probably stay similar between different jobs. Certain specific areas might have other levels of ambition than others, which makes this step still very important. The goals are also job specific and should be considered every time a new job/contract is being made in order to have goals that are specifically tailor-made for this job.

Exploration

Now that the ambition and the goals are clear, it is time for the next phase. This is the exploration phase. The exploration phase is meant to get as much information about the object(ive) and the organizations that are involved in the preparation and execution of the PBMC. This information is not only about the actual size of the job (contract), but also about the current state of the object of which the maintenance will be outsourced through this contract. This gives a total of 4 areas which the exploration phase is focused on:

- The own organization
- The market
- The scope of the contract
- The object

During the exploration phase, the goal is to get a clear view of the current state of the organization, the market, the job that needs to be done and the actual object in comparison to the set ambition and goals considering the new PBMC that is being prepared at that time. By comparing the current state with the ambition and goals, it should become clear where things are already pretty good, where improvements can be made and where drastic solutions are needed to achieve the goals in the first place. The information that is needed differs depending on the area it refers to. Furthermore, the impact of the four different areas will be explained and it will become clear that some may become more important in the decision-making process that others.

The state of the own **ORGANIZATION** forms an important aspect in the decision-making process. The own organization can be the cause of some opportunities or possibilities to be open or that some options aren’t even possible to begin with. This can have many different reasons and that’s why it is important to get the information that can give insight in these matters. The gathering of this information will be used for determining the strategies in the next phase and answering the questions about the different important aspects and considerations in the decision model.

Important aspects to consider here are: the capacity within the organization to manage the job, the internal knowledge about the specific components and procedures within the asset, the available funds for the repairs and renewal of components, the experience with the current asset, wishes and demands from within the organization (higher management) and more along this line.

The state of the **MARKET** is also important. What can be expected of the market? Is there enough knowledge available, what kind of market parties does the new contract attract and is this desirable? Can the risks of the job be trusted to the market or are the risks too big to put on one party? Eventually the exploration on this topic should provide insight of what can be expected of the market with respect to the current job/assignment and the planned contract.

The **SCOPE** of the contract is a different scope than was used in the other parts of this thesis. The scope that is mentioned here is the complete scope of the contract. This part of the exploration phase is aimed at getting the complete picture of everything that will be (or is at least planned to be) in the new contract. This is done by mapping every asset, systems and sub-systems that will be part of the contract, as well as all the tasks that need to be outsourced within this contract. This part tells nothing about the available information or the way things are going to be outsourced, but it is just an assessment of all the parts that need to be put in the contract.

The last part of the exploration phase is about the **OBJECT** itself. This time it is important to acquire as much information about the technical state and the history of the different assets, systems, and sub-systems that were stated in the previous part (scope of the contract). This part will be the core of the input for determining the strategies and moving through the decision model. The information that is found here will be used to answer the questions that many aspects and considerations raise about how to deal with the scope, performance requirements and the contribution of the contractor within the newly written PBMC.

Where the previous factors were mostly factual and managerial, this last factor is focused on the technical part of the objects that are being outsourced. During this phase insight has to be acquired about the everything that can be expected to happen during the duration of the new contract. That is where RCM and the FMECA come in. Complemented by available risk dossiers and an overview of all the known malfunctions of the previous years a realistic image can be created about the state of the tunnel. This will be used to gain insight in the reliability and predictability of the tunnel for the next contract period. Using this information, many of the considerations can be made.

Determination of strategies

At this stage, the ambition and the goals are set and information about the organization, the market, the scope and the object are present. It can occur that the ambition/goals are not in line with the current state of the organization, the market or the object. An example could be that the ambition is to keep the responsibility for as much of the work as possible, but the organization does not have enough capacity to realize that. The strategy can then be to pursue that ambition by hiring more people, that way the capacity problem can be solved. The other option is to specify the ambition some more and thereby lowering the required capacity. This can be done by specifying certain areas where the responsibility can be given to the contractor (lower capacity needed from the CA) and keep the most important/crucial/critical parts under CA Control and responsibility.

The chosen strategy will further influence what considerations will be made during the use of the decision-support method.

The decision-support method

At this point the decision-support method is used. The method consists of the 7 steps that where introduced and explained in chapter 4 and concluded with the final design of the decision-support method. During these steps, the final design of the decision-support method in appendix 9 is used in a structured way to review the most main decision criteria that were determined in chapter 3.3. These criteria are criticality, predictability, plannability, responsibility and measurability. In this section the of the decision-support method are just mentioned. The elaborate explanation is to be found in chapter 4 or Appendix 9, where the complete method is explained and visualized.

- ***Step 1: Case analysis using FMECA and redesigning the Risk Allocation Matrix***
- ***Step 2: Determine a Suitable Size/Scope***
- ***Step 3: Risk Allocation Matrix***
- ***Step 4: Determine a Suitable Contribution of the Contractor***
- ***Step 5: Determine Suitable Performance Requirements***
- ***Step 6: Cross-Check***
- ***Step 7: Suggested solution***

The proposed solution

The last step delivers a concept decision about the way outsourcing can be done. The method can however only take so many considerations into account and things can and probably will be missed. This concept decision is a starting point for experts to reach a conclusion. The concept results will be discussed and tested for feasibility within the context of the contract. The final decision will be made outside of the decision-making process.

Appendix 9

Final design of the decision-support method

Appendix 9: Final design of the decision-support method

The decision-support method is designed to bring all theory and practical experience that has been gathered in chapters 3 and 4 together in one clear methodology. Eventually this method will help the contract design team to take every step, make every necessary considerations, use all necessary information and the appropriate tools to make an informed decision about how to outsource certain parts of the contract through a PBMC. The method pays attention to the gathering of information and using that information to help identify the most appropriate options within the solution space.

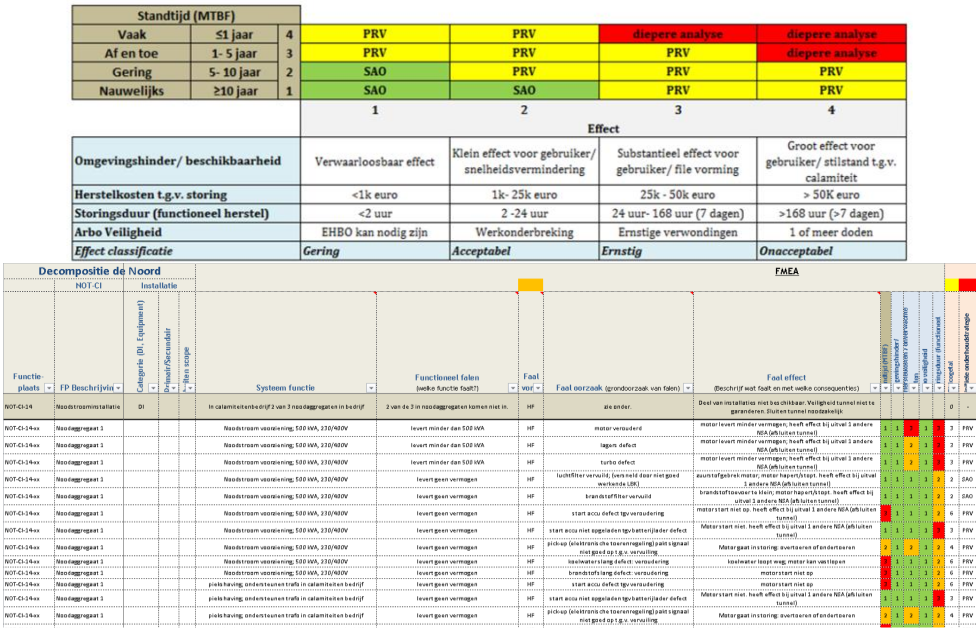
There is an important reason why this method is called a decision-support method, rather than a decision-making method or model. The use of this method is not by making simple yes or no decision. A great amount of expert judgement and knowledge about the assets is still necessary to make the eventual decision. The method however supports the contract design team in searching and finding necessary information, evaluating the options and come up with an informed conclusion about the suggested way of outsourcing through a number of steps. During these steps the most important decision criteria and important considerations are brought up in a structured way. That is how the decision-support method will help the contract design team in their decision-making process.

The method is divided into seven separate steps which will be explained in the remainder of this appendix.

Step 1: Case analysis using FMECA and transition of the risk allocation matrix

The first step is about information gathering. Three of the important decision criteria are predictability, plannability and criticality. In order to make the decision within the solution space, these criteria need to be evaluated beforehand. To do that information is needed. Information about these criteria with respect to the object/asset at hand can be gain through risk models. For this method it had been decided to use the RCM method and start with making an FMECA. The reason for the use of FMECA is the fact that it is easy to understand, able to be adapted to any situation (simple, quick, extensive) and can be varied in depth. It is therefore just as applicable to large contracts as it is to smaller jobs.

The method therefore starts with making an FMECA and gathering information about predictability, plannability and criticality of the entire scope of the contract. The risk matrix has to be made and the thorough FMECA insight has to be obtained in the failure modes of an asset/system/object and gathered in a risk register.



Standtijd (MTBF)						
Vaak	≤1 jaar	4	PRV	PRV	diepere analyse	diepere analyse
Af en toe	1- 5 jaar	3	PRV	PRV	PRV	diepere analyse
Gering	5- 10 jaar	2	SAO	PRV	PRV	PRV
Nauwelijks	≥10 jaar	1	SAO	SAO	PRV	PRV
			1	2	3	4
			Effect			
Omgevingshinder/ beschikbaarheid			Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing			<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)			<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid			EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie			***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Decompositie de Noord

NOT-CI | Installatie

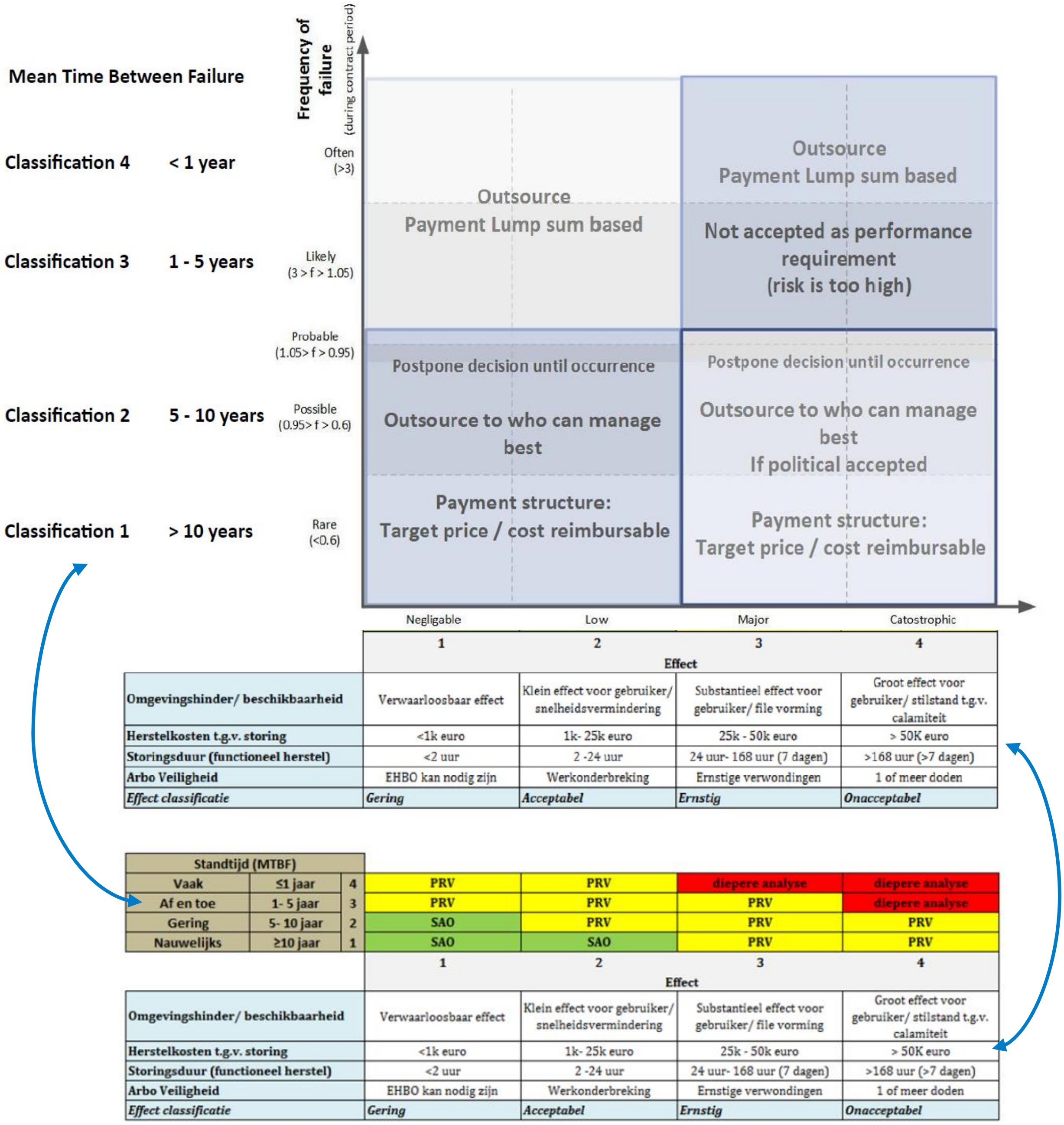
FMEA

Functie-plaats	FP Beschrijvin	Categorie (DI, Equipment)	Primair/Secundair	...iten scope	Systeem functie	Functioneel falen (welke functie faalt?)	Faal vor	Faal oorzaak (grondoorzaak van falen)	Faal effect (Beschrijf wat faalt en met welke consequenties)	...ndtijd (MTBF)	...gevingshinder/	...ten	...o veiligheid	...ringsduur (functioneel	...cogetal	...iele onderhoudstrategie
NOT-CI-14	Noodstroominstallatie	DI			In calamiteitenbedrijf 2 van 3 noodaggregaten in bedrijf	2 van de 3 in noodaggregaten komen niet in.	HF	zie onder.	Deel van installaties niet beschikbaar. Veiligheid tunnel niet te garanderen. Sluiten tunnel noodzakelijk						0	-
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	motor verouderd	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	3	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	lagers defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert minder dan 500 kVA	HF	turbo defect	motor levert minder vermogen; heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	2	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	luchtfilter vervuild; (versneld door niet goed werkende LBK)	zuurstofgebrek motor; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstoffilter vervuild	brandstoftoevoer te klein; motor hapert/stopt. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	2	2	SAO
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	koelwaterslang defect: veroudering	koelwater loopt weg; motor kan vastlopen	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				Noodstroom voorziening; 500 kVA, 230/400V	levert geen vermogen	HF	brandstofslang defect: veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu defect tgv veroudering	motorstart niet op	3	1	1	1	2	6	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	start accu niet opgeladen tgv batterijlader defect	Motorstart niet. heeft effect bij uitval 1 andere NSA (afsluiten tunnel)	1	1	1	1	3	3	PRV
NOT-CI-14-xx	Noodaggregaat 1				piekshaving; ondersteunen trafo in calamiteiten bedrijf	levert geen vermogen	HF	pick-up (elektronische toerenregeling) pakt signaal niet goed op t.g.v. vervuiling	Motor gaat in storing: overtoeren of ondertoeren	2	1	2	1	2	4	PRV

Figure A9.1: Example of the use of FMECA (risk matrix - *top* - & risk register - *bottom* -) (Imtech, 2013)

When the FMECA is done and the information is gathered, preparations will be made for the use of the risk allocation matrix in step 3. The risk allocation matrix needs to be adjusted to the object that is being evaluated. The model was originally designed for DBFM contracts for sluices. The impact of malfunctions and repair time is completely different in comparison to a tunnel or a highway. This risk matrix can be used to see what MTBF (mean time between failure) steps are used to make an educated estimation about the frequency of failure that can be used within the model. On the other axis the effects are evaluated, in case of the sluices, the effect was expressed in average repair time. The risk matrix also says something about different kind of effects and the acceptability of these effects. With this information, the model can be adjusted to the specific needs of a certain object.

The figure below (Figure A9.2) shows the original risk allocation matrix and the adaptation through the use of the risk matrix that was made during step one. The MTBF have been used to classify the frequency of failure and the effects have been coupled to the scale of the original model, making it usable with help of the risk register of the FMECA that was found at the beginning of this step.



	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
Storingsduur (functioneel herstel)	<2 uur	2 -24 uur	24 uur- 168 uur (7 dagen)	>168 uur (>7 dagen)
Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Standtijd (MTBF)						
Vaak	≤1 jaar	4	PRV	PRV	diepere analyse	diepere analyse
Af en toe	1- 5 jaar	3	PRV	PRV	PRV	diepere analyse
Gering	5- 10 jaar	2	SAO	PRV	PRV	PRV
Nauwelijks	≥10 jaar	1	SAO	SAO	PRV	PRV
			1	2	3	4
			Effect			

	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
Herstelkosten t.g.v. storing	<1k euro	1k- 25k euro	25k - 50k euro	> 50K euro
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Arbo Veiligheid	EHBO kan nodig zijn	Werkonderbreking	Ernstige verwondingen	1 of meer doden
Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A9.2: Transition of Risk Allocation Matrix (using the risk matrix) based on Brommet (2015) & Imtech (2015)

Step 2: Determine a suitable size/scope

In the first step information was gathered about the most important decision criteria. During this step, the first of the three main parameters is set. This is not final, but creates a starting point to continue on to step three. This step is used to find the biggest single element that can be outsourced as one piece.

This is done by using FMECA to obtain information about the criticality of certain systems, sub-systems or components within the total scope. The level where the criticality originates might help determine what size/scope should be used. The size/scope that is used to start with is the lowest size/scope where a system critical component can be found. After this size/scope is chosen, the remaining steps are performed. If the decision appears to be wrong during the performance of the remaining steps (it was too big of too small) the user is left with the possibility to adjust the size/scope along the way (both up and down) in accordance to the situation that is found.

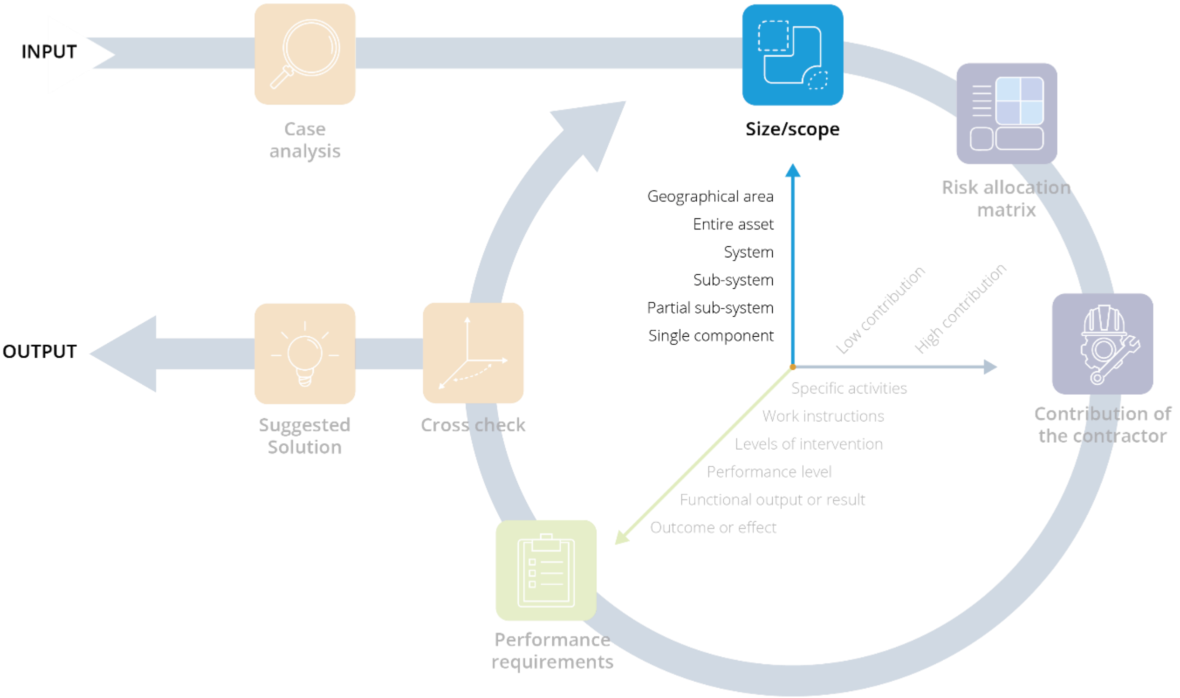


Figure A9.3: Solution space - size & scope

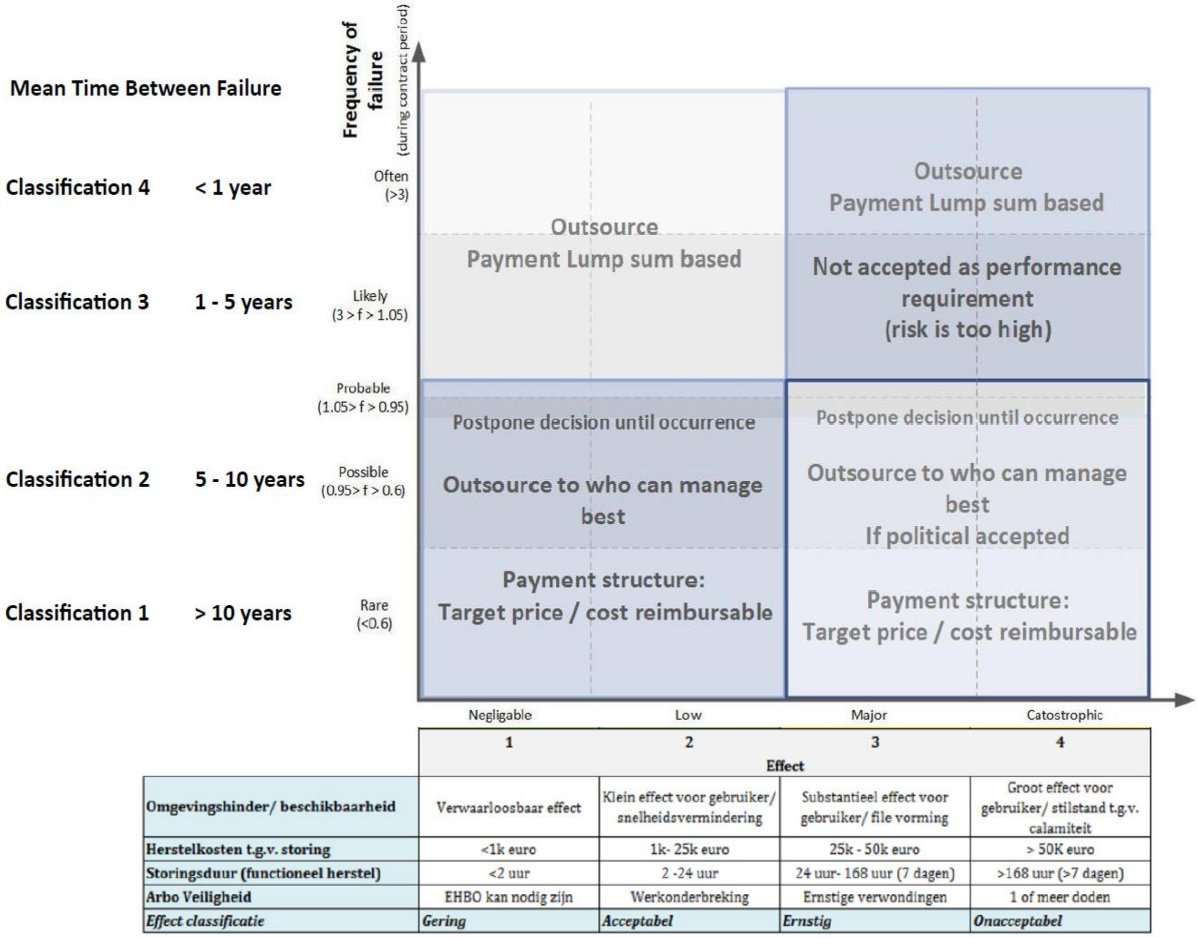
In order to choose an appropriate level, the information gathered from the FMECA should be used. The criticality of a certain part might be a reason to separate it from the rest and use that particular component, system of asset as a starting point. Predictability, however, can also be a deciding factor in choosing an appropriate level for size/scope to start with. When a system is very predictable, it might be easier to keep it together as a whole when outsourcing it. However, if a the sub-systems have a very diverse behavior with respect to predictability of the maintenance, it can be wise to lower a level at start by evaluating the separate sub-systems first. This process involves a high amount of expert judgement and experience, guided and supported by the information that is gained with the FMECA and the use of the most important decision criteria.

Step 3: Risk allocation matrix

The next step is to use the risk allocation matrix by Brommet. By using the risk allocation matrix, a first suggestion is done about the method of outsourcing that can be used based on predictability and plannability of maintenance of an object. Besides the two already mentioned decision criteria, risk division is also evaluated as part of using this matrix. This says something about where the responsibility for certain decision should be. For this step, the altered risk allocation matrix that was created in step 1 of the decision-support method is used. The altered risk allocation matrix can be found in figure A9.4 on the next page.

First the MTBF and the average downtime of that component needs to be found in the FMECA. This is standard data and should be available. The answers can be plugged into the risk allocation matrix and give a suggested answer to the question on how to outsource a certain part.

Secondly, the results need to be looked at in further detail. The first suggestion is based on the average that could be found by combining all individual parts into one big pile of data. Now it is key to take a closer look and try to find the extremes. These could be the parts with the highest frequency of failure (short MTBF and high probability) and the highest downtime. The possibility remains that on closer investigation it turns out to be wise to exclude the extremes from the bigger picture to increase the reliability of the results. This means that the size/scope for that part is then adjusted and an individual conclusion needs to be drawn for that specific part at the last step of the decision-support method. The outcome of this step will then be carried on to the next step.



	1	2	3	4
	Effect			
Omgevingshinder/ beschikbaarheid	Verwaarloosbaar effect	Klein effect voor gebruiker/ snelheidsvermindering	Substantieel effect voor gebruiker/ file vorming	Groot effect voor gebruiker/ stilstand t.g.v. calamiteit
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Effect classificatie	***Gering***	***Acceptabel***	***Ernstig***	***Onacceptabel***

Figure A9.4: Altered risk allocation matrix based on Brommet (2015) & Imtech (2015)

Step 4: Determine a suitable contribution of the contractor

Step 1 and step 3 have been used to gather and analyze the available information to initiate the decision-support method. The following step takes the decision criteria predictability and plannability a step further. This is where the amount of contribution of the contractor is decided. The information that is used to decide this can also be extracted from the FME(C)A. The results of the use of the risk allocations matrix are also taken into account when making the suggestion here.

From the risk allocation matrix an overall judgement can be derived concerning the predictability of the failures that occur. Besides the information that is provided from this matrix, the results from the FMECA can be used to define the predictability of failures. The MTBF gives an indication on the failure rate of a component. Interpretation of these results depend on the strategy that the CA is willing to choose. Shorter MTBF equals higher failure rates, but countered with a good maintenance strategy will be very plannable. Longer MTBF equals lower failure rates are less predictable thus harder to plan. This results to lower predictability and plannability. Eventually, the decision is highly dependent on the strategy of the CA and the expert judgement that is given during the execution of the decision-support method.

Note that the size/scope can be changed during this step due to the information that becomes available during this step. (Strongly, this also happened during the first run of the case study where two different approaches where suggested for different parts of the system)

Based on that information, the expert judgement and the strategy of the CA, a suggestion is made for the extent of contribution of the contractor.

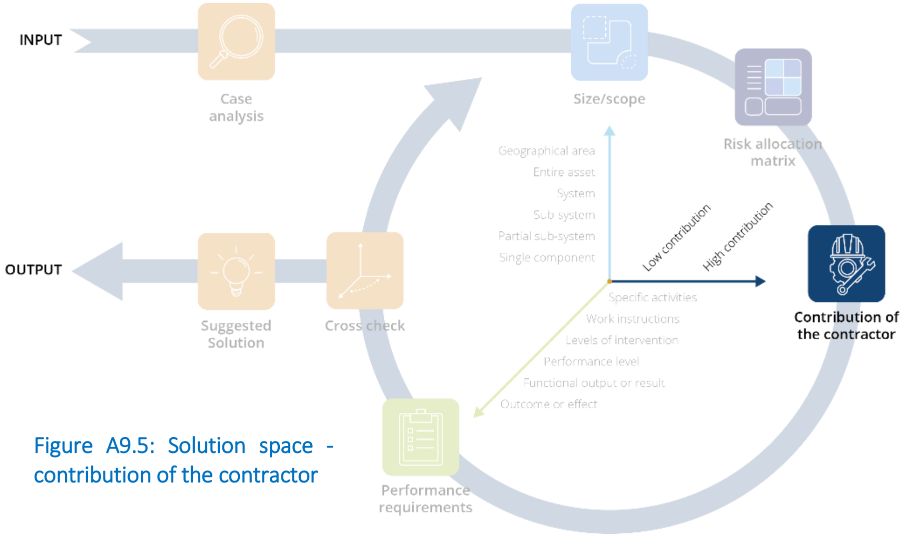


Figure A9.5: Solution space - contribution of the contractor

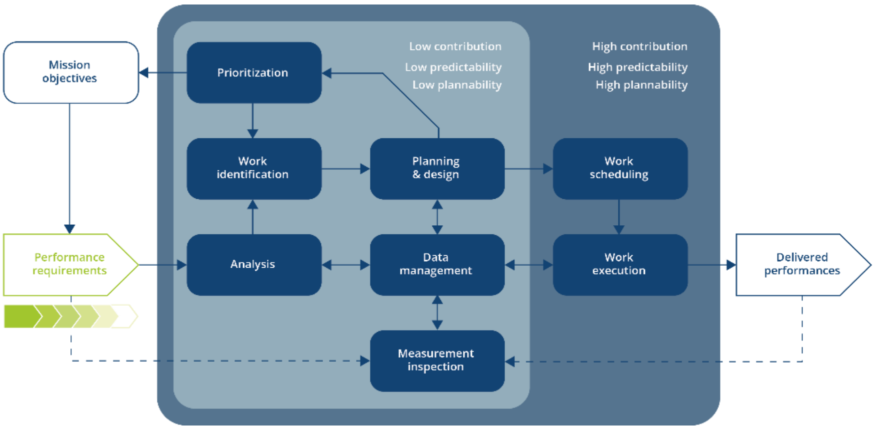


Figure A9.6: Six stage model based on (Schoenmaker, de Bruijn, & Herder, The dynamics of outsourcing maintenance of civil infrastructure in performance based contracts, 2013)

Step 5: Determine suitable performance requirements

In this step, the performance requirements are chosen. These are based on the measurability of the performances and the ambition of the organization. If performance can be measured easily, a higher level of performance requirements can be chosen. When performances are hard to measure, simple performance requirements might be more suitable.

The choices made here also heavily depend on the ambition and strategy that the organization wants to follow. If the organization has sufficient information about the behavior of an object and is satisfied with keeping the risk and control within the organization, they can easily use work instructions to outsource the work. This keeps the risk for the contractor low, and the control of the CA high. Thus, the results is always as it is expected by the CA. If the ambition is to give the contractor more freedom and challenge them to come up with innovative and progressive solutions, outsourcing using a higher level of performance requirements, for instance using performance levels or output-based requirements might be a more suitable option.

Eventually a suitable level of performance requirements should be chosen. Although the different levels and their meaning are explained throughout this thesis, the differences between some of them are small and one can argue that a certain way of using performance requirements can either fit within different levels. Keep in mind that the choice for a certain level of performance requirements comes with the motivation of reaching a certain goal. The choice is made because there is an idea on how that goal can be reached using a certain type of performance requirements. That reasoning and the way that the contract design team thinks that certain performance requirement will help reach that goal is the actual outcome of this step: what should be accomplished, how it should be accomplished, how can we put that in a performance requirement and in what way (level) are we going to ask it?

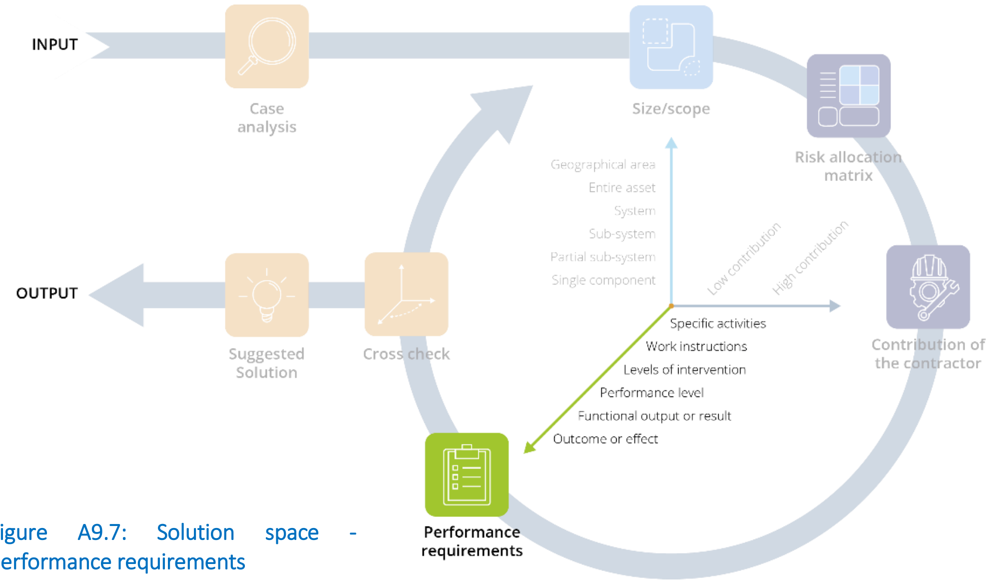


Figure A9.7: Solution space - performance requirements

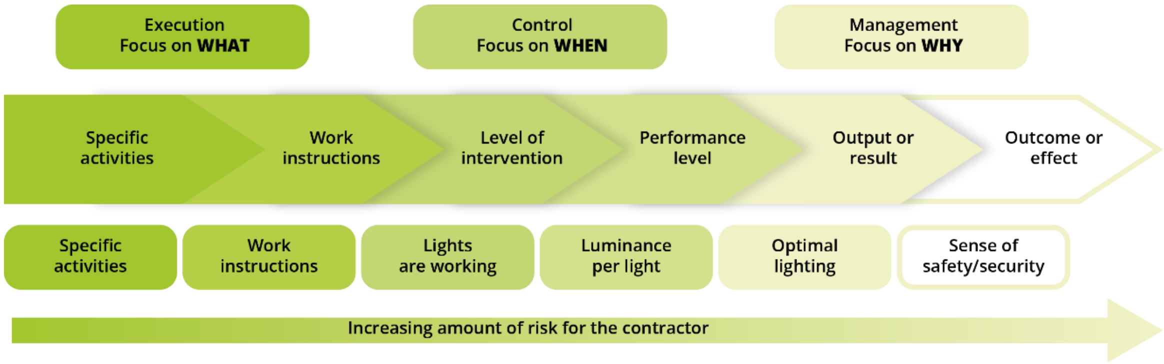


Figure A9.8: Levels of performance requirements based on (Schoenmaker, Prestatiegestuurd uitbesteden van onderhoud, 2017)

Step 6: Cross-check the interfaces between the parameters

The cross-check is a step that is introduced to check the interfaces between the parameters, and especially between the contribution of the contractor and the chosen performance requirements. The contribution of the contractor says something about the freedom and responsibilities of the contractor. The performance requirements defines what is to be expected from the contractor. It is important that these expectations match. If the contractor has a low contribution (less freedom and responsibility) by a high level of performance requirements is requested of them, chances are that this will not be possible. Then at least one of the parameters needs to be adjusted accordingly to make sure that they match again. Eventually all three parameters need to match in such a way that they do not conflict each other.

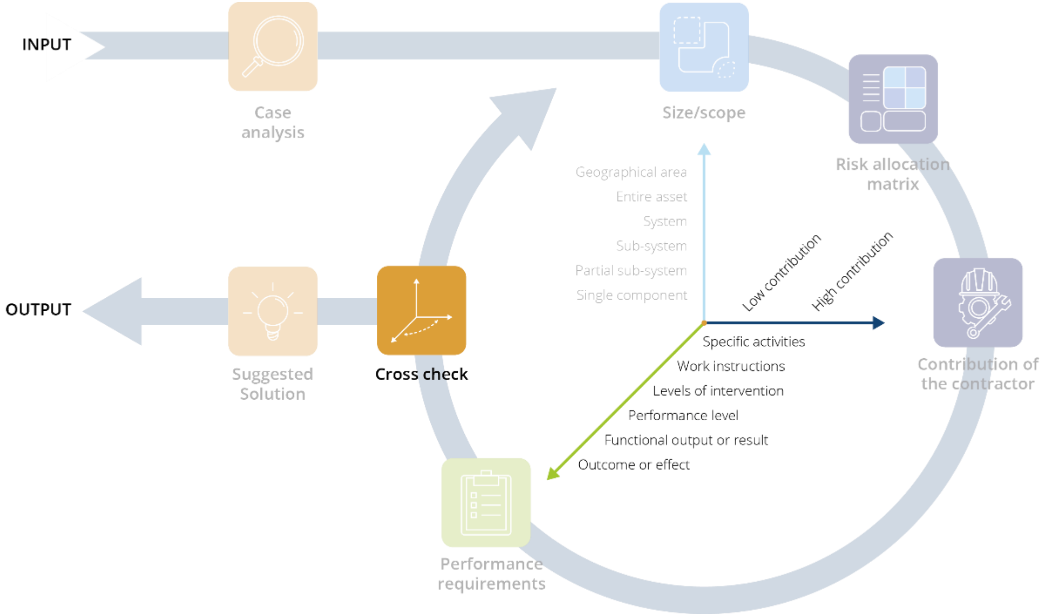


Figure A9.9: Solution space - cross-check

Step 7: Suggest a solution for the parameters

The last step of the process is to put down the proposed solutions for every part of the contract that is evaluated. This is also the eventual result of the decision-support method. The results are then put back in the bigger picture of the decision-making process. Up till now, the contract is cut into pieces and evaluated for single assets, systems, sub-systems or components, but in reality the contract can't be seen as single pieces. Therefore changes can be expected to the proposed solution when put back into context of the complete contract.

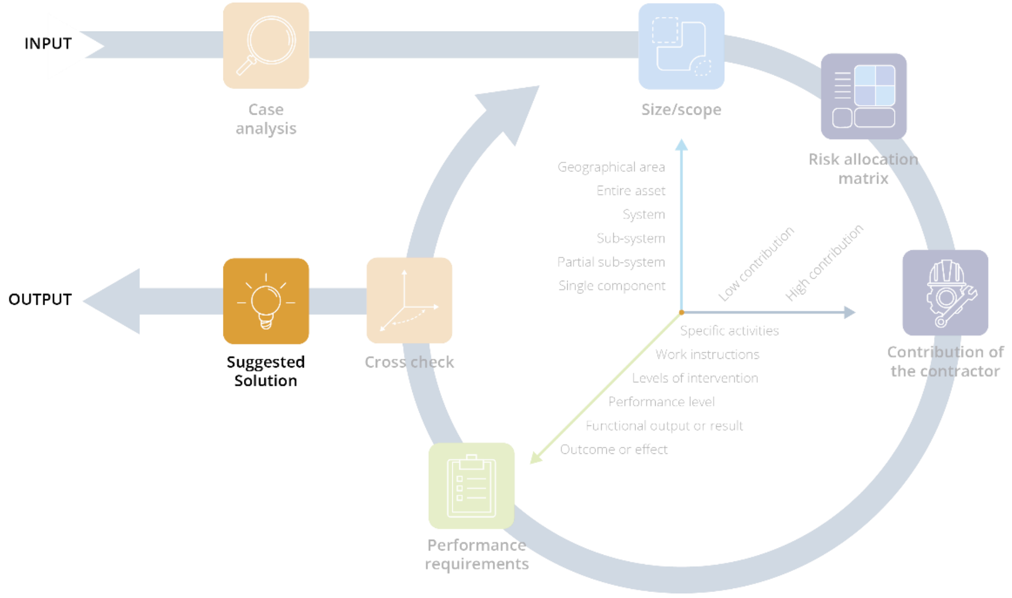


Figure A9.10: Solution space - suggested solution for the parameters

Practical application

The application of the method in practice will be a repetition of steps. This means that after step 1, the case analysis, step 2-7 are repeated for every individual part of the contract until everything that is included in the total scope of the contract is evaluated and provided with a suggested solution. After de cross check is performed, the suggested solution for that individual part is set aside as output. At the same time, the new cycle is started with a new part for which a new appropriate size/scope is decided. Then the other steps will follow automatically. This method is visualized in the figure below (Figure A9.11).

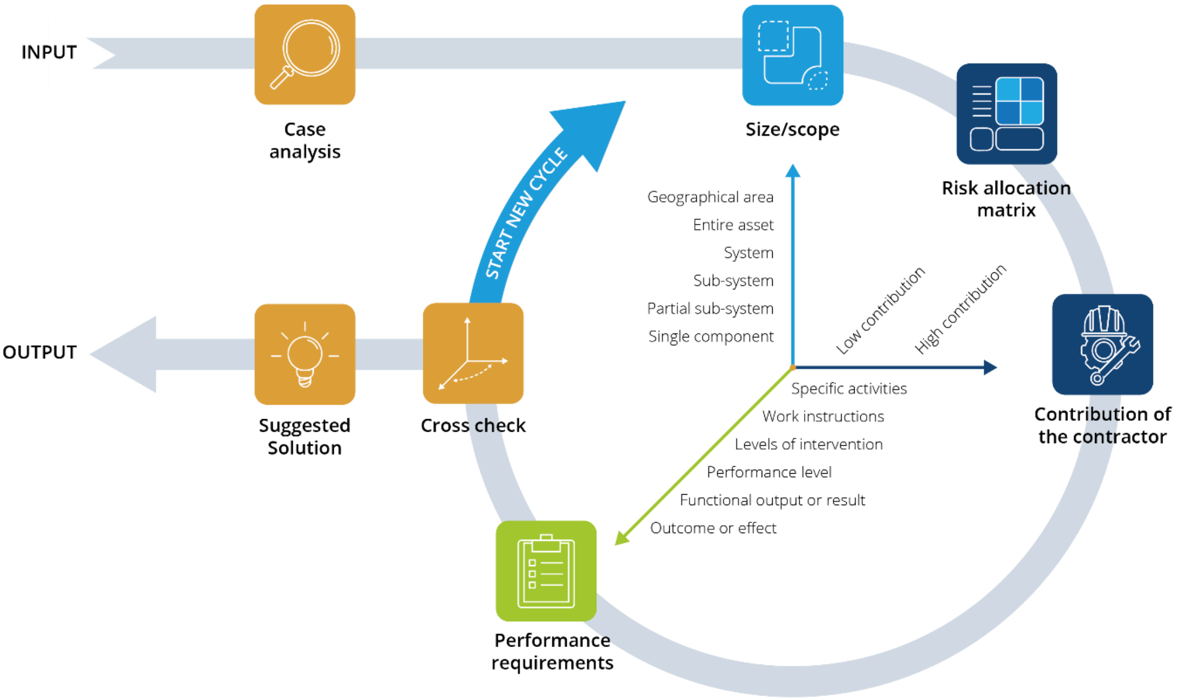


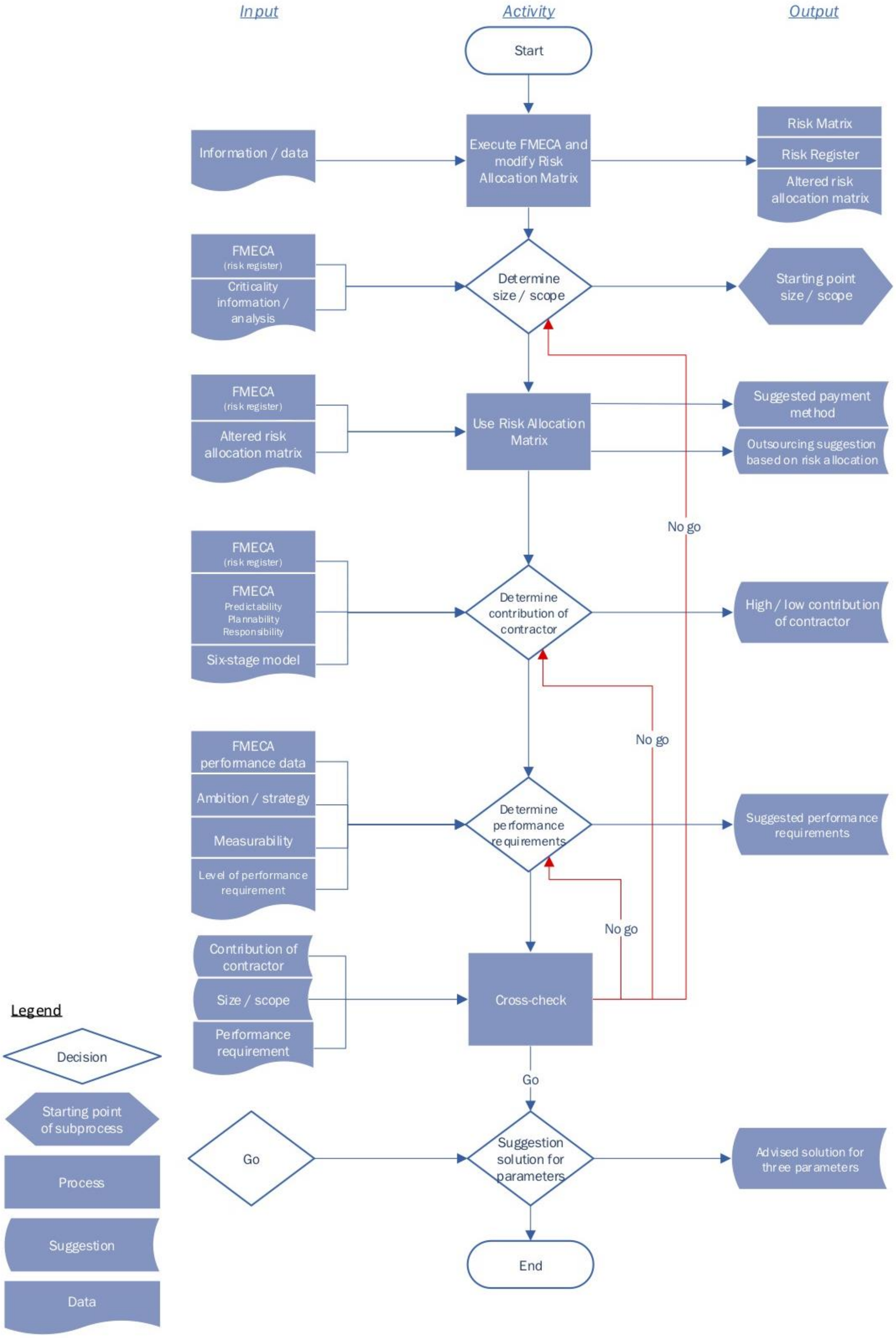
Figure A9.11: Decision-support method visualized

During the explanation of step 7 was referred to the fact that everything is evaluated in separate pieces. This is not the case because the eventual contract is the combination of all those separate pieces joined together. This means that, the risks for instance, must be evaluated again within the context of the entire contract. The eventual outcome might be different than the suggestions that where given in the decision-support method. This mainly relies on the expert judgement of the local circumstances and the knowledge about the capabilities of the potential contractors. This is therefore kept separate from the decision-support method. Part of the process is already integrated in the decision-making process which was covered in appendix 8. However more effort need to be put in that last step to that last step to come up with a valid final solution in the contract design process in its entirety . This is not part of the scope of this thesis and will be suggested as future research on this topic.

Appendix 10

Practical approach to the decision-support method

Appendix 10: Procedural approach to the decision-support method



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