Managing the costs of system unavailability in long–term maintenance contracts for hydraulic structures

C. Mertens | Master Thesis
Preface

This report is written for the completion of the master program Construction Management and Engineering at the Delft University of Technology. This master thesis contains an elaboration of a structured approach for making maintenance decisions for hydraulic structures which are controlled with the use of long-term maintenance contracts based on performance requirements in the Netherlands. I think this graduation project can be regarded as a manual for determining the most important risks and cost-effective solutions concerning maintenance for these structures. Service providers, which are responsible for the maintenance and operation of structures in the “wet” infrastructure of which maintenance is outsourced with the use of DBFM and PB contracts can use this approach in order to prioritize maintenance and give insight in risks and consequences of the most vulnerable parts of the hydraulic structure related to the availability.

I would like to thank my graduation committee from the TU Delft, which consists of Hans Bakker, Rob Schoenmaker and Jos Vrancken for their supervision, support and guidance during the period of my research. Although this period has been challenging, the members of my graduation committee kept supporting me and helping me with finding new interesting subjects for my research.

This master thesis is written during an internship at the engineering company Antea Group, which I would like to thank for giving me this opportunity, letting me make use of their knowledge and introducing me to the world of asset management. Most importantly, I want to thank my graduation supervisor at Antea Group, David de Jong for giving me knowledge, inspiration and helping me finish this research.

Last but not least, I would like to thank all my family and friends for their mental support and their continued confidence in me. Also, I would like to give a special thanks to my girlfriend Kelly for her ongoing support throughout this period of many ups and downs.

I hope my result will prove to be valuable for making maintenance decisions for hydraulic structures subject to long-term contracts.

Noordwijk, 30 October 2015

Coen Mertens
Executive summary

Introduction
Design, build, finance and maintain (DBFM) contracts and performance based contracts (PB) are increasingly used by the Dutch government to outsource maintenance on hydraulic structures in the “wet” infrastructure of the Netherlands (RWS, 2014). With these contracts, service providers become responsible for the maintenance of these hydraulic structures for long periods up to several decades. The payment mechanism in these type of contracts is based on the satisfaction of predefined performance requirements during this period. These requirements are described in terms of reliability, availability, maintainability and safety (RAMS).

One of the most interesting performance requirements which is used is in these types of contract is the requirement: “availability”. Certain functions of the hydraulic structure have to be available for a fixed percentage of time during the period in which the service provider is responsible for the maintenance and are described with the use of Service Level Agreements (SLA’s).

Objective
In order to keep satisfying these requirements on the structure, maintenance becomes necessary as components are subject to wear and tear over time, making them more vulnerable to failure. When the structure is not in use, or does not have to fulfil its functions preventive maintenance may be executed by the service provider in order to keep the structure functioning. If the structure fails to fulfil one of its functions during the period in which it has to function, the only type of maintenance possible is corrective maintenance which results in penalties due to not meeting the performance requirements.

As a result, preventive maintenance is desired by the service provider. This type of maintenance and therefore conducting maintenance in the periods in which it is allowed and no penalties are given as arranged in the contract can only be justified when the time to failure of components is known. If these properties are known for all components in the structure, preventive maintenance can be scheduled at the optimal moment and thereby no unnecessary costs are made by replacing them too early, not making use of their entire lifetime or risking penalties.

Although the previous paragraph suggest that preventive maintenance is the best solution to keep satisfying performance requirements in long-term maintenance contracts, previous research has shown that preventive maintenance is very difficult to justify. The moment in time at which components in hydraulic structures fail has been found incredibly unpredictable and some components are subject to random failures and therefore not sensitive to usage or ageing. Through the results of this previous research, it becomes clear that not only preventive maintenance but also corrective maintenance should be considered. Limiting the effects of a failure, reducing the probability of failures with the use of preventive measures or even other ways to reduce the unavailability of a structure should find their place in the maintenance regime of the service provider. Therefore this research focusses on finding a proper method for service providers in order to give them support in making maintenance decisions in the previously described contracts. A model needs to be developed which can prioritize maintenance needs for hydraulic structures and is able to find components in the system which contribute most to the unavailability of the system and thereby pose the major risk on penalties given by the asset owner based on the performance requirements.

Methodology
After searching for different methods to solve these problems, the RCM method (Reliability Centred Maintenance) together with FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis) and RPN (Risk Priority Numbering) has shown to be the most promising. Therefore, the main research question of this research is:

“How can Reliability Centred Maintenance (RCM) help service providers in making maintenance decisions for hydraulic structures during long-term maintenance contracts?”
The first step during this research is to check how the intended methods (RCM, FTA, FMEA, RPN) work and can be used to arrive at an appropriate application of those and therewith construct a new model which can help service providers in making and prioritizing maintenance decisions. In order to establish if these methods can and should be used together, their application is tested on a fictitious hydraulic structure which is a small pumping station with a manageable number of components.

A model is constructed in which the previous mentioned methods are all appointed their own place and the methods are linked to the different steps which are typical to the application of the RCM process. An example of a small pumping station is used to test the applicability of the model and subsequently, validation of the model is being studied through the application of the model on a case study which concerns a navigation lock in the Netherlands: The Meppelerdiepsluis. First, a system description and system boundaries are given, together with associated costs of components and performance requirements on the main function. Secondly a system decomposition is made which shows the relationships and interdependencies of the components. In order to investigate the main function of the system and how this function can fail an FMEA is conducted on the system. The FMEA also provides a basis for the next step. That is why, it is subsequently used to construct a fault tree of the system, with the top event of the FTA being a failure of the main function at question. The FTA is used in order to rank all the different components on their contribution to the unavailability of the main function based on their Fussell-Vesely importance. In this way a prioritization is created of all the associated failures modes. After prioritization, an extended FMEA is created in which a RPN is assigned to the different failure modes. The RPN is a multiplication of the probability of occurrence, their effect when occurring and the possibility to detect them prior to failure. The effects when occurring are based upon the unavailability penalties and the mean time to repair of the components. With the use of these calculated RPN’s a second prioritization can be made in which the highest RPN becomes the most interesting and worthwhile failure mode concerning the system at question to research possibilities for preventive measures. Based on these RPN’s, decisions for different maintenance actions can be made which are described in a newly developed decision tree. The choice can be made between five different options, depending on the component at hand and associated costs for the decision.

Conclusions

The RCM process together with the methods FMEA, FTA and RPN has proven to be a structured approach which can be used in order to help service providers in making and prioritizing maintenance decisions concerning hydraulic structures when DBFM(O) contracts are used, but does not offer a solution when PB contracts are used. Decisions concerning maintenance can and will be made based on the risk of system unavailability in the future, because this will result in lower reimbursements. The risk on system unavailability can be quantified using failure modes, their damage when occurring and their probability of occurring. With the method used in this research, the failure modes can be ranked according to their associated risk. Failure modes with the highest risks should subsequently be further investigated and options to reduce them should be considered based on their cost-effectiveness. Furthermore, the proposed model can help with controlling corrective maintenance. Although corrective maintenance cannot be planned, it is also impossible to avoid. Preventive measures can reduce the effects in terms of system unavailability when unexpected failures occur.

Recommendations

A better understanding of and more knowledge about component degradation and therewith more certainty about the time of failure will definitely contribute to more knowledge about failure behaviour and can help to justify preventive maintenance. Condition monitoring techniques should therefore be supported and further developed. Next to this, it is essential that data resulting from the application of such techniques is very carefully preserved and shared. The creation and sharing of data is essential to further develop knowledge in this field and let it result in benefits for both service provider and asset owner. When data eventually exists, other models such as dynamic fault trees with time-dependent failure rates can be used to schedule preventive maintenance.
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List of abbreviations

AD       Availability discount
DBFM     Design Build Finance and Maintain
FMEA     Failure Mode and Effect Analysis
FMECA    Failure Mode, Effect and Criticality Analysis
FTA      Fault Tree Analysis
GAC      Gross availability compensation
HAZOPS   Hazard and Operability Study
MEAT     Most Economically Advantageous Tender
MTTR     Mean Time To Repair
NAC      Net availability compensation
PBC      Performance based contracts
PD       Performance discount
PMS      Performance measuring system
PLC      Programmable Logic Controller
RAMS     Reliability, Availability, Maintainability and Safety
RCM      Reliability Centred Maintenance
RPN      Risk Priority Number
RWS      Rijkswaterstaat
SCADA    Supervisory Control And Data Acquisition
SLA      Service Level Agreement
Managing the costs of system unavailability in long-term performance contracts for hydraulic structures
1. Introduction

This research focuses on the application of RCM (Reliability Centred Maintenance) together with supporting methods in order to satisfy performance requirements in long-term maintenance contracts for hydraulic structures. Developments in the field of long-term maintenance contracts based on performance requirements, which are increasingly used by Rijkswaterstaat to outsource maintenance of the Dutch infrastructure, are the main reason for this research. DBFM (Design Build Finance and Maintain) and PB (Performance Based) contracts are new for the “wet” infrastructure and are used to allocate risks towards the parties which can control them the best, usually private parties instead of governmental institutions which used to bear these risks.

The first DBFM project in the “wet” infrastructure in the Netherlands is started this year and concerns a floodgate in Limmel. The design phase, building phase, financing and the maintenance phase of thirty years are all the responsibility for a private party within this contract. During the maintenance phase the party is paid for conducting maintenance with the use of payments based on the availability of the structure. Availability in this contexts is defined as: “The fraction of the time at which the required function can be executed under given circumstances”. The second DBFM contract is already awarded to a private party and concerns one of the largest navigation locks in the Netherlands in IJmuiden. The prospects are that these types of contracts will be increasingly used by the Dutch government in the future. If this trend continues, the result will be a change in market in the maintenance for civil engineering structures.

With these new types of contracts, service providers are paid based on satisfying performance requirements instead of executing prescribed maintenance tasks as they used to do. This new method of paying service providers calls for a new way of managing risks concerning maintenance which previously where the responsibility of the Dutch government. Therefore, a new model which can be used by service providers in order to quantify risks and thereby make decisions concerning maintenance has been developed and applied to an example of a hydraulic structure and a case study. After research into different methods and tools conclusions and recommendations are made about the possible application of the methods described in this research.
2. Problem definition

2.1. Background information

The largest part of the infrastructural network in the Netherlands is already there and aging. An important part of this infrastructure are hydraulic structures. Structures which are part of the “wet” infrastructure in the Netherlands play an important role in the import and export to and from the Netherlands and therefore are of significant importance to the economy. Next to this, these structures are often part of the protection against flooding of the Netherlands and provide the inhabitants of the Netherlands with dry feet. This is why the availability of hydraulic structures such as locks, dams, flood defences and storm surge barriers becomes increasingly important and therefore also the maintenance. Simply demolishing the old structures and building new structures when older ones no longer satisfy, takes a lot of time and money and results in an unnecessary service outage of this infrastructure.

2.2. Current situation

Rijkswaterstaat which is part of the Dutch Ministry of Infrastructure and Environment is the asset owner of most of these hydraulic structures. Its role is the execution of public works and water management, including the construction and maintenance of waterways and therefore the hydraulic structures which form a part of the “wet” infrastructure. Asset owners such as Rijkswaterstaat are using integrated contracts more often to outsource the management and maintenance of these structures in order to achieve higher quality against lower costs. For the procurement of new hydraulic structures, the asset management and maintenance becomes more often part of the contract and therefore another task for the service provider.

The outsourcing by the asset owner of this asset management and maintenance is increasingly done based on predefined performance requirements. These performance requirements are pre-set requirements concerning reliability, availability, maintainability and safety (RAMS) of the structure and are described in the “Leidraad RAMS” (RWS, 2010). In order to control their infrastructure based on these performance requirements on system level they make use of Design, Build, Finance and Maintain contracts (DBFM). The first DBFM project in the “wet” infrastructure is launched this year and concerns a floodgate in Limmel (OTAR, 2015).

The use of these DBFM contracts for hydraulic structures in the “wet” infrastructure is new and will be increasingly used by Rijkswaterstaat in order to outsource maintenance together with the design and construction of new hydraulic structures (RWS, 2014). Next to this, maintenance of existing hydraulic structures is also being outsourced based on the aforementioned performance requirements. These contracts cover extensive maintenance periods up to several decades during which service providers are being paid based on the delivered system performance rather than executing prescribed maintenance tasks like they used to do.
2.3. Theoretical background

The world of maintenance is generally very traditional and conservative. Methods and techniques which are used over several decades are still being used. Therefore, there has been relatively little attention for innovation, but the last few years things are changing. Due to the economic crisis there was and still is a lot of pressure on the maintenance budgets. While the Dutch government tries to achieve the same or better results with less money, the maintenance and repair sector in the Netherlands remains a very large sector in which yearly around 35 billion euros are spent (NVDO, 2010). If conducting smarter maintenance can lead to saving a small portion of this amount, the potential profits are promising.

Within the new ways of outsourcing maintenance by the Dutch government, service providers which are becoming responsible for satisfying pre-set performance requirements for hydraulic structures are being paid based on a bonus-malus system. If for instance the requirement on the availability of a navigation lock is set at 99%, the service provider will be fined when this requirement is not met. Therefore, it becomes increasingly interesting to conduct research into methods which can help to satisfy these pre-set requirements or methods which can be used to find an optimum between maintenance costs and performance.

In order to satisfy requirements on availability of a hydraulic structure, maintenance on the system is necessary. The purpose of maintenance management is to reduce the damaging effects of system failure and to maximize the system availability at minimal costs. Traditionally, maintenance can be divided into two different types of management which are: corrective maintenance as shown in Fig.1 and preventive maintenance shown in Fig.2. Corrective maintenance strives to reduce the severity of equipment failures once they occur. Other than preventive maintenance, corrective maintenance focuses on maintenance procedures that bring the systems function back in the shortest possible time, and looks for alternatives which can help to minimize system unavailability. Some of these alternatives are: spare parts, redundancy in the system or highly skilled maintenance personnel.

The second one is preventive maintenance, which strives to reduce the equipment failures before they occur. It is used to find methods which can identify potential failures, make changes or repairs, and prevent failures from happening. It is being applied before the system has failed and is usually based on predetermined intervals or prescribed criteria in order to keep the system available.

![Figure 1: Corrective maintenance (Vrijling & Van Gelder, 2002)](image-url)
Preventive maintenance seems to be the best option to conduct maintenance, but conducting maintenance too early (preventive) means replacement of parts of the system which are not yet worn-out and therefore making unnecessary costs (van Noortwijk, 2002). Next to this, preventive maintenance has generally attracted a lot more attention in the industry and academic research. Nevertheless, corrective maintenance should never be ignored, because even extensive preventive maintenance will never resolve all potential system failures. Random component failure will always be present, due to the unpredictability of failure and wear and tear which still exists. Even if in the near future research will be able to predict component failure, any system will still be subject to unpredictable external events which can result in the failure of a system function. With these two possibilities for random failure, the possibility that a critical system function fails randomly will always exist and therefore corrective maintenance actions should always be part of system maintenance (Sheut, C. 1994).

A service provider which earns money based on the previously mentioned maintenance contracts will always be interested in methods to reduce maintenance costs while still satisfying the requirements. Reliability centred maintenance can be used to find an optimum between the two types of traditional maintenance and help to make smarter and better founded decisions concerning the maintenance of such structures (Smith, D. J., 2011). It can be useful for service providers to satisfy pre-set performance requirements with a minimal deployment of resources and therefore minimal costs and efforts.

Besides the challenges which the service provider gets with these performance contracts, the biggest challenge with maintenance for both service provider and client remains determining the right moment for preventive maintenance. Structures which are used in different and more frequent ways than other similar structures will logically be subject to different maintenance needs. This asks for adjusting the maintenance to the usage of the structures and their environmental conditions, such as external loads, instead of using fixed, predetermined maintenance intervals as shown in the flowchart in Fig.3.
In order to adjust the maintenance intervals, knowledge is needed about how the usage influences the degradation of a structure. Therefore, knowledge about failure behaviour is very important and can subsequently be used in order to quantify degradation based on usage. At this time the most common way of quantifying failure behaviour is the experience based approach in which as much as possible data is gathered from past experience in order to deduce a mathematical relation which can describe the behaviour (Smith, J.D. 2011). Although this method is widely accepted and used, it remains subject to the well-known statement: “Past results are no guarantee for the future”. Another approach to quantify the relation between degradation and usage is degradation modelling. This approach focusses on understanding the physical failure mechanisms such as corrosion, wear and fatigue and finding the relation between usage and degradation (Tinga, T., 2013). A good example, which already is in an advanced stage, is chloride penetration in concrete and its relation with degradation (Xi, Y., 1999). Although some examples can be given, this way of modelling degradation is a relatively new approach and application for all the different components in a hydraulic structure is still very far away.

The ultimate goal in the future for both service providers and asset owners will be a structure, equipped with a system, able to measure the condition of all parts and components and therewith always find the optimal time for preventive maintenance. In order to arrive at this rather utopian point, lots of research into degradation needs to be conducted and can only be done when supported and or subsidized by the owner of these assets. Until this becomes a real possibility, other methods and models which can help with making maintenance decisions will remain interesting for service providers. Therefore, this research focuses on already developed methods (RCM) and their application on hydraulic structures in order to make maintenance decisions and satisfy performance requirements.

Reliability centred maintenance
Reliability centred maintenance is a systematic process and methodology for determining the most effective and efficient maintenance management for a specific system, for which a performance contract can be the starting point. It offers an optimum between corrective and preventive maintenance, because the failure of a system can be related to the consequences on reliability, availability, safety and costs. Reliability centred maintenance can be of great use when dealing with systems where reliability and availability are of crucial importance. Examples where reliability centred maintenance is already widely used are: nuclear facilities, aviation, chemical plants and defence. With the use of reliability centred maintenance, maintenance strategies are optimized so that the reliability and availability of the system is maintained using cost-effective maintenance techniques. Various recommended techniques which can be used when applying reliability centred maintenance are: Failure mode and effect analysis (FMEA), Fault tree analysis (FTA) and Hazard and operability studies (HAZOPS) (Rausand, M., & Vatn, J., 2008).

In a traditional maintenance contract, the knowledge on the failure behaviour of sub-systems (systems which are part of a larger system such as an electrical system or the mechanical parts of a structures) and the consequences on the primary function of the system is often not used. Sub-systems become increasingly important in the functioning of a system, especially when complex hydraulic structures are considered. Reliability centred maintenance deals with the reliability and availability of the sub-systems which are essential to ensure the primary tasks of the system in which the client is interested.

Risks in terms of reliability, availability, safety and costs to the system can be mapped beforehand, so costs can be reduced and money can be spent on the appropriate sub-systems and components. If during the analysis of a system, certain sub-systems prove to be essential for the primary tasks of the system, it can be smart to construct a redundant system or replace components which are sensitive to wear faster than usual (preventive). In terms of benefits, reliability centred maintenance can offer predictability and a better view on costs in the maintenance phase.
3. Research context

3.1 Research objective

The objective of this research is to examine if and how reliability centred maintenance can be applied to hydraulic structures and if it can give the necessary insight, to support maintenance decision making. This approach aims to be of use for service providers which are maintaining hydraulic structures. Furthermore, it aims to help the service provider to gain insight into what the most vulnerable parts of the structure are and thereby help the service provider with setting maintenance requirements and prioritize maintenance activities.

Reliability centred maintenance can give better insight into when, what and where maintenance has to be done and therefore it can be used to help with the calculation of the costs and efforts for maintenance during a given period. This can be done by prioritizing components in a hydraulic structure based on their contribution to unavailability. The result can be the application of a new maintenance regime which entails that maintenance is not based on the risk of failure of components anymore, but on the risk on unavailability of the structure.

3.2 Research framework

This research aims at developing a new model based on the RCM method together with other supporting methods and tools on a hydraulic structure. Research will be done into what long-term maintenance contracts entail, what performance requirements are and how these can be satisfied. In order to show if and how RCM and supporting methods can help with satisfying pre-set performance requirements, a new proposed model based on the RCM process will be created, applied and evaluated.

3.3 Research question

This research will focus on answering the following main research question: “How can Reliability Centred Maintenance (RCM) help service providers in making maintenance decisions for hydraulic structures during long-term maintenance contracts?”

To answer this research question, a set of sub questions is drafted. In order to gather more knowledge about the subject, the first questions are formulated as knowledge questions which help to find the right literature and will not be part of the conclusions in the last chapter. The other questions will help to give guidance during the research and help to answer the main research question. The sub-questions are:

- How are long-term maintenance contracts applied?
- How are performance requirements implemented in long-term maintenance contracts?
- What is Reliability Centred Maintenance (RCM) and how can it be implemented?
- Which methods can be used to support RCM?
- How can the availability of a hydraulic structure be calculated?
- How can subsystems or components which are critical for the requirement “availability” of the system be detected?
- Which choices can be made concerning maintenance actions and what are the accompanying consequences on availability?
- What are the benefits when making use of RCM?
3.4. Research approach

In order to answer the main research question, answers to the sub question are being searched for. The research approach is shown in Fig.4. A literature study will be conducted in order to research and give a clear description of what long-term maintenance contracts are, what maintenance actually entails, what performance requirements are and how they are proven and calculated for hydraulic structures. After this, the RCM method and supporting methods are researched in order to construct a new model to help service providers in making maintenance decisions. Subsequently, the proposed model will be applied to a fictitious example of a hydraulic structure in order to test it. After this, the proposed model will be applied to a case study to research the necessary inputs, possible outputs, weaknesses and strengths.

By analysing the contribution of components to the unavailability of the system, choices can be made to further investigate sub-systems and components in order to increase the availability of the system. For example, for components or sub-systems with a low contribution to the unavailability the choice can be made to maintain these in a corrective way based on the accompanying costs and/or repair time. Opposite to this, components and sub-systems which have a high contribution to the unavailability, choices can be made to maintain these with a new approach in order to find an optimum between costs and availability. In order to show how the new model based on RCM can help in finding this optimum, research has to be done into different methods which can be used to support RCM.

**Intended answer:**

The aim of this research is to give guidance to service providers and to help them make the best decisions for the maintenance of hydraulic structures in order to satisfy pre-set availability requirements in the most cost-effective way. When risks on unavailability can be shown beforehand, they can be reduced and availability killers and cost drivers can be either accepted or further investigated. A model which can help in making these decisions is the intended goal.

![Figure 4: Research approach](image-url)
4. Theoretical framework

In this chapter a theoretical overview is given in order to create a framework for the main research objective as described in chapter 3.1. Fig.5 shows the subjects in the theoretical framework and how to arrive at the creation of a new model. Firstly, the application and functioning of long-term maintenance contracts will be explained. Secondly, the concepts failure, maintenance and availability will be explained. After this the RCM method together will be described. In chapter 5, the possibility for application together with supporting methods will be researched, resulting in a new model. In chapter 6, the application of the model will be elaborated.

4.1. Long-term maintenance contracts

DBFM (Design, Build, Finance and Maintain) and PB (performance based) contracts are both increasingly used by the Dutch government in order to outsource activities which were previously part of their own responsibilities (OTAR, 2015). PB contracts can be part of a DBFM contract, but also single contracts which can be used to only outsource maintenance for an already existing asset for a given period of time. When the asset has to be designed, built, financed and maintained by the same consortium, a PB contract can be part of the DBFM contract for the maintenance phase. In both contracts the service provider is being paid during the maintenance phase based on the delivered performance. Main difference, but also an opportunity for the service provider is that in a DBFM contract, maintenance on the structure can already be taken into account in the design phase. During the design phase the service provider is able to change the design of the structures in order to reduce the maintenance requirement in the future.

These type of contracts are already in use in the “dry” infrastructure, but new to “wet” infrastructure related projects. Direct copying of the application of these contracts from the “dry” infrastructure towards the “wet” infrastructure is not possible, because of three main problems concerning “wet “ infrastructure projects, which are (RWS, 2013c):

- With hydraulic structures multiple functions concerning the structure need to be controlled
- The regime has to comply with requirements from the Dutch “Waterwet”
- Unpredictability of the failure of electro-mechanical installations and industrial automation

In order to find an answer to the first two sub-questions: “How are long-term maintenance contracts applied ?” and “How are performance requirements implemented in long-term maintenance contracts ?” a literature study is conducted and the answers to these two questions will be elaborated in the following paragraphs.
4.1.1. DBFM (Design, Build, Finance and Maintain)

A DBFM contract is part of the integrated type of contracts where different parts of the realisation and operational phase of a construction project are being assigned to one service provider.

When a DBFM contract is being tendered by an asset owner such as the Dutch government, a consortium (an organisation, which is founded by a number of parties to carry out a certain project) becomes responsible to design, build, finance and maintain an infrastructural asset. DBFM does not distinguish fixed, variable, prescribed or non-prescribed activities. The delivery of availability and maintaining it during the operational phase is key to the contract. The service provider runs all process steps, including the prioritization of maintenance actions. The role of the client is limited to (one-time) establishing of the performance requirements and monitoring the performance during the operational phase (PIM, 2012).

The definition “Availability” in this context corresponds to the availability of a certain function of a hydraulic structure (such as stopping high water levels or allowing ships to pass through a navigation lock) and is defined in: Leidraad Systems Engineering (RWS, 2009) as: “The fraction of the time at which the required function can be executed under given circumstances”. An availability requirement of, for example 99% corresponds to +/- 90 hours a year during which the function at question is allowed not be executed.

These contracts are being used by the government in order to create value for money. One of the most important reasons to choose DBFM contracts by the client are the benefits from synergy. When the different parts (design, build, finance and maintenance) are being outsourced separately, it becomes very difficult for the different service providers to take each other’s risks and costs into account. For example: an optimal aesthetic design can result in very high construction costs or a design with low building costs can result in very high costs for the maintenance. When all parts are assigned to one consortium or service provider, the idea is that this will create a strong incentive to find an optimum between design costs, building costs and maintenance costs. As a result of outsourcing this to one service provider, the total costs for the client will be lower (Koster, J.H.W. et al., 2008). Next to this, another important reason for the use of a DBFM contract, is that the client can discard different responsibilities concerning the project. For example: the client will no longer be responsible for the different interfaces between the parts of the contract. Mistakes in the design, building or maintenance phase will all be the responsibility of one party instead of different parties having separate legal relationships with the client.

4.1.2. Cash flow during DBFM contract

During the operational phase the service provider is being paid based on the availability and performance of the infrastructural asset. This entails that with the use of a DBFM contract the client actually buys a service instead of a product, because the client pays for the availability of the infrastructural asset (Ministerie van Financiën, 2012).

With the use of a DBFM contract, one consortium becomes responsible for the whole project: The design phase, building phase, financing of the project and the maintenance phase. In order to finance the project, the consortium looks for interested parties to finance the project. This funding is being reimbursed with availability reimbursement, which are paid monthly or every quarter of a year by the client. Furthermore, the consortium also receives payment during construction called “certificates”. During the operational phase the consortium is paid based on the availability and performance of the asset. The only costs for the consortium during this phase concern costs for both preventive and corrective maintenance together with penalties for unavailability. The consortium will therefore strive for a optimum between maintenance and penalties. The cashflow during a DBFM contract is shown in Fig.6, which shows an example when the contract is working perfectly for all parties.
Fig. 7 shows an example of the same cashflow, but in a more realistic way when performance requirements are not always met and random failures cause corrective maintenance. Especially during the first period after construction the reimbursement tend to be very low due to start up issues.

Figure 6: Cash flow during DBFM contract when working perfectly

Figure 7: Cashflow in DBFM in a more realistic perspective
The availability reimbursements are being paid based on the delivered performance which is measured with the use of a PMS (performance measuring system) as shown in Fig. 8. During the contract period, the PMS is used to objectively determine what payments the consortium deserves based on the delivered performance. Depending on the structure or system which is considered an appropriate PMS is developed.

**Figure 8: PMS (Performance measuring system)**

The PMS calculates the appropriate availability reimbursements for each quarter of a year. In order to calculate this, the availability of the system is measured and based on this an availability discount (penalty) is being calculated as shown in Fig. 9. Furthermore, not meeting other performance requirements (such as requirements on safety) besides availability can also result in a lower availability reimbursement.

**Figure 9: Calculation of availability discount in DBFM and Performance based contracts**
The standard payment mechanism for DBFM and performance based contracts is calculated following the flowchart in Fig.9. The reimbursements paid to the responsible consortium or service provider is generated by the availability of the asset. Reimbursements paid are calculated by the net availability compensation (NAC) which is a percentage of the gross availability compensation (GAC) paid every quarter of a year. The gross availability compensation (GAC) is reduced by the availability discount (AD) and the performance discount (PD) (RWS, 2013a). This results in the following formula, which is also shown in Fig.9:

\[ \text{NAC} = \text{GAC} - \text{AD} - \text{PD} \]

Basically, the consortium is paid for delivering performance instead of working with detailed building specifications from the client. This allows the consortium flexibility and freedom to decide in which way they want to deliver this performance. The contract will be a collection of agreements between the client and the consortium. Next to this it will be necessary for the consortium to have other types of contract with subcontractors. With this type of contract the consortium will be responsible for risks which were previously a concern of the client (in this case Rijkswaterstaat). In order to carry these risks the consortium needs to arrange an extensive package of insurances, save money in order to cover the costs of the risks or find other preventive measures.

One of the most important conclusions from studying these contracts is that, although the starting point of DBFM and PBC contracts is that it will not lead towards service providers insuring themselves against risks for which the client previously was not insured, this can still happen when the contract is created (Ministerie van Financiën, 2007). The contract forms the basis for the allocation of risks and depending on this allocation, the service provider might carry risks which turn out to be uninsurable. If uninsurability exists for the service provider, it will be necessary to give them protection against these risk. Extensive agreements on, for example failure due to force majeure (war, terrorism etc.) are necessary in order to establish which party bears what risk.

### 4.1.3. PBC (Performance based contracts)

Next to the use of DBFM contracts, PB contracts are also increasingly used both for “dry” and “wet” infrastructure (Laaper, S. 2014). PB contracts are being used by the Dutch government in order to outsource maintenance for multiple years. Within this contract the service provider is responsible for the maintenance of an asset. During the period of the contract, the concerning asset has to comply with the requirements on performance set in the contract. With the use of these contracts the performance content in the contract is increased while the activity content becomes less and less. The table below describes the possible advantages of using PBC instead of the traditional ways of outsourcing maintenance for both clients and service providers (Van Rhee, G. 2009).

<table>
<thead>
<tr>
<th>Traditional outsourcing of maintenance</th>
<th>Performance based contracts</th>
</tr>
</thead>
<tbody>
<tr>
<td>No guarantees on intended results</td>
<td>Interests are aligned</td>
</tr>
<tr>
<td>Risk of setbacks is for the client</td>
<td>Risks are for the party which can control them best</td>
</tr>
<tr>
<td>Often more hours spent than necessary</td>
<td>No unnecessary activities</td>
</tr>
<tr>
<td>Improvements are discouraged</td>
<td>Contract stimulates innovation</td>
</tr>
</tbody>
</table>

**Table 1: Traditional vs Performance based contracting**

When we look at the problems with traditional contracts and the solutions which PB contracts offer it becomes clear that PB can result in lower costs and/or higher performance of the asset when executed in the proper way. Same as with DBFM contracts, the service provider is punished when realized system performance is not in coherence with the prescribed performance requirements which are measured with a PMS as shown in Fig.8 and Fig.9. Within the output specifications on performance, the service provider has the freedom to organize his own maintenance concept for the asset. The preparation, execution, developing and continuously adapting of the maintenance concept in order to continuously improve the technical system based on experience is left to the service provider. If goals concerning performance are not met, the service provider is fined for not delivering. When higher technical performance is delivered, the service provider can be rewarded with a
bonus. The client’s role will be limited to only monitoring the process and focus on the results delivered by the service provider to achieve the prescribed system performance requirements and less on the execution of its activities.

4.1.4. Operational phase

After completion of the construction phase, hydraulic structures need to be operated. Hydraulic structures such as navigation locks are often used daily and therefore staff is needed. Traditionally, the staff which is responsible for the daily operation of these structures is hired and paid by the Dutch government. With the use of DBFM and PB contracts, the daily operations of the structures can also be made part of the contract and therewith these becomes another responsibility for the service provider. With a PB contract, this can be agreed in the contract and with DBFM this is known as a DBFMO contract, with the “O” representing the operational phase (Hamdan, Y., & Veekman, W., 2014). When operating the structure is part of the long-term contract, the service provider becomes responsible for hiring staff to operate the structure. This brings new responsibilities, but also some advantages. When the staff is employed by the service provider, the gap between operational and maintenance staff becomes smaller and thereby the knowledge about the structure easier to share and save. This can subsequently result in a better understanding of the degradation of the structure and therewith the maintenance needs, especially in long-term contracts.

4.1.5. Conclusions from the application of long-term maintenance contracts

The outsourcing of maintenance by the asset owner towards the service provider with the use of performance requirements and the accompanying revenue model as shown in Fig.9 brings more responsibilities for the service provider, but it also brings some new changes in ways of earning money for the service provider. When clients choose to keep more distance from the project and use the previously mentioned contracts, this will also result in a change of organisation at the service provider and next to this a change in their business model. Some of the most noticeable changes to be optimized by the service provider are:

- Conducting preventive maintenance can offer high availability and thereby assurance in satisfying the availability requirement and preventing penalties. Downside is that preventive maintenance is usually accompanied with high and sometimes unnecessary costs. Furthermore, it is very difficult to specify an optimum preventive maintenance interval when degradation of components is uncertain. Preventive maintenance for components which are only subject to random failure (for example: electric components) cannot be justified and therefore there is a need to find other preventive measures in order to increase and/or maintain the availability of the system.

- For components of which degradation can be measured and predicted, preventive maintenance will have the benefit that the moment can be chosen to such an extent that it will result in a minimum of nuisance to the users of the structures. Also, penalties for schedulable maintenance are much lower or even absent in comparison with unschedulable corrective maintenance.

- The use of higher quality components can result in less need for maintenance during the operational phase. The choice to use component with a higher quality can either be made during the design phase or when system redesign is an option during the operational phase.

- When the costs of preventive maintenance are lower than the costs of unavailability penalties, preventive maintenance can be the best maintenance strategy. Depending on the penalties an optimum between corrective and preventive maintenance can be made.

- When unavailability penalties are negligible, the choice will always be made for corrective maintenance and acceptance of unavailability of the system. Depending on the penalties the choice of maintenance on different components can be made, keeping in mind the contribution of the components on the availability of the whole system.
If operating the structure is also part of the long-term contract, new opportunities to gather knowledge about degradation of the system on a daily base arise. This can be used to gain more insight in the maintenance requirements and use it to plan maintenance and avoid penalties.

4.2. Availability and different types of unavailability

In this paragraph an explanation is given of availability of a system, the difference between availability and reliability and the different types of unavailability of a system. In order to find an answer to the sub-question in this research: “How can availability of an hydraulic structure be calculated?” research has been conducted into availability and requirements concerning availability. The results will be elaborated in the following paragraphs.

4.2.1. Availability as a performance requirement

In the literature, availability is described in various forms. The following description is from the Leidraad Systems Engineering (RWS, 2009):

“The fraction of the time at which the required function can be executed under given circumstances”

When the focus is on availability, unavailability and thereby a loss of function of the system should play an important role when making maintenance decisions. Traditionally, a loss of function/production was only perceived to be important in areas like manufacturing companies where the loss of function/production can be clearly defined in terms of unproduced units and thereby money.

When maintenance of hydraulic structures is concerned this is often based on the performance requirement availability with respect to the main functions of the structure. Hereby the service provider becomes responsible for the functioning of the system and is fined when the system becomes unavailable due to failure of components in the system. Traditionally from the perspective of the owner (RWS) of a navigation lock, the unavailability could be expressed as a loss of possible toll income, extra waiting time for shipping traffic or time spent making detours. Another example is a navigation lock which also fulfils a water retaining function. When the navigation lock cannot close, the risk of flooding of the hinterland increases, which is difficult to quantify in terms of money.

The performance requirement “availability” is one of the most important performance requirements within these types of contracts. The payment system as explained before in paragraph 4.1. is essentially based on the availability of the system. In the before mentioned contracts, availability is usually defined as a Service Level Agreement (SLA). This SLA is usually quantified as a percentage of a time period in which the system has to be available to carry out the main function of the system as agreed in the contract. The SLA of this performance requirement can change according to the agreements in the contracts, but is usually very high, especially in the case of structures which have functions such as flood prevention. A good example is the first DBFM project in the “wet” infrastructure, which is a flood gate in Limmel with a requirement on availability of 100% (RWS, 2013c).
An example of SLA’s and their associated allowable system unavailability time is shown in Table 2.

<table>
<thead>
<tr>
<th>SLA (%)</th>
<th>Monthly</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.0</td>
<td>7.3 hours</td>
<td>3.7 days</td>
</tr>
<tr>
<td>99.5</td>
<td>3.7 hours</td>
<td>1.8 days</td>
</tr>
<tr>
<td>99.8</td>
<td>1.5 hours</td>
<td>17.5 hours</td>
</tr>
<tr>
<td>99.9</td>
<td>43.8 minutes</td>
<td>8.8 hours</td>
</tr>
<tr>
<td>99.99</td>
<td>4.4 minutes</td>
<td>52.6 minutes</td>
</tr>
<tr>
<td>99.999</td>
<td>26.3 seconds</td>
<td>5.3 minutes</td>
</tr>
</tbody>
</table>

Table 2: SLA’s and associated allowable unavailability

When performance requirements are used and therewith service providers are paid with availability reimbursements, the unavailability of a system becomes easier quantifiable in terms of money. The availability reimbursements and therewith the penalties should be a reflection of the economic loss when a system function is unavailable. Also the height of the required SLA should be a reflection of the importance of the structure. The reimbursements from the client to the service provider when the system is properly functioning and the fines when the system fails for a certain period of time are easy to calculate in terms of money and therefore it becomes possible to quantify risks concerning unavailability of a system and make choices for either corrective or preventive maintenance, which will be explained later.
4.2.2. Availability, reliability and maintainability

Availability, reliability and maintainability are three different concepts. Reliability deals with: can a specific function of a system survive a certain period of time (the probability that the item will not fail). Maintainability is defined as: The ability of an item, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources (the probability that the item is successfully restored after failure) (O’connor, P., 1991). With these two concepts, another one arises, which is availability. This is needed to calculate the probability that the component/system is operational at a given time. Availability is a performance criterion for repairable systems that accounts for both the reliability and maintainability properties of a component or system.

Maintainability affects availability directly. The time taken to repair failures and to carry out routine preventive maintenance removes the system from the available state. A system which is repairable can have a high availability due to short repair times, but the reliability is not influenced by repairs. Therefore, availability is dependent on the reliability and maintainability of the system, which are two other RAMS requirements. In order to prove or calculate availability of a function of a system, data about the reliability of the sub-systems and components is needed together with data about repair times and delivery times and therefore about maintainability.

The difference and relation between reliability, availability and maintainability can be clearly described by the following example from the Leidraad RAMS (RWS, 2010).

“A car fails on average once a year. This tells something about the reliability of the car but nothing about the availability. In order to say something about the availability, additional information is necessary. This additional information concerns the period of time in which the car is not usable due to the failure. This period of time is a sum of: the period of time since the failure is noticed and the period of time necessary to repair the car (maintainability). So the unavailability of the car increases when the repair time increases and therewith the maintainability decreases.”

The relationship between the three different concepts is illustrated in Table 3. As can been seen in the table, if the reliability is constant this does not directly result in a high availability. If for instance the time to repair increases and therewith the maintainability decreases, the availability decreases as well. The other way around, this means that a system with a low constant reliability can still have a high availability as the maintainability influences the availability directly.

<table>
<thead>
<tr>
<th>Reliability</th>
<th>Maintainability</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>Decreases</td>
<td>Decreases</td>
</tr>
<tr>
<td>Constant</td>
<td>Increases</td>
<td>Increases</td>
</tr>
<tr>
<td>Increases</td>
<td>Constant</td>
<td>Increases</td>
</tr>
<tr>
<td>Decreases</td>
<td>Constant</td>
<td>Decreases</td>
</tr>
</tbody>
</table>

Table 3: Relationship between Reliability, Maintainability and Availability
4.2.3. Availability and unavailability

The availability and unavailability of a system are each other opposites. Unavailability is defined as the period of time that a sub-system or component cannot fulfil its function due to a component which has failed and is not restored yet. According to the reliability theory, the unavailability corresponds with the probability that a sub-system or component cannot perform its function at a certain moment in time. If we consider unavailability of a sub-system or component, it must be taken into account whether or not the failure of the sub-system or component is noticeable. Generally, if an element can fail unnoticeably, it is tested periodically to see whether or not the function can still be fulfilled. A good example is a mobile phone. If a phone is broken and in someone’s pocket, the phone cannot be reached. The owner of the phone will only notice this problem when he wants to make a call himself.

Unavailability can be divided into three types:

1. $U(sc)$ = Scheduled unavailability: Amount of hours during a period in which the indicated function cannot (fully) be fulfilled due to planned maintenance (Testing or periodical maintenance.)
2. $U(usc)$= Unscheduled unavailability: Amount of hours during a period in which the indicated function cannot (fully) be fulfilled due to unplanned maintenance( Random failures, damage and unexpected replacements)
3. $U(ex)$ = Unavailability due to exogenous factors: Amount of hours during a period in which the indicated function cannot be fulfilled due to exogenous factors (for example: storms, high water levels and obstructions as a result of other works), but not due to maintenance of any kind.

Unavailability exists when the considered system cannot fulfil one or more of its main functions. The unavailability of a system is determined by RWS in the document: “Vraagspecificatie Eisen Nat” (RWS, 2013b) as:

Total amount of time that the system is unavailable:

$$U(nfun) = U(sc) + U(usc) + U(ex)$$

Scheduled unavailability:

$$U(sc) = U(nfun) - U(ex) - U(usc)$$

Unscheduled unavailability:

$$U(usc) = U(nfun) - U(ex) - U(sc)$$

Where:

$U(nfun)$ = Total amount of hours during a period in which the indicated function cannot or not fully be fulfilled (not functional).

Unavailability due to schedulable causes and unavailability due to non-schedulable causes are dependent on each other. Schedulable causes are mostly preventive maintenance, inspections and testing which cause an unavailability of the system, but these measures usually result in a lower unavailability from non-schedulable causes. More preventive maintenance on a system will usually lead to less failures and therefore less non-schedulable causes with corrective maintenance. Hereby, it already becomes clear that an optimum between preventive maintenance and corrective maintenance can lead to optimal availability of a system when the costs of both maintenance and unavailability of the system are considered.
The relation between availability and unavailability can be described by the following formula:

\[
\text{Availability} = 1 - U(\text{unfun}) = 1 - (U(sc) + U(usc) + U(ex))
\]

4.2.4. Quantitative assessment of availability of a system

Quantitative assessment of availability of a system is necessary in order to prove a solid system design and meet the pre-set requirements concerning availability assigned by the client in the design phase of the construction process. One of the most important downsides in proving and calculating availability is that aging of the system is not taken into account. In order to prove the required availability, knowledge about the system, data concerning failure rates of components with associated recovery periods is necessary.

Ex ante, availability of a complex system can be calculated with the use of a quantitative Fault Tree Analysis. Fault tree analysis is a method which determines the contribution of individual failure of components on a certain top event. Top events (with respect to a function of the system) are usually the failure of the system as a whole, the failure of a sub-system or the failure of a chosen function of the system. This method is a generally accepted way of determining the reliability and availability of a system in the field of reliability engineering. In order to assess which components or sub-systems are most important in the system with regards to the availability a fault tree analysis is a quantitative method which can help to calculate the contribution of each sub-system or component on the availability of the system. With this method a consideration can be made to choose which sub-systems or components are most interesting for further investigation. The FTA method and its application will be further explained in paragraph 5.3. Ex-post, the availability can be calculated using the formulas given in paragraph 4.2.3. and be used to determine the availability discount.
4.3. Failure: Different types of failure and failure behaviour

Failure is defined in literature as: “The termination of the ability of an item to perform a required function” (O’Connor, P., 1991). This definition is very general, as failure can be interpreted from many different points of view and can be of many different types. Therefore this chapter gives an explanation of the different types of failure and the different types of failure behaviour.

4.3.1. Different types of failure

In order to calculate the unavailability or availability of a system, a clear distinction has to be made between the different types of failure. The different types are:

1. Hidden failure
2. Noticeable failure
3. Failure on demand
4. Failure during mission

Hidden failure
Failure mechanisms which are referred to as hidden failure, relate to components which are not used continuously, but can fail when the system is out of service. Only when these components are being used, the failure can be detected. The unavailability of such components is therefore not only given by the time to repair but also by the period that the failure of such a component is not noticed. Examples of hidden failure are: blocking of a gearbox, a relay may not function, the emergency generator does not start, etc.

Noticeable failure
Noticeable failure is characterized by the fact that when the failure mechanism occurs, this is almost immediately noticed (this can be visual as the system stops functioning, or because an error message is being issued, which is a typical measure against hidden failures). This allows immediate repair of the component after the failure of the component by a maintenance mechanic. The time that the component is not available is, therefore only the time that it cannot be used because it is being replaced. Another important condition for a noticeable failure, is that these components are continuously exposed to the appropriate failure mechanism, and therefore the failure is located at a random moment in time. Examples of noticeable failure are: collapse of sheet piling, failure of a camera, collapse of a door etc..

Failure on demand
Failure on demand is a type of failure, which refers to components that can only fail if they are being used. Such a failure mechanism has a fixed probability of failure, that does not change in time, or by an increase in usage. An example of such a failure is, a failure due to not starting of a component. Components which first have to start before they can be used are a good example of failure on demand. The probability of a motor not starting can be higher than the probability of the motor failing during use, making this a very important type of failure. Components which are subject to failure on demand, mostly are also subject to failure during mission. The unavailability due to one of these failures can be different and therefore it is necessary to consider both.
Failure during mission
Failure during mission refers to failure mechanisms which can only occur when the system is actually in use. The probability that the failure mechanism occurs is dependent on the period the component is actually used. Examples of failure during mission are: Premature stopping of an electric motor or collapse of an axle due to an overload.

4.3.2. Failure behaviour
For each failure mechanism an indication is needed why the component fails, which is referred to as failure behaviour. Generally three different behaviours are considered which are:

1. Instant failure
2. Aging
3. Failure due to an external cause.

Instant failure
Instant failures are almost always possible and not related to the technical condition of a component. An example are electrical components. Despite the condition of a component, it is possible that at virtually any time the component fails.

Aging
Aging can be observed by inspections. By adequate and timely maintenance, a failure mechanism can be prevented. An example are mechanical components which are subject to wear and tear and therefore become less reliable. Aging is characterized by an increasing probability of failure, but in many cases very difficult to model.

External cause
Examples of failure due to an external cause are: lightning, collision, frost, etc. These failures are caused by external events that occur outside the system boundaries and therefore their probability cannot or very little be influenced. Although the probability cannot be easily influenced, the possibility for preventive measures and thereby controlling their effects is usually possible.
4.3.3. Random failure

If component failure occurs random together with a high consequence on availability, corrective maintenance or taking preventive measures to reduce the effects of failure become the only logical choice for maintenance. Random failures cannot be predicted and therefore preventive maintenance will not result in increasing the reliability or availability of the system as the failure rate of the components after maintenance will remain the same. On the other hand, it will always be possible to research preventive measures which can help to reduce the effect or occurrence of a random failure.

Random failures are part of the so-called bathtub curve as shown in Fig.11 and are described by a constant failure rate which is the middle part of the bathtub curve. This bathtub curve is the result of three different causes of system failure:

- The first curve where the failure rate decreases is due to initial quality errors or the commissioning of the system: the so-called "infant mortality". An example is concrete which is exposed to loads before it is fully hardened or software problems in the completion phase.

- The second curve (actually a straight line) is the random failure curve. The failure rate is constant. The failures in this part are based on pure coincidence and cover a major part of the component life. Examples are electrical components, but also external causes.

- The third curve represent the wear-out period. During this period the components have reached their useful lifetime and the failure rate increases. The reason for this increase is degradation due to ageing and fatigue.

![Bathtub curve](image-url)
4.3.4. Formulas and calculations for system availability and unavailability

In order to calculate the availability and unavailability of a system, important properties of the components and subsystems are needed to conduct an FTA which are collected in an FMEA. When we only consider the failure mechanism noticeable failure, the following properties of each component are needed:

- The conditional failure rate: \( \lambda \) [-/hours] (Reliability)
- The MTTR (Mean time to repair) [hours] (Maintainability)
  (MTTR consist of: the repair time (which consists of the response and diagnostic time) and the delivery time of components)

After collection during the FMEA these properties are given to each basic event in the fault tree and subsequently the software program FaultTree+ calculates the availability or unavailability. FaultTree+ is one of the most popular software packages for conducting a fault tree analysis. After creating a fault tree diagram, failure and repair data can be assigned to the system components. The analysis is then performed, to calculate reliability and availability parameters for the system and identify critical components. Furthermore, the program can also calculate the minimal cut sets (unique combinations of component failures that can cause system failure), and the portion of the availability each component contributes to the whole unavailability, therefore showing the importance of each basic event and minimal cut set. When other types of failure than noticeable failure are considered, more properties are needed, but these properties do not relate to the components but to the properties of the whole system. Examples of these properties are: testing interval, mission time, hours a year in use etc.

Calculation of the unavailability

In the following subsections the calculation of the unavailability for the different types of failure as described in paragraph 4.3.1. is elaborated. The different formulas used in order to calculate the unavailability will be described and are applied in order to calculate the unavailability of the system. The formulas used are from the the book: Methods for determining and processing probabilities (Schüller, J. C. H. et al, 2005) and is known as the: “Red book”

In terms of “time to recover”, the symbol “\( \Theta \)” is used in all formulas. This is equal to MTTR which is known as the mean time to repair.

“\( \Theta \)” represents the time to recover and consist of \( \Theta = \Theta_{del} + \Theta_{rep} \)

Where:

\( \Theta \) = Recovery time [hours]
\( \Theta_{del} \) = Delivery time [hours]
\( \Theta_{rep} \) = Repair time [hours]

Noticeable failure

The unavailability as a result of noticeable failure is the time that the component cannot fulfil its function, because it is being repaired. This is being expressed as (Schüller, J. C. H. et al, 2005):

\[ Q_{nf} = \lambda * \Theta \]

Where:

\( Q_{nf} \) = Unavailability due to a noticeable failure [-]
\( \lambda \) = Failure frequency [-/hour]
Hidden failure
The unavailability as a result of hidden failure is the time that the component cannot fulfill its function, because it is being repaired, or because it has failed but the failure is not yet noticed. The most conventional way to express this is (Schüler, J. C. H. et al, 2005):

\[ Q_{hf} = \frac{1}{2} \lambda T + \lambda \theta \]

Where:
- \( Q_{hf} \) = Unavailability due to a hidden failure [-]
- \( T \) = Test interval of component [hours]
- \( \lambda \) = Failure probability per demand [-]
- \( \theta \) = Recovery time [hours]

The factor \( \frac{1}{2} \) is used, because the assumption is made that the demand for the component is at a random moment in the test interval. From this formulation it follows that failure can be identified by testing the component. If testing is being done more often, the test interval becomes smaller and therefore failure will be noticed earlier. Subsequently, the probability that the component cannot fulfill its function on the right moment will decrease.

Failure on demand
Unavailability as a result of failure on demand concerns failure mechanisms which are not subject to an increasing probability of failure over time. This unavailability is calculated with the following formula (Schüler, J. C. H. et al, 2005):

\[ Q_{fod} = \lambda + \frac{\tau}{T} + \frac{\lambda \theta}{T} \]

Where:
- \( Q_{fod} \) = Unavailability due to a failure on demand [-]
- \( \lambda \) = Failure probability per demand [-]
- \( \tau \) = Testing length [hours]
- \( T \) = Test interval of component [hours]
- \( \theta \) = Recovery time [hours]

Failure during mission
Unavailability as a result of failure during mission can be calculated with the same formula as failure on demand where the probability of failure is (Schüler, J. C. H. et al, 2005):

\[ \lambda_m = \lambda \times t_m \]

Where:
- \( \lambda_m \) = Failure probability during mission [-]
- \( t_m \) = Mission duration [hours]
4.4. Maintenance and risks reduction

Maintenance can be used in order to reduce the risks concerning unavailability of the system. Before choosing which maintenance action can be used for reducing the associated risk, it is convenient to make them measurable to a certain degree. If risks becomes measurable, a choice can be made to further investigate risks and/or accept them.

If risks are unacceptable (depending on the predetermined level of acceptability) measures should be taken to bring them back to an acceptable level. The choices for measures if possible are (Boomen, M, 2014):

- Usage dependent maintenance (Dependent on usage or time)
- Condition dependent maintenance (Condition inspection + preventive maintenance if necessary)
- Functional testing (Inspection for hidden failure mechanisms + repair when necessary)
- Modify component
- Replace component
- Take measures in order to reduce the effect when a failure occurs

For acceptable risks the choice can be:

- Corrective maintenance/Run-to-failure maintenance (repair when failure occurs)
- Condition or usage dependent maintenance (for economic reasons or obligations concerning warranty or insurance)

The choice between all of the maintenance concepts listed above are chosen from a consideration between:

- The identified risks
- The technical possibilities (condition of a component possible to measure/predict ?)
- Financial feasibility (preventive maintenance can be cheaper than corrective maintenance even if a component is not critical)
- Obligation concerning insurance or warranty (contract)
- Hoping it doesn’t fail during the maintenance period (which can also be a strategy)

The choices and considerations as listed above are part of a new way of looking at maintenance due to the responsibilities in long-term contracts on availability. Traditionally, maintenance decisions are different which will be explained in the following paragraph.

4.4.1. Traditional maintenance decision making

Traditionally, decisions for maintenance are being made based on the risk of failure of a component or subsystem. A very simple decision tree for making maintenance decisions for hydraulic structures which is also used by Rijkswaterstaat is shown in Fig.12. When risks are low, the choice is made for corrective maintenance, which entails repairing the component after a failure occurs. When risks are high together with a good understanding of the relevant failure mechanisms and therefore a clear view on when a failure occurs, the choice is made to conduct preventive maintenance based on: the usage of the component, time dependent or load dependent. When the risk is high, the confidence in the time to failure low and the measurability of the condition of the component is easy, condition dependent preventive maintenance will be the choice. The condition of the component will be assessed by doing inspections. When the condition of the component is very difficult to inspect, a choice can be made to improve the component, replace it with an easier measurable one or install redundancy. The traditional decision tree is also used by the asset owner to choose which maintenance can be outsourced. Traditionally this was the usage dependent preventive maintenance as it is easy to schedule and can thereby be put on the market in the form of a tender.
Figure 12: Maintenance decision tree (Jorissen, R.E., & Noortwijk, J.M., 2002)
4.4.2. Current maintenance practices on hydraulic structures

Hydraulic structures which are part of the “wet” infrastructure of the Netherlands are often structures which are composed of diverse sub-systems. Where for example a fixed bridge usually is composed of a foundation and concrete structure, hydraulic structures are dynamic systems with all sorts of moving components and therefore more subject to wear and tear.

When a hydraulic structure such as a navigation lock is considered, it can be stated that the structure roughly consist out of three different types of components which are:

- Electrical components (power supply, monitoring, information systems, control cabinets etc.)
- Moving mechanical components (hydraulic systems, door driving system, and electromechanical parts such as electric motors)
- Fixed civil engineering components (Concrete structure, sheet piling, granular materials)

All these different groups of components, which are part of hydraulic structures are subject to different aging mechanisms. Although most experts agree on the fact that these components age, the way they age is very different.

**Electrical components**

Electrical components are very often mass-produced and therefore the knowledge about the future behaviour of the components is often present due to lots of field data. The perception by experts of the reasons to replace these components are very different. While on the one hand experts say that these components do not age and are replaced because of the non-existence of spare parts due to a production stop and improved versions, others say they are replaced because they do age but how and why these aging mechanisms occur is very uncertain. Next to this, the possibilities of inspection of these components is very limited and therefore maintenance is often aimed at the minimum lifetime of these components. When data exists about the first failures of these components, these values are often used for the replacement interval, but are thereby a very conservative assumption.

**Mechanical and electromechanical components**

Mechanical and electromechanical components in hydraulic structures are often unique and specially designed for a certain structure and a special function. These components are subject to aging mechanisms such as wear and fatigue, because these are moving parts. Inspection of these components can be very difficult as they often are part of a sub-system which is badly accessible. Also, a system shut down is often necessary in order to inspect these parts.

**Civil engineering components**

Civil engineering components are mostly fixed and therefore subject to aging mechanisms such as corrosion and chloride penetration. Furthermore, they are often subject to varying loads and other external events. Inspection is often easy, but quantitative measurements and additional strength calculations are difficult and subject to uncertainty in future behaviour.
Managing the costs of system unavailability in long-term performance contracts for hydraulic structures
4.5. RCM

In order to create a new model which can help service providers in satisfying performance requirements in long-term maintenance contracts as described in paragraph 4.1. and to answer the sub-question: “What is Reliability Centred Maintenance (RCM) and how can it be implemented?”, RCM and its application possibilities for supporting maintenance decisions for hydraulic structures has been investigated. The RCM process, and how to implement it for a hydraulic structure is researched. Subsequently, a new model is proposed in chapter 5 and applied to an example of a hydraulic structure in chapter 6.

4.5.1. Reliability centred maintenance

Reliability centred maintenance (RCM) is an improvement technique within maintenance management. It has its origins in the aviation industry and after it had been perfected by John Moubray it is adopted in several other industries. It is seen as best practice for establishing and optimizing the preventive maintenance program of technical (sub) systems with the goal to achieve the highest possible availability at the lowest possible cost, considering the requirements imposed on the system. RCM does not aim to prevent the occurrence of failures, but to keep the effects of such failures within the acceptable limits (Moubray, J. 1997). The goals of RCM can be summarized as follows:

- Concentrate maintenance resources where they will do the most good;
- Eliminate unnecessary and ineffective maintenance;
- Devise the simplest and most cost-effective means of maintaining equipment or testing for degradation focusing on predictive or condition monitoring activities;
- Develop a documented basis for the maintenance program.

4.5.2. RCM process

The analysis process used with RCM is described in the book: Complex system maintenance (Kobbacy, K.A.H., & Murthy, D.P., 2008). It describes seven questions which should be answered in an RCM analysis which are:

1. What are the system functions and the associated performance standards?
2. In what way can it fail to fulfil its functions?
3. What can cause a functional failure?
4. What happens when a failure occurs?
5. What might be the consequences when the failure occurs?
6. What can be done to detect and prevent the failure?
7. What should be done when a suitable preventive task cannot be found?

These questions which are answered when conducting a RCM analysis can also be answered with regard to the availability of the system. Important to mention is that in this research the RCM process will be used from the perspective of the service provider and not the asset owner. The most important difference will be that the service providers will try to collect revenues by conducting clever maintenance and finding an optimum between costs and availability, while the asset owner tends to put the emphasis on the highest achievable reliability and availability.

The seven questions which need to be answered during the RCM process can be answered with the use of different methods and tools appropriate for finding the answer. When dealing with complex systems such as hydraulic structures where several different types of sub-systems and components are used, the appropriate tools for the RCM process have to be selected. Furthermore, the new way of contracting and therewith a new way of earning money for the service provider requires a new decision model for making decisions concerning maintenance actions.
4.5.3. Steps for implementing RCM analysis

There are several different methods for implementing RCM Analysis. In general they can be summarized into seven steps which are described in the book Reliability centred maintenance II by J. Moubray (Moubray, J. 1997) and in the book RCM- Gateway to World class Maintenance (Smith, A. M., & Hinchcliffe, G. R. 2004). The seven steps are further described below:

**Step 1: Defining functionality**
The first step in implementing RCM, is defining the functionality of the system which will be subject to the analysis. Naturally, it is essential that the system which is selected is critical in terms of effect on performance. The purpose of the asset, all its functions and the impact of its malfunction should be defined. The goal of this first step is to gather sufficient knowledge for an effective analysis without wasting too many resources.

**Step 2: Define the boundaries of the system**
The second step in the RCM process is to define system boundaries. This helps to specify what is included and what is not included in the system at question. With the boundaries being set, a complete list of components can be identified and no overlap with other systems can happen. Next to this, setting boundaries is essential to determine inputs, outputs and functions of the system.

**Step 3: Defining the ways that the system can fail (Failure modes)**
During this step the objective is to find all the ways in which the functioning of the system can fail. The ultimate goal of any RCM process is “to preserve system function”, therefore it is essential to define a complete list of system functions and the ways in which they can fail. The output of a system typically captures the function of the system. Therefore every output can be translated into a function statement. It is desirable to specify the acceptable level of performance desired by the asset owner. It is also desirable to define the function as quantitative as possible, it becomes very difficult to decide on maintenance strategies when the goals are not defined precisely. When all functions are described extensively and in the most quantitative way, it becomes easier to define ways in which the system can fail and thereby describing the failure modes.

**Step 4: Identify the cause of the failure modes**
With step 4 the analysis part of the RCM process starts. During this step and with the help of experienced maintenance experts and component experts the root causes of each of the identified failure modes in the previous step can be found. The way in which each functional failure is caused can be described by component failures resulting in a loss of function. There can be many causes which can result in component failure and therefore a loss of function but it can also be a failure in some human activity, examples are: software failure, external factors, maintenance mistakes etc.. The level in which the failure modes are described will be dependent on the situation (a nuclear facility needs more depth than a small production factory). Guidelines recommend that failure modes should be described in enough detail for it to be possible to select an appropriate failure management policy, but not in that much detail that there are excessive amounts of time needed for the analysis process itself.

**Step 5: Identify and evaluate the effects of failure**
During this step the effects of each failure mode (the way in which the component fails) are identified. Depending on the system at question the effects can include effects on safety, operations or on other (sub) systems. Also depending on the system under consideration and the choice in depth of the analysis, the criticality of each of these failure modes can be considered. In order to perform step 5 (and sometimes step 4) there are many techniques to give this a systematic approach. The result of these systematic approaches will determine the most important failure modes. This will be achieved by looking for an answer to the question: Does this failure mode result in a (partially or total) loss of system function? Next to this, it is also possible to identify the economic consequence of each of the failure modes.
Step 6: Prioritize function needs via the failure modes
The primary objective is to preserve system function. In order to do so there is an opportunity to do this in a systematic way. Not all functions are equally important and therefore not all functional failures and related components can be dealt with equally. In order to prioritize each failure mode it can be passed through an appropriate model which can be used to rank each failure mode.

Step 7: Select maintenance task for each failure mode
This step is the final step in the RCM process and deals with finding the most appropriate maintenance task for each of the previously found (and labelled important) failure modes. Most important is that the chosen maintenance task is economically and technically feasible. Appropriate means that when the task is being done, it will accomplish one of the reasons for doing RCM which are: prevent or mitigate a failure, detect onset of a failure or discover a hidden failure.
5. Introducing a new model

The RCM process is not a stand-alone method, but needs to be supported by different methods in order to be applied. To create a model which can help service providers satisfying performance requirements in long-term maintenance contracts, the RCM process is used as a guideline, but supporting tools are selected in order to create a model, which can be used to achieve the desired results. This new model will be described and explained in this chapter.

The first two steps in the RCM process are rather straightforward and therefore do not need supporting tools. To execute the third and fourth step in the process, the need for a supporting tool becomes clear. A structured way of identifying failure modes and ways in which the system can fail are usually supported with an FMEA or FMECA. The choice has been made for an FMEA and the method and choice is explained in paragraph 5.2. In order to find a method to support the fifth and sixth step in the process, research had been done into appropriate methods which have led to the choice for FTA, the method and choice will be explained in paragraph 5.3. Furthermore, the use of RPN is proposed in order to prioritize risks. This will be further explained in paragraph 5.4. When the maintenance decisions are made, it might be necessary to adapt the model concerning changes due to system redesign. This is shown in Fig.13 with the loop going back to system description. Lastly, a new decision tree is presented to give guidance for the seventh step in the process, which is explained in paragraph 5.5. The research into RCM and appropriate supporting methods have led to the proposition of a new model which is shown below in Fig 13.
5.1. System description and decomposition

The first step in the proposed model concerns giving a system description and decomposition of the chosen system. Furthermore, the context, the assumed conditions and the process need to be set. A block diagram needs to be made to clarify relations and dependencies between the components in the system. This is an essential step, because this forms the basis to conduct the following steps. The boundaries of the system need to be made very clear in order to define the scope of the following analysis. The responsibilities of the service provider need to be stated, so all associated risks can be identified. In addition, performance requirements set by the asset owner should be explored and gathered into a bill of requirements.

5.2. Failure Mode and Effect Analysis (FMEA)

The second step in the model is conducting an FMEA. An FMEA is an important part of RCM and is used in order to identify, prioritize and prevent potential failures in a qualitative way and forms the basis for a Fault tree analysis (FTA) which represent a quantitative risk analysis. With the use of a system decomposition in which different sub-systems, elements and components are described, failure modes can be appointed. Failure modes are described as: “The way in which a component functionally fails”. The cause of each failure mode can be of many different kinds and are called: “Failure mechanisms”. These failure mechanisms concern different types of causes which are: corrosion, fatigue, overload, external events, human failure, software failure etc. For each failure mechanism it is assessed if they concern a critical function and if they are normative in comparison with other failure mechanisms. Subsequently, the chance of happening of the failure modes can be quantified and an assessment of the effect on the top events, which are the main functions of the relevant system can be made. All failure modes which contribute to the occurrence of one or more of the undesirable events will be included in an FTA during the next step.

In order to conduct a quantitative system analysis concerning the availability of a system with the use of a fault tree analysis (FTA), several data is needed which is usually collected with the use of an FMEA. The unavailability or availability of the system is calculated with the use of an FTA. In an FTA all components and/or subsystems are incorporated and given different properties with the help of a previously made FMEA.

Why FMEA and not FMECA?

FMECA is an abbreviation for Failure Mode, Effects and Criticality Analysis. In an FMECA, different failure modes for a system are being considered and the accompanying effects are being appointed. With appointing criticality, the severity of the effects (both quantitative and qualitative) is given. Subsequently, the probability of occurrence can be plotted against the effect of each failure mechanism which results in an insight of the risks (RWS, 2011b).
Opposed to the FMECA, in an FMEA the criticality of failure modes is not appointed. One of the most important reasons is that an FMEA is often used as input for an FTA. In an FMECA, redundancy in a system and interaction between different systems is not taken into account. Criticality of systems such as navigation locks and other hydraulic structures is very difficult to assess due to the complexity of the system. Most hydraulic structures are systems which consist of several sub-systems and different kinds of components such as electric, civil and mechanical components. Next to this, several sub-systems or components are subject to redundancy in order to achieve their requirements on reliability.

An FTA can take these two very important system properties into account and considers the occurrence of a chosen top event. When comparing these analysis methods, the most significant difference is that failure modes with a high criticality in an FMECA can have a very small contribution to the not functioning of the system when looking at it through an FMEA and FTA due to redundancy in the system. When dealing with complex systems with a lot of redundancy and sub-systems it is a better choice to use FMEA together with an FTA and possible risks identification methods instead of an FMECA (Alvares, A.J., 2008).

### 5.3. Fault Tree Analysis (FTA)

As explained in the previous paragraph the choice is made to use FTA in order to conduct a quantitative analysis, as it is a proven method to describe complex systems. A FTA is a graphical method of describing the combination of events leading to a defined system failure. It is used to gain an understanding of a complex system and to exhaustively identify causes of failure. Next to this it is used to identify weaknesses in a system and to prioritize contributors to system failure. The United States Air Force together with Boeing and Bell laboratories developed the fault tree analysis technique in order to identify all possible causes which can cause an inadvertent nuclear missile launch (Lee, W. S. et al, 1985).

The system failure mode in an FTA is known as the top event which describes the main function of the system considered. The fault tree is used in order to model the paths of failure to the top event. A fault tree analysis basically involves only three logical possibilities and therefore three main symbols. These involve gates such that the input below these gates represent failures. Outputs above the gates represent the distribution of the failures, depending on the gate below (Berk, J. 2009). All basic events in the FTA have to be given their own properties. An FMEA and especially the data in an FMEA about component failure rates and MTTR form the basis for the construction of the FTA.
There are three basic gates which are used when constructing an FTA, these are shown in Fig. 17.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Causal Relation</th>
<th>Valid No of Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR</td>
<td>Output event occurs if any one of the input events occurs</td>
<td>≥ 2</td>
<td></td>
</tr>
<tr>
<td>AND</td>
<td>Output event occurs if all input events occur</td>
<td>≥ 2</td>
<td></td>
</tr>
<tr>
<td>VOTE</td>
<td>Output event occurs if m of the input events occur</td>
<td>≥ 3</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 17: Fault tree basic gates (Isograph, 2013)**

The OR gate is used if any inputs cause the specified output to occur such as in a series system. The AND gate is used if all inputs need to occur for the output to occur such as in a parallel (redundant) system. Next to these two, there are several special gates of which the VOTE gate is used mostly. The VOTE gate is similar to the AND gate, but in order for the output to occur a specified amount of inputs have to occur.

In order to construct a fault tree, additional symbols for basic events and intermediate events are also needed. These are described by the following symbols as shown in Fig. 18.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BASIC</td>
<td>Basic event for which failure and repair data is available</td>
</tr>
<tr>
<td></td>
<td>TRANSFER</td>
<td>Indicates that this part of the fault tree is developed in a different part of the diagram or on a different page</td>
</tr>
</tbody>
</table>

**Figure 18: Events in an FTA (Isograph, 2013)**

**Fussell-Vesely failure importance**

In order to investigate which sub-systems and components are critical for the failure of the main function of the system and therewith the requirement on system availability, the criticality of a component to the availability of the main function of the system can be calculated as a percentage of the total unavailability.

The Fussell-Vesely standard importance measure indicates a component’s contribution to the system unavailability or failure frequency for consequences or risk for risk categories. Increasing the availability of components with high importance values will have the most significant effect on system availability, consequence frequency or risk.
The standard Fussell-Vesely unavailability importance value for a component is given by the following formula (Isograph, 2013):

\[ I_{i}^{FV} = \frac{Q_{sys} - Q_{sys} (q_i = 0)}{Q_{sys}} \]

Where:

\( I_{i}^{FV} \) = Fussell-Vesely importance for component i.
\( Q_{sys} \) = System unavailability
\( Q_{sys} (q_i = 0) \) = System unavailability with the probability of component i set to 0.

With the use of the Fussell-Vesely failure importance, all the basic events and cutsets in the fault tree can be ranked according to their importance and/or contribution on the unavailability of the system. This ranking can later on be used in order to make choices for improving availability, with the highest ranking failure mode having the biggest effect on the unavailability.

5.4. Risk priority number (RPN)

To support decision making concerning maintenance, a method to extend the previously made FMEA with a Risk Priority Number is proposed.

Based on the Fussell-Vesely importance described in the previous chapter, some components have a negligible effect on the unavailability and will therefore not be further researched. The ones that will be subject to further investigation will be put in a reduced FMEA, which will be extended with three new features. These new features are:

- The amount of damage in €, which the failure mode causes in terms of penalties due to system unavailability.
- Probability that the failure will not be detected with a given detection method.
- The method of detecting the failure mode.

Because not all failure modes are equally detectable, each of the failure modes in the extended FMEA will get a numeric score on the probability that the failure will not be detected (depending on the detectability), ranging from 1 to 10 as shown in Table 4. Some failure modes are easily detectable and therefore the risk concerning the failure modes need to be reduced. The opposite goes for failure modes which are not easily detectable and therewith have a higher risk. When a failure mode results in unavailability of the system's main function this will cause a penalty. This is also included in the extended FMEA and described as the amount of damage in € when a failure occurs. Together with the probability of failure (which is already part of the previously made FMEA), these three numbers will be used to calculate the RPN (risk priority number) for each failure mode. The product of these three scores is the Risk Priority Number (RPN) for that specific failure mode in the form of a formula (Bertsche, B. 2008):

\[(\text{Probability of failure} \times \text{Probability of not detecting} \times \text{Damage}) = \text{RPN (Risk Priority Number)}\]
<table>
<thead>
<tr>
<th>Score</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cause certainly detected in time before the failure occurs</td>
<td>The probability that a detection method will notice the cause before failure is certain</td>
</tr>
<tr>
<td>2</td>
<td>Cause probably detected before the failure occurs</td>
<td>The probability that a detection method will notice the cause before failure is very high</td>
</tr>
<tr>
<td>3</td>
<td>High probability of the cause detected before failure occurs</td>
<td>The probability that a detection method will notice the cause before failure is high</td>
</tr>
<tr>
<td>4</td>
<td>Low probability of the cause detected before failure occurs</td>
<td>The probability that a detection method will notice the cause before failure is mediocre</td>
</tr>
<tr>
<td>5</td>
<td>Cause certainly not detected before failure occurs</td>
<td>The probability that a detection method will notice the cause before failure is negligible</td>
</tr>
</tbody>
</table>

Table 4: Detection scores
5.5. Maintenance decision making

With the use of new types of contracts described in paragraph 4.1., all the maintenance will become the responsibility of the service provider. When the maintenance is based on performance requirements set by the client such as availability, the maintenance decision tree for the traditional approach shown in Fig. 12 in paragraph 4.4.1. can be extended. From the perspective of the service provider, failure and especially random failure of components is associated with high costs due to penalties for not satisfying the performance requirements. The service provider is always looking for a maximization of revenues and therefore is not willing to take risks when corrective maintenance and possible unavailability of the system is concerned with the associated costs. Furthermore, inspections of components are not always possible and if so they are often costly and will result in a decrease in revenues especially when many are needed.

An extended decision tree for maintenance decisions appropriate to the new model and RCM from the perspective of the service provider is therefore proposed and shown below in Fig. 21.

![New decision tree from the perspective of a service provider](Figure 21: New decision tree from the perspective of a service provider)
In this extended maintenance decision making tree, there are some new features. The top half of the tree remains almost the same, but the emphasis is on availability instead of risk. Components with a high consequence on the availability will be subject to further research. If the confidence on the time to failure is high they will be subject to usage dependent preventive maintenance, if not the measurability of the condition of the component will determine if condition based preventive maintenance will be chosen or if a risk-based approach is needed. This risk-based approach is a new feature in the maintenance decision making tree. Risk in this context is defined as the probability of failure of a component multiplied with the consequence in terms of availability discounts due to unavailability of the system.

Most important assumption when risk based maintenance is chosen through this tree, is that component failure will occur random. There is no confidence in the time to failure and the measurability of the component’s condition is low. In this case the service provider can choose to investigate the contribution of these components to the unavailability of the system and therewith make choices for either corrective maintenance or preventive measures. These choices can be supported with the use of the proposed model and associated methods. After applying the model, a prioritization can be made of all the components in the system. Based on the RPN a list of all components is made where choices can be made and quantified in order to reduce the RPN score.

New opportunities for maintenance decisions
The downside of RCM is that it essentially only deals with optimization of preventive maintenance. Lots of research and propositions for models which can be used to schedule preventive maintenance and therefore optimization of efforts and costs have been created and can be found in literature with RCM being the one most widely in use. Downside to all of these models is that preventive maintenance is only realistic when components age and wear and when this can be described. When components age and wear, the failure rate of these will gradually increase making them more vulnerable to failure and therefore an optimum to replace them can be found. Finding an optimum replacement interval together with the clustering of preventive maintenance tasks can be very interesting and can reduce maintenance costs.

Opposite to components which age and wear during time, there are also components which are not subject to these mechanisms such as electrical components. Next to these components, other risks like collisions, fire, lightning etc. also do not show an increase in failure rate over time. These external risks can be allocated to the service provider and should be clearly described in the maintenance contract.

Preventive maintenance only makes sense if both of the following conditions are met (ReliaSoft, 2014):

- The component has an increasing failure rate. Or in other words, the failure rate of the component increases with time, implying wear-out. Preventive maintenance of a component that is assumed to have an exponential distribution (which implies a constant failure rate also known as the memoryless property) does not make sense.
- The overall cost of the preventive maintenance action must be less than the overall cost of a corrective action.

So with a constant failure rate preventive maintenance cannot be justified. When a component is replaced, the failure rate will remain the same resulting in no changes in reliability or availability of the system. Therefore, corrective maintenance or preventive measures to reduce the effects of failure remain the only logical choices.
Requirements for optimizing corrective maintenance or applying preventive measures:

1. Consequence of failure is high on system availability (otherwise no optimization needed)
2. Confidence in time to failure is low (otherwise preventive maintenance)
3. Measurability of the component is low (ageing is therefore not measurable and failures will occur random, otherwise preventive maintenance through inspection)

When these requirements are met, an optimization for corrective maintenance or preventive measures can be made with respect to the consequence on availability and costs. A choice can be made between: acceptance and/or insuring or saving in order to cover the risk, buying spare parts, testing (for components which are subject to failure on demand), research into measurability and component or system redesign. The difference between these choices is described below.

Spare part
One of the choices for service providers in maintenance, is having spare parts in stock. This reduces the mean time to repair (MTTR) of a certain component. The mean time to repair consists of the delivery time of the component and the repair time. When having a spare part in stock the delivery time is zero and therefore only the repair time remains. Furthermore, spare parts can solve the problem of suppliers being unable to deliver a certain component. With the use of an FTA, it can be examined which spare parts have the largest effect on the total availability of the system. When spare parts are cheap or subject to a very long delivery time together with a high failure rate the consideration can be made to choose for having spare parts. By calculating costs of having spare parts versus the availability of the system an optimum can be found (Oussoren, M. 2014). Although having spare parts lowers the MTTR of those components, there are also some disadvantages. The main disadvantages which need to be considered, before buying spare parts are:

- Storage of spare parts can be very expensive (up to 25% of the component price each year)
- The spare parts might never be used
- Some components are known to deteriorate, even when not in use

When the choice is made for buying a spare part, the MTTR of the component changes and therefore it can be seen as system redesign resulting in higher availability of the system as the repair time is reduced. After this choice is made, the model should be adapted concerning the changes due to spare parts. This is shown by the loop in the model in Fig. 13.

Accepting the risk, insuring or saving
The service provider can also make the choice to accept the risk and deal with the failure only when it occurs. This consideration can be made when either delivery times for the parts are very short or when the risk of failure is low to such an extent that the failure costs will be low enough as well. Furthermore, it can be a consideration to choose to have an insurance for such risks if the premiums on the insurance are acceptable. The possibility exists to insure risks on income (availability reimbursements) and material damages with different types of insurance. The first type is called: “Opstal en inventaris verzekering” and can cover external risks due to fire, flooding, explosions etc. and therewith damage to material. It does not cover damage due to wear and tear of the structure itself, but this can be covered with the so called “Machinebreuk verzekering”. These two insurances do not cover a loss of income due to damage on the structure, but only the damage to the structure itself. In order to insure a loss of income due to unavailability of the structure, a so called “Bedrijfsschade verzekering” can be arranged. The height of the risk premiums for those insurances is dependent on a large variety of factors, but often becomes incredibly high when high risks are concerned, which makes them unrealistic (Ministerie van Financien, 2007). When insuring becomes too expensive, accepting or saving remain the only options.
Test
Testing can be used in order to assess if a component has failed during not using the system. Hidden failures can be discovered when testing the system. Also, testing is a good measure to see if components which are subject to failure on demand are still working. If for instance a mechanical part is stuck due to pollution or external loads, this can be discovered during testing the system.

Redesign the components or sub-system
A choice for redesign can be made if there are possibilities for preventive measures. One of the most powerful and straightforward methods to apply a preventive measure for an engineer is building redundancy into the system. The duplication or even triplication of components in a system will result directly into a higher availability of the system due to a backup system in case of failure. Furthermore, redesign can be the application of preventive measures outside the system to reduce failure occurrence.

Research into the measurability of the component
When the condition of a component is impossible to measure, the choice can be made to do research into this measurability. Condition measuring systems or inspection methods in order to assess the components condition can provide critical data. If the condition of a component becomes measurable due to new measuring techniques, insight can be provided into the time of failure and preventive maintenance can again be justified with the creation of figures as shown in Fig.22. New technologies and further developed measuring methods might help to assess degradation in the future. A good example are electrical components, because they are often very difficult to measure and assess degradation. Next to electrical components, components which are part of a larger sub-system and very difficult to inspect due to low accessibility might also benefit from new inspection methods.

P-F interval
The last two mentioned options: research in measurability and redesign can help with identifying degradation and finding the so-called P-F interval (potential-to-functional failure). The P-F interval can be used in order to map and prevent component failure and is a commonly used concept when it comes to performing RCM (Goode, K. et al, 2000). The functional failure “F” as shown in Fig.22 describes the point where a component fails to perform a required function. This can be a total failure but also a partial failure which causes the component to not function properly or at the required level. Regardless of the sort of failure, at this point on the curve the component has to be fixed. If safety is of major importance, the functional failure point might not even be the actual failure point, but a predetermined point that should not be exceeded (Moubray, J. 1997). The potential failure “P” as shown in Fig.22 describes the point where a detectable symptom or warning occurs which gives notice that a functional failure is in the process of occurring. Some examples of potential failures are: cracking, vibration, smell, heat, etc. These symptoms are often detectable with a wide variety of methods. When applying RCM it is important to find an inspection method which detects the potential failure prior to the functional failure. Next to this it is very important to know what the time window can be between “P” and “F”, which can be achieved with continuously condition monitoring with the correct instruments.

Ideally, the complete curve should be known for each component, in order to construct a time and/or usage based maintenance plan. Previous research however, has shown that this is not yet possible due to a lack in such data and no sufficiently advanced condition monitoring techniques.

Figure 22: P-F interval (Asset Insights, 2013)
5.6. Maintenance plan

The last step in the model is the preparation of the maintenance plan for the hydraulic structure at question. After the previous step, redesign concerning spare parts, preventive measures and component redesign have been made part of the system and the model is adapted accordingly. Decisions are made based on the risks of the failure modes and the design of the system is completed. At this step, all the parts of the system have to be reviewed and the choices made in the previous step should be put in a maintenance plan. In this plan the maintenance strategies for each of the components should be specified. Intervals for either testing, inspecting or preventive replacement of components need to be set and maintenance experts should be appointed to implement this maintenance plan. If during the maintenance period, assumptions which are previously made prove to be incorrect, adjustments in the maintenance plan need to be made. The findings during the maintenance period can be used to adapt the parameters used in the proposed method and reassess the plan. If continuous condition monitoring is used, it can be useful to create a model in which this data can be put directly and calculate the changes in availability and increase or reduction in risk.
6. Application and testing

In order to explain how, and test if the proposed model with RCM and the supporting methods can be applied to help in making decisions concerning maintenance in long term contracts, a fictitious example of a simple hydraulic structure (a small pumping station) will be used. The steps explained in the description of the model will be executed and explained in order to investigate the applicability of the proposed model.

6.1. First step: System description and decomposition

First step in the proposed model concerns the question: What are the system functions and the associated performance standards? In order to carry out this first step and answer this question, a system needs to be selected and the boundaries need to be set.

In this example, a very simple pumping station is examined and a sketch of the structure is shown in Fig. 24. The assumption is made that this concerns a newly build pumping station of which the maintenance will be outsourced from a municipality towards the private sector with the use of a performance based contract. Within the system boundaries, the assumption is made that only the components listed in Table 5. are part of the maintenance contract. The pumping station is built to ensure that the water level on the left side does not exceeds a certain limit in order to protect the hinterland against flooding. Therewith, the main function of the pumping station is: “Retain water level below required maximum”.

System description

Fig.24 shows the components in the pumping station. One measuring component measures if the water level on the left side is exceeding the limits. If the water level is too high, the measuring component sends a signal towards the PLC which is controlled by the SCADA and consequently controls the pump and the valve. If a signal is given the pump starts pumping and the valve opens during the period in which the water level is too high. When the water level is back to the limit the measuring components stops sending a signal and the valve closes and the pump stops. All components are powered by a transformer which transforms the AC from the power grid to the appropriate power for the components. Every time a high water level on the left side occurs, this process is repeated.
Associated performance requirements and costs

In order to answer the question concerning the performance standards, the associated contract needs to be examined. For this example, a fictitious overview of some of the requirements and system properties is made and shown in Table 5 below. In this example, only technical failures are considered and events like fire, flood, etc. are not considered.

<table>
<thead>
<tr>
<th>Pumping station details</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability requirement (service level agreement)</td>
<td>99%</td>
</tr>
<tr>
<td>Maintenance period</td>
<td>30 years</td>
</tr>
<tr>
<td>Penalty for unplanned unavailability</td>
<td>€ 2,500,- / hour</td>
</tr>
<tr>
<td>Demands each year</td>
<td>On average 15 times annually</td>
</tr>
<tr>
<td>Time each demand</td>
<td>On average 3 days (72 hour)</td>
</tr>
<tr>
<td>Required main function</td>
<td>Retain water level</td>
</tr>
<tr>
<td>Component costs</td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>€ 25,000,-</td>
</tr>
<tr>
<td>Valve</td>
<td>€ 6,000,-</td>
</tr>
<tr>
<td>PLC</td>
<td>€ 5,000,-</td>
</tr>
<tr>
<td>SCADA</td>
<td>€ 5,000,-</td>
</tr>
<tr>
<td>Measuring component</td>
<td>€ 800,-</td>
</tr>
<tr>
<td>Power supply (transformer)</td>
<td>€ 10,000,-</td>
</tr>
<tr>
<td>Relay</td>
<td>€ 150,-</td>
</tr>
</tbody>
</table>

Table 5: Performance requirements and component costs

The performance requirement on the availability of the system is 99%. This means that each year the system is allowed to be unavailable for 1% during the time it is supposed to be available. Furthermore, a penalty of € 2500,- / hour is given when unscheduled maintenance is exceeding the 1 % as agreed in the contract.
System decomposition

In order to construct an FMEA and an FTA during the following steps, a system block diagram is necessary in order to show and examine how all of the components in the system are related and connected. A system block diagram for the example of the pumping station is made and shown in Fig. 25. In a system block diagram all the different parts of the system (within the predetermined system boundaries) are shown and relations between the different parts are indicated. The relation between the parts is very important in order to identify causes of failure in the FMEA and in a later stage to conduct an FTA. Furthermore, the system boundaries are defined more clearly by describing the scope of the analysis. In this example, the structure of the pumping station, external causes and human failure are not a part of the scope and therefore not subject to further analysis.

Figure 25: System block diagram
This system block diagram shows the relationship and interdependencies of all the components in the system within the pre-set boundaries. As one can see, the system is powered with alternated current from the local power grid. This power supply does form part of the system although it is outside the system boundaries. From the AC supply, power flows towards a transformer which supplies all the other components with power at the matching voltage. The water level measuring component puts the system into operation once too high water levels occur. It sends a signal to the PLC which is controlled with software system called “SCADA”. Once the PLC gets the signal from the measuring component, it sends a signal to the relays. The relays open and/or close in order to start the pump and the electric motor which drives the valve in order to open and close.

6.2. Second step: FMEA

In order to explain and show how FMEA forms a part of the proposed method and the RCM process, the same example of the pumping station will be further illustrated. The FMEA is used in order to answer the second, third and fourth question in the RCM process which are: “In what way does the system fail to fulfil the required functions?”, “What can cause a functional failure?” and “What happens when a failure occurs?”. This FMEA is being made in order to investigate the main function of the pumping station and how this function of the system can fail which is: Retaining water levels. In order to investigate system failure, and the effects when failure occurs, a table for an FMEA is being used. Firstly, the ways in which the system can fail are defined and after that the root causes are identified.

The system is decomposed into components and subcomponents or parts. A function description is being given with a corresponding failure mode. After these two steps, the cause of failure and the failure behaviour can be examined and documented in the FMEA. Next to this, additional data concerning the failure rate of a component and the MTTR of a component is collected. This data is essential for the following step in the process, which is constructing an FTA and calculating the system unavailability. Also, the effect of a certain failure is being described together with the effect on the main function of the system, which is the top event in the FTA. A part of the FMEA for the pumping station is shown below in Fig. 26. The complete FMEA is included in appendix A. During this step the effects of each failure mode are identified. Depending on the system at question and the choice in depth of the analysis, the effects can include effects on safety, operations or other (sub-)systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Subcomponent/Part</th>
<th>Function Description</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Failure rate (λ)</th>
<th>MTTR</th>
<th>Effect</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping station</td>
<td>PLC</td>
<td>CPU</td>
<td>Making calculations</td>
<td>CPU does not function</td>
<td>Component failure</td>
<td>5.2E-05</td>
<td>48</td>
<td>Pump and valve cannot be controlled</td>
<td>TAW</td>
</tr>
<tr>
<td>Pumping station</td>
<td>PLC</td>
<td>I/O module</td>
<td>Receiving input and output signals</td>
<td>I/O does not function</td>
<td>Component failure</td>
<td>9.0E-06</td>
<td>48</td>
<td>Pump and valve cannot be controlled</td>
<td>TAW</td>
</tr>
<tr>
<td>Pumping station</td>
<td>PLC</td>
<td>Power supply</td>
<td>Power delivery</td>
<td>Power supply does not function</td>
<td>Component failure</td>
<td>2.9E-05</td>
<td>48</td>
<td>Pump and valve cannot be controlled</td>
<td>TAW</td>
</tr>
<tr>
<td>Pumping station</td>
<td>PLC</td>
<td>Memory</td>
<td>Storage space for program</td>
<td>Memory does not function</td>
<td>Component failure</td>
<td>2.0E-05</td>
<td>48</td>
<td>Pump and valve cannot be controlled</td>
<td>TAW</td>
</tr>
</tbody>
</table>

Figure 26: Part of FMEA pumping station
6.3. Third step: FTA

After the FMEA is made, an FTA is used as a systematic approach to determine the most important failure modes. This will be achieved by looking for an answer to the question: Does this failure mode result in a (partially or total) loss of system function? Therefore, the effect of failures are considered and if it results in a system failure this is indicated in the FMEA. The primary objective is to preserve system function.

Not all functions are equally important and therefore not all functional failures and related components have to be dealt with equally. In order to prioritize each failure mode, an FTA is made, which is used to rank each of the failure modes based on their importance. The FTA for the pumping station is shown in Fig. 27 and also included in appendix A.

![Fault Tree Analysis (FTA) for Pumping Station](image)

After the construction of the fault tree, calculations can be made. As described in paragraph 5.3., the Fussell-Vesely importance is used in order to rank the failure mode according to their importance to the unavailability of the system. This ranking is shown below in Table 6.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Event</th>
<th>Fussell-Vesely</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump does not start</td>
<td>0.3374</td>
</tr>
<tr>
<td>2</td>
<td>Pump stops prematurely</td>
<td>0.1955</td>
</tr>
<tr>
<td>3</td>
<td>CPU failure</td>
<td>0.1788</td>
</tr>
<tr>
<td>4</td>
<td>Power supply PLC failure</td>
<td>0.1018</td>
</tr>
<tr>
<td>5</td>
<td>Valve does not open</td>
<td>0.04633</td>
</tr>
<tr>
<td>6</td>
<td>Valve does not close</td>
<td>0.04633</td>
</tr>
<tr>
<td>7</td>
<td>Memory failure</td>
<td>0.02057</td>
</tr>
<tr>
<td>8</td>
<td>I/O module failure</td>
<td>0.01851</td>
</tr>
<tr>
<td>9</td>
<td>SCADA failure</td>
<td>0.006913</td>
</tr>
<tr>
<td>10</td>
<td>Valve stop prematurely</td>
<td>0.002881</td>
</tr>
<tr>
<td>11</td>
<td>AC failure</td>
<td>0.001127</td>
</tr>
<tr>
<td>12</td>
<td>Water level sensor failure</td>
<td>0.0009877</td>
</tr>
<tr>
<td>13</td>
<td>Relay does not close</td>
<td>0.0005222</td>
</tr>
<tr>
<td>14</td>
<td>Relay opens prematurely</td>
<td>0.0005222</td>
</tr>
<tr>
<td>15</td>
<td>Relay failure</td>
<td>0.0005222</td>
</tr>
<tr>
<td>16</td>
<td>Transformer failure</td>
<td>0.0004115</td>
</tr>
</tbody>
</table>

Table 6: Fussell-Vesely importance
The Fussell-Vesely results from the pumping station show the ranking of the components and their contribution to system unavailability. In this example one can see that the valve, pump and several small components of the PLC have the largest effect on the system unavailability. After this ranking, the failure modes in the FMEA can be ranked accordingly. This is applied for the pumping station and shown in appendix A.

Based on this Fussell-Vesely ranking, decisions can be made to further investigate the different components. For components with a negligible contribution the choice can be made to ignore them and let the components run to failure and therewith choose for corrective maintenance. Components with a high contribution should not be ignored as they result in the highest costs when failure occurs. Therefore, these components should be further investigated. In this example the amount of components is very low, so all components will be subject to further research. In complex hydraulic structures such as navigation locks, flood gates etc., the components can be thousands. In that case, a prioritization with the use of Fussell-Vesely ranking can be very helpful to select components for further research.

After calculation of the Fussell-Vesely importance the theoretical availability can also be calculated. In this example the unavailability is 1.4 % (0.01415), resulting in a theoretical availability of the system of 98.6 % which does not fulfil the requirement.

6.4. Fourth step: RPN

In order to show how the FMEA can be extended with RPN’s and be used to prioritize failure modes and their effect on availability, the same example of the pumping station is further developed. The extended FMEA with RPN’s is shown in appendix A. For each of the failure modes a corresponding detection score (1-10) and the damage (€2500,-/hour) when a failure occurs is given. These parameters, together with the failure frequency (λ) are used to calculate the RPN which is shown in the last column. Depending on the limit agreed on, high RPN’s qualify for further research. As one can see the ranking on RPN is largely corresponding with the ranking on Fussell-Vesely. The prioritization of the RPN score’s is done with colours in the RPN column. The colour green corresponds to a low RPN and the colour red corresponds to a high RPN. Just as with the Fussell-Vesely score, this prioritization can be used to focus on the components with the highest risk concerning unavailability and therewith costs.
6.5. Fifth step: Maintenance decisions

This step is the final step in the method and deals with finding the most appropriate maintenance task for each of the previously found “important” failure modes. Most important is that the chosen maintenance measure is economically and technically feasible. Appropriate means that when the task is being done, it will accomplish one of the reasons for doing RCM which are: prevent or mitigate a failure, detect onset of a failure or discover a hidden failure.

Decisions for the pumping station

If we look at the extended FMEA of the pumping station, it clearly shows that the highest RPN score is assigned to the CPU, which is part of the PLC. This is a relatively inexpensive part of the system and therefore it will be the best option to consider buying a spare part as this will result in a lower MTTR which subsequently lowers the RPN. The delivery time will no longer exist and therewith the MTTR will be reduced from 50 hours to 2 hours, resulting in a RPN of 2,55 instead of 63,75. Exactly the same goes for the power supply of the PLC.

The decisions for these components will therefore be buying spares. The other two parts of the PLC which are the memory and the I/O module both have a relatively high score on RPN, which also makes them candidates for buying a spare part.

Another high RPN is assigned to the failure modes: Pump stops prematurely due to an overload and pump does not start. This is, as one can see, the result of the very long delivery time of the pump and therefore a high penalty on system unavailability. This pump is the most expensive part of the whole system and therefore it is unattractive to consider buying a spare. The price of € 25.000,- in relation with the potential damage of €1.885.000,- can be a consideration to buy a spare anyway, but other options might be cheaper. As a pump is a mechanical component it can be inspected and tested in a rather easy way. These inspections come at a certain price but can give good insight into the condition of the component. With the use of these inspections, insight can be gathered in the aging of the component and therefore planned preventive maintenance can be done. This will not result in a penalty which is as high as when unplanned maintenance needs to be done.

The failure modes of the valve and especially the not closing/opening due to dirt or other pollution also has a high RPN. In order to lower the RPN, a spare can be an option but the MTTR is subject to a very long repair time due to the difficult placement of this component. Due to the same reasons, inspection is very difficult as well. Therefore, it might be best to accept the situation and save money in case of a failure. Redesign in this case might be the best decision if the RPN needs to be lowered. In the case of redesign, building redundancy is one of the easiest methods to increase availability, but can be expensive. If another valve is installed with its own piping system, the system can switch if one of the two valves stops working for any reason. Considering the costs of the component, the same costs are assumed to be needed to build a redundant valve. With a redundant system the MTTR is lowered to the time it takes to switch to the other valve resulting in a much lower RPN.
The failure modes with low RPN’s do not result in a high penalty on availability due to a low MTTR or their probability of failure is very low. Depending on the price for spare parts, the choice can be made to let these parts run-to-failure and consider buying spare parts. Next to this, inspection or testing can also be used in order to measure the condition of these parts and opt for planned preventive maintenance.

6.6. Sixth step: Maintenance plan and redesign

As already shown in Fig. 13 in chapter 5, the proposed model offers a loop which is needed if redesign is chosen. Decisions made to buy spare parts result in lower MTTR for accompanying failure modes and therewith adapting the FMEA becomes necessary. Furthermore, redundancy as a maintenance decision and other redesign measures ask for adapting the FTA in order to make new calculations based on the redesigned system.

Therefore these decisions need to be made part of the system and subsequently minor changes need to be made in the FMEA and FTA. For the pumping station the decisions are included in the FTA and are shown in the new FTA in appendix A.

New calculations are made and the same method can again be used in order to perfect the system. The new calculations made with the FTA software show a theoretical unavailability of 0,008081 which corresponds to a theoretical availability of the system of 99.2 % which is enough to fulfil the requirement on availability (theoretically). After improvements to the system are made and the maintenance decisions for all components are made, a maintenance plan needs to be set-up. This document will be used to maintain the structure during its lifetime and will need to be updated regularly according to the condition of the structure.
7. Validation

In this chapter the proposed model, explained in chapter 5, is applied on a case study which concerns a navigation lock in the Netherlands: “De Meppelerdiepsluis”. This step is made in order to validate the proposed model and investigate possible downsides, improvements and investigate if it will lead to the intended results when applied to a real hydraulic structure.

7.1. Case study introduction

The choice has been made for “De Meppelerdiepsluis” as a case study, because this lock is a new, highly complex system and hydraulic structure which contains several different sub-systems and components such as mechanical, electrical and structural parts. This Navigation lock is situated at the river crossing of the “Meppelerdiep” and “het Zwarte Water” near the municipality of Zwartsluis as shown in Fig.28 below. The main function of the lock is preventing too high and too low water levels on either side of the lock. High water levels usually occur from the IJsselmeer on the east side of the lock. The lock separates the two waterways “het Zwarte Water” and “het Meppelerdiep” and thereby it is a bottleneck for the shipping of freight towards Meppel.

![Figure 28: Location of the Meppelerdiepsluis](image)

The Meppelerdiepsluis is currently being changed into a navigation lock by the construction company Strukton which is a subsidiary company of Oranjewoud, of which Antea Group is also a subsidiary. Before, the old lock was closed in case of high water levels resulting from high water levels and wind on the Ijsselmeer. In order to keep the water levels in the channels located behind the lock at the right level, the lock was closed. These types of locks are better known as flood gates. The main downside of flood gates is that it becomes impossible for shipping traffic to pass through the gate in case of a closure. The shipping traffic has to wait until lower water levels occur and the gate can be opened again, resulting in long delays and consequently higher costs for the shipping traffic. The flood gate is currently being replaced and is expected to be finished in 2017, because:

- The availability of the waterway is too low. The old flood gate was used when too high or too low water levels occurred, which resulted in a full closure of the waterway since the gate was unable to allow ships passing through;
- The flood gate did not meet the requirements from the “Waterwet”;
- The safety and fluency of the shipping did not meet the requirements from the “Richtlijn Vaarwegen”.

The old flood gate was designed for a lower class waterway (class III), which the Meppelerdiep initially belonged to. In the “Nota Mobiliteit”, the waterway Meppelerdiep is classified as belonging to class V waterways, therefore the flood gate became a bottleneck in the shipping corridor.
As a result of the problems mentioned before, the choice was made to replace the old flood gate with a new fully functional lock including the function to allow shipping traffic during high and low water periods. These types of locks are known as navigation locks. The lock is part of the primary flood defence system of the Netherlands, therefore it is needed that the system can fulfil this function and therewith fulfil the desired performance requirements in terms of availability. The most important performance requirements concerning the availability of the navigation lock are the following:

- Availability of the function “Stopping too high water levels”
- Availability of the function “Stopping too low water levels”
- Availability of the function “Pounding (allowing shipping traffic to pass)”

7.2. Future maintenance

Strukton, the contractor which is currently building this new navigation lock is planning to deliver the construction in 2017. After completion, Strukton will be responsible for the maintenance of the lock for a period of one year. This is an essential period after completion, because in this period the early failures will be revealed which are mostly a result of faulty assembly, this period is also described in Fig.4 and is known as “the infant mortality period”. After this one year period, the maintenance of the lock will be outsourced by Rijkswaterstaat towards a public party.

When looking at the recent developments in outsourcing and the use of long-term maintenance contracts by Rijkswaterstaat as explained in chapter 4, it is very likely that this trend will continue and the use of these contracts will increase in the future, especially for hydraulic structures in the “wet” infrastructure of the Netherlands. Nothing is certain about the future maintenance of this lock, but these developments make the use of a long-term maintenance contract very likely. It becomes a likely candidate for a performance based contract in which requirements concerning availability and reliability will be used to outsource maintenance, together with a payment system as described in paragraph 4.1.2. Maintenance on the surrounding water district is currently outsourced to a consortium which consists of BAM infratechniek and Van Den Herik. As this consortium is already maintaining the pumping stations, waterways and other locks surrounding the Meppelerdiepsluis, there is a high probability that they will become responsible for the Meppelerdiepsluis as well.

7.3. The new navigation lock

The new Meppelerdiepsluis, which is currently built is a 185 meter long navigation lock. The top gate and bottom gate are both designed as roller doors. The whole system is being controlled from the control centre on the east side of the lock as shown in the 3D-rendering in Fig. 29. As mentioned before, the lock is part of the primary flood defence system of the Netherlands and therefore one of the most important requirements on the lock is the chance of failure of 1 / 12.500 years. In order to satisfy this requirement the lock must be able to hold back water levels from the “Zwarte Water” up to +3,00 m relative to NAP. As the gates only serve to hold back high or low water levels, the lock will normally be freely navigable, because these water levels only occur a limited number of days each year. The gates are closed when water levels exceed +0,50m NAP or under the limit of -0,50M NAP, which occurs approximately 12 times each year and results in on average 16 days of closure. These high water levels usually occur during the autumn and winter period, but have also occurred during summer and spring in the past. Also the water levels in “het Zwarte water” are known to have a very fast rise when high water levels occur accompanied with strong winds on the lake: “IJsselmeer”. As a result of the uncertainty in the prediction of high water levels, the availability of the lock is of great importance.
Figure 29: 3D-rendering of the new Meppelerdiepsluis

The new navigation lock will usually be opened so shipping traffic can freely pass. As a result of the lock usually being opened, the water retaining function cannot always be guaranteed, which differs from a normal lock, for which the retaining function is normally always guaranteed. In order to perform this function to hold back high water levels, it is of importance that at least one of the gates can be put in a closed position. In a combination with the strict requirements on the lock, as it is part of the primary flood defence system, several measures in the design phase have already been implemented in order to increase the availability of the lock. The most important measures to enlarge availability and reliability taken in the design phase are:

- **Redundant driving**
  Both roller gates (top and bottom) are equipped with a double engine. Each gate can be moved by two engines including their own powertrain. If one of the engines fails, the gate can still be moved into a closed position. Furthermore, the powertrains of each engine are situated in their own engine room on either side of the gate minimalizing the chance of failure due to fire, lightning or flooding.

- **Multiple ways of operation and control**
  The gates can be closed in multiple ways. Normally the closure of the gates will be done from the control building. In case of failure to close the gates from the control building, there is a locally situated pendant control which allows the gates to be closed. This pendant control makes use of the same power supply, but can be switched to a secondary power supply located in a different engine room. This results in the possibility to close the gates, even if the primary power supply and engine room are unavailable.

- **Multiple ways of power delivery to the control system and driving system**
  In order to reduce the risk of not closing in case of power outage, there is a possibility to make use of the emergency power generator in the pumping station “Zedemuden” located next to the lock. In case of failure of this emergency power supply, there is also a possibility to connect a mobile emergency power generator to the main power supply, or even directly to one of the engine rooms.
7.4. Application of the model on the case study

To investigate if the proposed model can help with making maintenance decisions the model is applied to the navigation lock: “De Meppelerdiepsluis”. The same steps as elaborated in chapter 5 are conducted. In this case study the emphasis will be on the requirement on the availability of the function: “stopping high water levels”. Due to the complexity of the navigation lock and the time it takes to research a system function the choice is made to only research this function. This function of the navigation lock is subsequently subjected to the proposed model for supporting maintenance decision making.

7.4.1. System description

The most important sub-system in the navigation lock, which is responsible for the function stopping high water levels is the outer head. In case of high water levels in the waterways the roller door is closed and the water levels are retained. Water levels between +0.50 m NAP and +1.30 m NAP can be stopped by the inner gate and outer gate. When water levels above +1.30 m NAP occur, which happens about every 10 years, the outer gate becomes essential and therewith the ability to close the gate. As mentioned before, the driving system of the door is a redundant system so the door can still be closed or opened if one of the two driving systems fails. Furthermore, the system can be controlled in multiple ways and can be powered from different sources. The scope for this case study and the application of the model therefore is limited to the outer head and its associated systems. A 3D view of the outer head is shown in Fig. 30. Next to the components shown in this figure, the control system is located in the control building and also part of the scope.

Figure 30: 3D view outer head
In order to get a good understanding of all the sub-systems which are responsible for the function: “stopping high water levels”, a decomposition of the outer head is made and shown in Fig.31. Next to this simple decomposition, an associated system block diagram which was already made in the design phase is used in order to conduct step 1 in the model and to construct the subsequent FMEA and FTA. To investigate what the system functions and the associated performance standards are, this system decomposition and assumptions concerning the maintenance period are made, which will be described in the next paragraph.

Figure 31: Sub-systems and components in the outer head
7.4.2. Availability requirements

Rijkswaterstaat, which is the owner of the Meppelerdiepsluis has set several requirements concerning the availability of the lock (RWS, 2011). These need to be verified during the design phase and have a relation with the maintenance phase or will likely be turned into requirements on availability during the maintenance phase. One of the most important requirements set by Rijkswaterstaat concerning availability is the category A requirement, which reads as follows:

- Availability requirement MS110: Unschedulable maintenance Meppelerdiepsluis:

“The Navigation lock: Meppelerdiepsluis needs to have a maximum unavailability of 1% due to unscheduled causes.”

This availability requirement consequently concerns the main function at question: “stopping high water levels”. Schedulable causes are not subject to this requirement and therefore in most cases preventive maintenance can be scheduled in periods when the navigation lock does not have to perform its main functions. However, random failures which result in the not functioning of the system will always be part of this maximum unavailability due to unschedulable causes. This will consequently result in penalties when the maximum of 1% is exceeded or the resultant minimum of 99% is not met. This 1% results in a maximum unavailability of the system of 3,65 days/year. Next to this, preventive maintenance of components and sub-system which are subject to random failure, means replacement of parts of the system which are not jet worn-out and therefore making unnecessary costs. It should be clearly mentioned that assumptions are made concerning this requirement on availability during the lifetime of the navigation lock. An assumption of this availability requirement can be justified based on requirements set on the “Keersluis Limmel” which is the first DBFM project in the “wet” infrastructure and is subject to an availability requirement of 100% during the maintenance period for 30 years (RWS, 2013c).

7.4.3. FMEA

After a system decomposition and research into the performance requirements, an FMEA is used in order to assess the failure modes and effects concerning the function “stopping high water levels”. The FMEA for the function “stopping high water levels” and therefore a decomposition of the outer head of the navigation lock is presented in Appendix B. The FMEA shows an extensive list of all relevant failure modes, causes and data concerning failure rates and repair times of the failure of components in the outer head of the navigation lock. This FMEA will subsequently be used in order to construct an associated fault tree which considers the main function at question as the top event.

7.4.4. FTA

As previously explained in paragraph 5.3., FTA is used in order to model the paths of failure to the top event (in this case a failure to stop high water levels) in a graphical and quantitative manner. The software program Reliability workbench is used in order to calculate the importance of all the sub-systems and components to the failure and unavailability of the top event. Based on the Fussell-Vesely importance, the sub-systems and components are ranked according to their score. In this case study, this method is used in order to construct a top 20 of failure modes which have the highest contribution to the unavailability of the main function at question. This top 20 of failure modes is shown in Table 7.

Not all failure modes described in the FMEA are part of the FTA. Some failure modes have been bundled into one basic event with corresponding characteristics regarding their MTTR and failure frequencies in order to construct a less complicated FTA. Some failure modes which are connected through an “or” gate as shown in Fig. 32 are bundled together into a basic event as shown in Fig.33. Only when one of the underlying basic events is significant enough such as in this example, the choice was made to bundle them and create one basic event. In the example it can be seen that the basic event on the left side (Failure electrical components) in Fig.32 result in a Q of a factor of at least a 100 higher than the rest of the basic events, making this the biggest contributor to the event above.
After construction of the fault tree from the FMEA, calculations are made concerning (un)availability and are used to make a ranking of the failure modes in terms of their contribution on the unavailability of the main function of the system at question. The fault tree for the function “stopping high water levels” and therewith a graphical representation of the outer head is presented in Appendix C. The result of the calculations of the Fussell-Vesely importance and the resulting top 20 of failure modes which have the highest contribution on the unavailability of the system are shown in Table 7 below.

### Table 7: Result summary Fussell-Vesely

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Event</th>
<th>Fussell-Vesely</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Collision with roller door</td>
<td>0.6082</td>
</tr>
<tr>
<td>2</td>
<td>Threshold failure</td>
<td>0.1902</td>
</tr>
<tr>
<td>3</td>
<td>Wheel failure</td>
<td>0.07005</td>
</tr>
<tr>
<td>4</td>
<td>Rotation failure axle</td>
<td>0.04319</td>
</tr>
<tr>
<td>5</td>
<td>Frequency converter failure</td>
<td>0.0327</td>
</tr>
<tr>
<td>6</td>
<td>Movement of the door prevented by ice</td>
<td>0.02074</td>
</tr>
<tr>
<td>7</td>
<td>Control of Frequency inverter failure</td>
<td>0.01071</td>
</tr>
<tr>
<td>8</td>
<td>Obstacle on threshold</td>
<td>0.005177</td>
</tr>
<tr>
<td>9</td>
<td>Motor levelling component failure</td>
<td>0.004645</td>
</tr>
<tr>
<td>10</td>
<td>Rails failure overload</td>
<td>0.004643</td>
</tr>
<tr>
<td>11</td>
<td>Electric motor does not start</td>
<td>0.002645</td>
</tr>
<tr>
<td>12</td>
<td>Cable drum failure</td>
<td>0.001757</td>
</tr>
<tr>
<td>13</td>
<td>Dirt depot obstructed</td>
<td>0.001454</td>
</tr>
<tr>
<td>14</td>
<td>Levelling component damaged</td>
<td>0.001174</td>
</tr>
<tr>
<td>15</td>
<td>Power transformer failure</td>
<td>0.0007644</td>
</tr>
<tr>
<td>16</td>
<td>Manual switch failure</td>
<td>0.0007129</td>
</tr>
<tr>
<td>17</td>
<td>Push button failure</td>
<td>0.000684</td>
</tr>
<tr>
<td>18</td>
<td>Rails failure corrosion</td>
<td>0.0004842</td>
</tr>
<tr>
<td>19</td>
<td>Key switch failure</td>
<td>0.000379</td>
</tr>
<tr>
<td>20</td>
<td>Mobile generator delivered late</td>
<td>0.0003068</td>
</tr>
</tbody>
</table>
7.4.5. Reduced FMEA with RPN

After the previous steps, the top 20 failure modes are gathered in a reduced FMEA. The same method as described earlier in paragraph 5.4. is applied and will therefore not be explained again. The reduced FMEA is extended with three new features for each failure mode which are:

- The amount of damage the failure mode causes in terms of penalties due to unavailability
- Probability that the failure will not be detected with an appropriate detection method
- The method of detecting the failure mode

The product of the probability of the failure mode occurring, the probability of detection and the amount of damage when the failure mode occurs in terms of penalties due to unavailability results in a risk priority number for each of the failure modes. This RPN can subsequently be used to rank the failure modes based on their RPN. Failure modes with a high RPN are associated with the highest risk for the service provider in terms of not satisfying the performance requirement availability and therewith the highest risk in not receiving the full monthly or quarterly availability reimbursements in DBFM or PB contracts.

7.4.6. Costs of unavailability of the function “stopping high water levels”

In order to quantify the costs of unavailability due to unscheduled maintenance as a result of random failures, assumptions are made. During the construction period of the Meppelerdiepsluis, Strukton which is the contractor of this project is fined when the construction of the navigation lock results in an unscheduled unavailability of the crossing of the two waterways “Meppelerdiep” and “Zwarte water”. These penalties are should represent the costs to society in terms of economic damage in case of a closure of the crossing of these waterways.

In the contractual document: “Basisovereenkomst Meppelerdiepsluis” (RWS, 2012), the penalty is described. The penalties for this type of unavailability are set at €5000,- / hour. Based on this penalty, assumptions are made that during the maintenance period of the navigation lock this exact same penalty will be used in a performance based contract as an availability discount. With the use of this penalty, the costs of unavailability of the main function: “stopping high water levels” due to one of the failure modes can be calculated. This calculation is added in a new column the extended FMEA in Appendix D and it is named: Costs of unscheduled unavailability.

7.4.7. Maintenance decision making

With the use of the RPN’s calculated during the previous step, maintenance decisions can be supported. Twenty failure modes are added in the extended FMEA in this case study, because the amount of components in the outer head is very large. These twenty components and their associated failure modes have the highest contribution to unavailability in case of occurrence and therefore preventive measures can be taken in order to reduce the effects when occurring. According to the proposed decision model in paragraph 5.5. The service provider which is responsible for the maintenance of the lock for a period of thirty years can make five different choices depending on the type of failure mode. When a DBFM contract is used, system redesign becomes easier than when the structure is already finished and maintenance is outsourced with a PB contract, because choices can be made during the design phase. In this case the structure will be finished before the maintenance is outsourced, making complex redesign very difficult. Although the buying of spare parts is a single decision in the model, it has a relation with system redesign. Buying a spare part does not change the system directly, but the quantitative assessment of availability changes, as components will get a different MTTR resulting in a different contribution to the unavailability of the system. The five choices in the decision tree will be elaborated below and the failure modes in the top twenty will be allocated toward the most appropriate decision.
Redesign: For components with little relation with other components, the application of redundancy can be an option, but buying spare parts can result in almost the same risk reduction and therefore it can be easier and cheaper, because changes to the structure do not have to be made. In this case, a PB contract is used to outsource the maintenance and therefore redesign becomes more difficult than when a DBFM contract is used. When a DBFM contract is used, the redesign can be easier implemented, because the design phase is also owned by the service provider.

The first failure mode in the top twenty for which redesign remains a logical choice is the failure of the door due to a collision. The spare and repair costs are very high, to the extent that other options such as preventive measures to reduce the chance on a collisions become interesting. If for instance a measure can be found which prevents ships from colliding with the door and it is a relatively cheap measure in comparison with the costs of a spare door and the repair costs, this would be preferred. A good example of such a measure is the application of synthetic or steel cables, which are placed before the doors and tensioned in case of a closure. When a ship nearly hits the door, it first hits the cable which brakes the ship resulting in less damage to the door or even the ability to stop it completely.

In addition to the previously mentioned failure mode, redesign can also be an interesting decision for the failure mode: failure of the threshold due to scratching anchors. A preventive measure, such as a protecting barrier in front of the threshold can be applied to limit the chance of anchors damaging the threshold. Costs due to unscheduled unavailability in case of occurring are high to such an extent that this measure is interesting if it can be applied relatively cheap. Other components in the top twenty are either already redundant or buying spare parts is cheaper and easier due to no changes in the system design.

Research into the measurability: This option is not directly a risk reducing measure, but can result in one if the condition of components can be predicted with the use of monitoring and data gathering. Failure modes which only occur randomly such as collisions cannot benefit from this option. Failure modes which are known to have an increasing failure rate, but the predictability of the growth is low can benefit from this. The proposed model is used to prioritize the failure modes on their contribution to unavailability. Using this prioritization, the top failure modes become evident and therewith also a prioritization of possible failure modes to be researched or to apply condition monitoring on is made. Using this prioritization, it becomes clear where efforts can best be made for research into the measurability of the components condition.

In the case study, the failure modes which are subject to wear and tear are interesting for possible monitoring and research. If these are monitored such that the usage of the system, together with environmental conditions can be linked to the condition of the components, it will result in very valuable data, which can be used to predict the required maintenance as shown in Fig.3 in paragraph 2.3. Furthermore, this data can be used to predict degradation and the possibility to use this knowledge on other comparable systems with the same components. Consequently, this knowledge can be used to schedule preventive maintenance, resulting in less costs due to unscheduled unavailability.

If the failure modes in the top twenty are considered, especially the electrical components are interesting to research. These components make up a large proportion of the top twenty and predictability of the degradation is very limited. Most interesting parts are the electric motors for the door driving system, and the frequency inverter. Next to these electrical components, fatigue of the wheels and axle of the carriage of the door are interesting to research in order to increase the predictability of the degradation. It should be clearly mentioned that when first applied, condition monitoring is not a stand-alone measure, but should be accompanied with a spare part for the component at question, unless the threshold values are known and the measurements are accurate.
Spare part: The main reason for making the decision to buy spare parts is a reduction of the MTTR. The total time to repair a component decreases with the time it takes to make and deliver the components in question. This can often result in a very high risk reduction and becomes an interesting option for components which are relatively cheap, but are known to have a long delivery time together with a short repair time.

In the extended FMEA in Appendix D, a new column is added which is a calculation of the cost reduction on costs of unscheduled unavailability in case of having a spare part available. It clearly shows that for most of the failure modes, buying a spare part results in a very large cost reduction. Furthermore, a column which shows the total costs for having spare part including repair costs and considering storage for the period of thirty years at 25 % of the costs of a spare each year is added. Based on these amounts, the consideration to buy a spare can be made. When spare parts are relatively cheap, the choice for buying a spare part can be easily made. With this in mind, it is recommended to buy a spare for the following components: manual switch, key switch, push button, transformer PLC, frequency inverter and an electric motor for the levelling components.

A special case is the late delivery of an emergency power generator. If an emergency power generator would be bought and placed on-site, it would be more expensive than when it is delivered late. This can be seen by comparing the two columns: Total costs for having a spare and cost reduction on unavailability when having a spare. Therefore, the recommendation is to do nothing and accept late delivery in case of a power outage.

A rather unpredictable and special cause of failure is overload. This is very difficult to detect prior to failure or to measure, therefore spare parts become an interesting decision to reduce the risk. The cable drum and the threshold are both subject to this failure cause and part of the top twenty. In order to reduce the risk of a cable drum overload, it is recommended to buy a spare part, but it is a relatively expensive solution compared to other spares.

Accepting the risk or insuring: As previously described in paragraph 5.5. insuring risks of loss of income due to component failure is essentially impossible. The risk premiums become unrealistically high, as insurance companies do not want to take any chances. The risks for which the service provider prefers to be insured are mostly the risks which occur random such as a collision. When an insurance company does not cover these risks the only remaining choices become either searching for preventive measures or accept the risks and save money for it in order to cover the possible loss of income. Another option is to renegotiate on the allocation of these risks with the client. Good examples are the collision with the door and the scratching anchors. These kind of risks can only be reduced with expensive preventive measures or expensive spare parts. As the reduction in risk of these mitigating measures and therewith a higher availability of the system can be shown and calculated, this can be used in order to negotiate who will pay for these or let the client bear these risks. Another failure mode for which accepting remains the only logical choice is the late delivery of an emergency generator. Buying one and storing it results in very high costs relative to the cost of unavailability if it is delivered late and therefore the best option is to accept this risk.

Test: Testing can be used in order to find hidden failures, which will only show when the system is needed. In order to reduce the occurrence of these type of failure, the system or component can be tested to see if it is still working. Regular testing of a system which is irregularly used such as this navigation lock will result in less hidden failures. Therefore, it is recommended to test the system regularly, especially during the time in which the system is almost not expected to be needed. Not only the failure modes in this top twenty will benefit from this testing, but all the failure modes of the system which are subject to hidden failure.
7.5. Conclusions from case study

In order to validate the proposed model, it has been subjected to a case study. This is done to investigate possible downsides, improvements and investigate if it will lead to the intended results when applied to a real hydraulic structure.

The application of the proposed model has shown to be able to support maintenance decision making when maintenance of a newly built hydraulic structure is outsourced with the use of a PB contract. The model and especially the prioritization of the failure modes by the model have shown to be very useful in order to investigate which failure modes are most important and carry the highest risks when loss of possible income due to unscheduled unavailability of the system is concerned. In this way the cost drivers and availability killers can be detected and therewith efforts concerning maintenance can be done at the right place in the system. Furthermore, the application has shown that the decision to buy a spare part can have a very large effect on reducing the costs of unavailability in case of a failure. Even when costs to store spare parts are relatively high (25% each year), this decision can still be cheaper than not having a spare in case of a failure. It has also shown that when a PB contract is used, redesign becomes difficult. Risks, which can only be reduced with preventive measures and therewith redesign, are often expensive and should therefore be renegotiated with the client. Furthermore, external risks such as collisions, fire, etc., which used to be the responsibility of the client, can best remain the responsibility of the client, as they are able to control them the best and remain responsible towards the users of the structure even if these risks are allocated towards service providers.

The client needs to pay for the preventive measures or the availability reimbursements need to be high to such an extent that these measures can be covered by the service provider. Furthermore, the model also results in a prioritization of failure modes which are caused by mechanisms such as wear and tear. Thereby, the highest ranking failure modes with these causes should be monitored or research should be done into the degradation in order to construct a P-F interval and predict failure in the future.

During the case study, it has become clear that a lot of data is required in order to apply the proposed model. In this case, this data was available, because the design of the navigation lock was done by Antea Group and they were willing to share this data. When the design of the lock was conducted by another engineering company, difficulties might have occurred concerning this data. Main reason for this, is that engineering companies are not very willing to share their knowledge and data with other companies as it might endanger their position in the market. With this in mind, future application of the model when PB contracts are concerned and the design is in the hands of a different party, it is almost impossible to use the model. On the other hand, the model can be applied more easily when DBFM(O) contracts are used. The design phase is part of the contract and therewith the necessary data is often already created, which can be used when the model is applied.
8. Conclusions and recommendations

In this chapter the conclusions of this research are presented. Answers to the main research question and sub-questions are given, followed by recommendations for further research.

The main objective of this research is to assess whether the method RCM together with supporting methods can help service providers in making maintenance decisions within long-term maintenance contracts based on performance requirements. Long-term maintenance contracts, the RCM method and supporting methods have been studied in order to construct a model and subsequently apply it to an example and a case study to assess if the proposed model can support making maintenance decisions for hydraulic structures.

In order to find an answer to the main research question, a series of sub-questions is drafted and answered in this chapter. Results from the sub-questions contribute to answering the main research question which is:

”How can Reliability Centred Maintenance (RCM) help service providers in making maintenance decisions for hydraulic structures during long-term maintenance contracts?”

8.1. Conclusions (answers to sub-questions)

Sub-question: How is the availability of a hydraulic structure calculated?

The availability of a hydraulic structure can be calculated with the use of a fault tree which is based on an FMEA. All components and sub-systems within a hydraulic structure need to be described and put into a fault tree. Relationships between all components and redundancy in the system can be described with this tool and with this feature it differs from other tools. When making a fault tree, all components have to be given properties concerning their probability of failure and the mean time to repair them. Depending on the type of failure which the corresponding component is subject to, more properties may be necessary. These properties do not concern the components, but the whole system. These are: testing interval, mission time, etc. After construction of the tree and when properties are given to all components and therewith all the basic events in the tree, the theoretical availability of the system can be calculated. Although this method offers a solution when the availability of a certain system needs to be calculated, it uses data which is not always reliable and often subject to expert judgment, so called guesstimates. This subsequently makes the results from the method more unreliable, but still offers a solution for a quantitative analysis.

Sub-question: How can subsystems or components which are critical for the system requirement availability be detected?

The use of FMEA, FTA and ordering failure modes based on their risk with the use of risk priority numbers as explained throughout this research can help with prioritizing failure modes based on their contribution to system unavailability. Especially FMEA together with FTA instead of FMECA has been demonstrated to be a better method to detect the critical sub-systems and components. When performing an FMECA, the failure mechanisms are given a criticality, which is the probability of occurring multiplied with the effect of the failure mechanism. With FMEA, the criticality of a failure mode is not considered. Within an FTA, redundancy and interaction between different sub-systems is considered, which is not the case with an FMECA. When performing an FTA, failure mechanisms with a high criticality in an FMECA can eventually only have a very little share in the functioning of the system when researching them through an FMEA with FTA.
Sub-question: Which choices can be made concerning maintenance actions and what are the accompanying consequences on availability?

As described in paragraph 4.1, long-term maintenance contracts ask for a different way of thinking about maintenance. Letting components run to failure will always result in corrective maintenance and thereby result in penalties and lower reimbursements for the service provider. Previously, unavailability of hydraulic structures was a risk for the client: Rijkswaterstaat, but this risk is transferred towards service providers with the use of these types of contracts. As service providers are always interested in earning money and reducing risks, different maintenance actions become part of the possibilities. This can be regarded as controlling corrective maintenance with taking preventive measures before failure occurs. The effect of having spare parts for certain components can be so large, that it becomes interesting to consider buying them. Furthermore, high risks with nearly no possibility to lower them asks for renegotiating with the client or accepting them if availability reimbursements allow this. Next to this, it shows that it is better to let these risks remain part of the responsibilities of the client, because: The client can control them better, The client stays responsible towards the users of a structure even if these risks are allocated towards the service provider and keeping the responsibility for these risks can result in lower payments to the service provider. The failure of components, which are subject to aging, wear and tear, but no data about the speed of this deterioration, can have a large contribution to the unavailability of the system.

Decisions concerning research into the degradation of these components can have a great influence on the determination of the time to failure of such components. If data concerning failure is collected and new measuring techniques can be used, the prediction of failure becomes easier and preventive maintenance can be used. This will result in less unavailability and possibilities to justify preventive maintenance and schedule it when the system does not have to carry out its function resulting in higher reimbursements and lower penalties.

Sub-question: What are the benefits when making use of reliability centred maintenance?

The proposed model, which is based on the RCM process together with the used methods FMEA, FTA and RPN can be of great help in detecting critical sub-systems and components in complex hydraulic structures. Hydraulic structures are usually unique and complex systems with several different sub-systems and components. The proposed model is an extensive, but structured approach where system complexity can be researched and maintenance actions prioritized. Furthermore, it can help with finding the right preventive measures when corrective maintenance becomes necessary.
8.2. Conclusion (answer to the main research question)

This research has been conducted to find answers to the sub-questions, which are given in the previous paragraph. These answers helped with answering the main research question and this will be elaborated below.

Main research question: How can Reliability Centred Maintenance (RCM) help service providers in making maintenance decisions for hydraulic structures during long-term maintenance contracts?

The concise answer to this question is: RCM can help service providers with making maintenance decisions during long-term maintenance contracts, but is limited in its application. When DBFM(O) contracts are used, RCM can be applied, but needs to be accompanied with the methods: FMEA, FTA and RPN, in order to create useful results. When PB contract are used to outsource the maintenance on existing hydraulic structures the proposed model cannot be applied.

The proposed model can be used to rank all failure modes of a system according to their risk on system unavailability. From the perspective of the service provider, decisions concerning maintenance will be made based on the risk on system unavailability, because this will result in lower reimbursements. Failure modes with the highest risks should subsequently be further investigated and options to reduce them should be considered based on their cost-effectiveness.

The proposed model, which is based on the RCM process together with the tools and methods FMEA, FTA and RPN has proven to be a structured approach in order to help service providers in making and prioritizing maintenance decisions. The model used during this research is an extensive method which requires technical experts and is a relatively time consuming process. It can be conducted during the design phase in a DBFM(O) contract and lead to a better understanding of the system and therewith more knowledge about required maintenance. In order to let it be a successful method during the tender phase and let it result in a better design and thereby winning tenders, often too much time is needed to carry out this method for complex structures. If PB contracts are used, the model cannot be applied, because the design phase is conducted by a different party and therefore the necessary data is not available.

The results of using this method, highly depend on the estimation of the probability of failure of the different failure modes which are not all equally reliable and sometimes subject to expert judgement. If techniques become possible, which can predict degradation of components and thereby reduce random failures, it is recommended to use them on relatively expensive components with high consequences on system unavailability when a failure occurs. The use of these long-term contracts make research into these kind of measuring techniques almost compulsory, as more knowledge about degradation can result in better preventive maintenance. Using and improving these techniques together with the collection and preserving of this data will consequently result in higher predictability of component degradation which can be used in order to schedule preventive maintenance and result in higher availability.
8.3. Recommendations

In this chapter recommendations for future research and the application of the intended method in long-term maintenance contracts will be given. The main recommendations resulting from this research are:

**Focus on availability killers and cost drivers**
The proposed model, which is based on the RCM process together with the tools and methods FMEA, FTA and RPN has proven to be a structured approach in order to help service providers in making and prioritizing maintenance decisions concerning hydraulic structures when long-term maintenance contracts are used. If service providers make the decision to use this method in the future, it is essential to keep in mind that the method has to be used to focus on availability killers and cost drivers in order to let it be used as a supporting method. Moreover, a manual for the application of the model can be developed in order to let it be used by more people than only experts on this subject.

**Availability reimbursement and risk allocation**
The height of the availability reimbursement should be an accurate reflection of the risks which are allocated to the service provider. When risks such as collisions by shipping traffic, human failure and other external events become the responsibility of the service provider, high reimbursements are needed. When such risks are allocated towards a service provider, the availability reimbursement might become high to such an extent that it is better to let these risks be part of the responsibility of the client. Research into the appropriate height of the reimbursements and associated risks can give more insight in which risks should and can be allocated towards which party. Furthermore, the allocation of these risks will consequently determine the tender price.

The service provider which dares to take the least preventive measures and therewith the most risks will have the lowest bid, and when only the price is of consideration, win the tender.

**Support condition monitoring and gathering of data**
A better understanding of component degradation and therewith more certainty in the time of failure will definitely contribute to more knowledge about failure behaviour and can help to justify preventive maintenance. Condition monitoring techniques should therefore be supported and further developed. Furthermore, it is essential that data resulting from the application of such techniques is very carefully preserved and shared. The creation and sharing of data is essential to further develop knowledge in this field. In order to support the creation of degradation data, research into degradation of components needs to be subsidized or at least be supported by the government. If we want to arrive at a situation where the majority of the maintenance can be done preventive and therewith no unscheduled system unavailability, it is necessary that degradation can be linked to the usage and environmental conditions of components. There still is a long road ahead, but an opportunity might be awarding service providers for having the most innovative design concerning the gathering of this data and make it part of the system. A possibility can be found in making data gathering systems in the design subject to so called “MEAT” criteria (Most Economically Advantageous Tender, in Dutch EMVI), with which the service provider can win tenders.

When data eventually exists, models can be made which can be used to schedule preventive maintenance. An example of such a model is a dynamic fault tree, which is essentially the same as a normal fault tree, but all the components are given failure rates which are time-dependent. When this data is linked to a fault tree, the required maintenance and the moment can be calculated. Furthermore, the development of system unavailability over time can be shown beforehand.
DBFM(O) and PB

Especially DBFMO contracts, where the operational phase is also part of the activities of the service provider can be used to outsource maintenance with the best results. The detection of maintenance needs can be part of the activities of the operating staff. If this staff is hired by the service provider, there is a short link between the operating staff and maintenance staff and therewith earlier detection of maintenance needs and the possibility to schedule preventive maintenance. When DBFM or DBFMO contracts are used, the service provider becomes responsible for design flaws made during the design phase by himself. With PB contracts, the service provider was never responsible for the design and therefore they cannot be made responsible for mistakes made by the party which was responsible for the design. Therefore, the recommendation is made to limit the amount of risks allocated towards the service provider when the maintenance on hydraulic structures is outsourced with PB contracts.

Decision making framework

There are five different maintenance decisions given in this research from which a service provider can choose. The choice for one of these needs to be made, depending on the cost effectiveness of the measure. Although it already shows in this research that for some components, buying spare parts is the most cost-effective measure, redesign can also be very effective and this is not researched enough for each component. If redesign can be done cheaper than the costs of having spare parts, this can be a better decision. Furthermore, if inspection can be applied and the time to failure can be described accurate, spare parts or redesign become unnecessary. In order to make well founded decisions, a decision framework needs to be developed, which can help in choosing the appropriate decision for each component. All components and their possible maintenance actions should be investigated and considered. The height of the availability reimbursements will eventually be the main reason for making one of these decisions.
9. Discussion and reflection

In order to discuss the limitations of this research, the methodology and the results are discussed and reflected on in this chapter.

9.1. Discussion

The aim of this research was to find a method to support service providers with making maintenance decisions in long-term maintenance contracts for hydraulic structures. Therefore, the focus during this research was from the perspective of the service provider. Due to the fact that these contracts are new and not yet widely in use, assumptions concerning risk allocation are made. During the research, it is assumed that the service provider will be made responsible for the majority of risks concerning the functioning of a hydraulic structure, even external risks such as collisions, fire etc. Although these risks can be allocated towards the private sector, the responsibility towards the citizens of the Netherlands and the users of the hydraulic structures still remain the responsibility of the client, in this case Rijkswaterstaat. Therewith, it is better to let these risks remain the responsibility of Rijkswaterstaat and not those of a service provider.

Furthermore, the height of the availability reimbursements and the allocation of the risks towards the service provider are the two most important factors when making maintenance decisions. High reimbursements consequently allow risks to be transferred towards the service provider and a higher willingness to carry them.

Also, the assumption during this research is made that service providers are mainly interested in the highest possible availability reimbursements. Therewith, service providers become interested in ways of lowering the risks of unavailability and this does not always have to be in favour of the client. The result can be a structure, which knows a high enough availability, but lacks reliability. A structure which breaks down many times, but can be repaired very quickly can still meet requirements on availability.

With the use of the proposed model and especially FMEA and FTA, many component properties are needed. These usually concern delivery time, repair time and the probability of failure of the associated component. In order to apply the model, these properties are required, but uncertainty in these properties is often high and sometimes subject to expert judgement, which makes them unreliable. If these properties can be made more reliable, the model will consequently generate more reliable results.

9.2. Reflection

This paragraph contains my personal reflection on the process and results of my master thesis. First, a reflection on the process will be given, followed by a reflection on the result.

I started off this graduation program with the idea to unravel the secrets of preventive maintenance. The main research objective was to create a model in which failure rates of components in hydraulic structures are made time-dependent, resulting in a dynamic model with which preventive maintenance could be scheduled.

The research started with an extensive literature study during the first months and has led to the conclusion that little or no data is available on time-dependent failure rates of components used in hydraulic structures. This resulted in a major change of my thesis proposal and therewith a different research objective.

The previous approach proved impossible, but I still wanted to focus my research on improving maintenance on hydraulic structures in the Netherlands. The increasing use of long-term maintenance contracts by the Dutch government to outsource maintenance and thereby the allocation of risks towards service providers was the main reason for the next research. Within these contracts, availability of a hydraulic structure is used as a
Managing the costs of system unavailability in long-term performance contracts for hydraulic structures

Performance requirement and used to pay for the maintenance conducted by service providers. Therewith, from the perspective of the service provider, it became interesting to research what causes system unavailability and possible ways to prevent unavailability. If the research could help with finding the possible ways to lower unavailability, service providers could use this in order to prevent unavailability and receive full payments.

After researching existing methods, which are used to analyse systems and show maintenance needs, it became clear that a structured model based on the RCM process could be a promising model in order to help service providers in making maintenance decisions based on potential unavailability. Many different methods to analyse systems and schedule maintenance have been researched, but FMEA, FTA and RPN seemed the best methods to support RCM. A model has been created, which incorporates these methods and is applied to a hydraulic structure. The research and application has yielded good results and seems promising for future use, but has also raised some new questions, which will be described below.

In order to arrive at a desired situation, where all components, which are subject to wear and tear are maintained preventive, this model does not offer a solution. The model can be used to identify the most important failure modes of a system (concerning system unavailability), but not to schedule preventive maintenance. It can however be used in order to prioritize the components in a structure for which condition monitoring will have the largest effect in terms of the creation of valuable data to schedule preventive maintenance.

Long-term maintenance contracts, such as DBFM(O) and PB are used by Rijkswaterstaat to outsource maintenance with the use of performance requirements. During this research it became clear that the use of these contracts can bring many benefits, but especially for the client, in this case Rijkswaterstaat. The service provider, which becomes responsible for many more risks than with traditional contracts will not always directly profit from the use of these contracts. If a service provider wants to make more profits within such a contract, the easiest way to do so, is to accept more risks and conduct less maintenance, which is definitely not the indented result when these contracts are used by Rijkswaterstaat. In order to achieve the intended results, which are a more available and reliable hydraulic structure, it might be better the let some major risks be part of the responsibilities of the client and pay lower reimbursements to the service provider. Furthermore, Rijkswaterstaat also carries the responsibility for a healthy market, as it is the main and often the only client in this market. Service providers which are fined when performance requirements are not met, may go bankrupt, which can be blamed on Rijkswaterstaat.

During the creation and application of the model, questionable data has been used. In order to create and apply the model this was a necessity, as better data turned out to be unavailable. Especially the used failure rates of all components (λ), is considered to be constant when these methods are used, which subsequently means that preventive maintenance can never be justified. Although almost all expert agree on components having a changing failure rate over time, these are not known and used in these methods. This is also the main reason why preventive maintenance is done, but to be more certain about the moment of preventive maintenance, only more research into degradation versus usage and time can offer a real solution to this problem.
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Appendix A – FMEA and FTA pumping station
<table>
<thead>
<tr>
<th>System</th>
<th>Component</th>
<th>Subcomponent/part</th>
<th>Function Description</th>
<th>Failure mode</th>
<th>Failure cause</th>
<th>Probability (λ)</th>
<th>Time to deliver</th>
<th>Time to repair</th>
<th>MTTR</th>
<th>Effect</th>
<th>Unable carry out main function</th>
<th>Source</th>
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<tr>
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Appendix B – FMEA Case study
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**Failure Mode and Effects Analysis (FMEA)**
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<td>Port</td>
<td>Component</td>
<td>Subcomponents</td>
<td>Function description</td>
<td>Failure mode</td>
<td>Failure Cause</td>
<td>Mission time (t) [h]</td>
<td>Test interval (T) [h]</td>
<td>Repair time (μ) [h]</td>
<td>Failure probability per external cause</td>
<td>Failure data</td>
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<td>EXT: Frost, External malfunction</td>
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<td>PLC (Remote I/O), PLC (Remote I/O) does not function</td>
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<td>Failure frequency (λ)</td>
<td>Failure during mission</td>
<td>Failure on demand</td>
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<td>Hidden Failure</td>
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<td>Component failure</td>
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<td>Battery</td>
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<td>Battery failure</td>
<td>Component failure</td>
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**Failure and Effects Analysis (FMEA)**
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Appendix C – FTA Case study
1. CLOSURE OF THE OUTER HEAD FAILS

Failure to stop high water

Q = 2.806E-09
w = 8.036E-12

Failure to stop high water + 1.30 m NAP

Q = 0.0002287
w = 6.55E-07

WATER LEVEL BETWEEN +0.50 AND +1.30 NAP

Water level between +0.50 and +1.30 m NAP

Q = 0.001369
w = 8.03E-08

FAILURE TO STOP HIGH WATER +1.30 M NAP

Failure to stop high water + 1.30 m NAP

Q = 0.000622
w = 1.96E-07

1.1. WEST SIDE FAILS

Construction of west side fails - Closure

Q = 1.54E-07
w = 1.54E-07

Q = 2.14E-07
w = 2.14E-07

1.2. EAST SIDE FAILS

Construction of east side fails - Door

Q = 1.54E-07
w = 1.54E-07

Q = 2.14E-07
w = 2.14E-07

CONSTRUCTION AND DOOR NOT WATERTIGHT

Q = 1.205E-06
w = 1.96E-08

0.1. COLLISION BOAT WITH DOOR

Door fails due to collision

FR = 3E-08
MTTR = 4380
Q = 0.000131

MOVEMENT OF DOOR FAILS

The roller door is unable to be moved

Q = 9.565E-05
w = 6.055E-07

GUIDING OF DOOR FAILS

Guiding elements of the door fail

Q = 6.665E-05
w = 3.22E-08

DRIVING FAILS

Driving of the roller door fails

Q = 2.453E-05
w = 2.288E-07

3.1. MOVEMENT PREVENTED ICE

Ice prevents the door movement

FR = 3.44E-07
MTTR = 13
Q = 4.48E-06

DRIVING FAILS COMPLETELY

Multiple parts of the redundant drive fail

MOVEMENT LEFT SIDE FAILS

Door can not be moved from the left side

Q = 0.0007098
w = 8.09E-07

MOVEMENT RIGHT SIDE FAILS

Door can not be moved from the right side

Q = 0.0007097
w = 8.085E-07

STRUCTURAL FAILURE

Structural failure

Q = 4.68E-07
w = 0

MOVEMENT OF DOOR FAILS

The roller door is unable to be moved

Q = 9.565E-05
w = 6.055E-07

GUIDING OF DOOR FAILS

Guiding elements of the door fail

Q = 6.665E-05
w = 3.22E-08

DRIVING FAILS

Driving of the roller door fails

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Ice prevents the door movement

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MTTR = 13
Q = 4.48E-06

DRIVING FAILS COMPLETELY

Multiple parts of the redundant drive fail

MOVEMENT LEFT SIDE FAILS

Door can not be moved from the left side

Q = 0.0007098
w = 8.09E-07

MOVEMENT RIGHT SIDE FAILS

Door can not be moved from the right side

Q = 0.0007097
w = 8.085E-07

STRUCTURAL FAILURE

Structural failure

Q = 4.68E-07
w = 0
Construction and door not watertight

Q = 1.205E-06, w = 1.96E-08

Two or more components fail and therefore watertightness is not sufficient

1.2.3. LEVELING COMPONENTS FAIL TO CLOSE
Q = 0.0007021, w = 3.081E-06

One or more of the levelling components fail to close

2. OBSTACLE ON TRESHOLD
Obstacle on threshold, obstacle too big for depot (external)

FR = 1.5411E-05, Tau = 168, MTTR = 4
Q = 0.001355

2.2. DEPOT OBSTRUCTED
Dirt depot in front of door is obstructed

FR = 1.1416E-06, Tau = 168, MTTR = 24
Q = 0.000123

3.2. FAILURE TRESHOLD
Structural failure threshold

Q = 4.108E-05

CARRIAGE 1 FAILS
Q = 2.45E-05, w = 3.146E-08

First carriage fails

CARRIAGE 2 FAILS
Q = 2.45E-05, w = 3.146E-08

Second carriage fails

3.4.1. OVERLOADED
Carriage overloaded

FR = 2.2831E-11, Tau = 168, MTTR = 1796
Q = 3.635E-06

3.4.2. WHEEL FAILURE
Wheel does not turn

FR = 1.945E-08, MTTR = 778
Q = 1.513E-06

3.4.3. ROTATION FAILURE
No rotation wheel axle

FR = 1.1991E-08, MTTR = 778
Q = 9.329E-06
FTA Meppelerdiepsluis Failure to stop high water

4.1.R. SPRING BUFFER 2 FAILS
Spring buffer cable 2 does not function
FR = 2.893E-07
MTTR = 334
Q = 9.662E-05

4.2.R. CABLE 2 FAILS
Cable 2 does not function - breaks
FR = 9.952E-10
MTTR = 738
Q = 7.345E-07

4.3.R. CIRCULATION WHEEL FAILS
Circulation wheel fails - aging/overload
FR = 1.3541E-08
MTTR = 1472
Q = 1.993E-05

5.1. E2 DRIVE SHAFT CBL DRUM 2 FAILS
The driving shaft in engine room 2 fails
FR = 1.8272E-08
MTTR = 746
Q = 1.363E-05

5.2. E2 DRIVE SHAFT CBL DRUM 2 FAILS
The driving shaft on the right side fails
FR = 2.771E-07
MTTR = 10
Q = 0.0005685
w = 2.771E-07

4.6.R. BEARING OF CABLE DRUM FAILS
The bearing of the cable drum fails
FR = 8E-09
MTTR = 176
Q = 1.408E-06
w = 8E-09

5.2. E2 DRIVE SHAFT CBL DRUM 2 FAILS
The driving shaft on the right side fails
FR = 2.5103E-07
MTTR = 2206
Q = 0.000553
w = 2.5103E-07

5.2. E2 DRIVE SHAFT CBL DRUM 2 FAILS
The driving shaft on the right side fails
FR = 1.3457E-08
MTTR = 1472
Q = 1.993E-05
w = 1.3457E-08

The control of engine room 2 fails
Q = 0.0001146
w = 5.868E-06

Control of engine room is not available or does not function
Q = 0.0001173
w = 3.038E-07

Driving from engine room 1 fails
Q = 0.005326
w = 2.417E-05

Driving from engine room 2 fails
Q = 0.005214
w = 1.867E-05

The driving from engine room 2 fails
Q = 0.004504
w = 2.123E-05

Driving from engine room 2 fails
Q = 0.004494
w = 1.661E-05

The driving from engine room 1 fails
Q = 0.005326
w = 2.417E-05

The driving from engine room 1 fails
Q = 0.005214
w = 1.867E-05

Driving to engine room 1 fails
Q = 0.005326
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Driving to engine room 1 fails
Q = 0.005326
w = 2.417E-05

Driving to engine room 2 fails
The mechanical parts in engine room 2 fail.

Electric motor in engine room 2 does not function.

The power supply to engine room 2 fails.

Block break engine room 2 fail.

Frame of the electric motor fails.

The driving shaft in engine room 2 fails.

Control of engine room 2 fails.

No control signal to the components in engine room 2.

Emergency control fails.

The control in engine room 1 is not available or does not function.

No control signal to engine room 2.

System fails because peak voltage is not stopped lightning.

Engine room 1 is not available due to fire flooding or a structural failure.
7.4.3.1. E2 NO POWER DUE TO OUTAGE
No power due to a power outage
FR=1.8264E-05
MTTR=1.5
Q=2.74E-05

7.4.3.2. E2 POWER CABLE FAILS
Power cable fracture due to wear
FR=1E-07
MTTR=16
Q=1.6E-06

7.4.3.3. E2 SWITCH FAILS
Switch fails electrical components
FR=4.586E-06
MTTR=4
Q=1.834E-05

7.4.3.4. E2 TRANSFORMER FAILS
Transformer fails electrical components
FR=5.4237E-08
MTTR=8
Q=4.339E-07

7.4.3.5. E2 TRANSFORMER FAILS PEAK VOLTAGE
Transformer is overloaded
FR=3.676E-07
MTTR=2190
Q=0.000804

FTA Meppelerdiepsluis Failure to stop high water

8.3. KEY SWITCH FAILS
Key switch fails - failure of electrical components
FR=4.636E-06
MTTR=2
Q=9.272E-06

20.1. KEY SWITCH FAILS
Key switch in engine room 2 fail
FR=4.636E-06
MTTR=2
Q=9.272E-06

20.2.1. CONTROL PANEL FAIL-BREAKS
Control panel is broken
FR=4.5662E-08
MTTR=336
Q=1.534E-05

20.2.2. CONTROL PANEL FAIL
Control panel fails due to an error in the electrical components
FR=1.6073E-08
MTTR=26
Q=4.179E-07

20.2.3. PUSH BUTTON FAIL
Pushbutton on the control panel fails
FR=4.05E-07
MTTR=26
Q=0.000896
ELECTRIC MOTOR 1 FAILS

Q=0,004364 w=1,123E-05

Electric motor in engine room 1 does not function

CONTROL FAILS FREQUENCY INVERTER

The frequency inverter fails to control the electromotor

5.3.1. CONTROL OF FREQ INVERTER FAILS

Control frequency inverter fails due to frost, software failure or power supply

Q=0,000777

558

Q=0,000777

6

5.3.2. FREQUENCY INVERTER FAILS

Frequency inverter fails - failure electrical components

FR=4,3906E-06 Tau=168 MTTR=340

Q=0,001858

BLOCK BRAKE FAILS

The block brake fails

Q=6,627E-07 w=1,176E-08

6.1. ENDSWITCH FAILS

Endswitch fails

FR=6,434E-06 Tau=168 MTTR=74

Q=0,001016

6.5. STARTER FAILS

Starter fails - electrical

FR=1,14E-08 Tau=168 MTTR=50

6.6. HYDRAULICAL PUMP FAILS NO PRESS

No pressure from hydraulical pump - wear

FR=3,9493E-08 Tau=168 MTTR=4

6.3. CONTROL VALVES LEAKAGE

Control valves leakage

FR=5,2E-06 Tau=168 MTTR=4

6.4. CONTROL VALVES FAIL DUE TO DIRT

Control valves fail due to dirt

FR=1,7E-06 Tau=168 MTTR=2

6.3. CONTROL VALVES FAIL

Control valves fail

Q=0,0006036 w=6,896E-06

3.4.2. NO POWER TO ENGINE ROOM

Power to engine room fails

Q=9,058E-06 w=5,839E-07

7.1. MANUAL SWITCH FAILS

Manual switch fails

FR=4,586E-06 MTTR=6

Q=2,752E-05

7.2. CONTROL BUILDING UNAVAILABLE

Control building unavailable due to structural failure or fire

Q=7,452E-05

7.3.1. INDUSTRIAL FUSE FAILS

Industrial fuse fails

FR=1,6E-07 MTTR=4

Q=6,4E-07

7.3.2. RELAY FAILS EMERGE NCY POWER

Relay to control emergency power fails

FR=4,99E-08 MTTR=2

Q=9,98E-08

7.3.3. POWER SUPPLY CABLE FAILS

Power supply cable fails - wear/aging

FR=5E-08 MTTR=8

Q=4E-07

7.3.4. PRESSURE MET FULL

Pressure meter full

Q=3,04E-07 w=7,37E-08

2.3.1. MOTOR LVL

Motor does not function

Failure of mechanical components

FR=3,0325E-06 Tau=168 MTTR=140

Q=0,000678

2.3.2. RELAY LVL

Relay does not function

Failure electrical components

FR=2,2865E-08 Tau=168 MTTR=2

Q=1,966E-06

2.3.3. LEVELLING COMP DAMAGED

Levelling component is damaged or missing - external collision

FR=1,5E-08 MTTR=778

Q=1,167E-05

2.3.4. SPINDLE FAIL

Spindle fail

FR=1,2751E-08 MTTR=754

Q=9,614E-06

LOW VOLTAGE INSTALLATION FAILS

Low voltage installation does not deliver AC or secondairy emergency power

Q=2,369E-05 w=2,889E-06

VOLTAGE FROM LOWVOLTAGE INSTAL FAILS

Voltage from lowvoltage installation fails

Q=1,14E-06 w=2,599E-07

7.3. POWER SUPPLY CABLE OVERLOADING

Power supply cable overload

Q=6,08E-07 w=1,14E-07

MOBILE GEN FAILS

No power delivery from mobile generator

Q=0,09051 w=0,002733

POWER FROM CONTROL TO ENG FAIL

Power delivery from the control building to engine room fails

Q=9,934E-05 w=3,149E-06
2.3.3. LEVELLING COMP DAMAGED
levelling component is damaged or missing - external collision

FR=1,5E-08
MTTR=778
Q=1,167E-05

2.3.1. MOTOR LVL
Motor does not function
Failure of mechanical components

FR=3,0325E-06
Tau=168
MTTR=140
Q=0,000678

2.3.2. RELAY LVL
Relay does not function
Failure of electrical components

FR=2,2865E-08
Tau=168
MTTR=2
Q=1,966E-06

2.3.4. SPINDLE FAIL
Spindle fail

FR=1,2751E-08
MTTR=754
Q=9,614E-06
Power delivery fails

UPS fails
Switch fails

FTD Meppelerdiepsluis Failure to stop high water

No power delivery from mobile generator

Manual switch does not function
Manual switch is unable to switch
The mobile generator fails during use

No power delivery from emergency generator

Manual switch does not function
Manual switch is unable to switch
The mobile generator fails during use

Switching to mobile generator fails

FTD Meppelerdiepsluis Failure to stop high water

No power delivery from mobile generator

Manual switch does not function
Manual switch is unable to switch
The mobile generator fails during use

Low voltage installation does not deliver AC or secondary emergency power

7.4.1. LOW VOLT INSTAL FAILS F/L/PV
Low voltage installation not available due to fire, lightning or peak voltage

Q=8,092E-06
Q=8,092E-06

7.4.2. RAIL FAIL NO VOLTAGE
The rail does not deliver voltage due to failure

FR=1,5E-07
MTTR=56
Q=8,4E-06

NO POWER FROM AC

Q=0,0008521 w=2,335E-05

POWER FROM AC/EMERGENCY FAILS
Low voltage installation does not receive AC or secondary emergency power

7.1.1. LOW VOLT INSTAL FAILS
Low voltage installation does not deliver AC or secondary emergency power

Q=7,194E-06 w=2,739E-06

LOW VOLTAGE INSTALLATION FAILS
Low voltage installation does not deliver AC or secondary emergency power

Q=2,369E-05 w=2,889E-06

7.1.2. LOW VOLT FAILS SCW/220V
Low voltage fails due to fluctuations in the system

Q=2,79E-08 w=4,53E-12

14,62,65
7.4.3.1. NO POWER DUE TO OUTAGE
No power due to a power outage
FR = 1.8264E-05
MTTR = 1.5
Q = 2.74E-05

7.4.3.2. POWER CABLE FAILS
Power cable fracture due to wear
Transformer fails - electrical components
FR = 1E-07
MTTR = 16
Q = 1.6E-06

7.4.3.3. SWITCH FAILS
Switch fails - electrical components
FR = 4.586E-06
MTTR = 4
Q = 1.834E-05

7.4.3.4. TRANSFORMER FAILS
Transformer fails - electrical components
FR = 5.4237E-08
MTTR = 8
Q = 4.339E-07

7.4.3.5. TRANSFORMER FAILS PEAK VOLTAGE
Transformer is overloaded
FR = 3.676E-07
MTTR = 2190
Q = 0.000804

7.4.4.1. MOBILE GEN DOES NOT START
The mobile generator does not start
FR = 0.003
MTTR = 2
Q = 0.005964

7.4.4.2. MOBILE POWER SUPPLY STOPS
Mobile power supply stops prematurely
FR = 0.003
MTTR = 2
Q = 0.005964

7.4.4.3. SWITCH FAILS AC TO EMERGENCY
Switching ac to emergency fails
FR = 1.5E-07
MTTR = 8760
Q = 0.000668

7.4.4.4. DATA CABLE FAILS
Data cable fails - aging/wear
FR = 8E-07
MTTR = 8
Q = 6.4E-06

7.4.2. RAIL FAIL NO VOLTAGE
The rail does not deliver voltage due to failure
FR = 1.5E-07
MTTR = 56
Q = 8.4E-06

7.4.1. LOW VOLT INSTAL FAILS F/L/PV
Low voltage installation not available due to fire, lightning or peak voltage
Q = 8.092E-06
Q = 8.092E-06
No power supply to profinet

Transformer for electrical components

Power delivery fails

11.5.4. HARD DISK GUI FAIL
Hard disk of GUI fail
FR=2.8919E-06 MTTR=4 Q=1.157E-05

11.5.6. NETWORK INTERFACE GUI FAIL
Network interface of GUI fail
FR=3E-06 MTTR=4 Q=1.2E-05

11.5.2. MEMORY GUI FAILS
Memory of gui fails
FR=2.5875E-06 MTTR=4 Q=1.035E-05

11.5.3. POWER SUPPLY GUI FAIL
Power supply to gui fail
FR=2.6636E-06 MTTR=4 Q=1.065E-05

11.5.5. GRAPHICS CARD GUI FAIL
Graphics card of GUI fail
FR=4.1096E-06 MTTR=4 Q=1.644E-05

11.5.1. CPU GUI FAIL
CPU of GUI fails
FR=4.5662E-06 MTTR=4 Q=1.826E-05

GUI PC fail
FR=7.6E-07 Q=3.8E-05 w=7.6E-07

Event of GUI fail
FR=7.6E-07 Q=3.8E-05 w=7.6E-07
Appendix D – Extended FMEA Case study
## Failure Data

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<th>Function</th>
<th>Failure Mode</th>
<th>Failure Cause</th>
<th>Detection Methods</th>
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