Thesis
Abem Haile

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Assessment of Maintenance Strategies for the Next Generation Meuse Weirs

Case study: Weir in Grave

TU Delft

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Assessment of Maintenance Strategies for the Next Generation Meuse Weirs

Case study: Weir in Grave

By

A. Haile

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Student number	4449746	
Thesis committee	Prof. dr. ir. S. N. Jonkman	TU Delft, chairman
	Ir. W. F. Molenaar	TU Delft, daily supervisor
	Dr. Ir. M. Van den Boomen	TU Delft
	Ir. M. Baijens	Rijkswaterstaat

Cover page image Downstream side of Weir in Grave – Rijkswaterstaat, available at:
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TU Delft

Rijkswaterstaat
Ministerie van Infrastructuur en Waterstaat

Preface

This thesis is written as the final part of obtaining my degree as Master of Science in Civil Engineering. The research was carried out in collaboration with the University of Technology in Delft and Rijkswaterstaat.

This report is mainly intended for reading by hydraulic engineers interested in the application of Asset Management to hydraulic structures, specifically weirs. The reader is expected to have basic understanding of probability theory.

Readers interested in the approach of Rijkswaterstaat towards Asset Management are referred to chapter 3. Readers interested in the steps to assess maintenance strategies for weirs are referred to chapter 6. Readers interested in the case study are referred to chapters 7, 8 and 9.

Firstly I would like to thank the people that directly contributed to my work. To start off I would like to thank Bas Jonkman for the extensive feedback, leading the thesis meetings and for sharing his insights and perspectives. In addition I would like to thank Wilfred Molenaar for his support throughout the thesis project. His advice during our pleasant meetings helped me structure my thesis. Furthermore I would like to thank Martine van den Boomen for sharing her knowledge on Asset Management which helped shape up the theoretical backbone of the thesis. Likewise I would like to thank Marloes Baijens for providing vital references and valuable feedback. Lastly I would like to thank Peter Blanker for the feedback which he offered on the approach of this thesis.

Secondly I would like to thank the people who indirectly contributed to my work, not only during my master thesis, but during my whole study period. Very special thanks to my parents who supported me so I could focus on my studies. And lastly I would like to thank my friends who made sure that I had moments of relaxation every now and then.

Rotterdam, April 2022
Abem Haile

Summary

Introduction

The Meuse is a river in West-Europe which rises at the Langres Plateau and flows from France through Belgium and the Netherlands. The river has always been an important shipping route, even though its navigability has been problematic in the Netherlands. To solve this problem seven weirs were constructed in the Dutch part of the Meuse. They are located at Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave and Lith. Weirs are hydraulic structures and mainly control the upstream water level to allow for sufficient depth for shipping.

Structures such as weirs generally have a technical life span of 100 years, and because the Meuse weirs were built 100 years ago they are up for replacement. Rijkswaterstaat wishes to have uniformity in the designs of the next Meuse weirs. This decreases the amount of unique components which in turn leads to the reduction of repair and maintenance costs.

Objective

The objective of this thesis is to determine the most cost-efficient maintenance strategy for the next generation Meuse weirs. To reach this objective the following research question is defined:

How can one make an assessment of the performance of maintenance strategies for weirs and what is the optimal maintenance strategy for the next generation Meuse weirs?

Maintenance strategies can generally be divided into two types of maintenance:

- Corrective maintenance: This is performed in response to failure. When the consequences of failure are of mild severity this type of maintenance is justified.
- Preventive maintenance: Is performed in anticipation of failure or after deterioration of equipment is detected. When the consequences of failure are severe or unacceptable this type of maintenance is performed.

Case study

In this thesis a case study is used to set up the analysis. The case study consists of two weir alternatives that were proposed as the replacement for the weir in Grave (see figures 1 and 2 respectively). Since there is a wish to make the designs of the Meuse weirs uniform, the other Meuse weirs are to be replaced as well and could have the same design as the next weir in Grave.

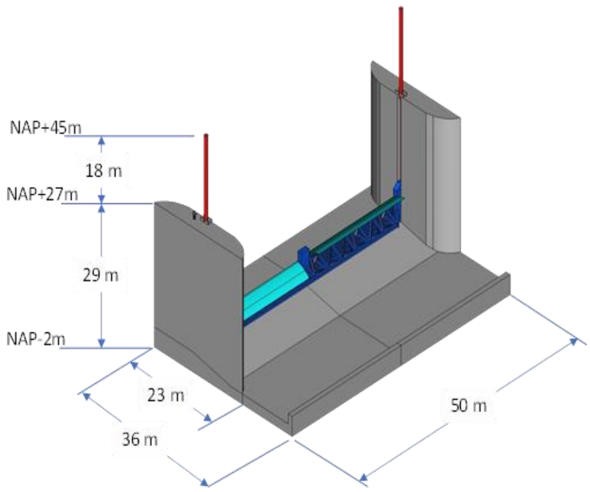

Figure 1: 3D Sketch of the lift gate alternative

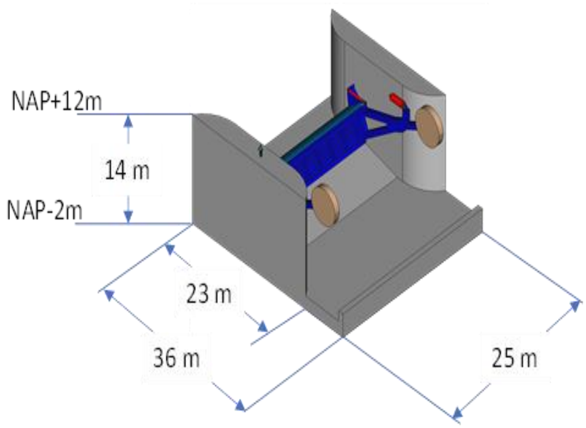

Figure 2: 3D Sketch of the radial gate alternative

Method

For both weir alternatives functional analyses were performed to determine top undesired events. These top undesired events are used as top events in fault trees to determine the availability of the weir alternatives under corrective maintenance and under preventive maintenance. The data needed to calculate the availability are extracted from the failure rate database for hydraulic structures by Rijkswaterstaat and reports of RAMS-analyses for weirs. The repair costs and maintenance costs are determined by using costs from maintenance plans of comparable weirs. This data is collected from the Rijkswaterstaat database. The maintenance costs are determined only under preventive maintenance, since there is no planned maintenance for a corrective maintenance strategy.

Results

The availability was calculated for both weirs for each the main weir functions under both corrective and preventive maintenance, results are shown in figure 3. As expected the availability for preventive maintenance is higher than the availability under corrective maintenance for both weirs. The largest contributions to the unavailability of the weirs are the ship collision failure mechanism and the hydraulic aggregate weir component.

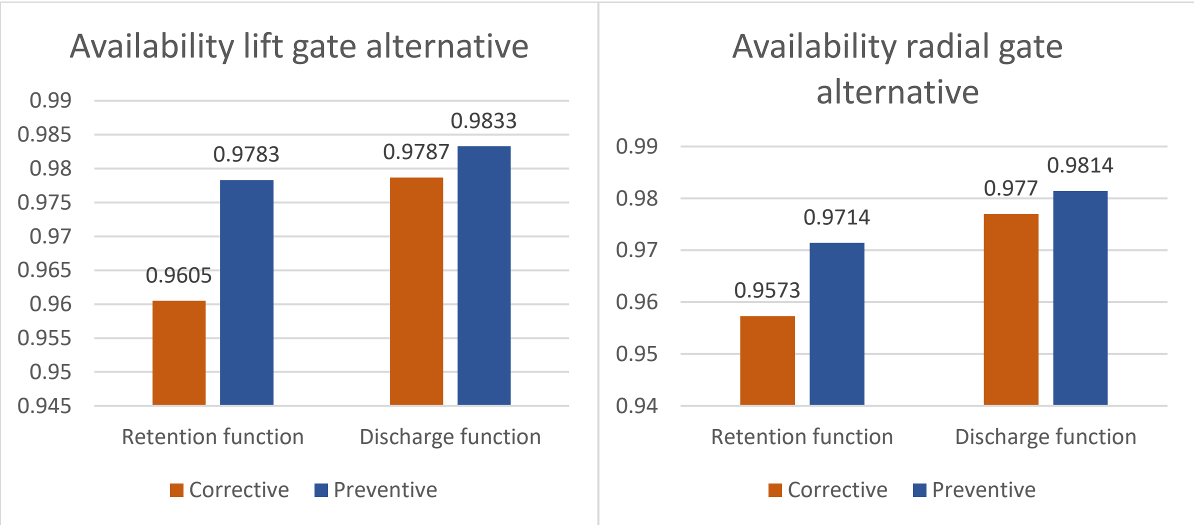

Figure 3: Availability results for each weir function under preventive and corrective maintenance

For both the lift gate alternative and the radial gate alternative the total costs under preventive maintenance seem to be lower compared to the costs under corrective maintenance (figure 4). The largest contributor to the repair costs are the hydraulic aggregate, however the largest contributor to the maintenance costs are the hydraulic cylinders.

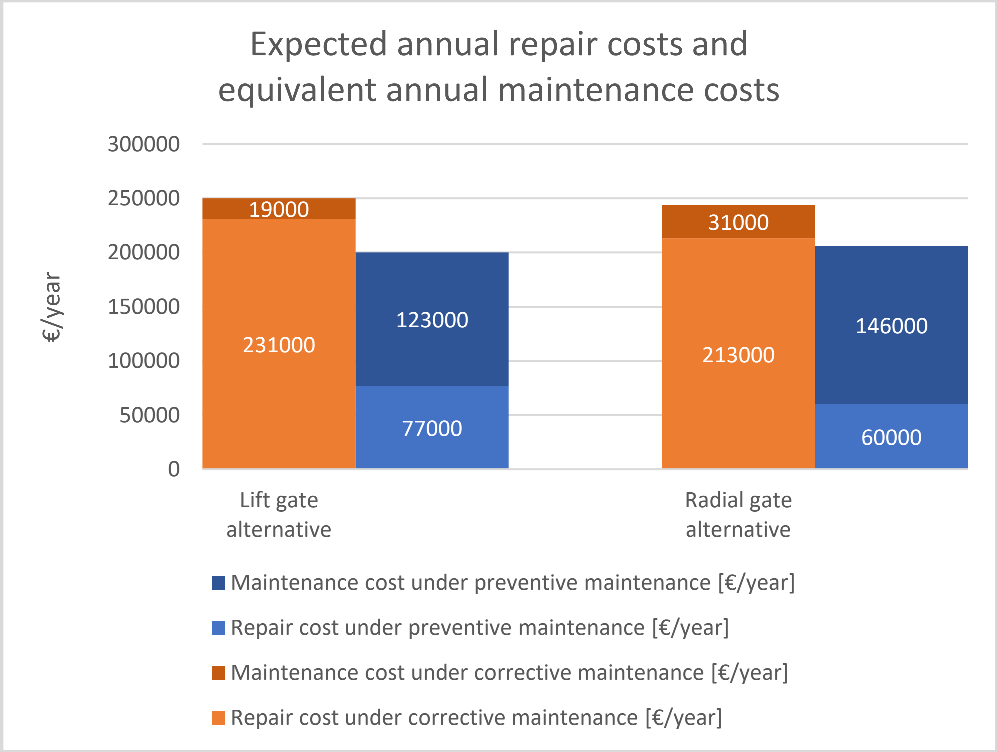

Figure 4: Expected annual repair costs and equivalent annual maintenance costs for both weir alternatives

Conclusion

Based on the results for both the availability and costs of both maintenance strategies in this report it seems that the preventive maintenance strategy performs better than the corrective maintenance strategy for both weir alternatives. The availability under preventive maintenance is higher and the total costs (maintenance costs and repair costs) are lower under preventive maintenance.

The availability of the weirs are mostly influenced by the failure mechanism of ship collision and the weir component "hydraulic aggregates". The largest contributor to the maintenance costs are the hydraulic cylinders and for the repair costs the most significant contributor are the hydraulic aggregates.

Ship collisions seem to influence the availability greatly, but has limited influence on the repair costs of the weirs. To reduce the unavailability due to ship collisions and therefore increase the availability of weirs one could reduce the repair time due to ship collisions. As it stands the repair time is assumed to be 3/4 of a year. This repair time can be reduced by having maintenance equipment readily available, such as dewatering structures or spare parts.

Contents

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List of acronyms

LCM	Life Cycle Management
RCM	Reliability Centered Maintenance
ECM	Economy Centered Maintenance
LCC	Life Cycle Costing
MEI	Mechanical and Electrical Installations
RAMS(SHEEP)	Reliability, Availability, Maintainability, Safety, Security, Health, Economics, Environment and Politics
MTTR	Mean Time To Repair
MTTF	Mean Time To Failure
TUE	Top Undesired Event
A	Availability
NA	Non-availability
FV	Fussel-vesely
MT	Maintenance Time
EAC	Equivalent Annual Cost

1 Introduction

In the literature there have been many studies on the optimising of maintenance plans for roads and bridges. Compared to other civil infrastructure, such as bridges, there has not been much development in effective maintenance for hydraulic structures.

There is no uniform guideline on how to perform maintenance for weirs at Rijkswaterstaat and there has not been much development in effective maintenance for hydraulic structures in the literature. This thesis proposes a method to assess maintenance strategies for weir structures according to the Life Cycle Management approach.

1.1 Thesis structure

The structure of the thesis is presented in figure 5. Chapter 1 is the introduction. In chapters 2 and 3 background information is given on weirs and asset management. Chapter 4 introduces the case study. The problem statement and research objective are elaborated in chapter 5. This leads to the research methodology in chapter 6. Chapter 7 gives a physical decomposition of the weir designs that are used for the case study. Chapter 7 together with chapter 8, in which the functional analysis for the weir designs is presented, form the basis for the analysis. In chapter 9 the results of the analysis are presented for the cases introduced in chapter 4. The thesis is wrapped up with the conclusions and recommendations.

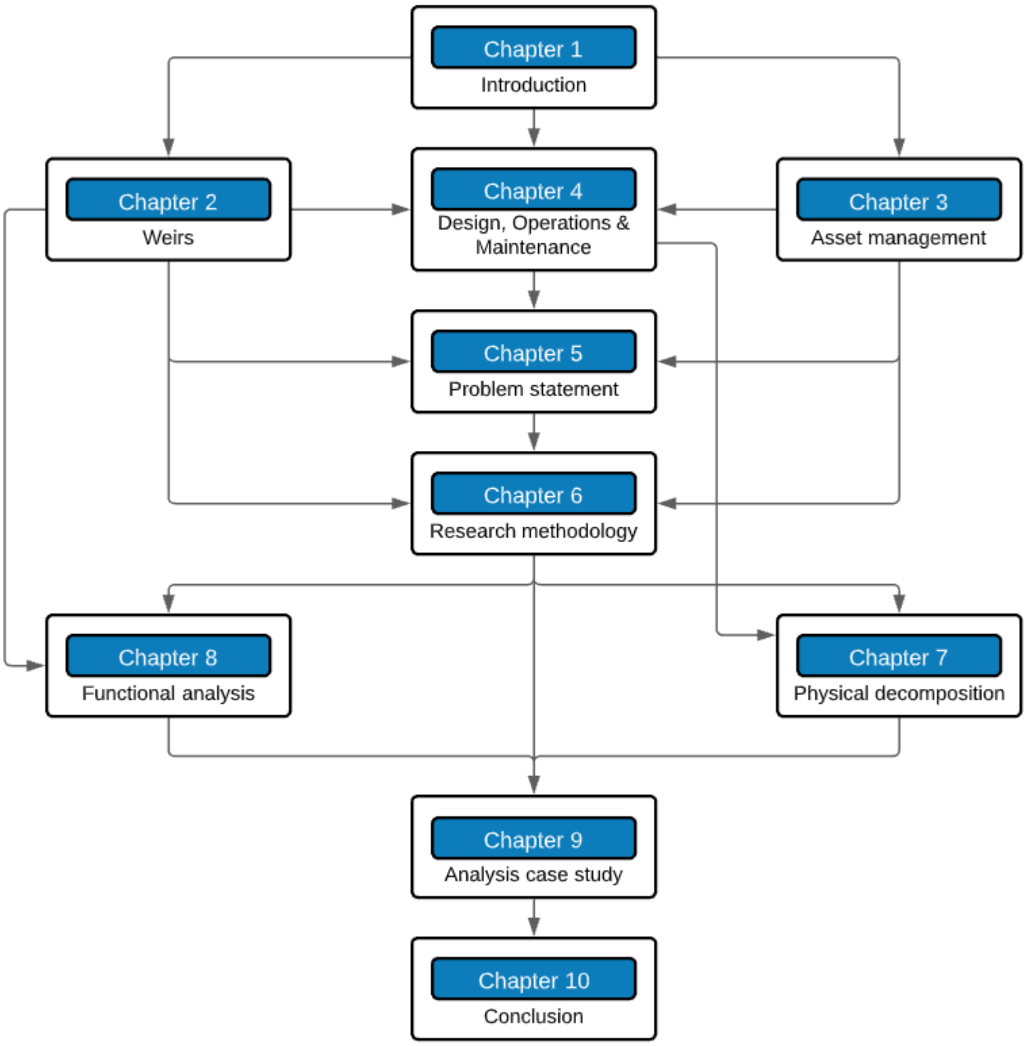


Figure 5: Visualised Thesis outline

2 Weirs

The Meuse is a river in West-Europe which rises at the Langres Plateau and flows from France through Belgium and the Netherlands (Ministerie van Verkeer en Waterstaat, 2008). The river has always been an important shipping route, even though its navigability has been problematic in the Netherlands (Martin, 2000). The navigability worsened in 1843 when the canal Bocholt-Herentals was erected. The canal took water from the Meuse to fertilize the soil in the Campine. The navigability problem was not solved until 1915, when the 'Meuse improvement' project was carried out.

One of the measures that was carried out is the construction of weirs. Seven weirs have been realised in the Dutch part of the Meuse. They are located at Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave and Lith (Illustrated in figure 6). Rijkswaterstaat is the executive agency of the ministry of Infrastructure and Water Management and manages the seven weirs along the river Meuse among the rest of the Dutch infrastructure. Rijkswaterstaats management of the Meuse weirs will be explained in more detail later in this chapter.

Figure 6: Map indicating the locations of weirs in the river Meuse (Rijkswaterstaat, 2007)

In this chapter weirs are explained in more detail. After this introduction paragraph 2.1 will go over the functions of weirs. Paragraph 2.2 decomposes the general weir structure into its main components. Paragraph 2.3 will go into more detail for the Meuse weirs that were introduced above. The chapter is concluded in paragraph 2.4.

2.1 Weir function

As mentioned in the introduction of chapter 2 the main purpose of a weir is to provide sufficient depth for shipping vessels. The weir acts as a barrier that holds upstream water, which results in a considerable gradient between the water level just upstream of the weir and the water level just downstream of the structure. To overcome this gradient navigation locks are built alongside weirs (figure 7).

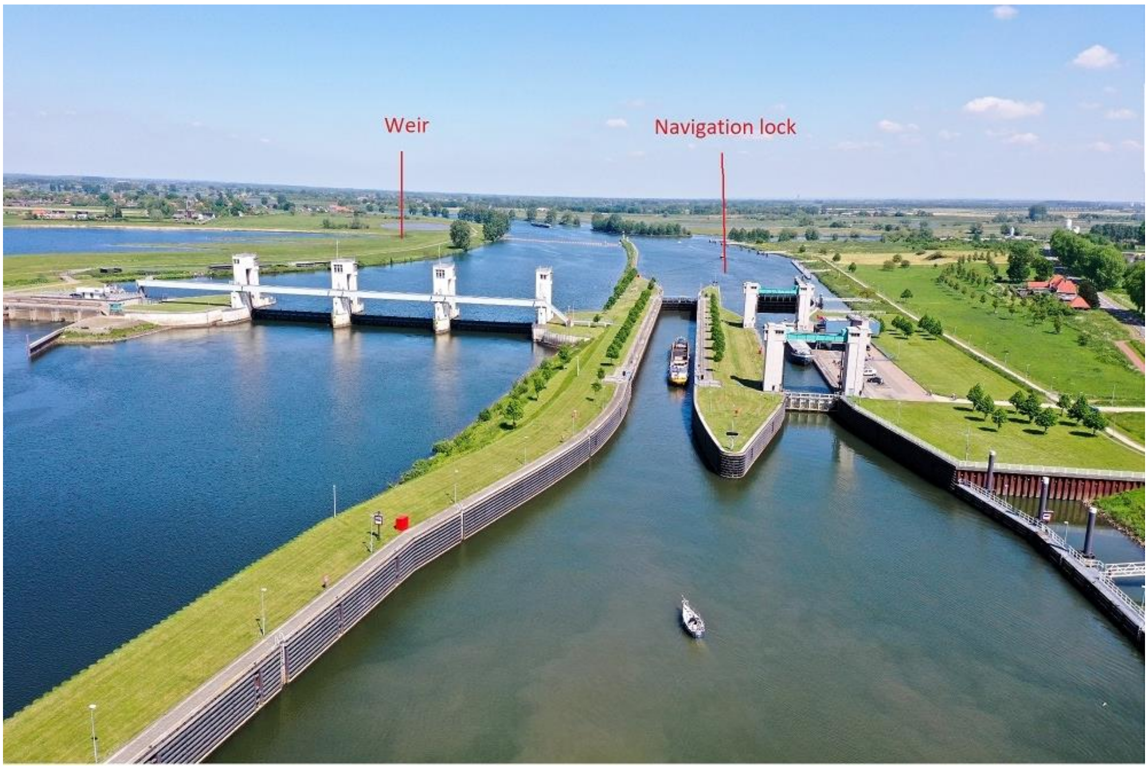


Figure 7: Drone shot of the lock-weir complex Lith (Rijkswaterstaat)

A lock links two sections of a waterway with different water levels and transfers vessels from one section to the other (Molenaar, 2020). An example of a navigation lock process is shown in figure 8.

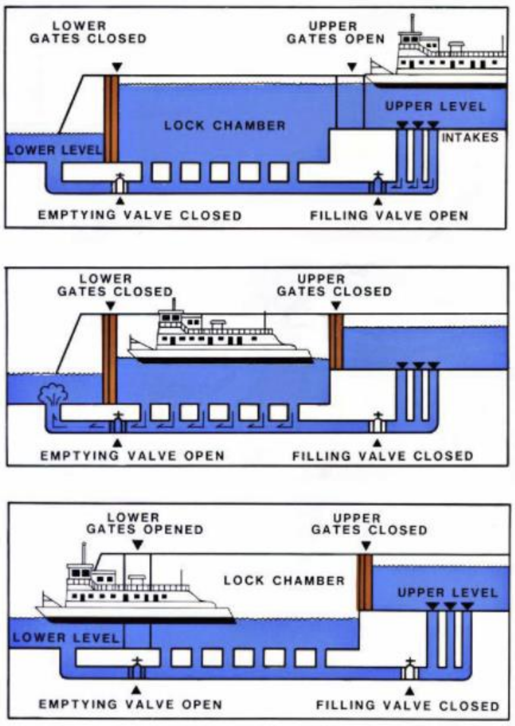


Figure 8: Navigation lock process upstream to downstream (AREC, 2010)

The lock chamber has a gate on both sides . In this example valves are used to either raise or lower the water level in the lock chamber, other mechanisms can be used however these will not be discussed (AREC, 2010). Filling valves allow water to enter the chamber to reach the water level of the upstream waterway section. The vessel enters the chamber and the emptying valve opens to lower the water level inside the chamber to the height of the lower waterway section. Now the chamber is opened and the vessel can leave.

Two main functions of a navigation lock are (Molenaar, 2020):

- *Ship passage*: As described above to transport vessels between two waterway sections with differing water levels.
- *Water retention*: Mainly to maintain the water level difference between two waterway sections.
- *Water quality management*: care may have to be taken about for example sediment or separation of fresh and salt water, depending on the environment of the lock.

Locks are not the focus in this thesis, however every Meuse weir is accompanied by a navigation lock and their functions are intertwined with each other. Therefore locks have to be mentioned.

The main function of a weir is to control the upstream water level to allow for sufficient depth for shipping (Rijkswaterstaat, 2020c). This is done by keeping a constant water level in the upstream reach. For example for the weir in Grave, it looks to keep the water level at Mook (a township several kilometers upstream of the weir in Grave) at a constant 7.91 m + NAP as long as the water level just upstream of the weir is at least 7.25 m + NAP (Rijkswaterstaat, 2021b). However during high water the weir must be able to be opened to prevent flooding. The main weir function can be divided into two sub-functions, the retention of water and discharge of water. The sub-functions are described as follows (Rijkswaterstaat, 2020c):

- *Retention of water:* the upstream water has to be retained to allow the upstream water level to rise to reach a sufficient water depth. The location where the required minimum water depth has to be maintained is usually located at the upstream begin of the river reach controlled by the weir.
- *Discharge of water:* to allow sufficient opening for river water to flow downstream. Without any transport of water from the upstream to downstream river reach, the water level upstream would rise beyond the desired constant water level and beyond acceptable flood safety levels for the polders or land along the river.

In times of (extreme) drought the weir could be kept completely closed to secure water intake upstream. In the case of river floods, high water the weir has to be opened up.

There is also a secondary function for weirs. During high water a weir can also allow vessels to pass through the weir openings (Rijkswaterstaat, 2021b):

- *Ship passage:* the weir allows vessels to pass through the weir openings during high water. Locks already provide a passage for vessels and with weirs also providing a passage during high water it reduces shipping blocks.

2.2 Weir structure breakdown

In this paragraph the weir structure is broken down into its components. A weir mainly consists of the concrete structure, the weir gates and mechanical and electrical installations (MEI). Figure 9 gives an overview of the concrete and steel structure of a general weir.

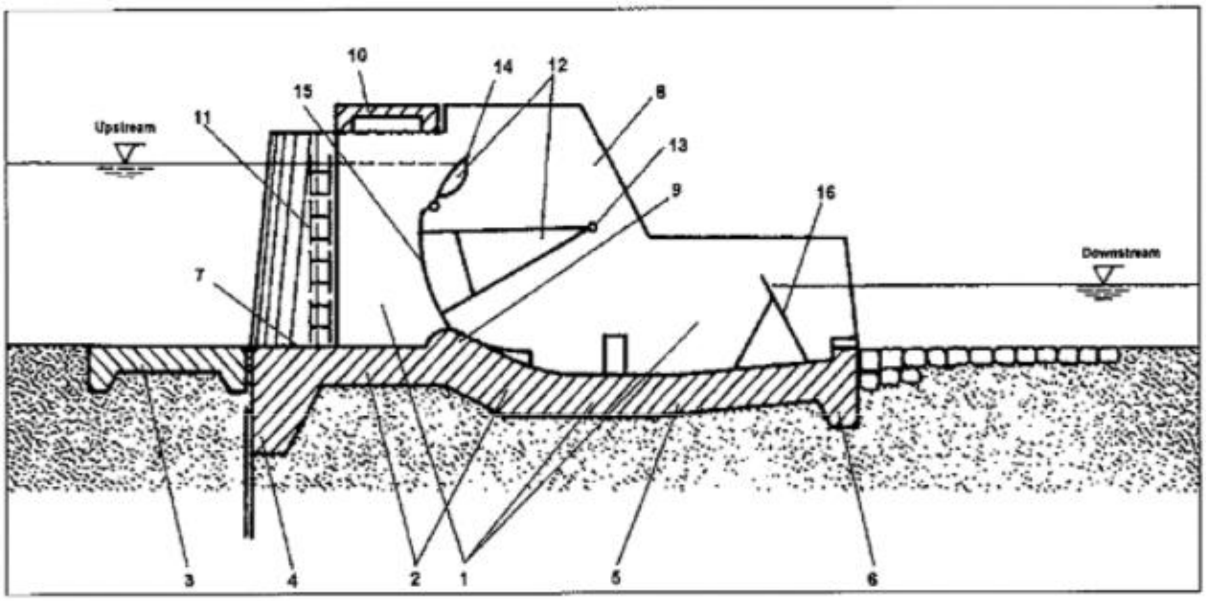


Figure 9: Sketch of a general weir structure (PIANC, 2006)

The main components from figure 9 are listed in the table below.

Table 1: List of components of a general weir structure from figure 9 (PIANC, 2006)

Component category	Component
Concrete weir structure (1)	Upstream floor (3)
	Upstream diaphragm wall (apron) with cutoffs (sheetpiles in this case) (4)
	Stilling basin (5)
	Downstream diaphragm wall (apron) (6)
	Intake floor (7)
	Weir pier (8)
Maintenance objects	Service bridge (10)
	Upstream dewatering structure or bulkheads (here: stop logs) (11)
	Downstream dewatering structure (here: bulkhead) (16)
Weir gates	Head gate (12)
	Control flap gate (14)

The following paragraphs explain the weir gates (paragraph 2.2.1) and the MEI (paragraph 2.2.2). The concrete weir structure (paragraph 2.2.3) and the maintenance objects are of lesser importance. Therefore these parts of the weir structure are covered in appendix A.1.

2.2.1 Weir gates

The gates serve all three weir functions. They allow the weir to retain water, to control the upstream water level and allow the discharge of water. The gates for weirs consist of two parts: a headgate and a control flap gate (see figure below). The water retaining function is mostly fulfilled by the headgate and to a smaller extent also the control flap gate. The water level control function is mostly fulfilled by the control flap gate.

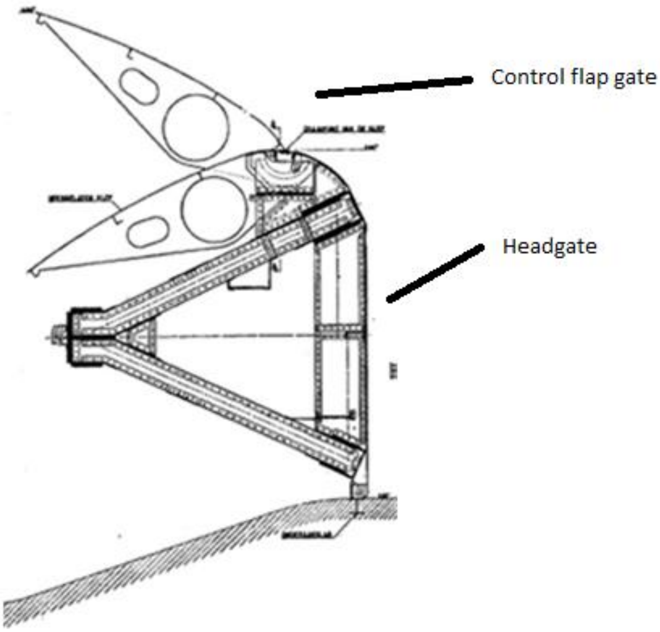


Figure 10: Side view of the gate of the weir in Linne (Rijkswaterstaat, 2021b)

Table 2 gives an overview of the different types of weir gates. The gate types from a structural viewpoint mainly differ in their transmission of load and the means to move (PIANC, 2006). When considering a suitable gate type the load transmission, boundary conditions and costs are considered. Appendix A.1.1 goes into more detail on the different weir gate types.

Table 2: List of different weir gate types (PIANC, 2006)

	Description (See Tables 5.1-5.3)	**Other types or variants to considerer**	**Foundation & Operator Supports** (transmission of loads)
Flap Gate	Skin plate generally curved, stiffened, and hinged on the floor.	- Torque tube - Wicket gate - Obermeyer gate (see inflatable weir Table 5.2)	Hinged on the floor by several points on the lower and downstream side of the gate.
Radial Gate	Skin plate (usually curved) - linked to 2 arms, - hinged on the piers.	- Reverse radial gate with upstream arms and trunnions. - Flap gate on the top of radial gate.	Hinged (trunnions) in 2 points at the ends of the arms on the piers.
Vertical Lift Gate	Leaf with a rectangular skin plate, stiffened with stiff vertical and horizontal members. Often with a wheel carriage on each side but sliding gates are also considered (i.e. for emergency closure).	- Double leaf gate, superposed. - With a flap at the upper part.	On the lateral end-sides of the gate (in slots) with cables or hydraulic cylinders.
Sector Gate	Plate formed of an upstream circular curved plate and a downstream flat plate, articulated at the bottom of the upstream side of the gate.	Drum gate is not very different but with an axis on the upstream side	Hinged at the bottom of the downstream plate.
Inflatable	Sealed tube made of flexible material (usually reinforced membrane). Inflatable by air or water.	Inflatable air-bags that support metallic flaps (Obermeyer system). This alternative may also be considered as a flap gate.	Anchored to the sill by stiff bolts (1 or 2 lines), These require careful design and maintenance to insure reliability in an inflatable weir.

2.2.2 Mechanical and electrical installations (MEI)

The mechanical and electrical installations consist of gate drives, gate control systems and the electrical supplies. Appendix A.1.2 goes into more detail on these components.

Gate drives

Gates are operated by electromechanical drives raising the gates by ropes or chains, or by hydraulic cylinders (Lewin, 2001). There is another mechanism that has been developed more recently in the form of inflatable air-bags (PIANC, 2006).

Electromechanical gate drives are the most common type of drive system for hydraulic gates (Daniel, et al., 2019). Electromechanical drives consist of electric motors that control the speed at which gates close under their weight (Lewin, 2001). Gates can be operated with a single motor, but gates will often be provided with two motors in case one fails. This can significantly increase a structures reliability and availability. The electromechanical drives are used mostly in combination with a hoisting system (ASCE, 2012).

Figure 11: Hoisting mechanism of the weir Nederrijn en Lek (BiermanHenket)

Cylinder based operating systems use a pneumatic or hydraulic cylinder with a rod that telescopes out of one end (ASCE, 2012). The hydraulic hoists allows for more ease when adjusting the gate speed or operating loads.

The hydraulic power is generated by a hydraulic power unit consisting of one or multiple pumps, valves and controls mounted on a fluid tank (Daniel, et al., 2019). Hoses transport the fluid to the cylinder. Valves control the pressure and volume of the fluid. The hydraulic fluid pressurises the system and drives the cylinder, it also functions as a lubricant. Figure 12 shows an example of a weir gate driven by a hydraulic cylinder.

Figure 12: Wicket weir gate driven by hydraulic cylinders (PIANC, 2006)

Inflatable air-bags are a relatively new gate type (Gebhardt, 2013). These air-bags have low capital and maintenance costs. It consists of a rubber membraned filled with air or water and is clamped to the weir body with one or two fixing bars (figure 13). These inflatable weirs have been used in the USA and Japan for more than 50 years, and due to positive experiences and economic value are increasingly used. By controlling the pressure in the air bags the upstream water level is maintained by the gates. The gate system is attached to the foundation structure with anchor bolts.

Figure 13: Obermeyer Spillway Gates, inflatable weir (Obermeyer Hydro, 2018)

Gate drives allow for the movement of gates. The gate drives for the control flap gates can regulate the water level upstream and the gate drives for the headgate allow the weir to open up in case of extremely high water discharges.

Gate controls

Gates are opened remotely or automatic, on site or from a distant location (ASCE, 2012). Local controls should be located in order for operations personnel to have safe access during events such as floods. Operations personnel will need to be available to trouble shoot at the gate location and operate the gate.

Electrical supplies

Installations in structures usually make use of electricity through high to mid voltage grid (DHV AIB, 1998). When the primary source of power shuts down there needs to be a back up to keep essential processes going, in the form of emergency power generators. These generators use diesel fuel. To keep the power generator from overheating ventilations and cooling water supplies are installed.

2.2.3 Concrete weir structure

The concrete superstructure is the main load carrier of the weir and facilitates the gates and MEI. But it does not serve any specific weir function. Some of the components listed in figure 9 are explained in appendix A.1.3.

2.3 Meuse weirs

The seven weirs in the Meuse were built between 1926 and 1936. According to a prognosis report from Rijkswaterstaat (Rijkswaterstaat, 2019b) the weirs must be renovated or replaced before 2050. Rijkswaterstaat follows a protocol for replacement and renovation projects. This process is illustrated in figure 14.

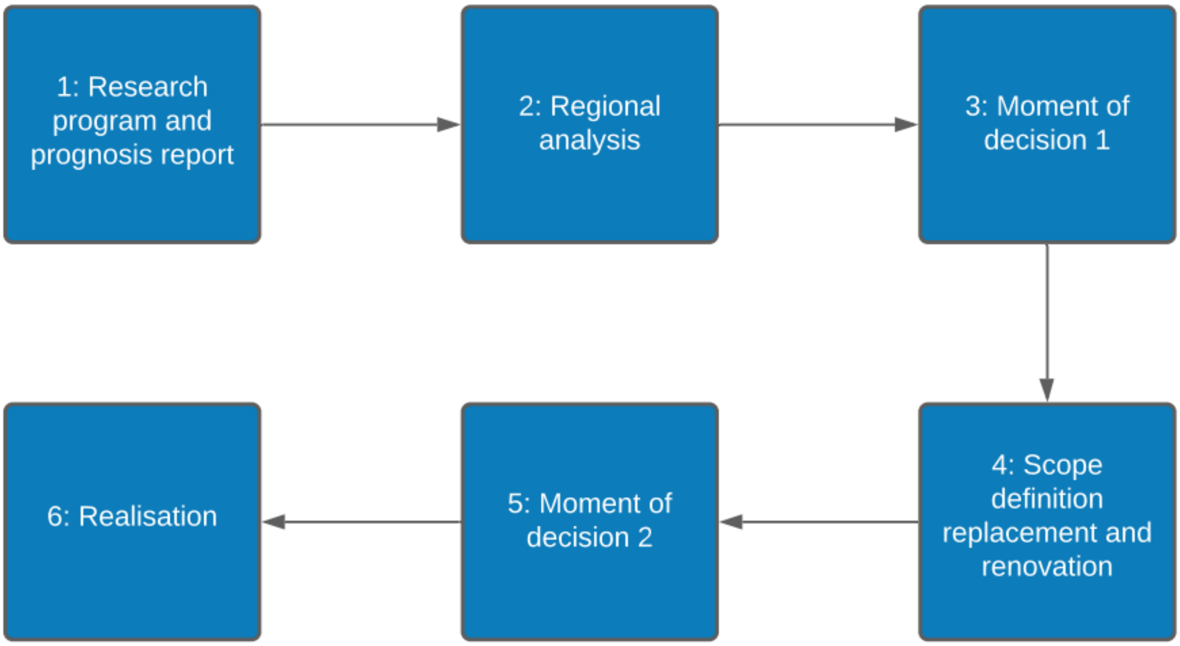


Figure 14: Rijkswaterstaats process for Replacement & Renovation (Vervanging & Renovatie) (Rijkswaterstaat, 2015)

Each step in the process is explained below (Rijkswaterstaat, 2015):

1) In the first step research is done on the current state of the infrastructure managed by Rijkswaterstaat. On the basis of inspections, statistical analyses are done on the lifespan of all objects until 2050. Cost estimations are also made for all objects. The analysis is documented in a prognosis report.
2) Regional recommendations are added to the prognosis report. The following are added to the prognosis report:
    - The cost estimations are adjusted such that the estimations are object specific and more accurate.
    - Improvements are made in the planning.
3) Based on the regional analyses a proposal is made to the board of Rijkswaterstaat.

4) Once the proposal is accepted research is done to determine the scope of the replacement of the objects in question. A choice for a preferred alternative is made out of the alternatives that were investigated.
5) A request is made for the execution of the replacement and renovation project.
6) The replacement or renovation measure can be realised.

Except for the weir in Grave the Meuse weirs are expected to have their technical life span end between 2030 and 2040 (Rijkswaterstaat, 2019b). For the weir in Grave the technical life span is expected to end in 2028.

The choice was made to replace the weirs because of the following reasons (Rijkswaterstaat, 2021b):

- There is no remote control over the weir.
- The labor safety for opening the poirée part of the weir is insufficient.
- The weirs are not sufficiently maintainable.

The new weirs have to satisfy the fore mentioned insufficiencies. The first weir to be replaced is the one in Grave, for which Rijkswaterstaat has developed preliminary conceptual weir alternatives based on two typical modules. These designs will be presented in chapter 4. The designs are made such that they could be replicated for the replacement of the other Meuse weirs. It still has to be decided whether a maintenance bridge or a maintenance tunnel has to be provided. This leads to a combination of four alternatives (two modules, for each either a bridge or tunnel).

Some particular wishes for the design of the next generation weirs stand out from the preliminary design report (Rijkswaterstaat, 2021b):

- Ship collision: In case of calamities (such as ship collisions) structures should be accessible for emergency services. This can be linked to the accessibility of the weir for maintenance workers and their equipment. There is a wish to protect weirs from ship collisions after the ship collision incident of the Grave weir, however not much thought has been put into the reduction of the impact of ship collisions.
- Maintenance: A wish from Rijkswaterstaat is to have a uniform design for the Meuse weirs and in particular the electrical and mechanical parts of the weir. This reduces the amount of components. Which in turn reduces the amount of spare parts in stock, components are more readily available and repairs can be performed faster. Since the weir in Grave is the first to be replaced it is of importance to take the standardization of the Meuse weirs into account when designing the next weir in Grave.
- Labor safety: There were no particular wishes, the weir designs have to comply with the labor safety code (Arboveiligheid).
- Machine safety: There were no particular wishes, the weir designs have to comply with the machine safety code (Machinerichtlijn).
- Remote control: The current weir in Grave is operated locally, while other Meuse weirs such as the ones in Borgharen, Lith, Roermond and Belfeld are operated from a control center in Maasbracht. The control center makes it easier to regulate and coordinate the water levels over the entire Meuse river. The next Meuse weirs should be operated from the control center, but should also be able to be operated locally as a backup. In case connection is lost between a weir in the control center.

2.4 Conclusion

This chapter was meant as a partial introduction of the thesis topic. The second half is introduced in the next chapter. The weir function (paragraph 2.1) and weir structure breakdown (paragraph 2.2) are used in chapter 9 on the fault tree analysis. Paragraph 2.3 introduced the ongoing Meuse weir replacement project, the contents of this paragraph is used in chapter 4 (the Grave weir design modules are used as a case study in this thesis).

3 Asset management (Operation & Maintenance)

At the end of the previous chapter some design problems were introduced. These design problems mostly pertain maintenance, which is a part of asset management. This chapter introduces the concept of asset management. The ISO 55000 gives the following definition of asset management:

Co-ordinated activity of an organisation to realise value from assets.

A more practical description is given by (Hastings, 2015):

Asset management is concerned with applying technical and financial judgement and sound management practices to deciding what assets are needed to meet an organisations aims, and then to acquiring and logistically sustaining the assets over their whole life, through to disposal.

This definition of asset management is from the perspective of the asset manager. For the purpose of this thesis it is preferable to take the perspective of the asset (weir). Figure 15 illustrates the main stages of the asset life cycle:

- identification of business/organisation opportunities or needs;
- selection of physical and financial options;
- acquisition of asset;
- logistic support, such as maintenance facilities and spares;
- operation and maintenance of asset;
- end of life of asset.

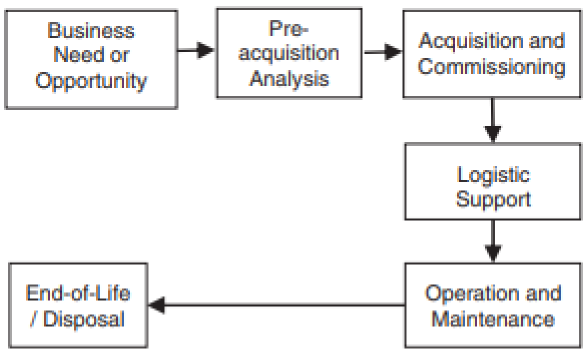


Figure 15: Flow chart of an assets Life Cycle (Hastings, 2015)

The previous chapter mentioned Life Cycle Management, this concept will be explained and linked to asset management in paragraph 3.1. This thesis focusses on the operation and maintenance part of asset management (figure 15) and specifically maintenance. Paragraph 3.2 explains maintenance, the types of maintenance and how Rijkswaterstaat performs maintenance. Paragraph 3.3 introduces a performance-based risk analysis method developed by Rijkswaterstaat which connects the idea of Life Cycle Management and maintenance. The chapter is concluded with chapter 3.4

3.1 Life Cycle Management

The literature relates the term 'Life Cycle Management' (LCM) with the optimisation of an assets service life. From the literature three definitions for LCM stand out:

(1) In general terms LCM is a management approach to infrastructure construction to achieve cost effective functionality and quality to generate maximum income for Whole Life Cost (WLC) (TU Delft, 2020b). WLC relate not only to the direct cost of construction, maintenance,

etc. of the structure itself but also to indirect costs and probable benefits related to its use and the environment in which it is located.

(2) LCM is the overall strategy to be used in managing a structure through its development and service life, with the aim of improving its efficiency from a business/engineering point of view, ensuring it meets the associated performance requirements defined at the time of design or as may be subsequently modified during the service life of the structure (Yokota, 2016).

(3) LCM is widely recognised as an effective tool for maximizing the cost-effectiveness of implementing intervention actions that improve condition and safety and extend the service life of deteriorating infrastructure (Dong, et al., 2017).

These definitions slightly differ from each other. However the common idea is that the LCM approach looks to maximise the cost-effectiveness of actions throughout a systems entire life cycle, while fulfilling the systems prime functional requirements. To link back the LCM approach to asset management, the LCM approach looks to maximise cost efficiency through each step of the progress in figure 15. For the purpose of this thesis the LCM approach is implemented in the maintenance step.

3.2 Maintenance

A production facility cannot be left entirely to itself for prolonged periods. It needs adjustments, occasional repairs and supervision to continue operating at the expected level of performance. This means operation that is safe, efficient and reliable (Wunderlich, 2005). There are two types of maintenance:

- Corrective maintenance: This is performed in response to failure. When the consequences of failure are of mild severity this type of maintenance is justified (TU Delft, 2020b).
- Preventive maintenance: Is performed in anticipation of failure or after deterioration of equipment is detected (Wunderlich, 2005). When the consequences of failure are severe or unacceptable this type of maintenance is performed.

The consequences for the failure of infrastructure is mostly severe, so infrastructure is maintained through preventive maintenance. Even under a preventive maintenance plan assets can still fail unexpectedly, when this happens corrective maintenance is performed.

3.2.1 Objective focused maintenance

For maintenance to be performed adequately, its objective needs to be defined. Objectives are, for example, ensuring safety, minimising cost, completing work on time (Wunderlich, 2005). Emphasis can be placed on certain objectives to center maintenance around it, such as Economy Centered Maintenance and Reliability Centered Maintenance (RCM). In case of RCM the highest priority is allocated to the service reliability of the system, while serving other objectives at a satisfactory level.

LCM and RCM

Important to note is that in case of RCM reliability is the top priority, this can lead to compromising safety by skipping preventive shut down to avoid service disruption. Or over-maintaining and therefore unnecessarily increasing costs. RCM and the LCM approach differ as the latter tries to maximise cost-effectiveness or minimise costs. Asset management within Rijkswaterstaat seeks to ensure an optimal balance between performance, risks and costs for all of its assets (Rijkswaterstaat, 2018a).

3.2.2 Maintenance by Rijkswaterstaat

Maintenance and repairs to Rijkswaterstaat's assets are controlled by the manager in the region (Baijens, 2021). However the maintenance measures are not taken by Rijkswaterstaat but put up for tender through contracts. In the case of weirs maintenance plans are object specific, there is no uniform guideline on how maintenance should be performed. Rijkswaterstaat uses a document called the "basisspecificatie" that provide uniformly applicable requirements for each type of asset, maintenance included (Rijkswaterstaat, 2018c). However there is no such document for weirs.

Rijkswaterstaat uses the term Asset management to describe a method to effectively maintain its assets (Rijkswaterstaat, 2021b). A balance has to be struck between performance and costs (Rijkswaterstaat, 2018a). This gives insight on the individual assets, but also on the effects of maintenance on the performance of the entire network.

The objective is to optimise the performance of infrastructure. Optimisation in this case is making a balance between the costs, performance and risks of assets. The performance markers for infrastructure is explained in the next paragraph 3.3.

Rijkswaterstaats guideline on performance based risk analysis describes how Rijkswaterstaat optimises their maintenance plans (Rijkswaterstaat, 2018a). It is based on economic optimisation at the component level. Rijkswaterstaat uses Isograph's RCM-Cost software which creates maintenance plans for each individual component on the basis of minimum life cycle costs.

3.3 RAMS(SHEEP)

Rijkswaterstaat manages a great number of objects ranging from roads to bridges. To assess the quality and performance of the Dutch infrastructure certain criteria are developed. These criteria are the RAMSSHEEP criteria (Rijkswaterstaat, 2018a). RAMSSHEEP stands for Reliability, Availability, Maintainability, Safety, Security, Health, Economics, Environment and Politics. These criteria are called aspects, and failing to comply with aspect requirements presents risks to the infrastructure network.

The RAMSSHEEP criteria are developed to evaluate the performance of infrastructure and develop maintenance plans. The focus of this thesis is on developing/evaluating performance-based maintenance plans. The foundation of these types of maintenance plans is a quantitative risk analysis, so not all RAMSHEEP criteria are taken into account. This analysis focusses solely on Reliability and Availability.

Reliability

The definition of reliability by Rijkswaterstaat is similar to the definition used by the IEC code for Reliability Block Diagrams (IEC, 2016):

The probability of performing as required, without failure, for a given time interval, under given conditions.

Availability

Unlike reliability, availability does take into account repairs for systems. The code defines availability as follows (IEC, 2016):

The probability of being in up-state at a given instant.

The "up state" is the state of being able to perform as required. The inverse of the availability (unavailability) is the probability of being in down state at a given instant. This "down state" is the time in which the system has failed and is being repaired. Reliability mainly depends on the failure rate, while availability is dependent on both the failure rate and repair times.

Maintainability

Maintainability is the degree of security that the maintenance works required for the satisfactory functioning of the system will actually be completed as scheduled (Rijkswaterstaat, 2018a). Maintainability is related to availability, as making a system more maintainable means the reduction of maintenance time and repair times. Specifically the reduction of repair times increases a systems availability. The maintainability of a weir structure should be taken into account in its design. For example, having dewatering structures readily available at all times can reduce maintenance and repair times.

Safety

In the performance-based risk analysis guideline of Rijkswaterstaat safety is defined as (Rijkswaterstaat, 2018a):

The probability that a system does not cause human casualties over a particular period of time and under certain conditions.

This definition is similar to the definition of reliability, in which the consequences for safety are in terms of human casualties and the consequences for reliability are in terms of damage. Safety takes into account the safety of system users, the staff operating and maintaining objects and local residents.

3.4 Conclusion

This chapter introduced the important concepts of this thesis, namely LCM and RAMS. The application of these concepts in this report are explained in chapter 6 Research methodology. Questions have been stated in this chapter, these questions will come back in the next chapter Problem statement and research objective. The combination of chapters 2 and 3 are the basis for the research objective of this thesis.

4 Design, Operation & Maintenance for 7 new weirs in the Meuse

In chapter 2 the design alternatives for the weir in Grave were mentioned. The designs are introduced in this chapter in paragraph 4.1. Paragraph 4.2 goes over maintenance measures for the current Meuse weirs. The last paragraph gives design questions from the preliminary design report for the weir in Grave.

4.1 Weir design cases

The weir in Grave will be replaced and not renovated (Rijkswaterstaat, 2021b). This is because the current weir cannot be controlled from a distance, and handling of the weir is not safe for workers. Since there is a wish to make the designs of the Meuse weirs uniform, the other Meuse weirs are to be replaced as well. The design of the new weir should fulfill the functional requirements of the current weir, while also taking into account future developments.

To determine the gate design different gate types were evaluated based on 14 criteria, such as reliability, maintainability, minimum leakage. The evaluation will not be covered in this report. The evaluation lead to two alternatives. These two gate alternatives that are proposed in the design study report (Rijkswaterstaat, 2021b) are a lift gate and a radial gate. The gates, the concrete structure and the movement works combined is defined as a module.

Lift gate module

The first weir module is a design with lift gates and high lifting towers. Figure 17 shows that there are two lift gates (headgates) and figure 16 shows one lift gate. To each headgate two control flap gates are attached, each control flap gate is 25 m wide.

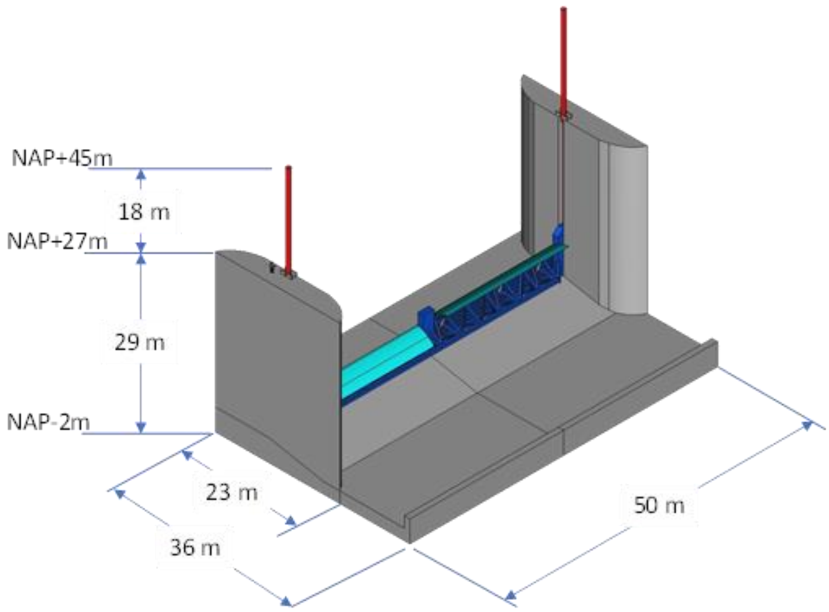


Figure 16: 3D Sketch of the lift gate alternative (Rijkswaterstaat, 2021b)

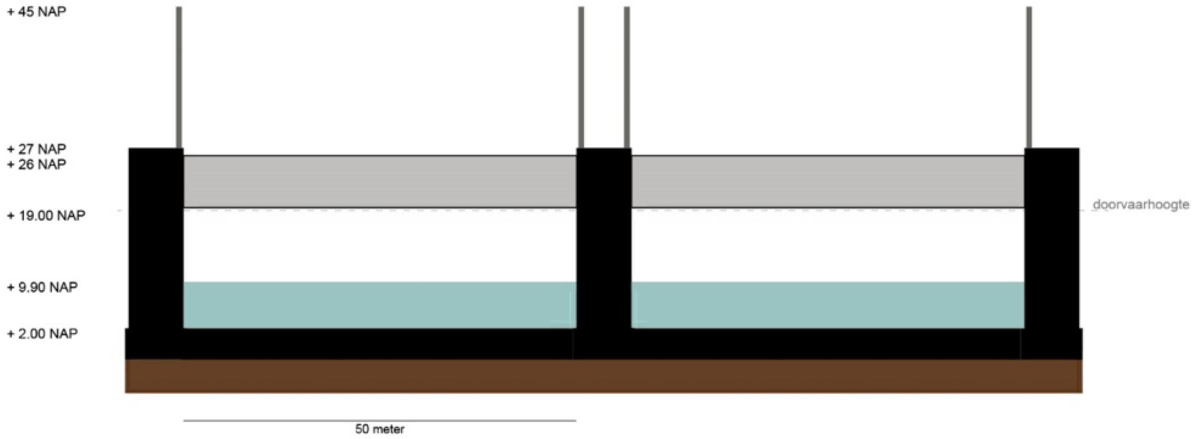


Figure 17: Front view of the lift gate alternative (Rijkswaterstaat, 2021b)

Radial gate module

The second weir module is a design with radial gates and short piers. Figure 19 shows that there are four radial gates (headgates), figure 18 shows one of the four radial gate. Each headgate has one control flap gate.

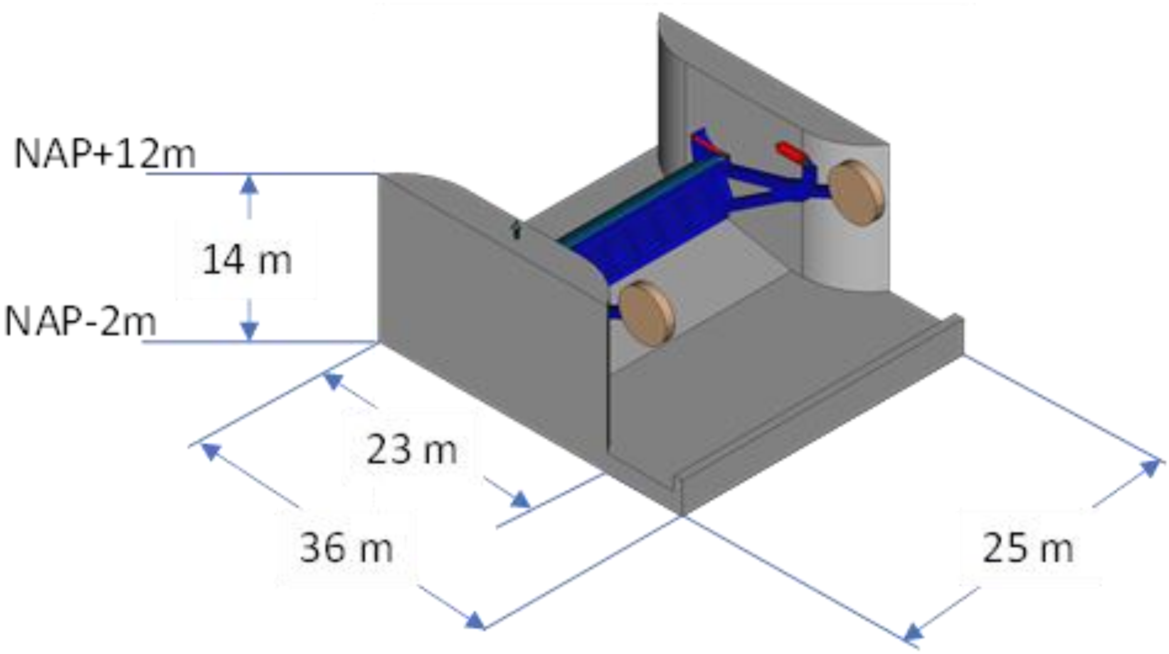


Figure 18: 3D Sketch of the radial gate alternative (Rijkswaterstaat, 2021b)

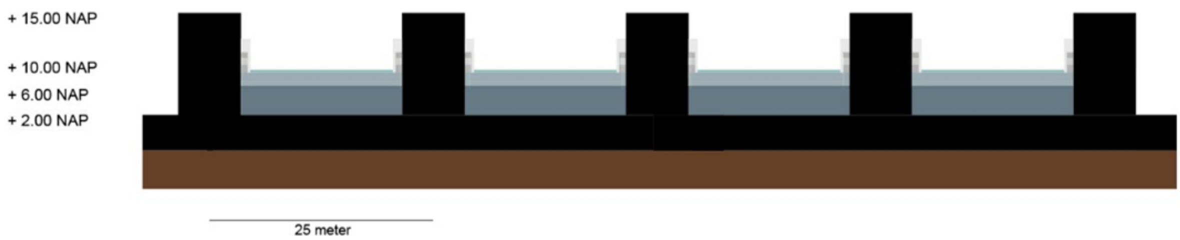


Figure 19: Front view of the radial gate alternative (Rijkswaterstaat, 2021b)

4.2 Maintenance of weirs

In paragraph 4.2.1 the maintenance measures and repairs are introduced. Workers require access to the weir components that have to be maintained or repaired, this is discussed in paragraph 4.2.2. The safety of maintenance workers is considered in paragraph 4.2.3

4.2.1 Maintenance measures and repairs

Small maintenance

Lubricating movable objects and cleaning covers most of the small maintenance works. In the case of extensive cleaning degreaser can be used in closed of environments, such as installation rooms where the movement works are cleaned. The contamination of surface water with degreaser should be prevented. To this end degreaser can only be applied on to a cleaning rag or removed using a cleaning rag. Table 3 gives an overview of the maintenance measures, the equipment needed to perform the tasks and their frequency.

Table 3: Specific maintenance tasks for the mechanical installations (Rijkswaterstaat, 2018b)

Maintenance object	**Maintenance measure**	**Equipment**	**Frequency**
Installation rooms	Cleaning the installation rooms	Brooms, cleaning rags, degreasers	Twice a year
Gates	Cleaning of gates	Brooms, cleaning rags, degreasers	Twice a year
Piers and abutments	Cleaning of piers and abutments	Brooms, cleaning rags, degreasers	Twice a year
Movable objects	Lubricate movable objects according to instructions	Oilcan	
Movement works	Taking oil samples		Once a year
	Oil change in the hydraulic tank		
	Hydraulic hoses have to be replaced when damaged		Once every 5 years (if located in outdoor environment), once every 10 years (if located in indoor environment)
	Steel cables are to be maintained according to the regulations from the NEN 3233		
	Chains are to be maintained according to the regulations from the DIN 8150		
	Fill up oil to minimum level if needed		Once a month
	Check if oil seals do not leak and replace if needed	Absorption cloths	Every 3 months

Large maintenance

Especially movable parts of the weir such as the gate and driving mechanism endure wear. One way to repair or replace these elements is by creating a dry dock around the gates. This can be done using the piers and abutments, and by utilising stopping logs that retain the river water. Grooves in the piers and concrete floor allow the stop logs to slide in. once the stop logs are installed the space can be pumped dry to allow for maintenance.

Another way is to use a single row of stoplogs either downstream or upstream of the weir (Bezuyen, 2000). The stoplogs take over the retaining function of the weir. The gate can be lifted above water for maintenance.

Table 4: List of large maintenance activities for each weir component (Haarsma, 2021) (Nebest, 2010)

Maintenance object	Maintenance measure	Frequency
Gates	Conservation gates	Once every 15 years
Movement works	Replacing lifting device	Once every 40 years
Gate driving mechanism	Replacing drives	Once every 25 years
Piers, lifting towers	Restoring concrete damage to piers and lifting towers	Once every 30 years

Repairs due to extreme events

In the last five years there have been two incidents with vessels colliding with Meuse weirs (see appendix A). Ship collisions are events that have a low probability of occurrence, but often a large impact (large repair costs and economic damage). The recent incidents suggest that ship collisions might need to be taken into consideration. In this report ship collisions are taken into account by adding it as a failure mechanism in the fault tree analysis (chapter 9).

4.2.2 Maintainability

To perform any of the maintenance activities mentioned above the weir structure has to be accessible. The accessibility requirements differ depending on the type and the scale of the maintenance.

For small maintenance the equipment for most maintenance measures consists of brooms, degreasers, cleaning rags and grease guns. Since these maintenance activities are done about every two months most equipment can be stored on site in the installation rooms. However when changing the oil in a hydraulic tank about 50 liter is needed. The hydraulic tank should be accessible without the use of ladders. To clean the weir gates a dry dock is created using stoplogs. Workers should be able to get inside the dock by using a ladder for example.

Large maintenance consists mostly of replacements. Most can be done from the river side by creating a dry lock and using a pontoon to perform the replacement measures. These are for measures such as replacing gates, drives and movement works.

In case of a calamity the weir should be accessible for emergency services and their equipment. The weir should be accessible from the land side and river side. For the land side the service vehicle should be parked on a paved parking position. The parking position can be designed for the vehicle that takes up the largest space. The weir should be accessible from the river side in case of high water when emergency services are not accessible from land.

Table 5: List of process requirements

Requirements
All weir elements have to be accessible for maintenance workers and their equipment.
Maintenance workers have to be able to perform their activities safely.
The piers must be able to facilitate stoplogs to create dry docks.
Indoor weir elements that need large equipment for maintenance, such as hydraulic tanks, have to be accessible without stairs or ladders.
The piers must have enough space for a electromechanical/hydraulic drive.
Electrical installations have to be indoors.
The weir must be accessible for emergency services.

4.2.2.1 Accessibility designs

For maintenance of the weir the structure must be accessible. To allow for accessibility of the middle piers of the weir 2 suggestions have been made (Rijkswaterstaat, 2021b). One is to construct bridges between the piers, the other is to construct a tunnel underneath the weir. These structures will allow transportation of materials, installation parts and workers.

Bridge

Figure 20 illustrates the alternatives with a bridge. To design the bridge two parameters are of importance, the minimum width needed for transportation of materials and the weight capacity needed for this transportation.

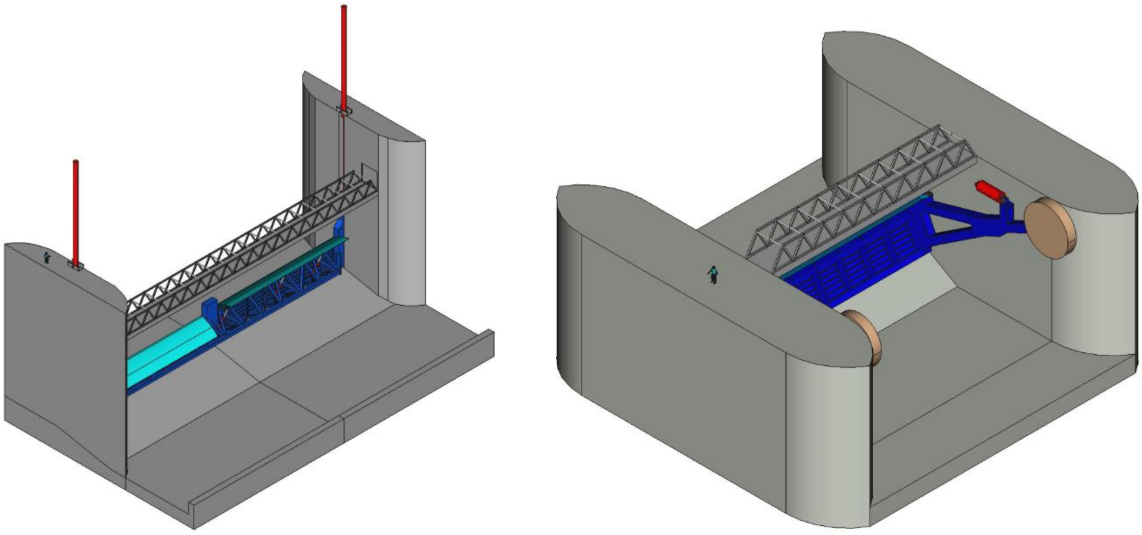


Figure 20: Bridge for the lift gate alternative (left) and radial gate (right) (Rijkswaterstaat, 2021b)

Tunnel

Limiting factors for the tunnel will mostly be its width and height. Figure 21 gives a variety of possible tunnel dimensions for the lift gate alternative.

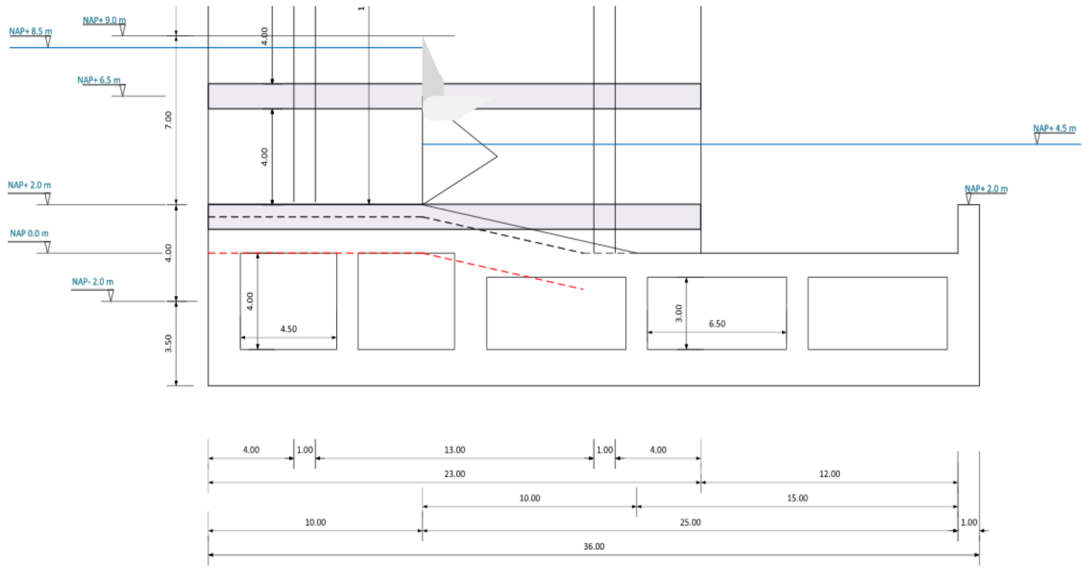


Figure 21: Possible tunnels for the lift gate (Rijkswaterstaat, 2021b)

4.2.3 Safety

The current Meuse weirs are mostly operated manually (Haarsma, 2021). This leads to a labor intensive and dangerous work environment. For example in 2007 the Meuse river experienced high water and the weir in Linne had to be opened. Figure 22 shows the work environment for the maintenance workers.

Figure 22: Work environment when opening the weir in Linne (Haarsma, 2021)

The work environment for the maintenance workers were too dangerous and this raised attention. To this end in 2011 a crane was installed for the weir in Sambeek (figure 23). This crane had automatic controls and was deemed reliable.

Figure 23: The crane machine in Sambeek allowing for automation of maintenance activities (Haarsma, 2021)

The Meuse weirs have been inspected for labor safety. The inspections have been performed in the years 2009 and 2010. The findings are generally similar (Iv-Industrie, 2009):

- Ommision of handrails;
- No facilities to prevent falling of the stoney part of the weir;
- Ladders not being properly maintained.

The safety criterium considers only injuries or other harms to maintenance workers, the risks of harms to the environment, properties, animals, etc. are not considered. This criterium consists of four categories on which the weir alternatives can be assessed, these are as follows:

- mechanical dangers;
- electrical dangers;
- emergency supplies;
- structural facilities.

The safety aspect is not covered in this thesis, however it is elaborated in this paragraph since it is an important aspect.

4.3 Design questions

From the preliminary conceptual weir design report for Grave certain questions arose considering the LCM approach. These questions are based on the wish to make all the Meuse weirs uniform in design.

- Is the use of tunnels for the maintenance of the weirs (expensive) more beneficial than a simple bridge (cheaper)?
- Dewatering structures that are used for regular maintenance could also be used for repairs after extreme events (ship collision). However in this case more dewatering structures have to be readily available. Is this cost efficient?
- As a consequence of the uniformity wish, the Meuse rivers could all have the same design. Which means that the dewatering structures can be shared amongst the 7 weirs. How many dewatering structures are needed for the 7 weirs?
- How impactful is the risk of ship collision on the performance of weirs?

5 Problem statement and research objective

In this chapter the research gap is described in paragraph 5.1. Paragraph 5.2 presents the problem statement. Paragraph 5.3 presents the main research question with the sub research questions.

5.1 Research gap

In the literature there have been many studies on the optimising of maintenance plans for roads and bridges (Attema, et al., 2016), (Strauss, et al., 2008), (Catbas, et al., 2014), (Sabatino, et al., 2016), (Khaled, et al., 2002), (Mehany, et al., 2016), (Sancho, et al., 2021). One paper by (Yokota, 2016) presented a methodology with which the life cycle management was developed for the maintenance of shore protection facilities. The function of a shore protection facility is to conserve coastal areas and protect hinterland from high waves, storm surges, etc. Compared to other civil infrastructure, such as bridges, there is not much development in effective maintenance for hydraulic structures. Most of the forementioned structures have a single function while weirs serve multiple functions, water management, flood safety and shipping.

5.2 Problem statement

Based on chapters 2 and 3 the following problems arise. There is no uniform guideline on how to perform maintenance for weirs at Rijkswaterstaat. There has not been much development in effective maintenance for hydraulic structures in the literature.

On a different note one of the design wishes from Rijkswaterstaat in chapter 2 poses an opportunity. As Rijkswaterstaat wishes to standardise the Meuse weirs it can reduce the amount of components and spare parts in stock. Parts are therefore more readily available and repairs can be done faster. This could make corrective maintenance for certain components cheaper.

5.3 Research objective and questions

The objective of this thesis is to determine the most cost-efficient maintenance strategy for the next generation Meuse weirs. To reach this objective the following research question is defined:

How can one make an assessment of the performance of maintenance strategies for weirs and what is the optimal maintenance strategy for the next generation Meuse weirs?

The following sub-questions were derived from the main research question:

1) How is the performance of maintenance strategies for weirs quantitatively assessed?
2) What is the optimal maintenance strategy for the next generation Meuse weirs?
3) To which weir components are the availability and costs sensitive?
4) What is the influence of ship collisions on the availability and repair costs of weirs?

6 Research methodology

This chapter explains the design of the research. It starts off with the research steps that are taken in the thesis (paragraph 6.1). That is followed up by exploring the methods used in the research (paragraph 6.2). The chapter is closed with an example case that illustrates the research steps (paragraph 6.3).

6.1 Research steps

The research steps are listed below:

- Two weir alternatives are provided by Rijkswaterstaat, which are the preliminary conceptual designs for the next weir in Grave.
- Based on the weir functions, a functional analysis is performed to determine functional requirements for the weir alternatives.
- Based on the functional requirements and physical decomposition (the physical decomposition is done in chapter 7) the top undesired events are determined for both weir alternatives (the top undesired events are determined in chapter 8 and used in chapter 9).
- Fault trees are made for the top undesired events.
- Two maintenance strategies are implemented, corrective and preventive maintenance (as explained in paragraph 3.2). The preventive maintenance strategy is based on the maintenance plan of the weir in Lith (Nebest, 2010).
- Corrective maintenance is only performed in response to failure or malfunction. Preventive maintenance on the other hand is performed in anticipation of failure, equipment has maintenance plans to avoid or prevent breakdowns, however even under preventive maintenance failure is still possible. So the failure rate of components under corrective maintenance and preventive maintenance should differ.
- Using the fault trees the availability is calculated for both weir alternatives under both maintenance strategies for each top undesired event. The formula to calculate the availability is provided in the next paragraph. The data needed to calculate the availability are extracted from the failure rate database for hydraulic structures by Rijkswaterstaat (Rijkswaterstaat, 2016) and reports including RAMS-analyses for the Meuse weirs (Iv-Infra, 2010a), (Iv-infra, 2010b), (Iv-infra, 2010c), (Iv-infra, 2010d).
- Next to the availability, which only takes into account the non-functionality of a system due to failure, the scheduled downtime for both weirs is calculated (this is only done for preventive maintenance). The scheduled downtime is the downtime due to maintenance and can be calculated from the planned maintenance schedule. This scheduled downtime is of importance to weirs as explained in paragraph 3.3.
- The repair costs and maintenance costs are determined by using costs from maintenance plans of comparable weirs. The data is collected from the Rijkswaterstaat database. The maintenance costs are determined only under preventive maintenance, since there is no planned maintenance for a corrective maintenance strategy.

Most of these steps are illustrated in paragraph 6.3 using an example case with two oversimplified fictitious weirs.

6.2 Methods

6.2.1 Reliability

The definition of reliability by Rijkswaterstaat is similar to the definition used by the IEC code for Reliability Block Diagrams (IEC, 2016):

The probability of performing as required, without failure, for a given time interval, under given conditions.

This definition means that reliability is the probability that a component functions given that the system does not fail. In the case of repairable systems (weirs are repairable systems), components can only be repaired if the entire system functions as the failure of the individual components occurs (IEC, 2016). This means that reliability does not take into account the fact that repairable systems can fail multiple times through their life span, because these systems can be repaired after they have failed. For this reason reliability is not a proper performance criterium.

6.2.2 Availability

Unlike reliability, availability does take into account repairs for systems. The code defines availability as follows (IEC, 2016):

The probability of being in up-state at a given instant.

The "up state" is the state of being able to perform as required. The inverse of the availability (unavailability or non-availability) is the probability of being in down state at a given instant. This "down state" is the time in which the system has failed and is being repaired.

Availability is a portion of the time in which an object works (Van den Boomen, 2015). For example if the availability of a weir gate is 98%, it would mean that the weir gate functions for 98% of the time and would not function 2% of the time. If one year is taken it would mean that the weir gate does not function for about 0.02 * 365 = 7.3 days per year and functions for 365 - 7.3 = 357.7 days a year.

When a system is available it is ready to function, a system that is out of service is unavailable (Wunderlich, 2005). Availability is the probability that the system functions. In paragraph 3.2 two types of maintenance were explained, corrective and preventive maintenance. Corrective maintenance is performed only in response to failure, while preventive maintenance is performed in anticipation of failure. However, even under a preventive maintenance plan assets can still fail unexpectedly. When an asset fails corrective maintenance is performed.

Availability calculation

The availability [$A_i(t)$] of a system component in the simplest case can be expressed by a constant failure rate λ_i and a constant repair rate μ_i (IEC, 2016). This leads to the following formula:

$$A_i(t) = \frac{\mu_i}{\lambda_i + \mu_i} + \frac{\lambda_i}{\lambda_i + \mu_i} exp[-(\lambda_i + \mu_i)t].$$

This is the case if the availability of a component follows an exponential parametric distribution.

When the components can be quickly repaired (the mean time to repair is significantly smaller than the mean time to failure, $MTTR_i << MTTF_i$), the asymptotic values are reached quickly. In such cases the availability can be reduced to the steady state availability.

The steady state availability ($t \to \infty$) is:

$$A_i = \frac{\mu_i}{\lambda_i + \mu_i} = \frac{1/MTTR_i}{1/MTTF_i + 1/MTTR_i} = \frac{1}{\frac{MTTR_i}{MTTF_i} + 1} = \frac{MTTF_i}{MTTR_i + MTTF_i}.$$

The mean time to repair for weir components is significantly smaller than the mean time to failure. So for in this thesis the formula for the steady state availability is used.

Vesely-Fussell importance factor

The Fussell-Vesely importance factor measures the probability that, when a certain top undesired event occurs, the failure of an event participates in at least one of the minimal cut sets having caused the top undesired event (IEC, 2016). Cut sets are combinations of failure events that can cause a top undesired event. A cut set is considered a minimal cut set if removal of any of the events within the minimal cut set results in the combination of remaining events in the cut set not being able to cause the top undesired event. Considering a minimal cut set $C(b_i)$ for a failure event b_i. The formula for the Vesely-Fussell importance factor is as follows:

$$FV_S(B_i,t) = \frac{P\left[\cup_j\ C(b_i)_j\right]}{P_{TUE}}.$$

Where P_{TUE} is the probability for the top undesired event. For the purpose of this thesis the probability is expressed as the availability. The forementioned formula is difficult to calculate, so the formula can be approximated, given that the probability that the top undesired event occurs is low. The approximation is described as follows:

$$FV_S(B_i,t) \approx \frac{P\left[\sum_j\ C(b_i)_j\right]}{P\left[\sum_{i,j} C(b_i)_j\right]}.$$

This formula is the sum of probabilities of minimal cut sets containing failure event b_i divided by the sum of probabilities of all minimal cut sets. An example from (Rausand, 2004) is used to illustrate the approximated formula.

Given is a system with five components (with non-availabilities NA_i, for i = 1,2,…,5), the failure events are the components not being available (Rausand, 2004). Figure 24 shows the structure with its components. The top undesired event is the system not being connected from one side to the other side. The minimal cut sets are $C_1 = \{1, 2\}$, $C_2 = \{4, 5\}$, $C_3 = \{1, 3, 5\}$, $C_4 = \{2, 3, 4\}$.

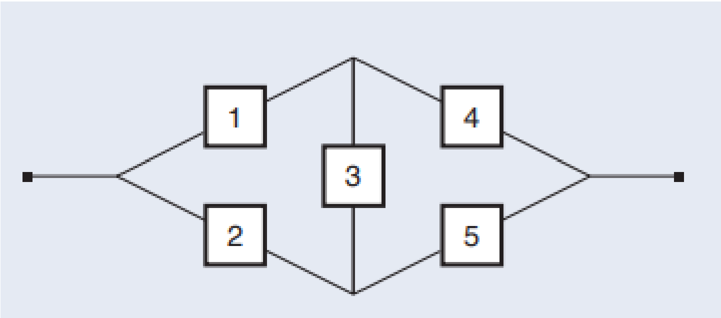


Figure 24: Bridge system used as an example to calculate the Vesely-Fussell importance factor (Rausand, 2004)

The Vesely-Fussell importance factor for example, for component 3, can be approximated as follows:

$$FV_S(3,t) \approx \frac{NA_{C3} + NA_{C4}}{NA_0} = \frac{NA_1 * NA_3 * NA_5 + NA_2 * NA_3 * NA_4}{NA_0}.$$

Where NA_0 is the unavailability (non-availability) of the top undesired event (the bridge not being connected from one side to the other). The unavailability of the top undesired event NA_0 can be approximated with an upper bound approximation:

$$NA_0 \approx 1 - (1 - NA_{C1}) * (1 - NA_{C2}) * (1 - NA_{C3}) * (1 - NA_{C4}) * (1 - NA_{C5}).$$

The importance factors will not be calculated in the example case, because Isograph's software Reliability Workbench will be used in the actual case.

6.2.3 Fault tree analysis

The fault tree analysis is the most well-known evaluation method, mostly due to the standardised symbols (Klaassen, et al., 1988). The method is used to calculate the system availability (top event) based on the availability of components (bottom events). An example of a fault tree is shown in the figure below.

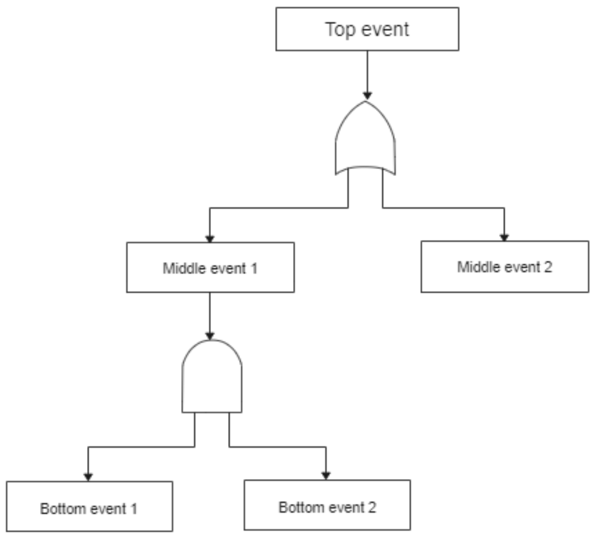
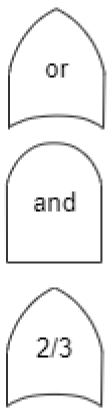


Figure 25: Example of a fault tree

Where the symbols are the or-port and the and-port. The or-port indicates that the upper event occurs if any of the lower events occur. So in the case figure 25, the top event will occur if either the middle event 1 or middle event 2 or both middle events occur at the same time. The and-port indicates that the upper event occurs if all lower events occur. So middle event 1 occurs if bottom events 1 and 2 occur at the same time.



$$A = A_1 * A_2 * A_3 \ldots$$
$$NA = 1 - (1 - NA_1)(1 - NA_2)(1 - NA_3) \ldots$$

$$A = 1 - (1 - A_1) * (1 - A_2) * (1 - A_3) \ldots$$
$$NA = NA_1 * NA_1 * NA_1 \ldots$$

$$A = A_1 * A_2 + A_2 * A_3 + A_1 * A_3 - 2 * A_1 * A_2 * A_3$$
$$NA = NA_1 * NA_2 * NA_1 + NA_1 * NA_2 * A_3 + NA_2 * NA_3 * A_1 + NA_1 * NA_3 * A_2$$

Figure 26: OR-port, AND-port, Voting OR-gate with their respective formulas for availability and non-availability (or unavailability)

The formulas provided in figure 26 only hold if the events in the fault trees are independent of each other. In this thesis the fault tree analysis is used to determine the availability under corrective maintenance and under preventive maintenance for 2 weir systems (so 2x2 are 4 results). Using the formula from paragraph 5.2.1 the availability or non-availability of individual components within a fault tree can be calculated. The bottom gate in figure 26 is a Voting OR-gate, which means that the output event occurs if m-out-of-n input events occur. In the example a 2 out of 3 gate is used which signifies that at least two out of three input events have to occur for the output event to occur. Using the formulas from figure 26 the availability of sub-systems, such as “Middle event 1” from figure 25, can be calculated. With these formulas the availability of the top event can be calculated.

The availability of a repaired component depends both on its failure rate and on the repair resources (IEC, 2016). These resources are limited, which results in a dependency between the events. Therefore, events are independent only if the repair resources are unlimited. This assumption can be made when dealing with repairable systems.

6.2.4 Life Cycle Costs

Assets such as roads, bridges, weirs often have a long service life (Van den Boomen, et al., 2018). With long life cycles comes the time value of money in investments and maintenance expenditures. To include the time value of money two LCC techniques are presented: the single payment present worth factor and the equal payment series capital recovery factor.

Single payment present worth factor

The present worth factor (P/F,r,t) transforms a future value F to its present value P.

$$(P/F,r,t) = \frac{1}{(1+r)^t}.$$

The parameters r and t are discount rate and time of occurrence respectively. General inflation is incorporated by using the real discount rate. In general the discount rate should at least cover the long-term average costs of capital.

Capital recovery/annuity factor

The annuity factor (A/P,r,t) transforms a present value into equivalent annual costs (EAC).

$$(A/P,r,t) = \frac{r(1+r)^t}{(1+r)^t - 1}.$$

The expression (A/P,r,t) reads as: find A (EAC) given present value P, discount rate r and number of time units t. In the case that for each life cycle identical replacements take place with identical life cycle costs, the EAC of one life cycle is the same EAC of an infinite number of replacement cycles.

Implementation

The costs for weirs are categorised as the expected repair costs and the maintenance costs. The expected repair costs are the costs related to weir components failing.

The expected repair costs can be determined by multiplying the failure rate of each weir component with its respective repair cost. The failure rates are taken per year resulting in annual expected repair costs.

A weir structure has a life span of 100 years. So cash flows of preventive maintenance activities are projected on a timeline of 100 years and discounted to their present values. This present value is transformed to Equivalent Annual Costs over the life cycle of 100 years.

6.3 Example case

For this example two fictitious overly simplified weir alternatives are made up. The first weir alternative has 3 gates and the second weir alternative has 4 gates (see figure 27). The specific design of the weirs is not of importance, since the example case is only used to illustrate the research steps. Both are assumed to have a life span of 100 years.

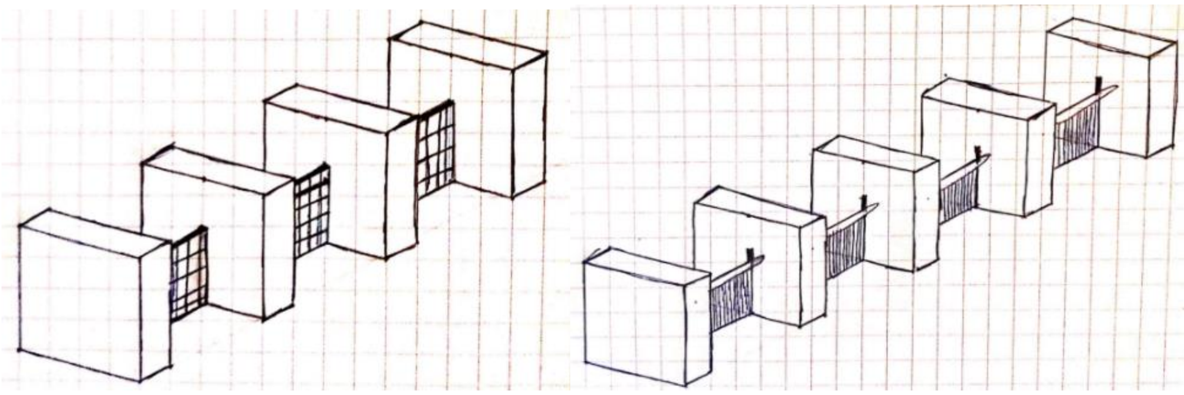


Figure 27: Weir 1 (left side) and weir 2 (right side) example case

In paragraph 2.1 the weir functions were introduced. In this example only the water level controlling function is taken into account. Some of the research steps are skipped to keep this example case simple. The steps that are skipped are the functional analysis, determining the failure requirements, and the process to determine the top undesired event for each function. The top undesired events will instead be assumed.

For the water level control function the following top undesired event (TUE) is chosen: "*At least one weir opening cannot be adjusted."*. The top undesired event holds for both weir alternatives.

For this simple example case, for both weirs the components are limited to:

- the gates,
- the power supply (which includes electrical installations).

The fault trees for the top undesired event of each weir alternative are shown in figures 28 and 29. In figures 28 and 29 the failure rate of the middle events "Failure individual gates" is not calculated, because the non-availability of this event can be calculated from the non-availability of events "Failure gate i", where i = 1,2,3,(4).

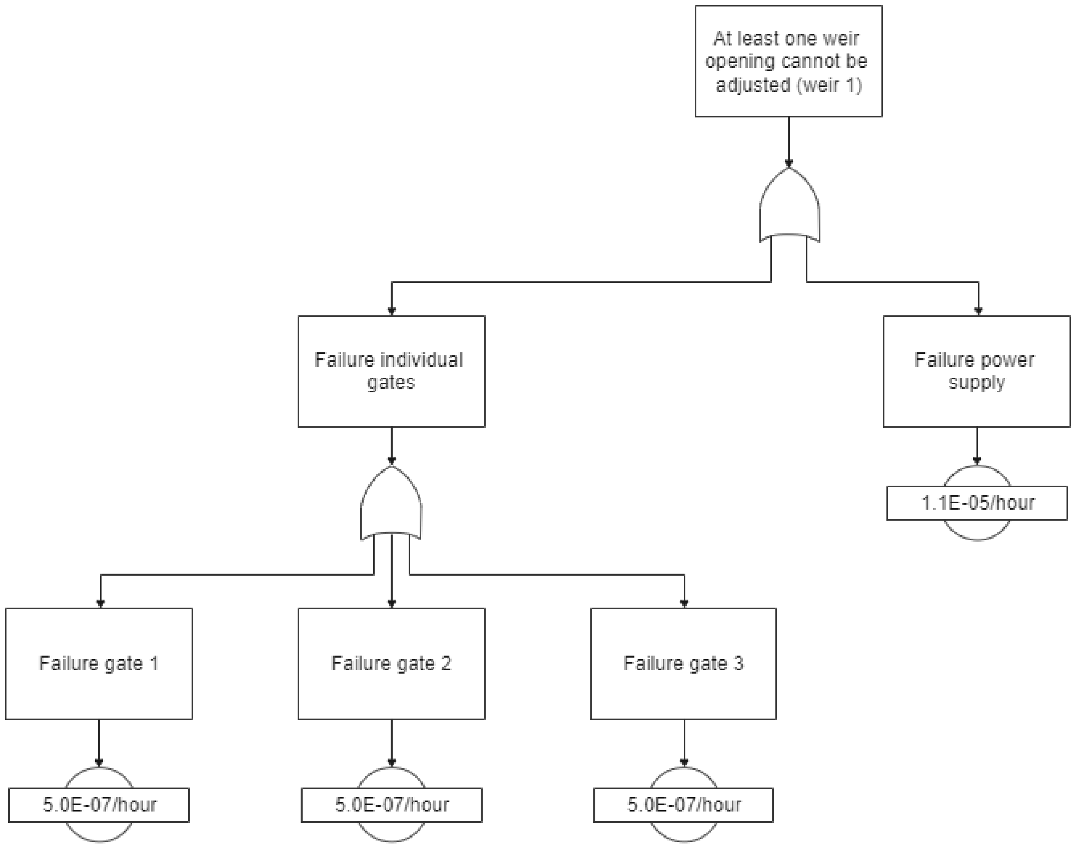


Figure 28: Fault tree weir alternative 1 (example case)

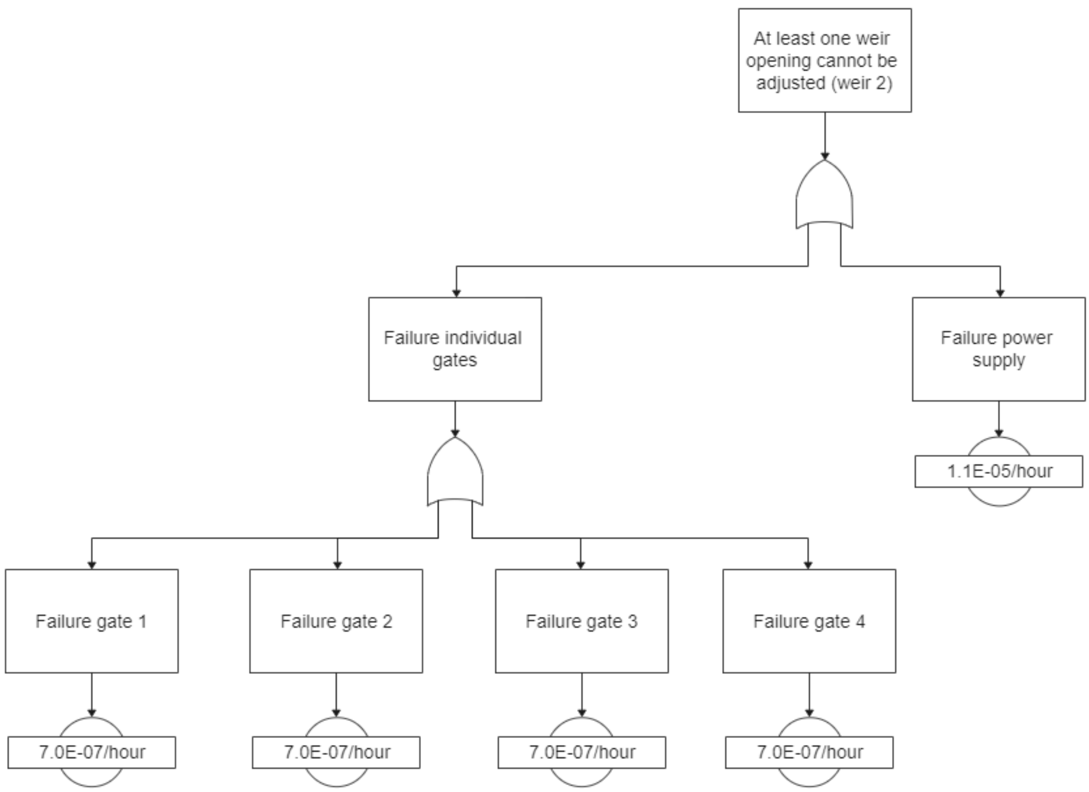


Figure 29: Fault tree weir alternative 2 (example case)

The fault trees of each weir is made up of the following three failure events:

- Failure of the gates: The gates include both the driving mechanism (electromechanical or hydraulic) and the steel structure itself. The driving components allow the weir gates to open and close. The failure rate of gates is mostly dependent on the failure rate of the driving mechanism, since that part has a much larger failure rate than the steel structure. A failure rate per hour was assumed for each weir alternative based on the rate at which control gates cannot be opened. The values presented in the fault trees are around the same order of magnitude as the rate at which control flap gates cannot be opened from the Rijkswaterstaat database (Rijkswaterstaat, 2016).
- Failure power supply: The power supply with electrical installations powers the movement works and allows it to operate. A failure rate per hour was assumed for each weir alternative based on the failure rate for an electrical motor. The values presented in the fault trees are around the same order of magnitude as the failure rate from the Rijkswaterstaat database (Rijkswaterstaat, 2016).

The failure rates for the preventive maintenance strategy

Even under a preventive maintenance strategy, a weir can still fail unexpectedly. The failure rates presented in the fault trees are associated with a moderate maintenance plan, which is the current maintenance plan of the weir in Lith (Nebest, 2010). The maintenance interval for the individual gates and power supply are presented in table 6. The failure rates under preventive maintenance are presented in table 7.

Table 6: Preventive maintenance plan (example case)

Failure events	**Maintenance interval [years]**
Failure gate i (1,2,3)	25
Failure power supply	10

Table 7: Input failure rates preventive maintenance (example case)

Failure events	**Failure rate weir 1 [1/hour]**	**Failure rate weir 2 [1/hour]**
Failure gate i (1,2,3)	5.0E-07	7.0E-07
Failure power supply	1.1E-05	1.1E-05

The failure rates for the corrective maintenance strategy

Under corrective maintenance a structure is only repaired after failure has occurred. This means that there are no maintenance plans to conserve components or inspections. In this case components under corrective maintenance would fail more often than the components of a weir under preventive maintenance. The failure rates for components under a corrective maintenance strategy are assumed to be equal to the maintenance frequency of those components under preventive maintenance.

Table 8: Input failure rates corrective maintenance (example case)

Failure events	**Failure rate weir 1 [1/hour]**	**Failure rate weir 2 [1/hour]**
Failure gate i (1,2,3)	4.5E-06	4.5E-06
Failure power supply	1.1E-05	1.1E-05

Availability under corrective maintenance

The steady-state availability under corrective maintenance can be determined using the following formula:

$$A = \frac{MTTF}{MTTR + MTTF}.$$

Where MTTF stands for the mean time to failure and MTTR stands for the mean time to repair. The mean time to repair and mean time to failure of each failure event from the fault trees is presented in the table below. The time to repair is gathered from RAMS-analysis reports on the current Meuse weirs, while the time to failure is determined using the failure rate of each failure event (MTTF = 1/F).

Table 9: Input values under corrective maintenance (example case)

Failure events	**MTTF weir 1 (hours)**	**MTTF weir 2 (hours)**	**MTTR weir 1 (hours)**	**MTTR weir 2 (hours)**
Failure gate i (1,2,3)	2.22E+06	2.22E+06	2000	1500
Failure power supply	9.09E+04	9.09E+04	10	10

Firstly the non-availability for each basic failure event in a fault tree is calculated (basic failure events are the failure of gates, and failure power supply):

$$NA_i = 1 - A_i = 1 - \frac{MTTF_i}{MTTR_i + MTTF_i}.$$

With the fault trees, input values from table 9, and the formula above the non-availability for each top undesired event can be determined, which in turn gives the availability of the weir for each top undesired event.

Weir alternative 1

The non-availability of weir alternative 1 for the TUE under corrective maintenance is calculated using the following formula:

$$NA_{TUE\ weir\ 1} = 1 - \left(\left(1 - NA_{gate\ 1}\right) * \left(1 - NA_{gate\ 2}\right) * \left(1 - NA_{gate\ 3}\right)\right) * \left(1 - NA_{power\ supply}\right).$$

The results are shown in figure 30.

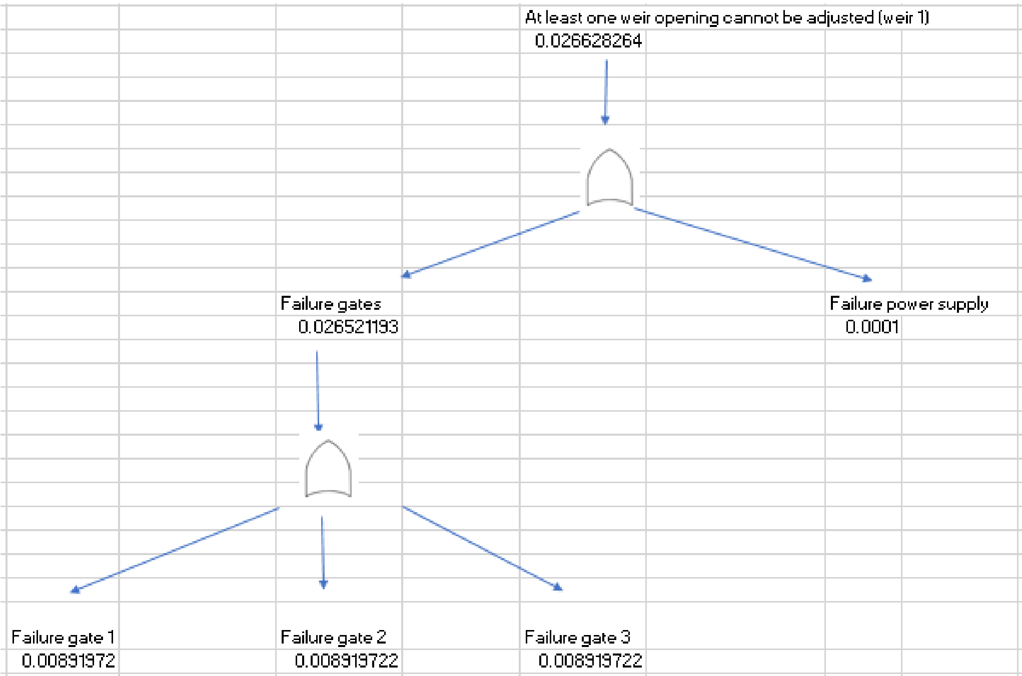


Figure 30: Non-availability calculation TUE weir alternative 1 under corrective maintenance (example case)

Weir alternative 2

The non-availability of weir alternative 2 for the TUE under corrective maintenance is calculated using the following formula:

$$NA_{TUE\ weir\ 2} = 1 - \left(\left(1 - NA_{gate\ 1}\right) * \left(1 - NA_{gate\ 2}\right) * \left(1 - NA_{gate\ 3}\right) * \left(1 - NA_{gate\ 4}\right)\right) * \left(1 - NA_{power\ supply}\right).$$

The results are shown in figure 31.

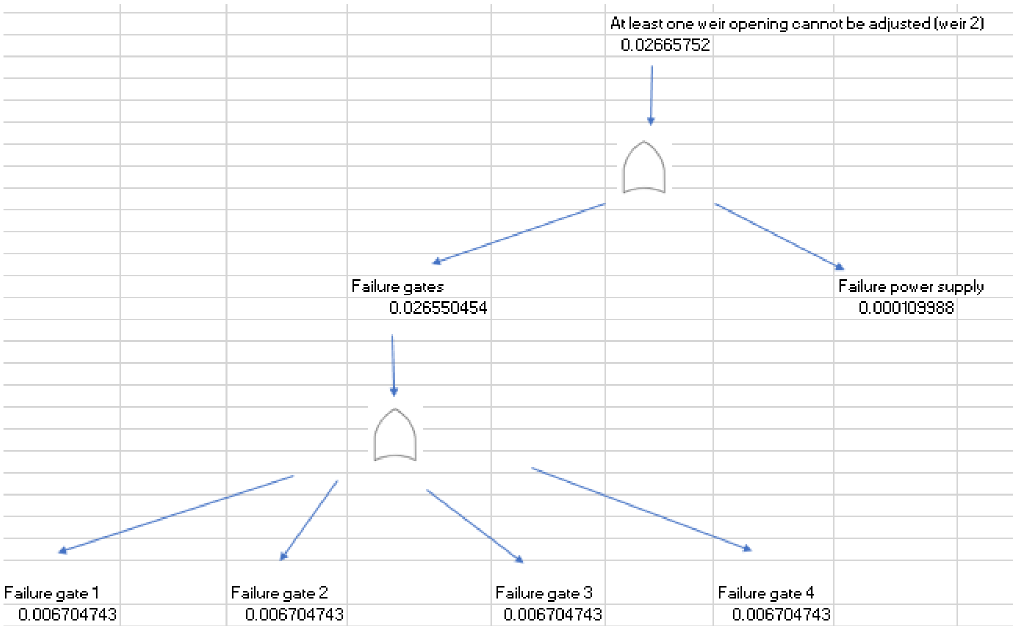


Figure 31: Non-availability calculation TUE weir alternative 2 under corrective maintenance (example case)

Availability under preventive maintenance

Even under preventive maintenance failure can occur. The same formulas as shown above are used to determine the availability under preventive maintenance. The only difference is that the failure rates of components under preventive maintenance are smaller. In the case of unexpected failure under both preventive and corrective maintenance, one is not prepared, so the repair times are the same under both maintenance strategies.

Table 10: Input values under preventive maintenance (example case)

Failure events	MTTF weir 1 (hours)	MTTF weir 2 (hours)	MTTR weir 1 (hours)	MTTR weir 2 (hours)
Failure gate i (1,2,3)	2.0E+06	1.43E+06	2000	1500
Failure power supply	9.09E+04	9.09E+04	10	10

Only the results will be shown since the calculations are the same as in the case for the availability under corrective maintenance.

Weir alternative 1

The non-availability of weir alternative 1 for the TUE under preventive maintenance is presented in figure 32.

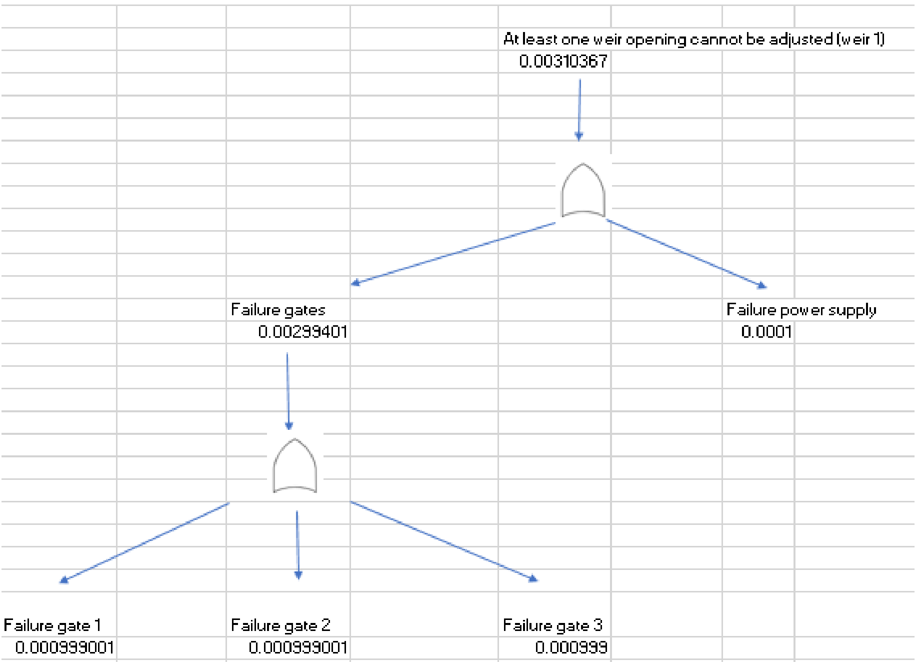


Figure 32: Non-availability calculation TUE weir alternative 1 under preventive maintenance (example case)

Weir alternative 2

The non-availability of weir alternative 2 for the TUE under preventive maintenance is presented in figure 33.

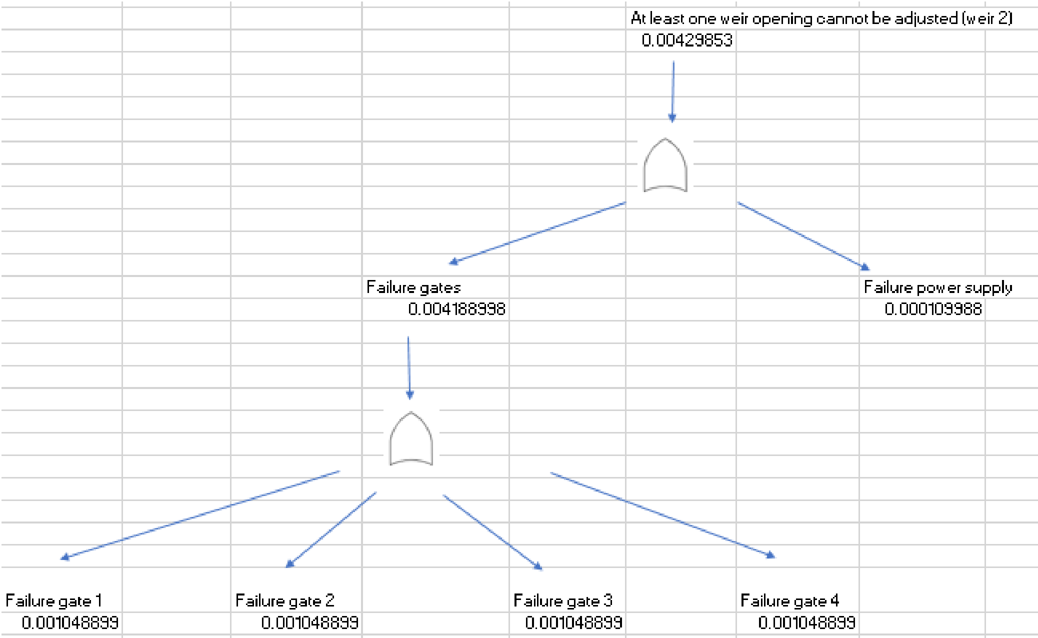


Figure 33: Non-availability calculation TUE weir alternative 2 under preventive maintenance (example case)

Table 11 summarises the results from the non-availability calculations and presents the results in availability. This is done by taking the inverse of the non-availability for each top undesired event.

Table 11: List of the availability under both maintenance strategies for both weirs

	Weir 1	Weir 2
Corrective	0.9734	0.9733
Preventive	0.9969	0.9957

Expected repair costs under corrective maintenance

Table 12 shows for each weir the expected repair cost due to failure per year. The repair costs per unit are determined from the maintenance costs of the components. In reality repair is always more costly than maintenance. References for repair costs are hard to come by, so an assumption is made that the repair costs are twice as expensive as maintenance costs. The maintenance costs are covered in a later paragraph. To calculate the expected annual repair cost the failure rates are multiplied by 8760 hours (amount of hours in a year). The failure rate is multiplied by the repair cost per unit and the amount of units.

Table 12: Expected repair costs under corrective maintenance example case

	Failure rate weir 1 [1/hour]	Failure rate weir 2 [1/hour]	Repair cost per unit [€]	Units weir 1	Units weir 2	Expected repair costs weir 1 [€/year]	Expected repair costs weir 2 [€/year]
Gates	4.50E-06	4.50E-06	500,000	3	4	59,130	78,840
Power supply	1.10E-05	1.10E-05	20,000	1	1	1,927	1,927
Total						61,057	80,767

Expected repair costs under preventive maintenance

The cost due to weir failure per year is presented in table 13.

Table 13: Expected repair costs under preventive maintenance example case

	Failure rate weir 1 [1/hour]	Failure rate weir 2 [1/hour]	Repair cost per unit [€]	Units weir 1	Units weir 2	Expected repair costs weir 1 [€/year]	Expected repair costs weir 2 [€/year]
Gates	5.00E-07	7.00E-07	500,000	3	4	6,570	12,264
Power supply	1.10E-05	1.10E-05	20,000	1	1	1,927	1,927
Total						8,497	14,191

Equivalent annual preventive maintenance cost

There is a time element that needs to be taken into account when determining the costs due to maintenance. Since maintenance is performed in certain intervals and these intervals can be several years as indicated by table 14. The effect of time on the value of costs have to be included using the present worth factor and the annuity factor to determine an equivalent cost per year. The present worth factor is calculated for each time a weir component is maintained, for example for the movement works it is every 25 years which halts at 100 years since that is the structures lifespan. Each present worth factor is multiplied by the current cost of maintenance and those results are summed up to be the present value of maintenance. The present value is multiplied with the annuity factor to determine a equivalent cost per year. The calculations can be found in appendix C. The discount rate is assumed to be 1.60% (Rijkswaterstaat, 2020d).

The maintenance cost is based on the maintenance plan of the weir in Lith (Nebest, 2010). The maintenance cost for a gate is based on the maintenance cost of one of the gates in Lith (the cost does not include the maintenance cost of the movement works). The maintenance cost of the power supply is based on the maintenance cost of an electrical motor from the weir in Sambeek (Rijkswaterstaat, 2014). The reason for using the cost of the electrical motor is because the failure rate for the power supply is based on the failure rate of an electrical motor.

Table 14: Equivalent annual preventive maintenance cost example case

	Maintenance cost per unit [€/unit]	Units weir 1	Units weir 2	Maintenance interval [year]	Equivalent annual cost weir 1 [€/year]	Equivalent annual cost weir 2 [€/year]
Gates	250,000	3	4	25	24,635	32,846
Power supply	10,000	1	1	10	930	930
Total					25,565	33,776

Results

In figure 34 the availability under corrective and preventive maintenance are illustrated for both weirs. There is not much difference in availability between the weirs, but there is a significant difference in availability between the two maintenance strategies.

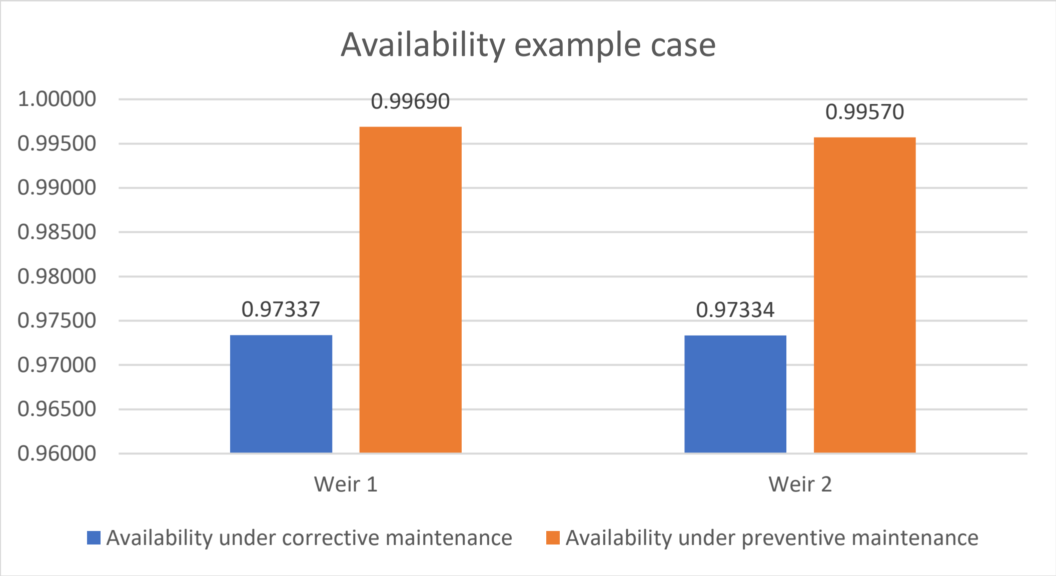


Figure 34: Availability results example case

Figure 35 illustrates the costs for both weirs under both maintenance strategies. The grey bar is the equivalent annual maintenance cost under preventive maintenance and the orange bar is the expected repair cost under preventive maintenance. Since even under preventive maintenance components can still fail. The bars are stacked on top of each other, because both represent annual costs and can be compared to the costs under corrective maintenance, which is represented by the blue bar. The blue bar is the expected annual repair cost under corrective maintenance. There are no maintenance cost under corrective maintenance, because under corrective maintenance preventive maintenance is not performed, only repairs after components fail.

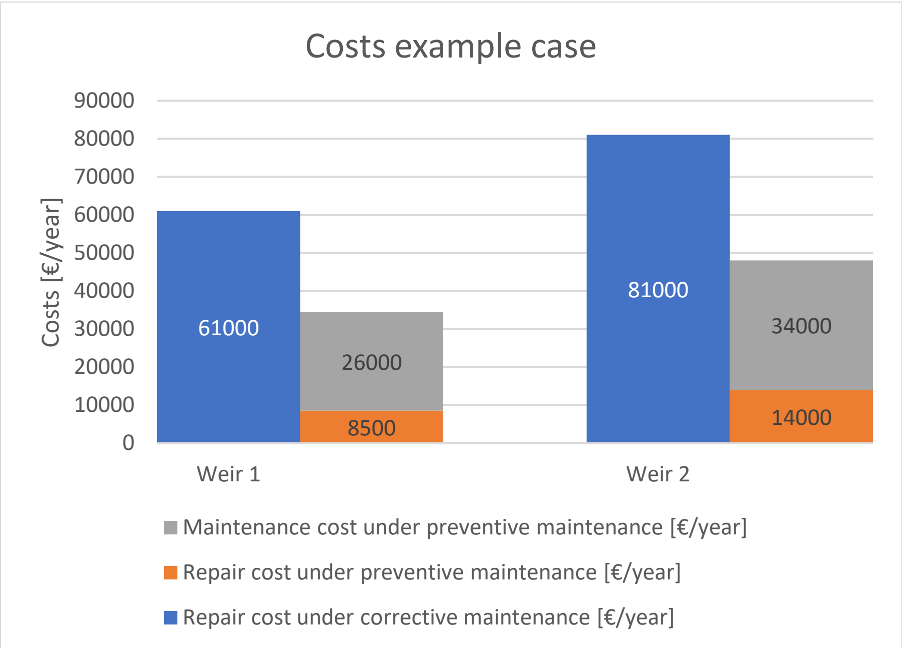


Figure 35: Costs results example case

From both the availability (figure 34) and the costs (figure 35) it can be concluded that a preventive maintenance strategy is superior to a corrective maintenance strategy. The power supply does not have much influence on the availability or costs of the weir, the difference in availability and costs between preventive maintenance and corrective maintenance is attributed to the gates. The top undesired event for both weir alternatives is repeated for ease of reading: "*At least one weir opening cannot be adjusted."*. However in this small scale calculation components and external events (such as ship collision) are left out. The results might differ if more components and failure mechanisms are taken into account.

7 Physical decomposition weir cases

In chapter 4 two weir designs are mentioned which were proposed in a design study report for the replacement of the current weir in Grave (Rijkswaterstaat, 2021b). The two designs are distinguished from each other by their gate types, the first design has lift gates and the second design has radial gates. The gates, the concrete structure and the movement works combined is defined as a module. The first weir module is a design with lift gates and tall lifting towers. The second weir module is a design with radial gates and short piers. As mentioned in the research methodology the first steps for the analysis are to perform a physical decomposition and a functional analysis. In this chapter the physical decomposition of the two weir modules is presented in the paragraphs 7.1 (the first module) and 7.2 (the second module).

7.1 Alternative 1: The lift gate module

This alternative consists of two passages each 50 meters wide. This allows for the passage of vessels with a CEMT-class of Vb.

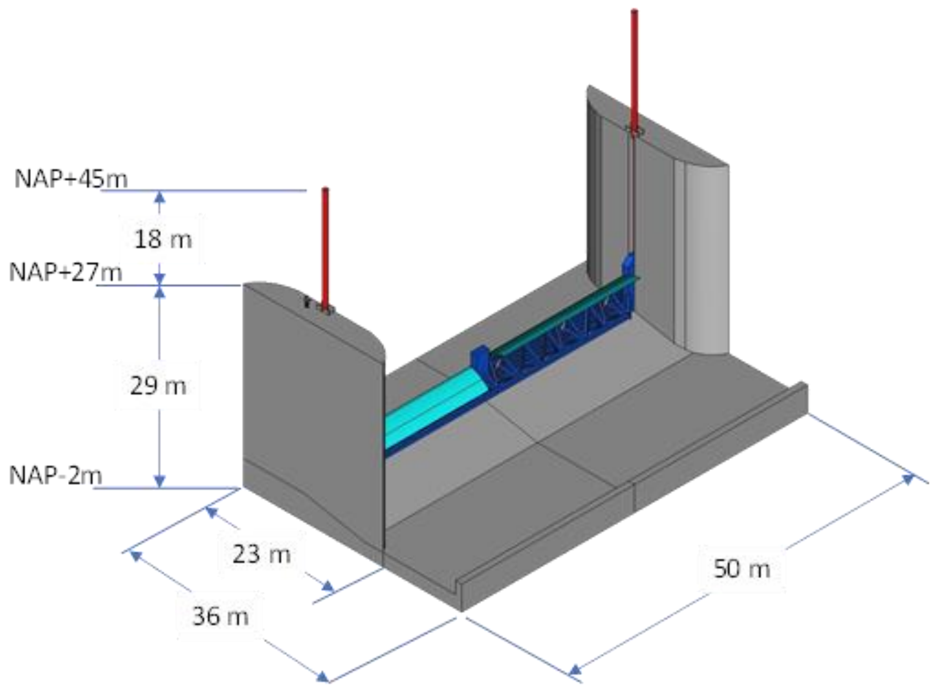


Figure 36: 3D Sketch lift gate alternative (Rijkswaterstaat, 2021b)

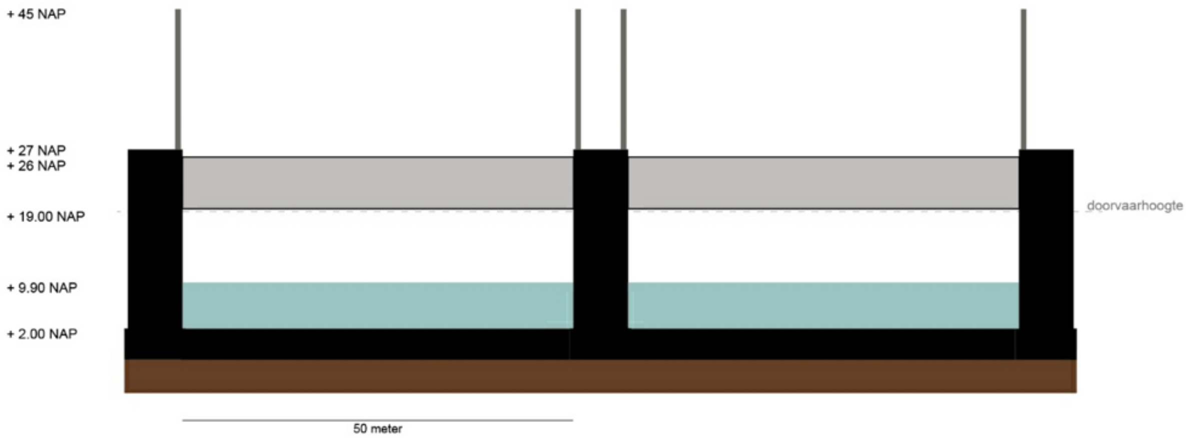


Figure 37: Front view lift gate alternative (Rijkswaterstaat, 2021b)

Lift gates

A side view sketch of the lift gate is shown in figure 38. The lift gate consists of a headgate (the part that retains most of the river water) and control flap gates (this part of the lift gate regulates the upstream water level).

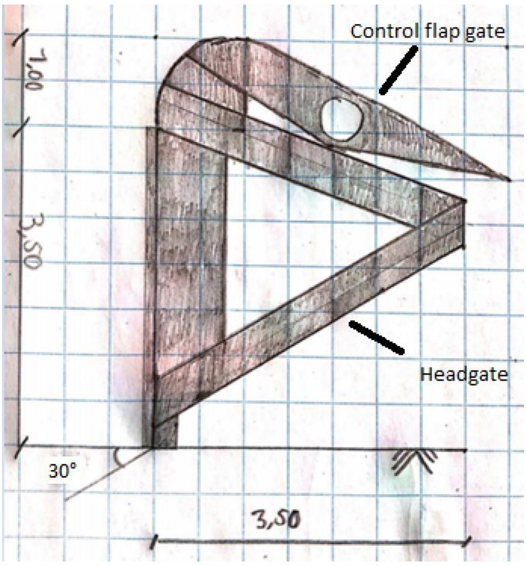


Figure 38: Side view of the lift gate [m]

Headgate

The headgate of the lift gate module is presented in figures 39 and 40. For each passageway there is one headgate, so two headgates in total. Each headgate consists of a skin plate with a 20 mm thickness, T-shaped plate stiffeners, and a truss construction with a triangular shape. Every component of the gate has a steel class of S355. The gate is 50 meters long, the height is 4.5 m and the width is 3.5 m. Hydraulic cylinders are used for the movement works of the headgates. Each headgate utilises two hydraulic cylinders.

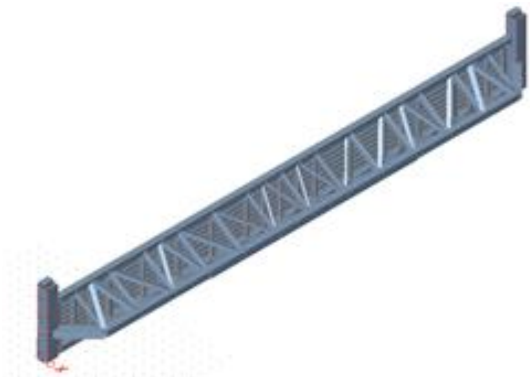


Figure 39: The headgate (Rijkswaterstaat, 2021b)

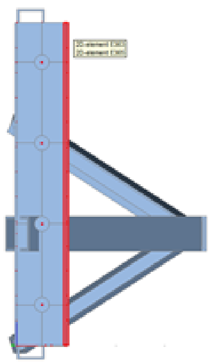


Figure 40: Side view of the headgate (Rijkswaterstaat, 2021b)

Control flap gate

Each headgate has two control flap gates attached to it through hinged supports. Each control flap gate has three hydraulic cylinders attached to push the flap gate (Rijkswaterstaat, 2021b). Three cylinders are chosen to distribute the load more evenly over the construction. The head gates are attached to hydraulic cylinders on each side. The design of the control flap gate is based on the weir in Lith (figure 41).

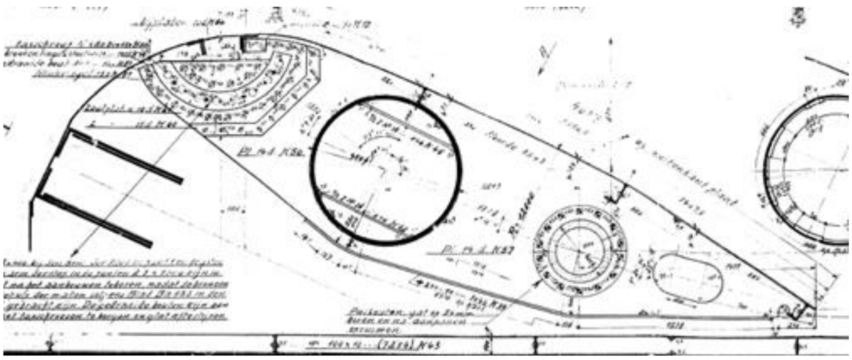


Figure 41: The flap gate weir Lith (Rijkswaterstaat, 2021b)

Concrete piers

The movement works are provided with hydraulic aggregates. A hydraulic aggregate is a pump/motor combination with an oil reservoir. By pumping the hydraulic fluid (oil) under low pressure into one side of the cylinder it can move and exert a large force. One hydraulic aggregate can provide oil for the hydraulic cylinders of both the head gate and control flap gate. Figure 42 is the schematic for the river pier. In which the pump/motor combination is depicted as “pomp”, the oil reservoir is shown and the hydraulic cylinders are the circles next to each gate. One of the benefits of using hydraulic aggregates is that each hydraulic aggregate can be provided with two pumps with their own electrical motor. If either a pump or a motor fails, the hydraulic aggregate is still operational with half the speed.

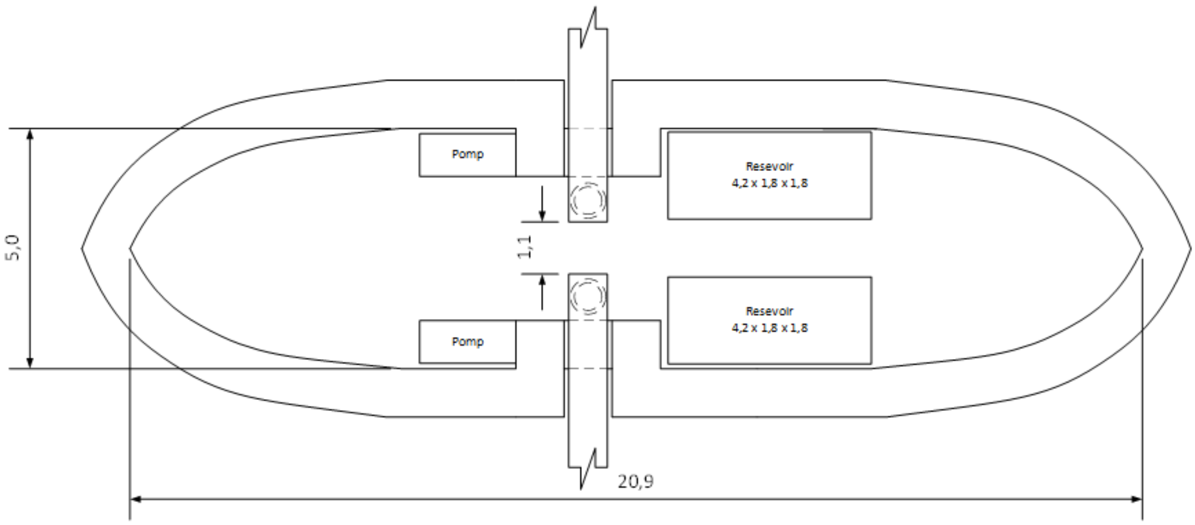


Figure 42: Schematic river pier lift gate module (Rijkswaterstaat, 2021b)

There are three lifting towers or piers in total, two abutments and one river pier. The abutments are similar to the river pier, except for the abutments only supporting one gate. So there is only one hydraulic cylinder for the headgate and one hydraulic aggregate supporting it.

The components of the lift gate module are summarised in the following table 15.

Table 15: Physical decomposition of the lift gate module

Components	Description	Total number of units
Lift gates	There are two lift gates, each lift gate consists of a headgate and two control flap gates	2
Headgates	There are two headgates, see figure 43	2
Control flap gates	Two control flap gates are attached to each headgate, see figure 42	4
Hydraulic cylinders	Each headgate uses two hydraulic cylinders and each control flap gate uses three hydraulic cylinders	16
Concrete lifting towers/piers	There are three piers, two abutments and one river side pier	3
Hydraulic aggregates	The river pier has two hydraulic aggregates and the abutments use one hydraulic aggregate	4
Electromotor and pumps	Each hydraulic aggregate uses two sets of electromotors and pumps	8
Power supply	The main power supply is connected to the power grid. If the power grid shuts down an emergency power supply takes over	1

7.2 Alternative 2: The radial gate module

This alternative is supposed to only fulfill the functions of water level control, water retention and the discharge of water function, and not allow for ship passage. This means that the weir can have four passages each 25 meters wide. The navigation lock has to be used at all times for ship passage.

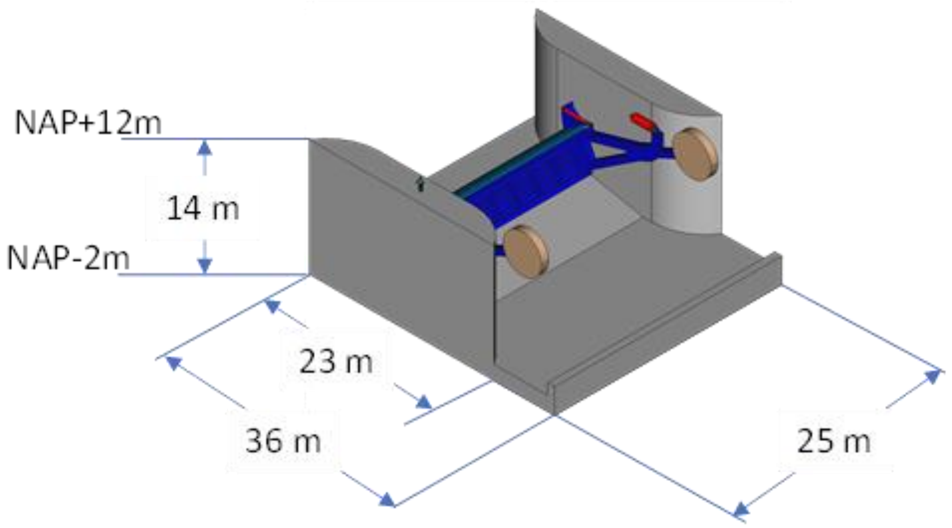


Figure 43: 3D Sketch radial gate alternative (Rijkswaterstaat, 2021b)

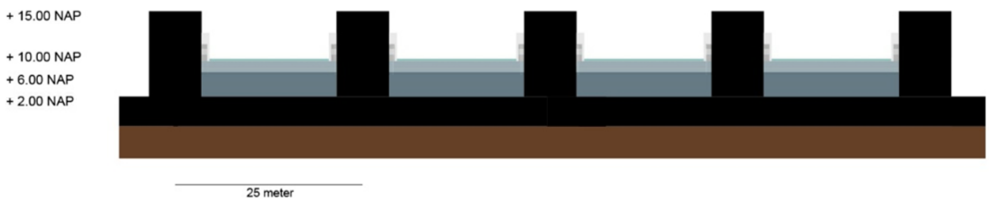


Figure 44: Front view radial gate alternative (Rijkswaterstaat, 2021b)

This alternative has a radial gate shape with a stiffened skinplate with a thickness of 16 mm, and two arms on each gate end. Just like the first module this gate variant also consists fo a headgate (the radial gate) and a control flap gate for each headgate. The control flap gates are the same as the ones for the lift gate module. All components of the gate have a steel class of S355. The total length of the gate is 25 m, the height is 4.5 m . The radius of the gate is 13 meters and the pivot point is located at a height of 10 m + NAP. The weir sill is at a height of 2 m + NAP, the top of the weir gate is at 6.5 m + NAP.

The radial gate module has 4 headgates. Each radial gate consists of two hydraulic cylinders. A control flap gate is attached to each radial gate through hinged supports. Two hydraulic cylinders are used that pull the flap gate from the sides. This makes it so that the hydraulic cylinders are always above the water surface, except for the case where there is high water. The pier schemes are the same as the ones from the lift gate module.

Table 16: Physical decomposition of the radial gate module

Components	Description	Total number of units
Radial gates	There are four radial gates, each radial gate consists of a headgate and a control flap gates	4
Headgates	There are two headgates, see figure 43	4
Control flap gates	One control flap gates are attached to each headgate, see figure 44	4
Hydraulic cylinders	Each headgate uses two hydraulic cylinders and each control flap gate uses two hydraulic cylinders	16
Concrete piers	There are five piers, two abutments and three river side piers	5
Hydraulic aggregates	The river pier has two hydraulic aggregates and the abutments use one hydraulic aggregate	8
Electromotor and pumps	Each hydraulic aggregate uses two sets of electromotors and pumps	16
Power supply	The main power supply is connected to the power grid. If the power grid shuts down an emergency power supply takes over	1

7.3 Conclusion

As mentioned in the research methodology the first steps of the analysis is to perform a physical decomposition and functional analysis. This chapter expanded on the design of the two weir alternatives that are used for the case study. A physical decomposition of the alternatives resulted in tables 15 and 16 which summarise the components of each alternative. The components are used to determine the failure mechanisms for the fault tree analyses. To determine the top events of the fault trees in chapter 9 the functional analysis is done in the next chapter.

8 Functional analysis

This chapter covers the functional analysis to determine the top undesired events used in the fault trees of chapter 9. The main weir function is to control the upstream water level. This function is divided into two sub-functions, the retention of water and discharge of water. The sub-functions are described as follows (Rijkswaterstaat, 2021b):

- *Retention of water:* the upstream water has to be retained to allow the upstream water level to rise to reach a sufficient water depth. The location where the required minimum water depth has to be maintained is usually located at the upstream begin of the river reach controlled by the weir.
- *Discharge of water:* to allow sufficient opening for river water to flow downstream. Without any transport of water from the upstream to downstream river reach, the water level upstream would rise beyond the desired constant water level and beyond acceptable flood safety levels for the polders or land along the river.

In times of (extreme) drought the weir could be kept completely closed to secure water intake upstream. In the case of river floods, high water the weir has to be opened up.

There is also a secondary function for weirs. During high water a weir can also allow vessels to pass through the weir openings (Rijkswaterstaat, 2021b):

- *Ship passage:* the weir allows vessels to pass through the weir openings during high water. Locks already provide a passage for vessels and with weirs also providing a passage during high water it reduces shipping blocks.

The functional analysis comes from a design report for the next weir in Grave by (Rijkswaterstaat, 2021b).

8.1 Retention of water

8.1.1 Water retention

To establish a minimum water depth upstream the weir must retain water. The current retained water level by the weir in Grave is 7.91 m + NAP at Mook (Rijkswaterstaat, 2021b). This water level should be sustained as long as possible. However the water level at Grave must not drop down below 7.25 m + NAP. The current weirs sill is at a height of 2.7 m + NAP. This can be lowered to 2 m + NAP, and with a sill thickness of 1.5 m the retention height is about 6.0 m. This height should be sufficient for ship passage, which will be discussed in paragraph 8.3.

8.1.2 Water depth

The minimum water depth for each class is 1.4 times the draught of the maximum allowable vessel class, the allowable vessel class is discussed in paragraph 8.3 ship passage (Rijkswaterstaat, 2021b). In this case the draught is 3.5 m, so the minimum water depth should be 4.90 m. The height suggested in the previous paragraph on the water retention function of 6.5 meter is sufficient.

8.2 Discharge of water

In the previous section the water retaining function of weirs has been discussed. In the case of high water discharges in the river Meuse, water retention will raise water levels and could potentially lead to floods upstream. To prevent this weirs should allow the river to flow downstream. If the water level at the upstream part of Grave reaches 8.60 m + NAP the weir should be opened up completely (Rijkswaterstaat, 2021b).

8.3 Ship passage

In case of high river discharges weirs have to be opened up. In some cases weirs that are opened also allow vessels to pass through.

Since weirs allow for a certain minimum water depth upstream for shipping, the water level downstream and upstream of the weir differ. To bridge this gap weirs are accompanied by sluices or navigation locks. These structures consist of an enclosed chamber in a waterway used to transport vessels from one to another water level (TU Delft, 2020a). Under normal circumstances weirs do not allow for ship passage, however in the case of high river discharges the weirs are opened allowing vessels to pass through.

To this end the dimensions for the weir have to be designed such that all vessels that sail through the river Meuse can also pass the weir. The CEMT class for the river Meuse is Va (figure 45). However the Meuse route will be upgraded to a CEMT class of Vb. In large sections of the Meuse river the draught is 3.5 m. There are some locations where dredging needs to take place to fulfill the draught requirement. There are four aspects that have to be checked for the ship passage. Those are the water depth, vertical clearance, horizontal clearance and location of the weir. These are determined using the guidelines for waterways from Rijkswaterstaat.

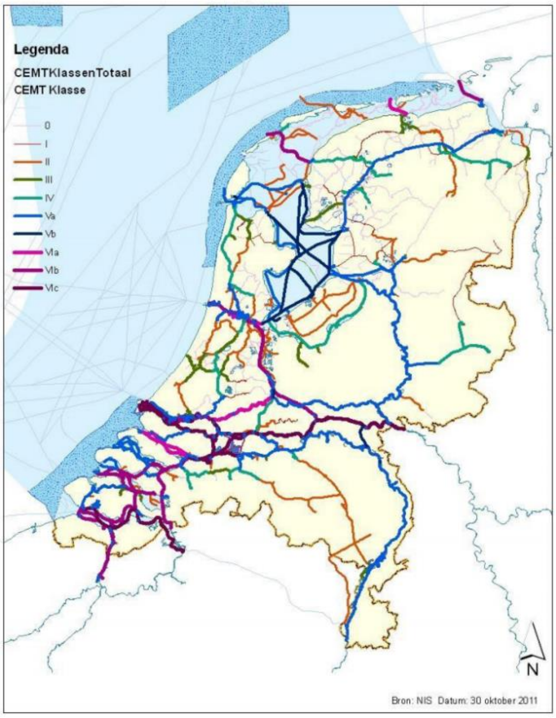


Figure 45: All Dutch waterways with CEMT classes (Rijkswaterstaat, 2013)

8.3.1 Horizontal clearance

The total width of the weir will be about 120 m, for this width two passage openings is appropriate. The minimum width of each passage opening will be calculated according to the guidelines for navigation locks. For class Vb waterways a minimum passage width of 2.0 B is prescribed, in which B is the maximum vessel width (Rijkswaterstaat, 2013). In case there is a cross-current the minimum passage width can be increased by 0.1 B or 0.2 B depending on the current velocity. A minimum passage width of 2.2 B is taken for each opening.

The maximum allowed shipping width in Grave is 15.5 m. So the minimum passage width is calculated to be 2.2 x 15.5 = 34.1 m. For the passage of vessels twice the minimum passage width should be available during high water, one for vessels moving downstream and another one for vessels moving upstream.

B.3.2 Vertical clearance

The weir should have sufficient height for vessels to pass through without complications. The vertical clearance is a minimum passage height taken from the normative high water level. For a class Vb waterway the vertical clearance should be a minimum of 9.10 m. According to (KNMI, 2015) the design high water level is at 9.66 m + NAP. The bottom of the weir gate when opened should be at a height of at least 18.76 m + NAP.

B.3.3 Location weir

For a vessel to sail safely the axis of the weir should align with the axis of the waterway profile. This will give sufficient view for incoming traffic (Rijkswaterstaat, 2017). To allow for sufficient view a weir cannot be situated within a distance of 2*L from a crossing, where L is the length of a class Vb vessel. There has to be a straight section 1.5*L in front of and behind a weir. The length for a class Vb vessel is about 193 m. The straight sections need to have a length of at least 290 meter.

8.4 Functional requirements

The functional analysis has produced functional requirements for the design of the weir. These requirements are listed in table 17.

Table 17: Functional requirements

Functions	Requirement
Retention of water	The weir should be able to maintain a retained water level of at least 7.25 m + NAP at Grave.
Retention of water	To allow for navigation of the design vessel of CEMT-class Vb a minimum water depth of 4.90 m must be ensured.
Discharge of water	The weir must be opened up completely once the upstream water level reaches 8.60 m + NAP. This corresponds with a river discharge of 1800 m^3/s for both weir alternatives.
Ship passage	The weir is designed for vessels of a CEMT-class Vb.
Ship passage	The weir should have a minimum passage width of 34.1 m.
Ship passage	The vertical clearance during a design high water level of 9.66 m + NAP is 9.10 m. The bottom of the weir gate when opened should be at a height of at least 18.76 m + NAP.
Ship passage	The weir must provide an opening for both downstream and upstream moving vessels once the upstream water level reaches 8.60 m + NAP

The two weir alternatives (lift alternative and radial gate alternative) were designed such that the functional requirements are fulfilled. Except for the discharge of water requirement which is not fulfilled by the radial gate alternative.

8.5 Functional failure criteria

The failure criteria are based on the functional requirements from table 18. Some functional requirements are requirements for the design (for example the weir providing a certain minimum passage width). These requirements are not used to determine failure criteria. The failure criteria are used to determine the top unwanted events for each function for each weir alternative.

Table 18: Functional failure criteria

Functions	Criterium
Retention of water	The weir cannot maintain a retained water level of at least 7.25 m + NAP at Grave.
Discharge of water	The weir cannot be opened up completely during high water
Ship passage	The weir cannot provide an opening for both downstream and upstream moving vessels during high water

8.5 Top undesired events

In this paragraph the top undesired events for each weir alternative is determined based on the failure criteria.

Retention of water

The current weir in Grave tries to maintain a water level of 7.91 m + NAP at Mook (which is further upstream). As the river discharge increases, to maintain that water level upstream the slope increases, which decreases the water level at Grave (Rijkswaterstaat, 2021a). For the water retention function the weir should at least maintain a water level of 7.25 m + NAP at Grave. This means that in the extreme event that the river discharge drops to 0 m^3/s the weir should be closed completely. The TUE is: “At least one of the weir openings cannot be closed.”.

Discharge of water

For the function discharge of water function all weir openings must be opened. Which means that the top unwanted event for the discharge of water function for both weirs is: “At least one weir gate fails to open.”

Ship passage

For the ship passage the minimum passage width is 34.1 m (Rijkswaterstaat, 2021a). Twice the minimum passage width is larger than the width of a lift headgate, which spans over 50 m. The TUE is the same as in the case of the discharge of water: that at least one of the weir headgates cannot be opened.

Table 19: Top undesired event for each function (lift gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.L	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.L	At least one of the headgates of the weir fails to open.
Ship passage	TUE 3	At least one of the headgates of the weir fails to open.

The radial gate alternative does not allow for ship passage. So that function is not included.

Table 20: Top undesired event for each function (radial gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.R	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.R	At least one of the headgates of the weir fails to open.

8.6 Conclusion

In this chapter a functional analysis was performed to determine the top undesired events for each weir function and weir alternative. Firstly functional requirements were determined for the weir in Grave based on guidelines. Afterwards the functional requirements were transformed to functional failure criteria, which in turn were used to determine the top undesired events. These top undesired events are used as the top event for the fault trees in the next chapter.

9 Analysis case study

9.1 Availability, scheduled and unexpected downtime

In chapter 2 the weir functions were introduced. For these functions a functional analysis was performed based on the report for the preliminary designs of the next weir in Grave (Rijkswaterstaat, 2021b) to determine the top undesired events. The top undesired events are shown in the tables below and serve as the top events of the fault trees.

Table 21: Top undesired event for each function (lift gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.L	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.L	At least one of the headgates of the weir fails to open.
Ship passage	TUE 3	At least one of the headgates of the weir fails to open.

Table 22: Top undesired event for each function (radial gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.R	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.R	At least one of the headgates of the weir fails to open.

As mentioned in paragraph 7.2 the radial gate alternative was not designed to allow for ship passage. For TUE 1.L and TUE 1.R a key detail is left out because of the short description of the events. If a component needs repairs, for example the headgate. Dewatering structures are placed to temporarily retain water. Technically this would mean that during repairs that flow-through opening is closed, however as long as the weir cannot close the opening by itself it is considered failure.

The top undesired event TUE 2.L and TUE 3 can be described by the same fault tree, because the description of both events are the same. So in total there are 4 unique fault trees (two for the lift gate alternative and two for the radial gate alternative).

In this chapter the broad outlines of the fault trees are presented. For the entire fault trees see appendix D. The calculations to determine the availabilities of the top undesired events were done in Python, the script can be found in appendix F. The non-availabilities that are shown in this chapter corresponds with a preventive maintenance strategy.

9.1.1 Failure water retention, lift gate alternative (TUE 1.L)

The failure of the water retention function for the lift gate alternative is covered in this paragraph, with TUE 1.L as the top event of the fault tree. The water retention function is not fulfilled in the case that “at least one of the flow-through openings of the weir cannot be closed”. Figure 46 shows the fault tree for this undesired event.

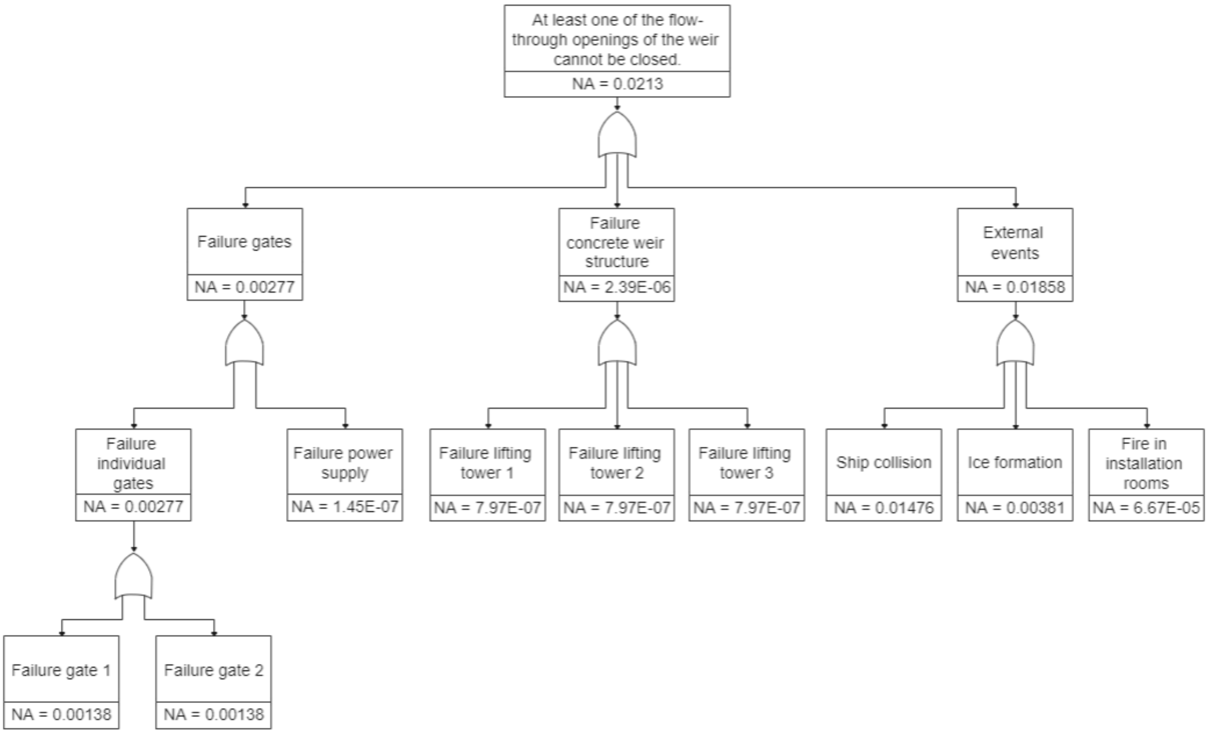


Figure 46: Failure water retention function, lift gate alternative (TUE 1.L)

For the retention of water all gates must work, this includes both the control flap gates and headgates. The lift gate alternative consists of two gates. If either one of the gates fail it will lead to failure of the system. The failure of the power supply is also taken into account, if there is no power none of the gates can be operated. The failure of gates 1 and 2 include the failure of the control flap gates, headgates, their movement works (hydraulic cylinders) and the hydraulic aggregate. If any of these components fail the gate fails.

The structural failure of the weir consists of the failure of the lifting tower structures. The concrete structures are the main load carriers of the weir and facilitate the gates and MEI. Even though they do not serve any specific weir function, they facilitate weir components that serve the weir functions.

There are three external events that are taken into account. Ship collision, ice formation and fire in the installation rooms. A significant ship collision will severely damage the weir gates. Ice formation can also lead to significant damage to weir gates and the weir must be opened up completely. In this case the weir cannot retain water. Fire in the installation rooms can lead to severe damage to the electrical installations. These events can lead to weir gates not being operable or retain water.

9.1.2 Failure discharge of water and ship passage (TUE 2.L and TUE 3)

The difference between the undesired event of the previous paragraph and the undesired event from figure 47 lies in the gates and external events. The ship passage function cannot be fulfilled when at least one of the headgates fails to open. Which means that only the headgate is taken into account and the control flap gate with its movement works is not relevant for this function.

For the external events only the ‘Ship collision’ and ‘Fire in installation rooms’ remain and the ’Ice formation’ failure mechanism is not taken into account, since the ice formation failure function only affects the water retention function.

Figure 47: Failure discharge of water function and ship passage function, lift gate alternative (TUE 2.L and TUE 3)

9.1.3 Retention of water, radial gate alternative TUE 1.R

For the retention of water function of the radial gate alternative the same failure mechanisms from paragraph 9.1 apply. The only difference is that the components for the radial gate alternatives differ from the components of the lift gate alternative, for example the radial gate alternative has four headgates instead of two headgates like the lift gate alternative.

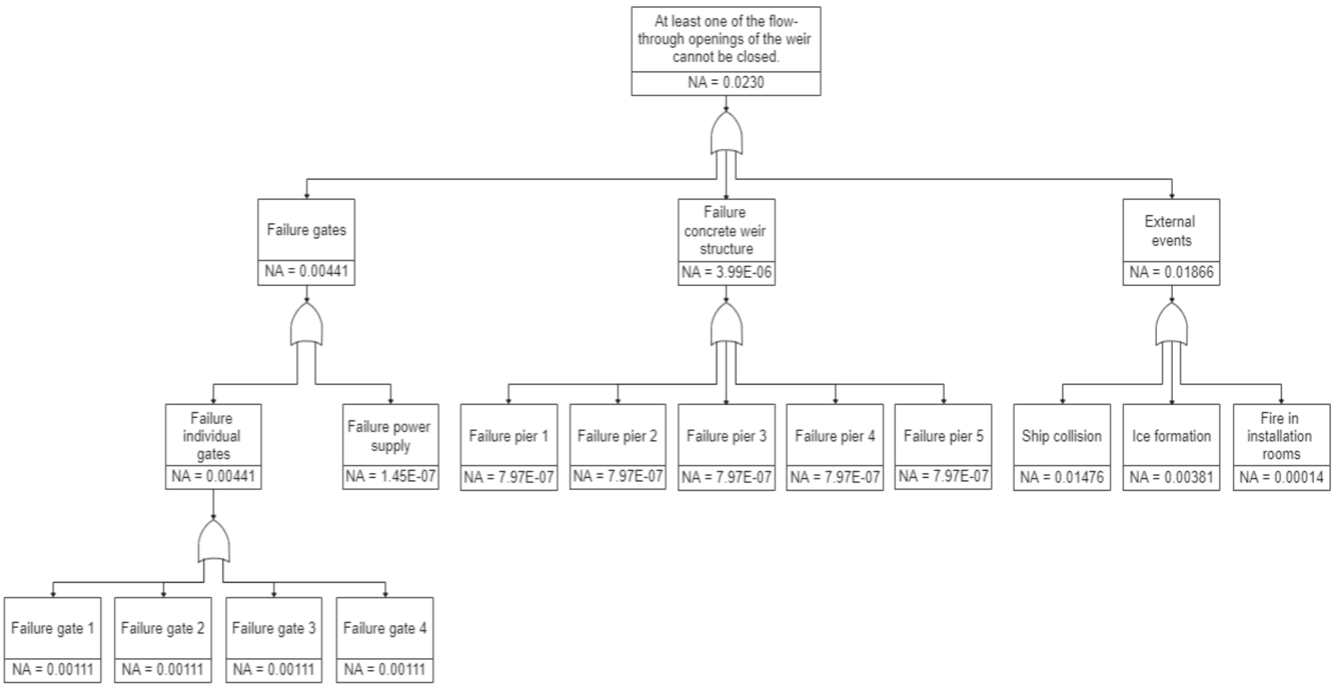


Figure 48: Failure water retention function, radial gate alternative (TUE 1.R)

9.1.4 Discharge of water, radial gate alternative TUE 2.R

For the discharge of water function of the radial gate alternative the same failure mechanisms from paragraph 9.1.3 apply. The only difference is that the components for the radial gate alternatives differ from the components of the lift gate alternative.

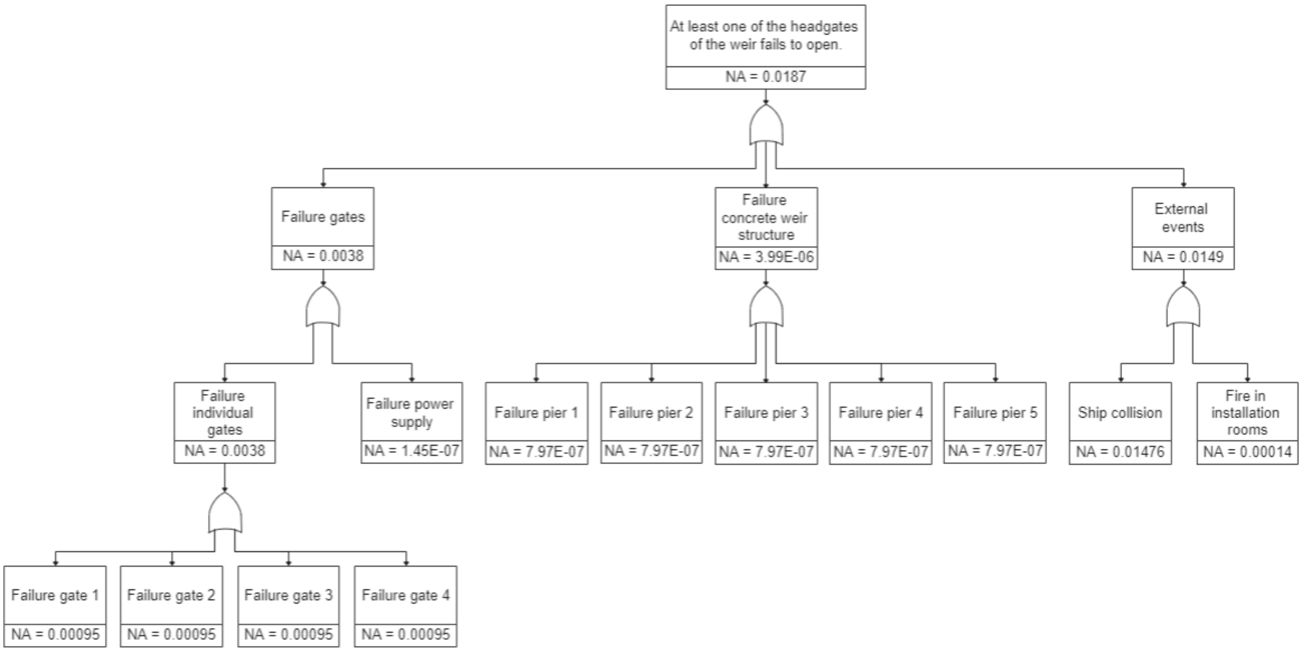


Figure 49: Failure discharge of water function, radial gate alternative (TUE 2.R)

9.1.5 Results

The input values for the calculations, and the calculations for the results below can be found in appendix E and G respectively. The top undesired events are repeated in this chapter for ease of reading.

Table 23: Top undesired event for each function (lift gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.L	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.L	At least one of the headgates of the weir fails to open.
Ship passage	TUE 3	At least one of the headgates of the weir fails to open.

Table 24: Top undesired event for each function (radial gate alternative)

Functions	I.D.	TUE
Retention of water	TUE 1.R	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.R	At least one of the headgates of the weir fails to open.

The availability was calculated for both weirs for each top undesired event under both corrective and preventive maintenance. The results are shown in figure 50. As expected the availability for preventive maintenance is higher than the availability under corrective maintenance for both weirs.

The availability for each top undesired event is slightly higher for the lift gate alternative. This can be explained by the radial gate alternative having more headgates and also more hydraulic aggregates than the lift gate alternative. No distinction was made in the failure rates of the headgates and hydraulic aggregates, so more components means more components that can fail.

Another thing to note is that the difference between the first top undesired event and the second top undesired event is larger under corrective maintenance than under preventive maintenance for both weir alternatives. The reasoning behind this is that TUE 1.L/1.R take both the headgates and control flap gates into account, while TUE 2.L/2.R only take the headgates into account. Taking more components into account increases the bandwidth for the availability. A difference in the failure rates for TUE 1.L/1.R results in a larger difference in availability than for TUE 2.L/2.R.

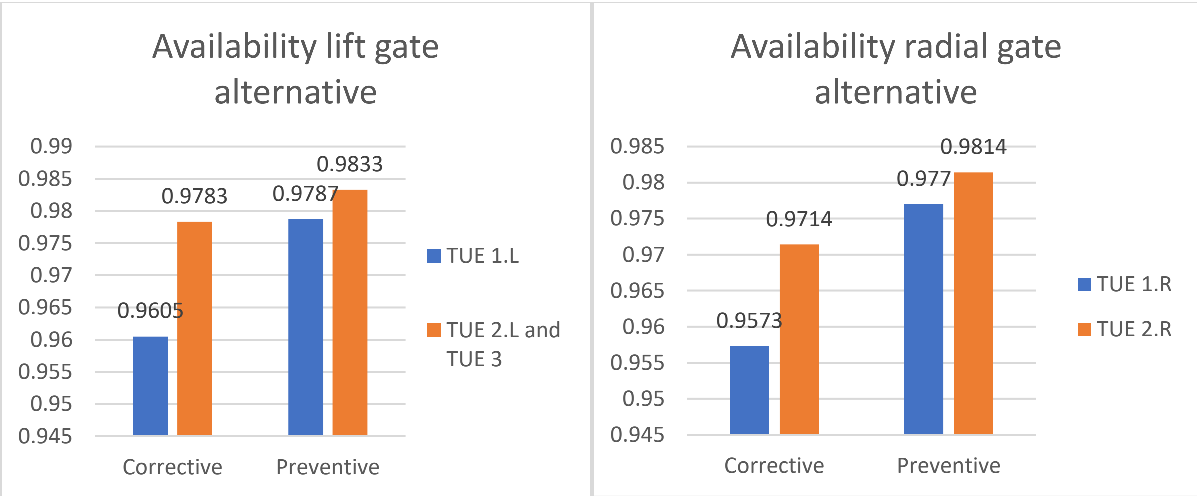


Figure 50: Availability for each top undesired event under each maintenance strategy results lift gate alternative left, radial gate alternative right

Unavailability contributions

The Fussel-Vesely importance factor is a way to measure the impact of a failure event on the probability that a certain top undesired event occurs. The Fussell-Vesely importance factors of the main failure events averaged over the top undesired events of both weir alternatives under preventive maintenance are presented in figures 51 (upper bound ship collision rate) and 51 (lower bound ship collision rate). The upper bound is a ship collision rate of once every 50 years, and the lower bound is a ship collision rate of once every 500 years. The upper bound rate is determined using data from the last 10 years, however a ship collision rate of once every 50 years seemed too frequent. So a lower bound ship collision rate was also determined. For a more elaborate explanation see appendix B. The importance factors were determined by using Isograph's Reliability Workbench software.

Figure 51 shows that the external events (ice formation and ship collision) on average have the largest contribution to the unavailability of the top undesired events. The contributions are 70% and 15% for ice formation and ship collision respectively. The large contribution of the ship collision failure mechanism comes from the combination of a large failure rate (order 10^{-6}) and a large repair time (3/4th of a year).

The other relatively big contributors are the hydraulic aggregate and hydraulic cylinders. Mostly the hydraulic aggregate followed up by the movement works (hydraulic cylinders). These components have relatively high failure rates compared to the concrete weir structure and the steel weir structure. The "other" events are the failure of the power supply, steel weir structure and concrete weir structure. The steel and concrete components have small failure rates (in the order of 10^{-10} – 10^{-8}). For the power supply the contributions are not actually 0%, but are rounded up to zero.

This is not unexpected as the failure of the power supply was denoted with an 'and-gate' with the power grid shutdown and the failure of the emergency power supply. The 'and-gate' gives the subsystem robust since failure of the power supply requires both the power grid to shut down and the emergency power supply to fail. Even though both these failure mechanisms have a relatively high failure rate in the order of 10^{-5}/hour, the MTTR are small (within a day) resulting in a small unavailability.

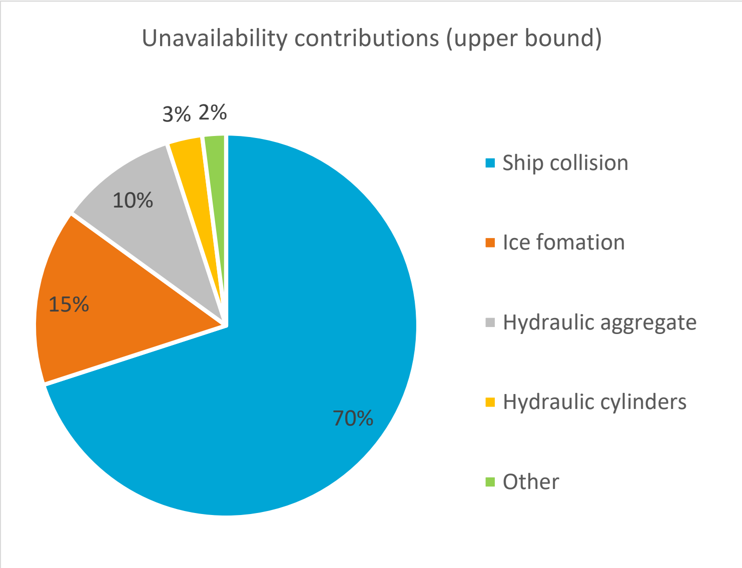


Figure 51: Fussell-Vesely importance factors averaged over the top undesired events of both weir alternatives under preventive maintenance (Ship collision once every 50 years)

From figure 52 it can be seen that even with the lower bound ship collision rate, ship collisions have a large contribution to the total unavailability.

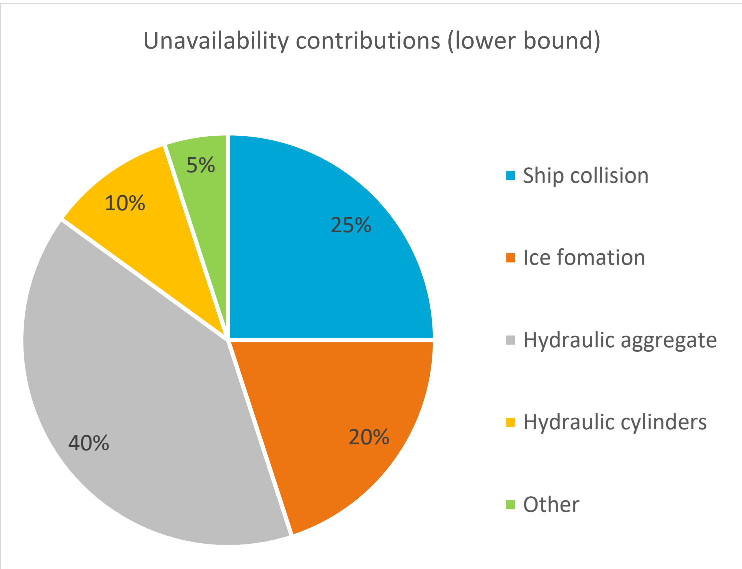


Figure 52: Fussell-Vesely importance factors averaged over the top undesired events of both weir alternatives under preventive maintenance (Ship collision once every 500 years)

Scheduled and unexpected downtime

Figure 53 shows the downtime for both weir alternatives. The planned downtime is based on the total maintenance time over the entire lifetime of the weirs (100 years). The scheduled downtime is determined with the maintenance interval and maintenance time (MT) of each maintainable component (table 25). The origin of the values for the maintenance interval and maintenance time are given in appendix E and the calculations are done in appendix F.

Table 25: Maintenance plan moderate

Maintenance object	**Maintenance measure**	**Interval [years]**	**MT [hours]**
Gates (headgates with control flap gates), radial gate	Conservation gate	15	336
Gates (headgates with control flap gates), lift gate	Conservation gate	15	672
Movement works, radial gate	Replacing hydraulic cylinders of one gate	40	336
Movement works, lift gate	Replacing hydraulic cylinders of one gate	40	504
Piers, lifting towers	Restoring concrete damage to piers and lifting towers	30	168
Hydraulic aggregate	Replacing hydraulic aggregate	25	336

The unexpected downtime is based on the unavailability of each top undesired event over the lifetime of the weirs.

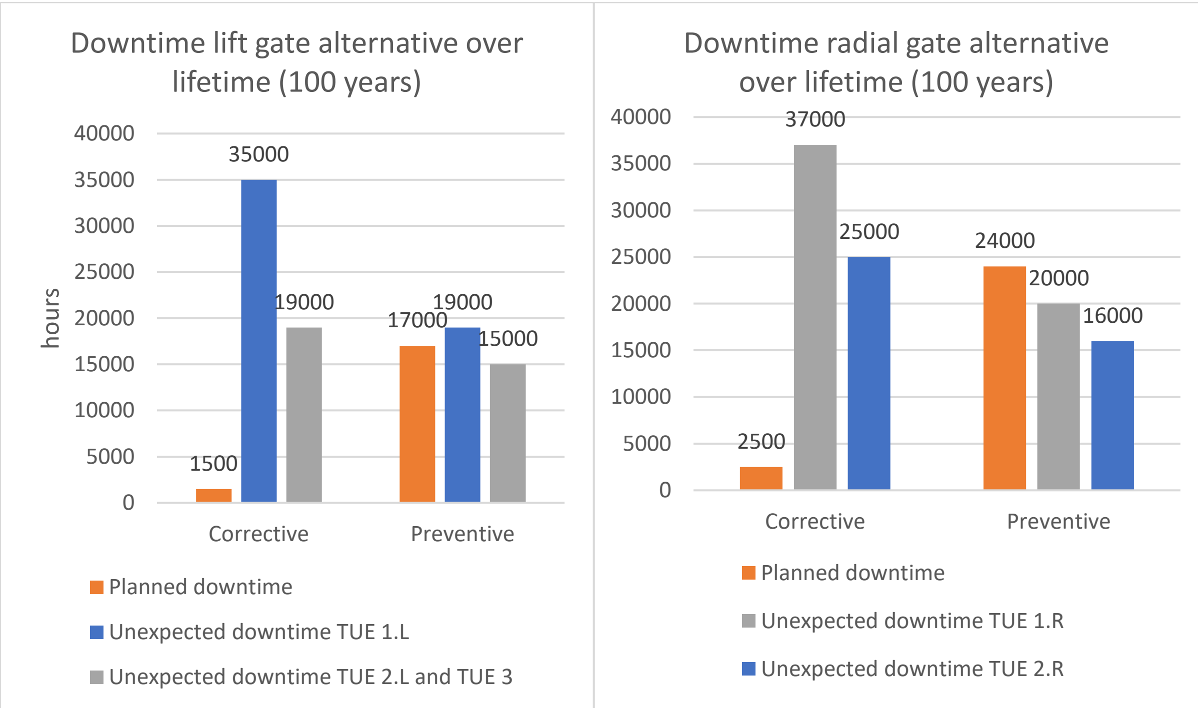


Figure 53: Planned and unexpected downtime results

The difference between the contributions of the lift gate alternative and radial gate alternative is in the maintenance time of the gates and the maintenance time of the hydraulic aggregate (table 26).

The radial gate alternative has more gates, so more hydraulic aggregates than the lift gate alternative. Since the hydraulic aggregates in the river piers have two sets of hydraulic aggregates instead of the maintenance time increasing proportionally to the increase in total piers between the radial and lift alternative (so times 5/3), it has doubled. This explains the larger contribution of the planned downtime for the maintenance of the hydraulic aggregate.

For the contribution of the planned downtime for the maintenance of the gates there is a difference between the lift gate alternative and radial gate alternative. The radial gate alternative has more gates than the lift gate alternative, however the lift gate alternative has larger gates, so the maintenance of a single gate of the lift gate alternative takes longer. In the end the absolute maintenance time for gates of the two alternatives are similar. But since the absolute maintenance time of the concrete structure, hydraulic cylinders and hydraulic aggregates are larger with the radial gate alternative, the contribution of the maintenance time for the gates of the radial gate alternative has decreased.

Table 26: planned downtime contribution (preventive maintenance)

	Lift gate alternative	**Radial gate alternative**
Maintenance time lifting tower/pier	9%	10%
Maintenance time gate	47%	34%
Maintenance time hydraulic cylinder	12%	11%
Maintenance time hydraulic aggregate	32%	45%

9.2 Repair and maintenance costs

The expected repair cost and maintenance costs are presented in figure 54. Even under corrective maintenance preventive maintenance is performed. This is explained in appendix E, the consequences of the concrete structure failing are too severe, so even under corrective maintenance preventive measures have to be taken. The repair costs and maintenance costs per unit for the weir components and failure events are shown in tables 27 and 28 respectively. The explanation for these costs can be found in appendix E. The calculations for the results that are presented in this paragraph can be found in appendix F.

Table 27: Repair costs for weir components

	Cost/unit [€/unit]
Movement works	
Replace hydraulic cylinders	170,000
Steel weir structure	
Replace headgates (radial gate)	450,000
Replace headgates (lift gate)	900,000
Replace control flap gates	225,000
Hydraulic aggregate	
Replace pump	20,000
Replace electromotor	20,000
External events	
Ship collision (lift gate)	2,710,000
Ship collision (radial gate)	1,805,000
Fire in installation room (river pier)	160,000
Fire in installation room (abutment)	80,000

Table 28: Costs of preventive maintenance measures

	Cost/unit [€/unit]	Sources	Frequency [1/year]
Movement works			
Replace hydraulic cylinders	170,000	(Rijkswaterstaat, 2014)	1/40
Lifting tower/pier			
Concrete renovation concrete structure	250,000	(Rijkswaterstaat, 2014)	1/30
Steel weir structure			
Conserve headgates (radial gate)	144,000	(Nebest, 2010)	1/15
Conserve headgates (lift gate)	288,000		1/15
Conserve control flap gates	74,000	(Nebest, 2010)	1/15
Hydraulic aggregates			
Replace hydraulic aggregate	80,000	Based on replacement costs pump and electromotor	1/25

The costs are as expected, with the repair costs being larger under corrective maintenance and preventive costs being larger under preventive maintenance. And it seems that the total costs under preventive maintenance is lower than the total costs under corrective maintenance.

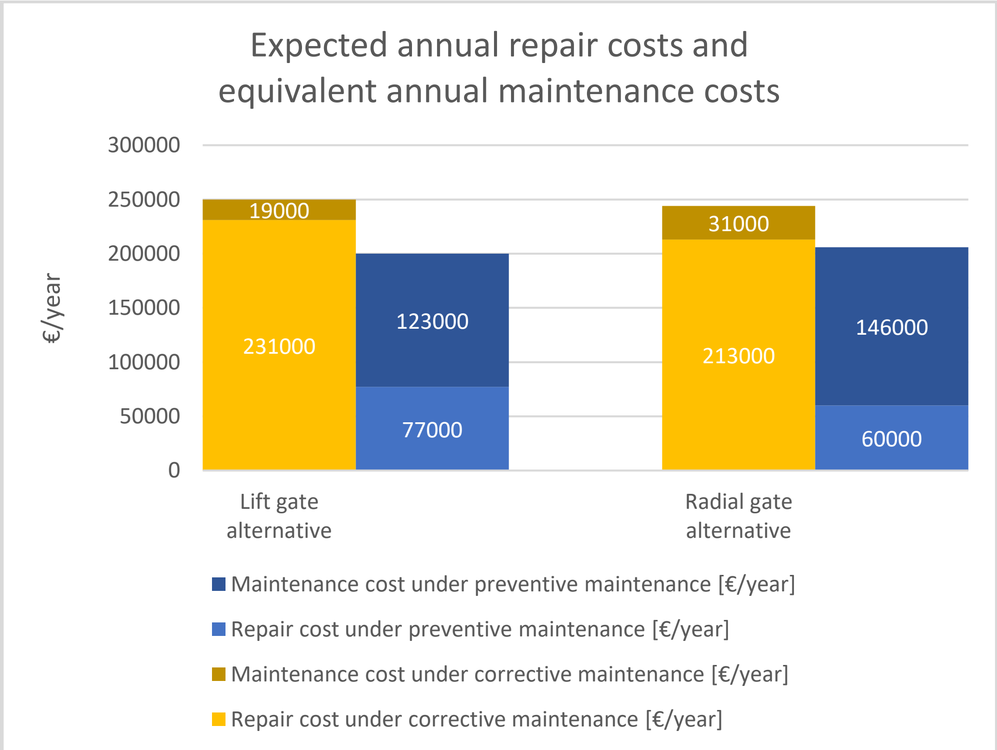


Figure 54: Expected repair and maintenance costs results

Figure 55 shows the contributions of the preventive maintenance cost under preventive maintenance. The largest contributor are the hydraulic cylinders, this is mostly due to the fact that both the hydraulic cylinders of the control flap gate and the headgate are combined. Otherwise the maintenance costs are spread out fairly evenly.

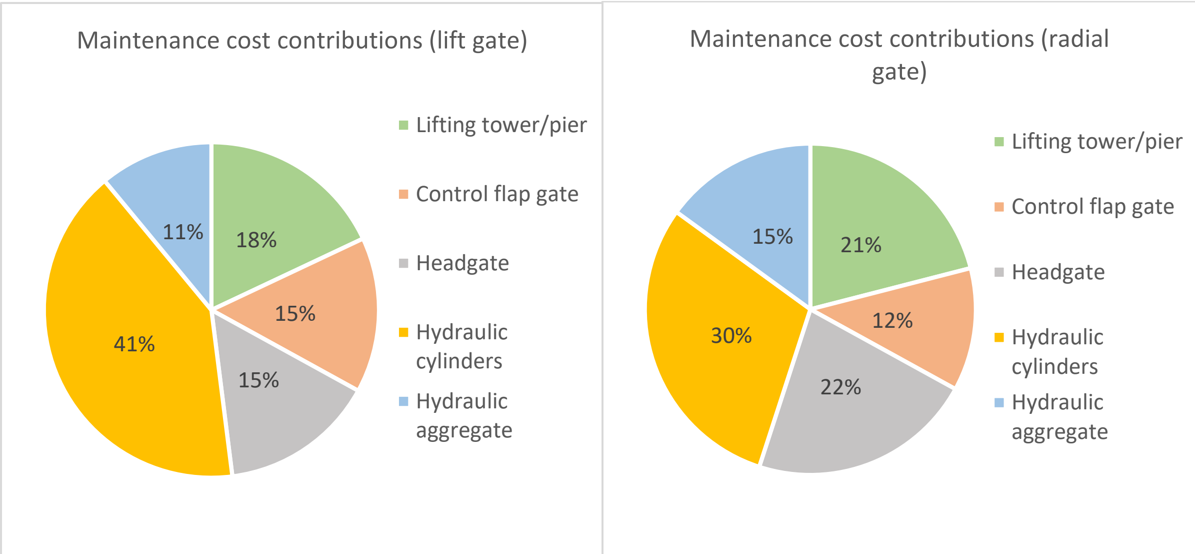


Figure 55: Preventive maintenance cost contributions for the lift gate alternative (left) and the radial gate alternative (right)

Figure 56 shows the contributions of the expected repair costs averaged over the weir alternatives using the upper bound failure rate for ship collision. The ship collision, hydraulic cylinders and hydraulic aggregates are the most expensive and that is to be expected. The hydraulic cylinders are mostly expensive because there is a large amount of hydraulic cylinders (16 cylinders) and the replacement costs are relatively high.

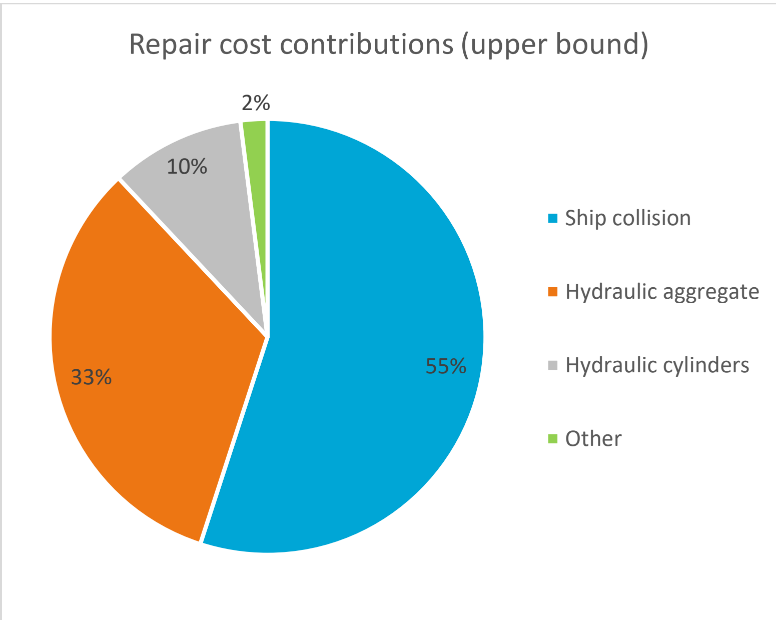


Figure 56: Expected repair cost contributions averaged over the two weir alternatives (Ship collision once every 50 years)

Comparing the results from figure 56 with the results from figure 57 which shows the contributions of the expected repair costs using the lower bound failure rate for ship collision, the contribution on the repair costs for ship collisions has significantly reduced. Only under preventive maintenance are the repair costs for ship collisions significant.

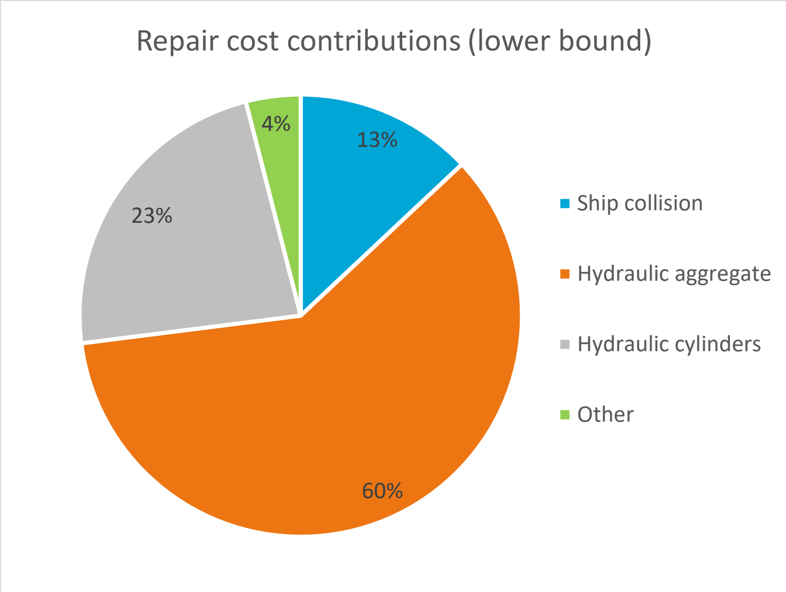


Figure 57: Expected repair cost contributions averaged over the two weir alternatives (Ship collision once every 500 years)

9.3 Conclusion

This chapter shows the results of the analysis to determine the availability, repair costs and maintenance costs for both weir alternatives and maintenance strategies. With these results the last three out of four sub-research questions can be answered. For each sub-question key observations from this chapter are given as bullet points.

- What is the optimal maintenance strategy for the next generation Meuse weirs?
  - Preventive maintenance leads to higher availability and lower total costs.
- To which weir components are the availability and costs sensitive?
  - The hydraulic aggregate has a substantial influence on the availability and have high repair costs.
  - The hydraulic cylinders do not influence the availability much, but have large maintenance costs.
- What is the influence of ship collisions on the availability and repair costs of weirs?
  - Ship collisions have a large contribution to the (non-)availability with both the upper and lower bound ship collision rate. However its influence on the expected repair costs is only substantial with the upper bound ship collision rate.

10 Conclusion and recommendations

The main objective of this report is to develop cost-efficient maintenance strategies for the next generation Meuse weirs. For which the preliminary designs of the next weir in Grave were used as a case study. This chapter answers the research questions proposed in chapter 5 and recommendations for further research are also provided.

10.1 Conclusions

The objective of this thesis is to determine the most cost-efficient maintenance strategy for the next generation Meuse weirs. To reach this objective the following research question was defined:

How can one make an assessment of the performance of maintenance strategies for weirs and what is the optimal maintenance strategy for the next generation Meuse weirs?

The main research objective was divided into four sub-questions to answer the main research questions. The sub-questions are as follows:

1) How is the performance of maintenance strategies for weirs quantitatively assessed?
2) What is the optimal maintenance strategy for the next generation Meuse weirs?
3) To which weir components are the availability and costs sensitive?
4) What is the influence of ship collisions on the availability and repair costs of weirs?

The first two sub-questions combined directly answer the main research question, the third and fourth do not directly help in answering the main research question, but have added value to the overall research. Below, an elaborate answer is given to each sub-question, that combined answer the main research question.

1. How is the performance of maintenance strategies for weirs quantitatively assessed?

In this thesis an assessment was made based on two criteria, namely the Availability and the costs. Where the costs were divided into repair costs due to components failing and costs of scheduled maintenance.

- Availability: The term is defined as the probability that a system performs as required. For a weir this means that the requirements to perform the water level regulation and ship passage functions are met. The availability of a weir is calculated in a fault tree from the unavailability (the inverse of the availability) of individual components. The unavailability of components is calculated with the failure rate and repair time of said components.
- Expected repair costs: The expected repair costs of weirs are determined by multiplying the failure rate of each individual component with its respective repair cost and summing up the costs. Annual failure rates are used to match the maintenance costs.
- Equivalent annual maintenance costs: Cash flows of maintenance activities are projected on a weirs timeline and discounted to their present values. This present value is transformed to Equivalent Annual Costs over the life cycle.

For the availability the requirements for the weir functions have to be determined. To determine the requirements for the weir functions a functional analysis is performed which determine top undesired events. The top undesired events are the top events in the fault tree analysis to determine the weir availability.

Next to the functional requirement, the weir components are to be determined. A physical decomposition is made of the weir system into its components. The functional analysis with the physical decomposition are used to fill out the fault trees for the weir system. And with the physical decomposition the repair and maintenance costs are determined.

To answer the sub question the term "maintenance strategy" has to be defined. There are generally two maintenance strategies:

- Corrective maintenance: This is performed in response to failure. When the consequences of failure are of mild severity this type of maintenance is justified (TU Delft, 2020b).
- Preventive maintenance: Is performed in anticipation of failure or after deterioration of equipment is detected (Wunderlich, 2005). When the consequences of failure are severe or unacceptable this type of maintenance is performed.

The main difference between the two strategies is that under corrective maintenance in general no scheduled maintenance is performed and only repairs. While under preventive maintenance both scheduled maintenance and repairs are performed, because even under preventive maintenance components can still fail. This means that under corrective maintenance one can expect higher failure rates compared to preventive maintenance. This generally means that under corrective maintenance one can expect a comparatively smaller availability, larger expected repair costs, but lower maintenance costs.

To assess the performance of the maintenance strategies the repair costs and maintenance costs is summed up for each strategy, which reduces the assessment to two parameters (the availability and the costs).

2. What is the optimal maintenance strategy for the next generation Meuse weirs?

Based on the results for the availability and costs of both maintenance strategies in this report it seems that the preventive maintenance strategy performs better than the corrective maintenance strategy for both weir alternatives. The availability under preventive maintenance is about 1% to 2% larger than the availability under corrective maintenance, which does not seem significant. However looking at the unavailability, the unavailability under preventive maintenance is about 25% to 50% (depending on the top undesired event) of the unavailability under corrective maintenance. The costs under preventive maintenance are about 15% to 20% less than the costs under corrective maintenance.

3. To which weir components are the availability and costs sensitive?

The largest contributors to the weir unavailability are ship collision (70%), ice formation (15%), the hydraulic aggregate (10%) and the hydraulic cylinders (3%), using the upper bound ship collision rate of once every 50 years and averaging over the top undesired events of both weir alternatives. Which means that about 85% of the unavailability is attributed to accidental events and only 15% to the failure of individual components. However with the lower bound ship collision rate the contributions are as follows: ship collision (25%), ice formation (25%), the hydraulic aggregate (40%) and the hydraulic cylinders (10%). In this case about 50% of the unavailability can be contributed to accidental events and 50% to the failure of components.

Ship collisions are covered in the next sub question. Ice formation only affects the water retaining function of the weir, since the weir has to be opened when ice formation occurs. And ice formation occurs only in the winter, when the river discharges are large and weirs do not have to be closed all the way, so the unavailability due to ice formation is not very problematic.

The hydraulic aggregates of both weir alternatives consist of two pumps with their own electromotor. If one of the pump/electromotor sets the other set takes over at 50% of the speed.

The hydraulic aggregates are denoted with a AND-gate which makes the system robust. However the failure rates of the pumps are in the order of 10^{-4}, which is large compared to the failure rates of other components which are in the order of around 10^{-5}. There are a large number of hydraulic cylinders, about 16, for both weir alternatives. However its contribution to the unavailability is negligible at around 3% or 10%. This can be attributed to the small failure rate of hydraulic cylinders (in the order of 10^{-7}).

The largest contributors to the repair costs under preventive maintenance are ship collision (60%), the hydraulic aggregate (30%), and the hydraulic cylinders (10%) using the upper bound ship collision rate. However the contributions for the maintenance cost (which are slightly larger than the repair costs) are 35% for the hydraulic cylinders and 12% for the hydraulic aggregate, averaged over the weir alternatives and functions.

In short for the hydraulic aggregate the following is concluded:

- Out of all the weir components the hydraulic aggregates have the largest influence on the availability and total repair costs of the weirs.

For the hydraulic cylinder the following can be concluded:

- The hydraulic cylinders do not have a large influence on the availability of the weirs, however the component has the largest contribution to the total maintenance costs.

4. What is the influence of ship collisions on the availability and repair costs of weirs?

The influence of ship collisions on the performance of weirs can be determined by looking at its contribution to the availability (or rather unavailability) of the weirs and its contribution to repair costs.

Based on the results ship collisions have a substantial impact on the availability of both weirs with both the upper bound ship collision rate (contribution to unavailability of 70%) and lower bound ship collision rate (contribution to unavailability of 25%). To reduce the unavailability due to ship collisions one could reduce the repair time due to ship collisions. As it stands the repair time is assumed to be 3/4 of a year. This repair time can be reduced by having maintenance equipment readily available, such as dewatering structures or spare parts.

For the repair costs the upper bound ship collision has a contribution of 55%, while the lower bound ship collision has a contribution of 13%. In the case of the upper bound ship collision rate the contribution is significant, and in the case of the lower bound ship collision rate the contribution is not significant.

10.2 Recommendations

Ship collision rates

In this thesis the ship collision rate that was used for the calculations is based on the frequency at which ship collisions have occurred at 10 Dutch weirs in the last 10 years. There have been two significant ship collisions, one with the weir in Grave and another one with the weir in Linne. The data on ship collisions with weirs is limited, since those do not occur often. To account for the lack of data a Bayesian Based Network (BBN) was used that focused on the environment and decision of the vessel crew.

The model was created to determine the probability of ship grounding and could not be used for this thesis. However a BBN could be the solution for the lack of ship collision data. Parameters such as the meteorological conditions, condition of the crew, and the probability for human errors could be taken into account specifically for ship collisions with weirs.

RAMS(SHEEP)

The only aspect that was taken into account in this report was the availability. Two other aspects that can be considered are the maintainability and safety. Maintainability is defined as the probability that a system can be repaired or subjected to preventive maintenance within a specific period of time and under certain conditions (Rijkswaterstaat, 2018a). This aspect is linked to the availability aspect. Safety is the probability that a system does not cause casualties over a period of time under certain circumstances (Rijkswaterstaat, 2018a). As mentioned in chapter 4 safety has been a problem with the maintenance of weirs, since many of the maintenance measures require manual labor under unsafe conditions.

Possible follow up research

As of now the maintenance strategy assessment was done specifically for the preliminary design of the next weir in Grave. Because of Rijkswaterstaats wish for uniformity of the weir designs, the results of the assessment can be extended to the other Meuse weirs as well. The uniformity of weir designs reduces the amount of unique components over all the Meuse weirs. How many spare parts are needed? How much maintenance equipment is needed to maintain all 7 weirs effectively, while minimising costs? Where should spare parts be stored? The current thesis does not answer these questions, but it can be used as a basis.

Reliability of weirs during floods

In the summer of 2021 the province of Limburg was flooded (for more information see appendix A). In two days the precipitation accumulated to 160 – 180 mm over a large area. During the flood all weirs had to be opened, however the movement works of the weir in Sambeek failed, resulting in the weir not opening completely. This did not pose a threat as the weir was open enough. But in the case that the weir could not open at all, it could have been catastrophic, with the debris and the flood pushing against the weir.

In this thesis the focus was on the maintenance of weirs and the aspect availability was used as one of the parameters to assess the maintenance strategies. However to determine the probability that a weir functions during floods requires a different type of analysis using the aspect reliability. This is beyond the scope of the thesis and was therefor not explored, however such an analysis can be useful since it is critical for weirs to function properly during floods.

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Appendix A: Extra background Meuse weirs

This appendix gives more background information on weirs and specifically the Meuse weirs. It is an extension to chapter 2. Paragraph A.1 goes into more detail on the general weir structure introduced in chapter 2. Paragraphs A.2 (examples of weirs around the world), A.3 (shipping in the Meuse river), A.4 (Meuse floods) and A.5 (ship collisions with Meuse weirs) are extensions to the introduction of chapter 2.

A.1 Weir structure

For ease of reading the structure breakdown from paragraph 2.2 is presented again below.

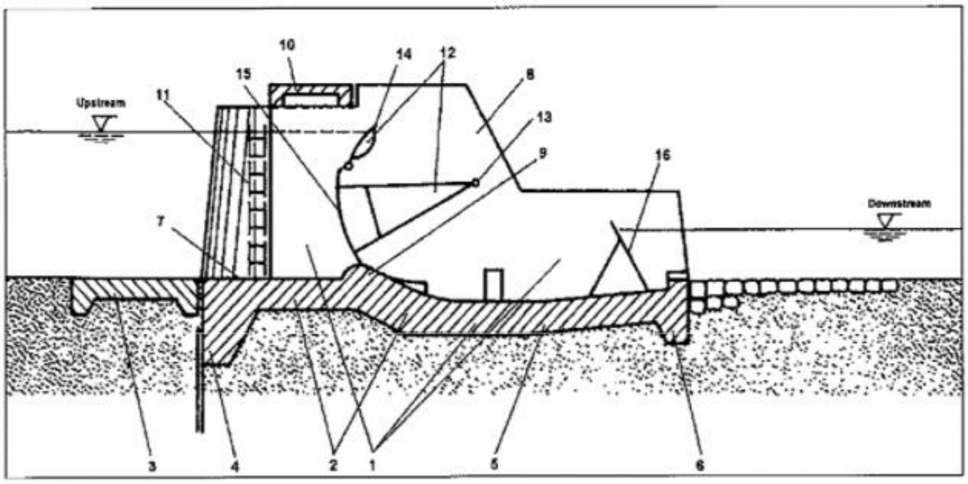

Figure 58: Weir structure (PIANC, 2006)

The components from figure 58 are listed in the table below.

Table 29: Components from figure 58 (PIANC, 2006)

Component category	Component
Concrete weir structure (1)	Upstream floor (3)
	Upstream diaphragm wall (apron) with cutoffs (sheetpiles in this case) (4)
	Stilling basin (5)
	Downstream diaphragm wall (apron) (6)
	Intake floor (7)
	Weir pier (8)
Maintenance objects	Service bridge (10)
	Upstream dewatering structure or bulkheads (here: stop logs) (11)
	Downstream dewatering structure (here: bulkhead) (16)

Paragraph A.1.1 will go over more gate types. Paragraph A.1.2 goes into more detail on the MEI and paragraph A.1.3 goes over the concrete weir structure and maintenance objects listed in table 29.

A.1.1 Weir gate types

The gate types presented in table 30 are explained in more detail in this paragraph. Except for the inflatable gate type which has been explained in paragraph 2.2.2.

Table 30: Weir gate types (PIANC, 2006)

	Description (See Tables 5.1-5.3)	Other types or variants to considerer	Foundation & Operator Supports (transmission of loads)
Flap Gate	Skin plate generally curved, stiffened, and hinged on the floor.	- Torque tube - Wicket gate - Obermeyer gate (see inflatable weir Table 5.2)	Hinged on the floor by several points on the lower and downstream side of the gate.
Radial Gate	Skin plate (usually curved) - linked to 2 arms, - hinged on the piers.	- Reverse radial gate with upstream arms and trunnions. - Flap gate on the top of radial gate.	Hinged (trunnions) in 2 points at the ends of the arms on the piers.
Vertical Lift Gate	Leaf with a rectangular skin plate, stiffened with stiff vertical and horizontal members. Often with a wheel carriage on each side but sliding gates are also considered (i.e. for emergency closure).	- Double leaf gate, superposed. - With a flap at the upper part.	On the lateral end-sides of the gate (in slots) with cables or hydraulic cylinders.
Sector Gate	Plate formed of an upstream circular curved plate and a downstream flat plate, articulated at the bottom of the upstream side of the gate.	Drum gate is not very different but with an axis on the upstream side	Hinged at the bottom of the downstream plate.
Inflatable	Sealed tube made of flexible material (usually reinforced membrane). Inflatable by air or water.	Inflatable air-bags that support metallic flaps (Obermeyer system). This alternative may also be considered as a flap gate.	Anchored to the sill by stiff bolts (1 or 2 lines), These require careful design and maintenance to insure reliability in an inflatable weir.

Flap gate

The surface of this gate type is either curved or straight and is fixed at the sill (Erbisti, 2004). If the gate is designed in the shape of a fish belly, it can span up to 20 m, because the shape offers resistance against torsion. Fully raised the gate make an angle of about 60 degrees with the horizontal. When the gate is opened up it lays flat on the bed, presenting no obstacle for the water flow.

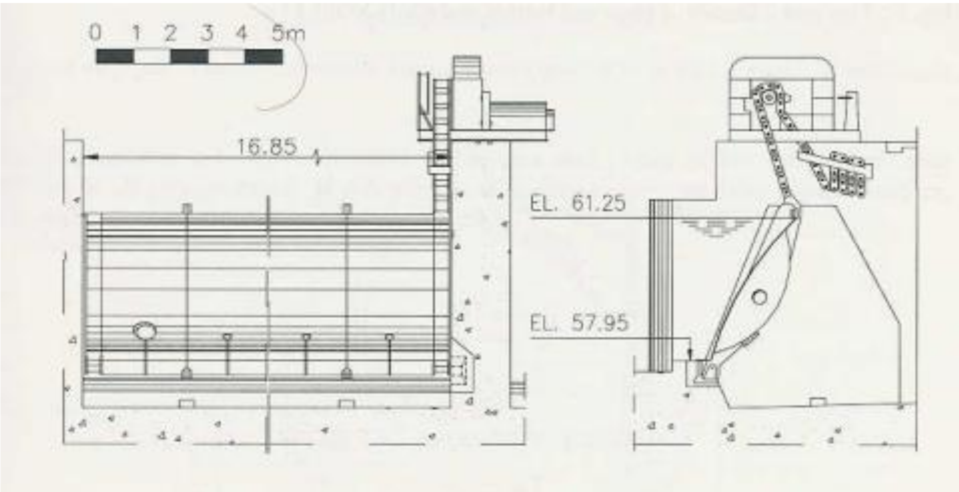

Figure 59: Flap gate (Erbisti, 2004)

Radial gate (segment gate)

The radial gate has a curved skin plate supported by radial arms that transfer the gate forces to fixed bearings (Erbisti, 2004). It rotates around a horizontal axis that aligns with the center of the skin plate. This causes the resultant of the water pressure to be aligned with the bearings, the gates are not pushed upwards or downwards.

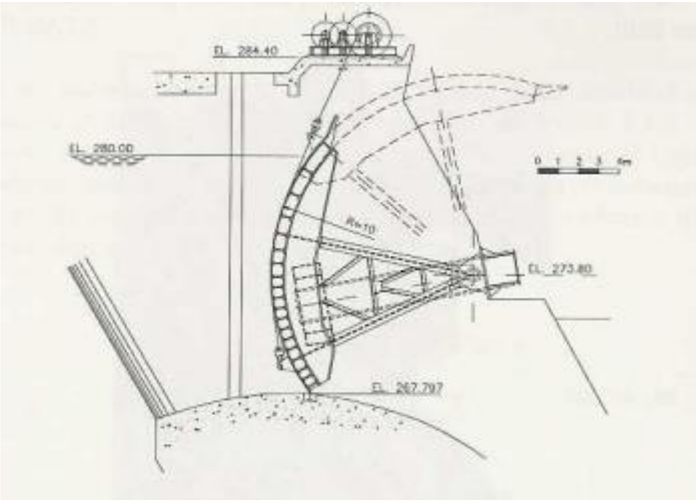

Figure 60: Radial gate (Erbisti, 2004)

Vertical lift gate

The vertical lift gate is a simple flat gate that slides up and down (Erbisti, 2004). The gate is embedded to the concrete piers. This design is simple and requires little maintenance. Another characteristic is that the gates have a uniform transmission of the hydrostatic water pressure to the concrete structure.

Figure 61: Vertical lift gate (Erbisti, 2004)

Sector gate

The skin plate of a sector gate is curved like that of the radial gate (Erbisti, 2004), but the gate profile has the aspect of a circular sector. In its raised state the gate is kept up by the water pressure on the inner face of the upper radial side. The gate is operated hydraulic and hoists are not required.

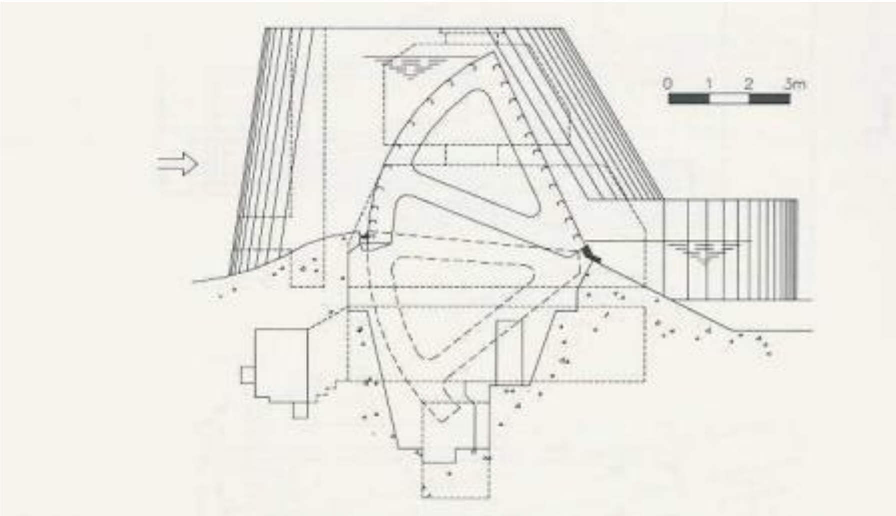

Figure 62: Sector gate (Erbisti, 2004)

A.1.2 MEI

The mechanical and electrical installations consist of gate drives, gate control systems and the electrical supplies.

Gate drives

Gates are operated by electromechanical drives raising the gates by ropes or chains, or by hydraulic cylinders (Lewin, 2001). There is another mechanism that has been developed more recently in the form of inflatable air-bags (PIANC, 2006).

Electromechanical drive

Electromechanical gate drives are the most common type of drive system for hydraulic gates (Daniel, et al., 2019). Electromechanical drives consist of electric motors that control the speed at which gates close under their weight (Lewin, 2001). Gates can be operated with a single motor, but gates will often be provided with two motors in case one fails. This can significantly increase a structures reliability and availability. The electromechanical drives are used mostly in combination with the following operating system types (ASCE, 2012):

- <u>Wire rope hoists</u>: The hoists operates with a rotating drum that winds the wire as it lifts the load.
- <u>Roller chain hoists</u>: Roller chain hoists pull the chains on one side and as it rotates sends out the chains on the back side, similar to a bike chain.

For electromechanical drives squirrel-cage induction motors are often used in gate installations, because of the minimal maintenance requirements due to the ability of using two motors. When one is out the other can take over. The squirrel-cage induction motor is named as such because the rotor looks like a squirrel cage. When an alternating current runs through the stator windings, a rotating magnetic field is produced. This induces a current in the rotor winding and produces a magnetic field. The interaction of the magnetic fields results in a torque on the squirrel cage rotor.

The main advantages of electromechanical drives are:

- proven design;
- greater life span than a hydraulic cylinder system;
- inherent acceleration and deceleration built into the design;
- generally less complicated controls required;
- ease of operation to understand and troubleshoot.

The main disadvantages of electromechanical drives are:

- more components requiring grease or lubrication;
- components can be difficult to replace and remove;
- operating components are generally custom built with long replacement time;
- more components to maintain.

Figure 63: Hoisting mechanism of the weir Nederrijn en Lek (BiermanHenket)

Hydraulic drive

Cylinder based operating systems use a pneumatic or hydraulic cylinder with a rod that telescopes out of one end (ASCE, 2012). The hydraulic cylinder is most commonly used. The hydraulic hoists allows for more ease when adjusting the gate speed or operating loads.

The hydraulic power is generated by a hydraulic power unit consisting of one or multiple pumps, valves and controls mounted on a fluid tank (Daniel, et al., 2019). Hoses transport the fluid to the cylinder. Valves control the pressure and volume of the fluid. The hydraulic fluid pressurises the system and drives the cylinder, it also functions as a lubricant. Figure 64 is an example of a weir gate driven by a hydraulic cylinder.

The main advantages of a hydraulic drive are (Daniel, et al., 2019):

- hydraulic power units can be placed at a considerable distance from the cylinders;
- operating speed can be varied and adjusted;
- there are fewer moving parts to be maintained compared to an electromechanical drive;
- accurate and flexible control of speed and position;
- inherent shock absorption.

The main disadvantages of a hydraulic drive are (Daniel, et al., 2019):

- requires a more complex pumping and control system;
- system operates at high pressure;
- gate can drift if pressure is taken off system;
- require effective filtration system for hydraulic oil.

Figure 64: Wicket weir gate, hydraulic cylinder (PIANC, 2006)

Inflatable air-bags

Inflatable air-bags are a relatively new gate type (Gebhardt, 2013). These air-bags have low capital and maintenance costs. It consists of a rubber membraned filled with air or water and is clamped to the weir body with one or two fixing bars (figure below). These inflatable weirs have been used in the USA and Japan for more than 50 years, and due to positive experiences and economic value are increasingly used. By controlling the pressure in the air bags the upstream water level is maintained by the gates. The gate system is attached to the foundation structure with anchor bolt.

Figure 65: Obermeyer Spillway Gates, inflatable weir (Obermeyer Hydro, 2018)

Gate drives allow for the movement of gates. The gate drives for the control flap gates can regulate the water level upstream and the gate drives for the headgate allow the weir to open up in case of extremely high water discharges.

Gate controls

Gates are opened remotely or automatic, on site or from a distant location (ASCE, 2012). Local controls should be located in order for operations personnel to have safe access during events such as floods. Operations personnel will need to be available to trouble shoot at the gate location and operate the gate.

Power outages are a common problem. Back-up generators or portable generators are needed during the outage. Where manual hoist back-up is provided when hydraulic hoist fails, manual hoist operation is physically demanding. The operations personnel should be physically able to do the manual labor. The operation plan should describe requirements for manual operations including strength requirements and number of personnel needed.

For manual controls the following variants are used (Lewin, 2001):

- Local control of motorised operation: Increasing the outflow in steps. At its simplest level gate openings may be determined by the operator based on experience in responding to a signal indicating river or reservoir level. This configuration allows the operator the best vantage point to observe the gate operation. However this configuration is labor intensive compared to remote or automated control systems.
- Remote control of motorised operation: This may be located remote from the spillway, barrage or weir, or may be carried out from a center controlling a number of dams.
- Computer assisted control: Extensive input data may require the use of a computer to determine how gates should be operated. For example by using hydrometeorological models. The data may be keyed in manually or the computer may operate on signals received direct from the gauging stations and control instruments.

For automatic methods the following variants are used (Lewin, 2001):

- Cascade controls: The distance between the retention level and maximum reservoir level is divided into steps, each corresponding to a gate opening. On reaching a specific water level the gate hoist motion starts and the gates open in sequence to their predetermined height. Cascade control is generally used in conjunction with power actuation of gates, either by electric motor driven winches or by oil hydraulic cylinders.
- Electromechanical level control: The electromechanical level control determines when the retention level is reached using a predetermined rise in water level. This initiates opening of gates in sequence. When the upper limit of the water level control band is reached the gates are opened until the levels fall below the upper limit, then motions are stopped.
- The computer controlled system: The computer controlled system moves the gates after determining desired outflow based on the measured inflow. Control instructions are issued by a computer to maintain upstream water level.

Electrical supplies

Emergency power generators

Installations in structures usually make use of electricity through high to mid voltage grid (DHV AIB, 1998). When the primary source of power shuts down there needs to be a back up to keep essential processes going, in the form of emergency power generators. These generators use diesel fuel. To keep the power generator from overheating ventilations and cooling water supplies are installed.

Climate installations

Installation rooms are ventilated with ventilation systems (Rijkswaterstaat, 2018b). During winters the temperatures in the installation rooms get extremely low. This has an effect on the durability of the installations. Heating systems are applied to regulate the temperature inside the installation rooms.

Lighting installations

There are three objects that need to be lit: the weir, the installation room and the terrain of the weir. Weirs need to be visible at night by shippers. When maintenance engineers or inspectors visit the installation room, they will need light to work. The terrain of the weir has to be visible for workers to visit the installation room.

A.1.3 Concrete structure

The concrete superstructure is the main load carrier of the weir and facilitates the gates and MEI as mentioned in paragraph 2.2.3. This paragraph elaborates on the concrete structure objects listed in table 29. The maintenance objects are also included in this paragraph.

Apron and cutoff walls

A water level difference across a structure can cause a groundwater flow in permeable soil under the structure, the groundwater flow phenomenon is called seepage (Voorendt, et al., 2020). Seepage does not usually pose a threat, however if the flow velocity is sufficiently high soil particles start to erode. If the water flows out at ground level sand boils can be seen. The erosion of the sand particles progresses upstream forming a continuous pipe if the erosion does not stop (piping). Eventually the structure is undermined and collapses.

The issue of piping was first treated by Bligh. He found that the stability of a weir on porous foundation depended on the seepage length or percolation path, which is the shortest path that the groundwater can follow from one side of the structure to the other side (see the right illustration in figure 66). He established empirical coefficients named the percolation factor that related the head difference with the seepage length. The following criterium determines is the structure is safe from piping:

$$L - c * H \geq 0;$$

where c is the percolation factor (which depends on the soil type), L is the seepage length and H is the head difference.

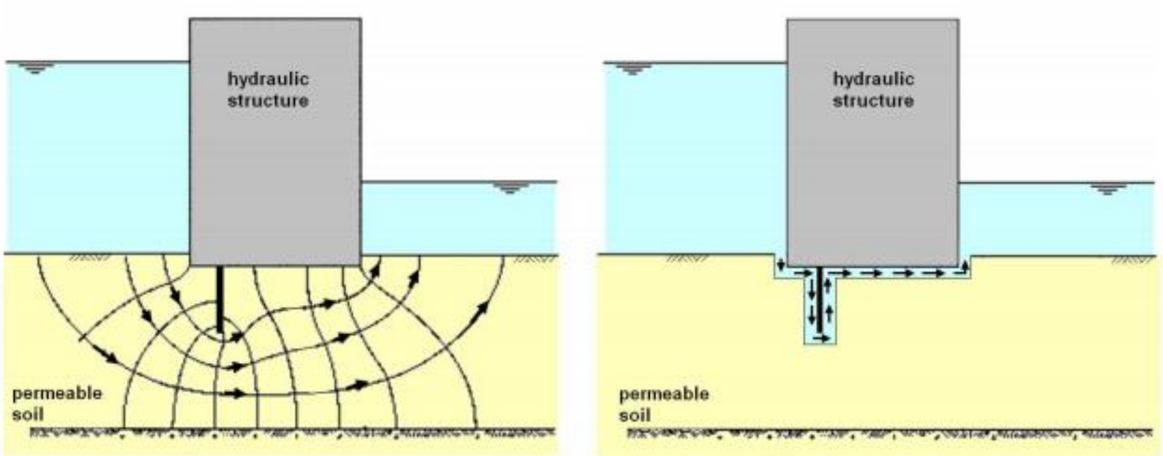

Figure 66: Piping under a hydraulic structure (Voorendt, et al., 2020)

Aprons and cutoff walls increase the seepage length of the structure which in turn decreases the probability that piping occurs.

Stilling basin

A weir regulates the upstream water level such that the upstream water depth is sufficient for shipping. This results in a higher water level just upstream of the weir compared the water level just downstream of the weir. The water that goes over the weir and plunges just downstream of the weir. This energy with which the water plunges downward depends on the height difference between the upstream and downstream water level. The downstream water has a supercritical flow which transitions to a subcritical flow (hydraulic jump) (Chanson, 2008). In the space in which the river water plunges and a hydraulic jump forms a lot of energy is dissipated. This dissipation of water causes turbulence and erodes the river bed. To prevent this erosion a stilling basin is implemented (figure 67). It is a concrete floor on top of the river bed that covers the space of the hydraulic jump.

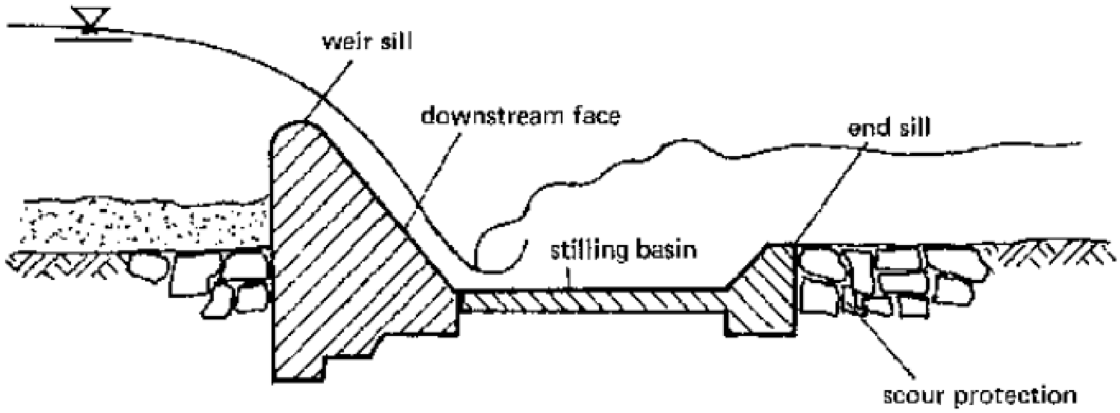

Figure 67: Stilling basin (Lauterjung, et al., 1989)

Pier

The piers hold the mechanical and electrical installations of the weir. They also hold the gates at place.

Maintenance objects

In table 29 some components are listed under the category "maintenance objects". These components are not made out of concrete, but are supported by the concrete structure. These components are explained below.

Service bridge

Weir structures generally span over the width of a river. For the maintenance of weirs the entire structure must be accessible, this includes the piers in the river. To allow for accessibility of the middle piers service bridges are constructed between piers. The bridges will allow maintenance workers to get to the river piers.

Dewatering structure: Bulkheads/stoplogs

For the maintenance or repairs of hydraulic structures temporary closure structures are required that can allow for a dry working environment (PIANC, 2006). One on the downstream end of the structure and another on the upstream end of the structure so that the space in between can be dewatered. Examples of such closure structures are stoplogs and bulkheads.

Stoplogs are beams that fit into slots in the sidewalls of an opening (PIANC, 2006). If the stoplogs have to seal a large height, the stoplogs can be composed of multiple elements (Erbisti, 2004). These are called stoplog panels. Stoplogs are sealed on their sides and between panels. The panels may be identical or designed such that each resists the corresponding pressure. The second design is cheaper, however the installation must follow a sequence.

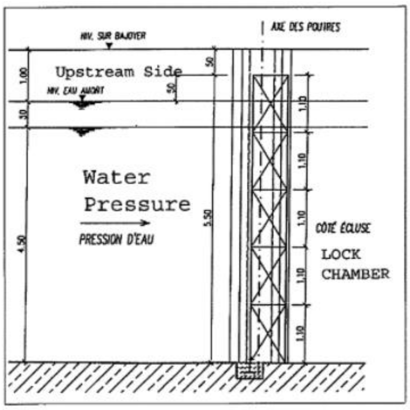

Figure 68: Stoplog sideview (PIANC, 2006)

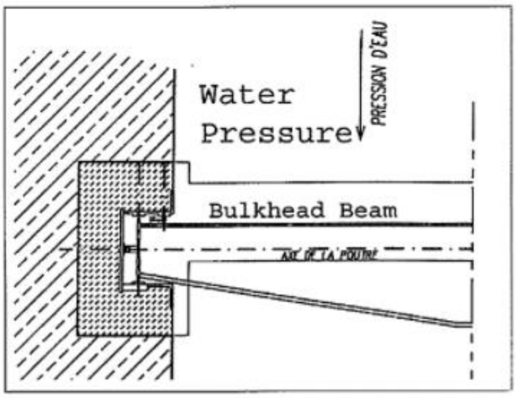

Figure 69: Stoplog top view (PIANC, 2006)

Bulkheads are similar to stoplogs, but differ as bulkheads are generally a one piece construction rather than sectional or modular (PIANC, 2006). Figure 70 is an example of a self-supported bulkhead with watertight membrane.

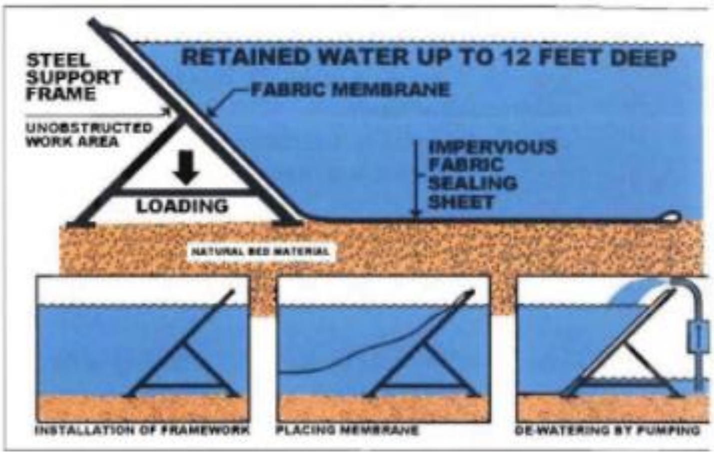

Figure 70: Pallet barrier (PIANC, 2006)

A.2 Examples of weirs

Weir in Grave

The weir in Grave (figure 71) was built in 1926 and is unique, due to the weir structure being part of the John S. Thompson bridge (Rijkswaterstaat, 2018). Underneath the west side of the bridge there are 11 steel columns. Per steel column there are three panels that stand on top of each other. On the other side there are 9 steel columns, which makes a total of 20 steel columns with 3 panels per steel column. The panels are remotely controlled at the lock to open up or close the weir using a cable mechanism.

Figure 71: Weir in Grave (Canon van Nederland, sd)

Lagan weir (Belfast, Northern Ireland)

An example of a weir is the Lagan weir in Belfast, Northern Ireland. It crosses the river between the Queen Elizabeth Bridge and the M3 Lagan bridge. Before the opening of the weir low tide would regularly reveal mud flats and brought a foul-smelling stench to the river side (Young, 2017). As the weir controls the water level of the river, even during low tide the river would not reveal the mud flats.

Figure 72: Lagan weir (Lawell, 2013)

Figure 73: Lagan weir close up head gate (Albert Bridge, 2015)

A.3 Meuse river: Shipping

The river Meuse rises at the Langres Plateau and flows through France and Belgium to reach the Netherlands at Eijsden (Ministerie van Verkeer en Waterstaat, 2008). The water catchment area is 36.000 km^2, about 7.700 km^2 of that area lies in the Netherlands (figure 74). The catchment area of the river does not lie on mountains, so most of the water flowing in the river is rain water.

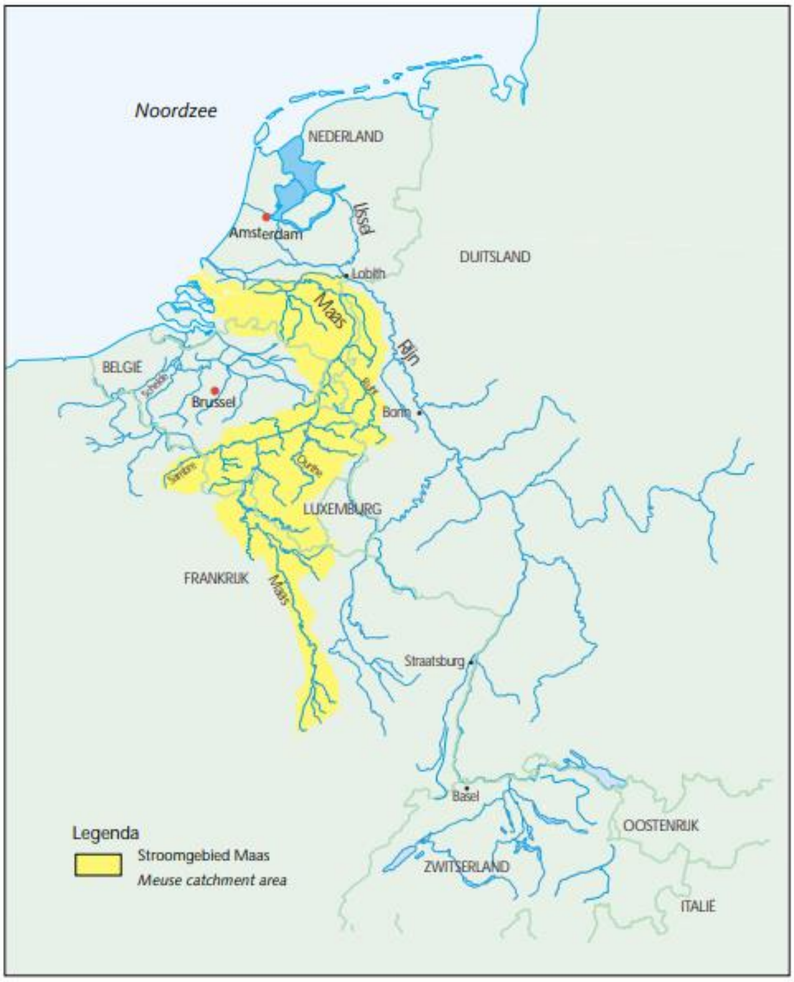

Figure 74: Catchment area of the river Meuse (Rijkswaterstaat, 1996)

In the past the Meuse river became more important for shipping during periods of high water discharges (Rijkswaterstaat, 1989). In the summer months the water level in the river would be insufficient for shipping, due to low rainfall. In the years between 1920 and 1935 weirs and sluices were built along the river (at Borgharen, Linne, Roermond, Belfeld, Sambeek, Grave and Lith). These structures made the river navigable all year round.

Between 1960 and 1975 the capacity of the Meuse river was increased (Rijkswaterstaat, 1989). This was achieved by building new sluices at Born, Maasbracht, Belfeld, Sambeek and Grave. The increased capacity made the river navigable for CEMT-class V vessels.

In the 21st century the vessel sizes seem to be increasing for inland shipping. Figure 75 shows the amount of inland passages for each CEMT-class between the years 2009 and 2018. The data shows that the amount of vessels smaller than CEMT-class Va are decreasing, while the amount of vessels equal or larger than CEMT-class Va are increasing.

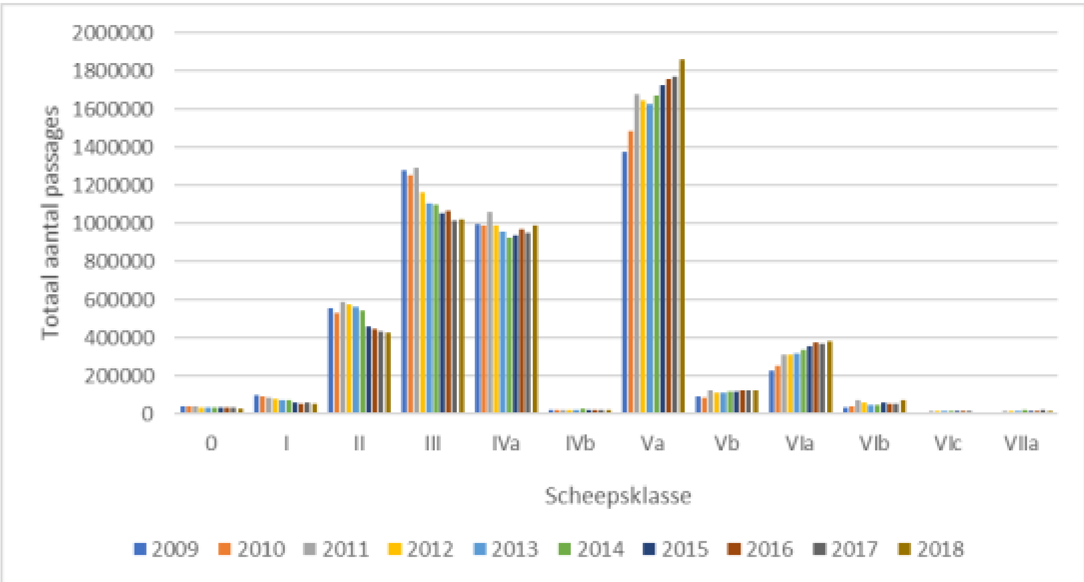

Figure 75: Total amount of inland passages over the Dutch waterways per CEMT-class (Rijkswaterstaat, 2019a)

This development is better illustrated in figure 76. Which shows the relative growth of each CEMT-class compared to the amount of passages in 2009 (=100%). The passages of CEMT-class I have been halved in 10 years, while the passages of CEMT-class VIc and VIIa have more than doubled.

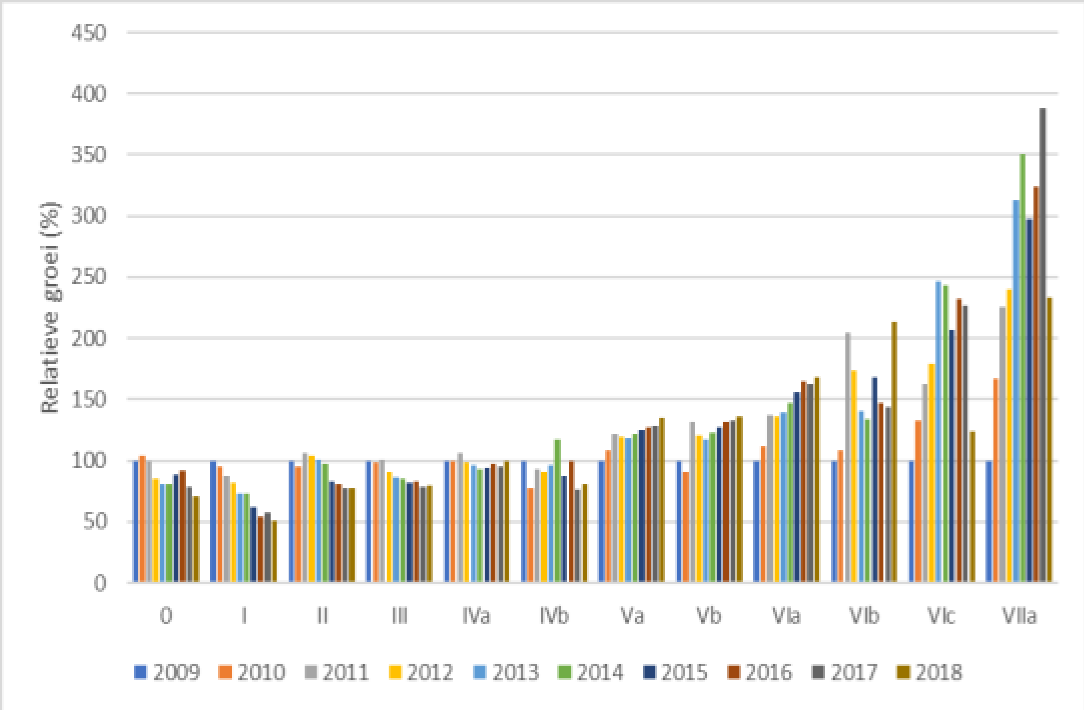

Figure 76: Relative growth per CEMT-class of inland passages over the Dutch waterways (Rijkswaterstaat, 2019)

A.4 Floods

1993

In 1993 a large part of Limburg was flooded (Rijkswaterstaat, 1994). A peak discharge was recorded at Borgharen of 3120 m^3/s, which is larger than the largest known discharge so far (1926) with a peak discharge recorded at Borgharen of 3000 m^3/s.

Important to note about the two floods is that the peak discharge in 1993 occurred with a water level of NAP + 45.90 m, while the peak discharge in 1926 occurred with a water level of NAP + 46.10 m (Rijkswaterstaat, 1994). The peak discharge in 1993 was larger even though the water level was smaller. This can be explained by the developments to the river system (canalisation of the Meuse, lowering of the summer bed). About 10,000 people had to be evacuated.

1995

Two years after the flood in 1993 another flood occurred due to extremely high discharges in the river Meuse (Rijkswaterstaat, 1995). Large stretches of uninhabited and inhabited areas in Limburg were flooded. The peak water discharge measured at Borgharen was 2870 m^3/s, which is slightly smaller than the peak water discharge in 1993.

The extreme water discharge was caused by high precipitation in the catchment area of the Meuse (Rijkswaterstaat, 1995). The effects of the urbanisation of the past century and the Meuse weirs were also investigated. The urbanisation has an accelerating effect on the frequency of moderately high water, but this effect does not extend to extremely high water. The Meuse weirs were investigated for their potential effect on the water level during floods. The Meuse weirs did not have an increasing effect on the water levels during floods.

2021

About 16 years after the flood in 1995 the province of Limburg was yet again flooded (ENW, 2021). A key difference with the forementioned floods is that this flood occurred during the summer while the other floods happened in the winter. In two days the precipitation accumulated to 160 – 180 mm over a large area. Heavy rains rarely occur and have never been registered in the summer season.

The floods led to severe economic losses in the area. The damage in the Netherlands was estimated to be between 350 and 600 million euros (ENW, 2021). Which is significantly larger compared to the damages by the floods in 1993 and 1995 (converted to 2021 the prices are about 200 and 125 million euros respectively). Along the flooded rivers about 50,000 people have been evacuated.

During the flood all weirs had to be opened, however the movement works of the weir in Sambeek failed, resulting in the weir not opening completely. This did not pose a threat as the weir was open enough. But in the case that the weir could not open at all, it could have been catastrophic, with the debris and the flood pushing against the weir.

Figure 77: Sluice Sambeek flood 2021 (ENW, 2021)

Dike reinforcement programmes

As part of the 'Meuseworks' project Rijkswaterstaat looks to reinforce dikes to improve flood protection (Rijkswaterstaat, 2021a). The water authorities in Limburg and Rijkswaterstaat took it upon them to protect most civilians and businesses against floods according to the legal standards before the end of 2020. The measure taken to accomplish the objective was to reinforce 18 dikes along the river Meuse in Limburg (figure 78).

Figure 78: Dike reinforcements in Limburg (Rijkswaterstaat, 2021)

With the 'Meuseworks' project almost completed the flood safety projects are not finished. The water authority Limburg has been working on the Flood Safety Programme (Rijkswaterstaat, 2021a). The Flood Safety Programme (Hoogwaterbeschermingsprogramma) works to reinforce all the dikes and sluices in the Netherlands in order to prevent floods before 2050 (HWBP, 2021).

A.5 Ship collisions

The ship collisions mentioned in paragraph 4.2.1 are covered in this paragraph.

Linne

In February 2020 a vessel collided with the weir in Linne. The first action to take place is to restore the water retaining functionality of the weir (Haarsma, 2021). To restore the water retaining function a dike was built on the upstream and downstream side of the Poirée part of the weir (figure 79). A temporary dike was constructed over the entire width of the dike. It took about 2 weeks to construct the dike. The estimated economic costs for the weir in Linne is € 20,000,000 (Nieuw Links Maasgouw, 2020).

Figure 79: Weir repair Linne (Rijkswaterstaat, 2020)

Grave

On December 2016 a 2000 ton benzene inland vessel collided with the weir in Grave (Onderzoeksraad voor veiligheid, 2018). Parts of the gate came off through which water started flowing downstream. This led to the weir being damaged severely and the water level between Grave and Sambeek dropping by about 3 meters with all the consequences for navigation. The economic damage caused by the ship collision was about € 20,000,000 (NOS, 2017).

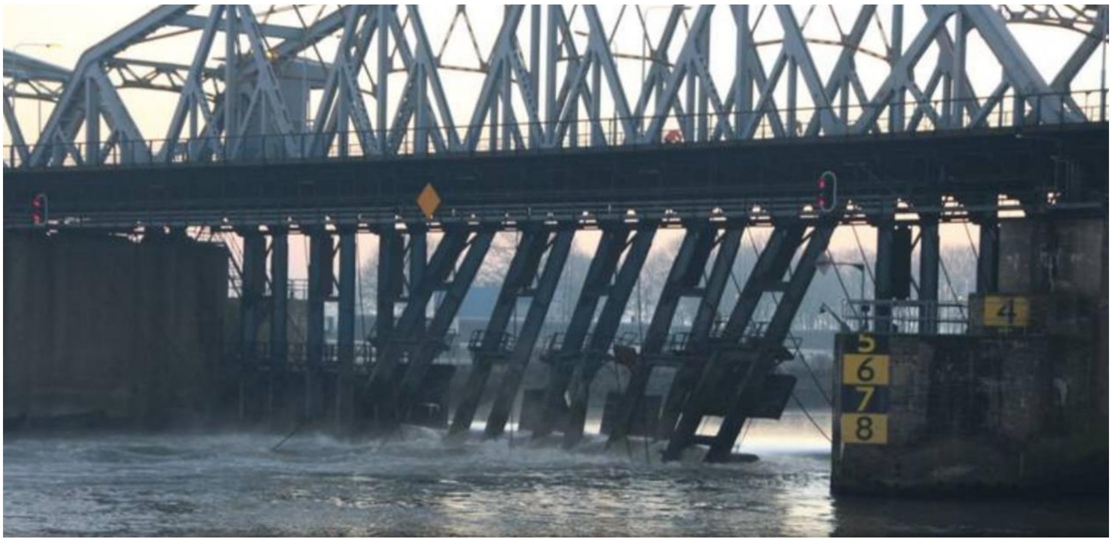

Figure 80: Weir in Grave damaged by the ship collision (Rebecca, 2017)

Appendix B: Ship collision

To determine the rate of significant ship collisions (which is to say that the water retaining function of the weir is compromised) two methods were used. The first method used ship collision data and determines the frequency at which vessels collide with weirs (paragraph B.1). The second method is a Bayesian belief network that determines the failure rate through the traffic situation and behavior of vessel crew members (paragraph B.2). Paragraph B.3 discusses the results from both methods.

B.1: Ship collision frequency

A report was published by (Rijkswaterstaat, 2020a) which covered the number of ship collisions with weirs in the Netherlands. The data covers all ship collisions between 2010 and 2019 that occurred at 10 Dutch weirs. The weirs include the seven Meuse weirs as well as the weirs in Driel, Hagestein and Amerongen. There were three ship collisions in the years between 2010 and 2019. This includes the ship collision in Grave (mentioned in paragraph A.5) and two collisions at Belfeld.

The two collisions at Belfeld were not significant. The ship collision with the weir in Linne (mentioned in paragraph A.5) happened in February 2020, so this was not included in the data. However for this thesis this event is taken into account.

Which leaves two significant ship collisions over 10 weirs in 10 years. The failure rate for ship collisions is determined by dividing the number of ship collisions by the number of weirs and the timescale of the data. This comes out to a ship collision frequency of 0.02/year or 2.28E-06/hour. This means that a ship collision with a weir occurs once every 50 years.

B.2: Bayesian Belief Network (BBN)

The second method to determine the frequency of a ship collision is based on a thesis by (Jansen, 2019) on ship collisions with temporary structures. This approach focusses on the environment and decisions that can lead to a ship collision. The model that was used in the thesis was proposed by (Mazaheri, et al., 2016). The model is a Bayesian Belief Network (BBN) that assesses the probability of ship-grounding accidents. A BBN is a probabilistic graphical model that represents conditional dependencies between random variables through a graph (Güney, 2019). The data used come from (DNV, 2005) and (Hänninen, et al., 2012), which are based on grounding accident reports from the Finnish and British authorities.

To use the model for the situation in Grave some assumptions are made. Firstly the structure of the model is kept the same and data relating to human behavior are assumed to be the same for Grave. There is also the fact that the original model looks at ship grounding instead of ship collision. Since ship grounding accidents are mostly caused by human errors because of inadequate information or improper navigational operations it can be argued that the model can also be used for ship collision with a weir. The data for meteorological conditions have been changed to fit the situation in Grave.

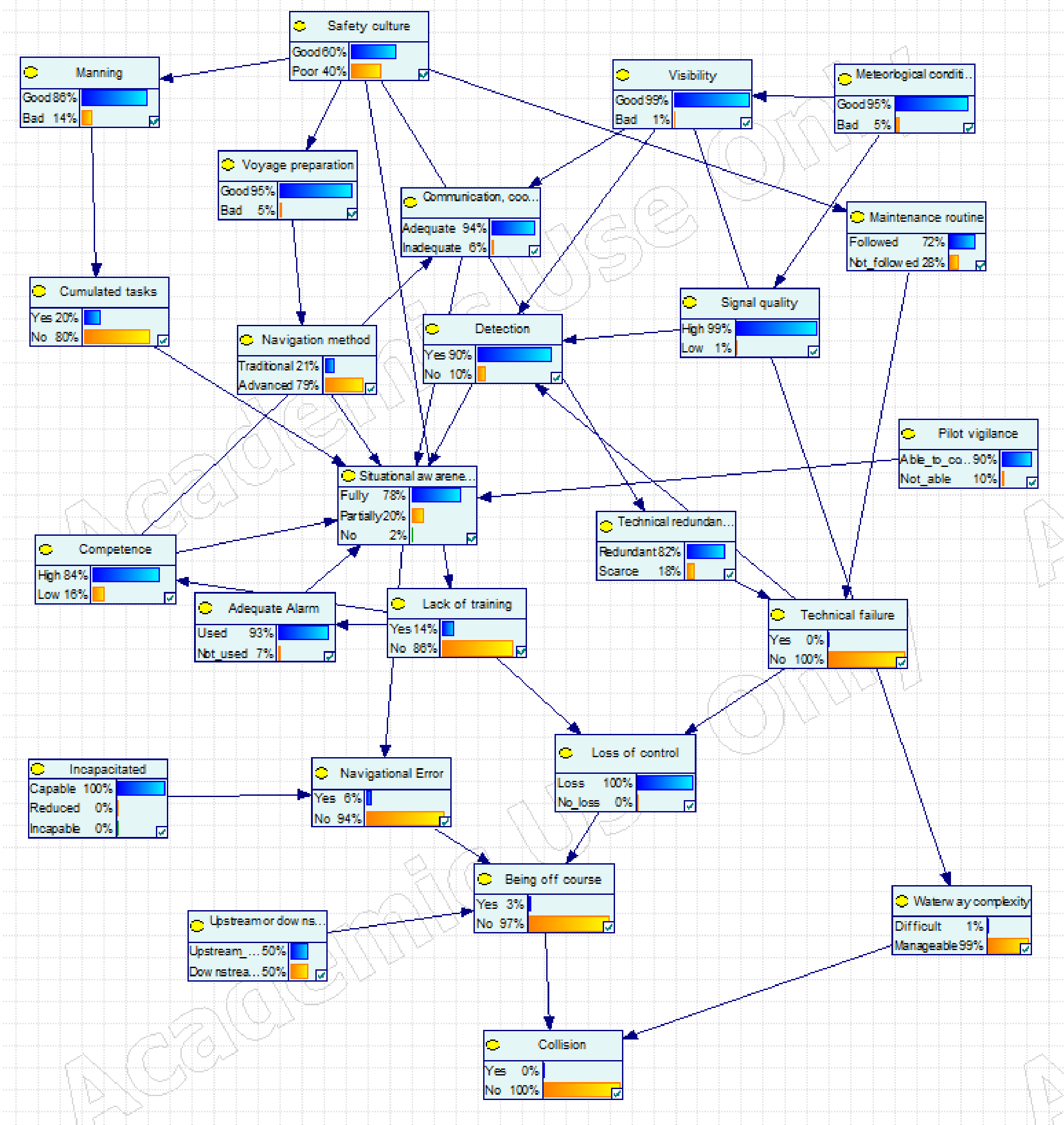

Figure 81: Bayesian Belief Network to determine the frequency of ship collision

If a ship collides with a weir the gates can be punctured. In this case we assume that the weir cannot retain water in case of a ship collision independent of the vessel type. The probability of a ship collision is determined using the BBN of figure 82 and it is 6E-05 per vessel. The amount of inland vessels that pass through the lock in Grave in 2018 was 12,000 (Binnenvaartcijfers, 2018). Using this amount of ship passages it would give a ship collision frequency of 0.72 ship collisions per year.

BBN model Nodes

Adequate alarm

Lack of training	Yes	No
Used	0.8	0.95
Not_used	0.2	0.05

Adequate alarm is whether the crew uses the alarm to alert for grounding and is based on the amount of training. The probabilities are based on (DNV, 2005) and (Mazaheri, et al., 2016).

Being off course

Navigational Error	Yes					
Loss of control	No		Partial		Total	
Upstream or do...	Upstream_g...	Downstrea...	Upstream_g...	Downstrea...	Upstream_g...	Downstrea...
Yes	0.7	0.3	0.85	0.5	0.95	0.7
No	0.3	0.7	0.15	0.5	0.05	0.3

Navigational Error	No					
Loss of control	No		Partial		Total	
Upstream or do...	Upstream_g...	Downstrea...	Upstream_g...	Downstrea...	Upstream_g...	Downstrea...
Yes	0	0	0.6	0.5	0.8	0.6
No	1	1	0.4	0.5	0.2	0.4

The vessel being on or off course is dependent on 'Navigational Error' and 'Loss of control' and whether the vessel is upstream or downstream going. The probabilities are based on (Mazaheri, et al., 2016).

Collision

Waterway com...	Difficult		Manageable	
Being of course	Yes	No	Yes	No
Yes	0.000624	6.24e-05	0.000524	4.44e-05
No	0.999376	0.9999376	0.999476	0.9999556

This is the end node which is dependent on the nodes 'Being off course' and 'Waterway complexity'. The probabilities are based on (DNV, 2005).

Communication, cooperation, monitoring

Competence	High		Low	
Visibility	Good	Bad	Good	Bad
Adequate	0.95	0.85	0.9	0.8
Inadequate	0.05	0.15	0.1	0.2

It describes whether the crew on the vessel communicates well with each other. probabilities in this node are based on (Hänninen, et al., 2012) and engineering judgement.

Competence

Lack of training	Yes	No
High	0.5	0.9
Low	0.5	0.1

Competence is a combination of knowledge, skills and attitude. The probabilities are based on (DNV, 2005).

Cumulated tasks

Manning	Good	Bad
Yes	0.1	0.8
No	0.9	0.2

Having many tasks on the bridge of a ship can lead to unawareness of your surroundings. The probabilities are based on (Mazaheri, et al., 2016).

Detection

Signal quality	High				Low			
Visibility	Good		Bad		Good		Bad	
Technical failure	Yes	No	Yes	No	Yes	No	Yes	No
Yes	0.6	0.9	0.5	0.85	0.6	0.7	0.2	0.4
No	0.4	0.1	0.5	0.15	0.4	0.3	0.8	0.6

This node describes whether danger can be detected and is dependent on 'Signal quality' and 'Visibility'. The probabilities are based on (DNV, 2005).

Incapacitated

Capable	0.99996
Reduced	1e-05
Incapable	3e-05

The physical capability of the captain. With reduced being ill for example and incapable when the captain is not present or asleep. The probabilities are based on (DNV, 2005).

Lack of training

Safety culture	Good	Poor
Yes	0.1	0.2
No	0.9	0.8

The lack of training among the crew influences their competence to handle the ship. The training itself is influenced by the safety culture present on the ship. The probabilities are based on (Hänninen, et al., 2012).

Loss of control

Lack of training	Yes		No	
Technical failure	Yes	No	Yes	No
Loss	0	1	1	1
No_loss	1	0	0	0

Loss of control of the ship is dependent on 'Technical failures' and 'Lack of training'. The probabilities are based on (DNV, 2005).

Maintenance routine

Safety culture	Good	Poor
Followed	0.8	0.6
Not_followed	0.2	0.4

Whether the maintenance routine is followed on the ship or not. This is dependent on the 'Safety culture' present on the ship. The probabilities are based on (DNV, 2005).

Manning

Safety culture	Good	Poor
Good	0.9	0.8
Bad	0.1	0.2

Whether there is an adequate amount of manning on the ship. This is dependent on 'Safety culture' present on the ship. The probabilities are based on (DNV, 2005).

Meteorological conditions

Good	0.966
Bad	0.034

For the meteorological conditions there are two categories, good and bad. The bad meteorological condition is characterised by fog. According to the KNMI the average fog duration in the year of 2000 was about 300 hours (KNMI, 2015). The probability of fog in a year is assumed to be the fog duration in 2000 divided by the amount of hours in a year, which is 300/8760 = 0.034. The probability for bad meteorological conditions is 0.034, so the probability for good meteorological conditions is 0.966.

Navigation method

Voyage prepar...	Good	Bad
Traditional	0.2	0.4
Advanced	0.8	0.6

The method used to navigate the river and it is dependent on the 'Voyage preparation'. The probabilities are based on (Hänninen, et al., 2012).

Navigational error

Incapacitated	Capable			Reduced			Incapable		
Situational awa...	Fully	Partially	No	Fully	Partially	No	Fully	Partially	No
Yes	0.01	0.25	0.4	0.1	0.4	0.5	0.5	0.7	0.8
No	0.99	0.75	0.6	0.9	0.6	0.5	0.5	0.3	0.2

Navigational errors are based on the captain being 'Incapacitated' and the crew having 'Situational Awareness'. The probabilities are based on engineering judgment.

Pilot vigilance

Able_to_correct	0.9
Not_able	0.1

The ability of the pilot to correct a critical course. The probabilities are based on (DNV, 2005).

Safety culture

Good	0.6
Poor	0.4

How well the vessel operator deals with safety issues. The probabilities are based on (DNV, 2005).

Signal quality

Meteorlogical c...	Good	Bad
High	0.999	0.8
Low	0.001	0.2

The signal quality on the radar display is influenced by the 'Meteorological conditions'. The probabilities are based on (DNV, 2005).

Situational awareness

Competence	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High	High
Cumulated tasks	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No
Detection	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	No	No	No
Communication...	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate
Navigation met...	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced
Fully	0.9	0.85	0.85	0.8	0	0	0	0	0.9	0.85	0.85	0.8	0	0	0	0
Partially	0.1	0.15	0.15	0.2	0.85	0.85	0.65	0.65	0.1	0.15	0.15	0.2	0.85	0.85	0.65	0.65
No	0	0	0	0	0.15	0.15	0.35	0.35	0	0	0	0	0.15	0.15	0.35	0.35

Competence	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Cumulated tasks	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No
Detection	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	No	No	No
Communication...	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate	Adequate	Adequate	Inadequate	Inadequate
Navigation met...	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced	Traditional	Advanced
Fully	0.85	0.8	0.8	0.75	0	0	0	0	0.8	0.75	0.7	0.75	0	0	0	0
Partially	0.15	0.2	0.2	0.25	0.8	0.8	0.6	0.6	0.2	0.25	0.3	0.25	0.8	0.8	0.6	0.6
No	0	0	0	0	0.2	0.2	0.4	0.4	0	0	0	0	0.2	0.2	0.4	0.4

The situational awareness of the crew on the ship. This node is dependent on several other nodes. The probabilities are based on engineering judgment.

Technical failure

Technical redu...	Redundant	Redundant	Scarce	Scarce
Maintenance ro...	Followed	Not_followed	Followed	Not_followed
Yes	9e-07	1.5e-06	9e-06	1.5e-05
No	0.9999991	0.9999985	0.999991	0.999985

Technical failure is dependent on the 'Maintenance routine' and 'Technical redundancy'. The probabilities are based on (DNV, 2005).

Technical redundancy

Safety culture	Good	Poor
Redundant	0.9	0.7
Scarce	0.1	0.3

The overall redundancy of equipment on-board the ship. The probabilities are based on (DNV, 2005).

Upstream or downstream course

Upstream_going	0.5
Downstream_going	0.5

The distribution of the upstream and downstream going vessels. It is assumed that 50% go upstream and the other 50% downstream.

Visibility

Meteorlogical c...	Good	Bad
Good	1	0.85
Bad	0	0.15

Visibility is dependent on 'Meteorological conditions'. The probabilities are based on (DNV, 2005).

Voyage preparation

Safety culture	Good	Poor
Good	0.99	0.9
Bad	0.01	0.1

The voyage preparation indicates the quality of the passage planning, this node has more effect on grounding than on ship collision. So the probabilities are based on (DNV, 2005) and engineering judgement.

Waterway complexity

Visibility	Good	Bad
Difficult	0.01	0.2
Manageable	0.99	0.8

The complexity of the waterway experienced, which is dependent on the visibility. The probabilities are based on engineering judgment.

B.3: Discussion

From the ship collisions frequency calculation a ship collision frequency of 0.02 per year was determined which corresponds with a ship collision once every 50 years. From the BBN calculation a ship collision of 0.72 per year was determined which corresponds with a ship collision once every 1.4 years. The ship collision frequency from the BBN calculations is unrealistically high and cannot be used. The reason that the frequency from the BBN calculation is so high is because the model was originally used for ship groundings. Ship groundings occur fairly frequently and it shows in the model results.

For this thesis the result from paragraph B.1 (ship collision frequency) is used as the value for ship collision frequency. The data that was used for the ship collision frequency was data over a 10 year span. The current Meuse weirs exist for 100 years, since no data was found on the amount of significant ship collisions with the Meuse weirs over those 100 years, a lower limit ship collision frequency can also be used for the analysis in this thesis. The data that was used showed 2 significant ship collisions for 10 weirs over 10 years, this would be the upper limit. The lower limit would be 2 significant ship collisions for 10 weirs over 100 years. So an upper limit ship collision frequency of 0.02 per year (2.28E-06/hour) and a lower limit collision frequency of 0.002 per year (2.28E-07/hour).

Appendix C: Python script example case maintenance cost

The calculations for the equivalent annual maintenance costs from the research methodology are shown in this appendix. Screenshots of the Python script are presented as figures and explained. The explanation is only given for the first weir alternative, since the calculations of the second weir alternative are identical. The only difference are the input values.

```
#Weir 1
def Weir1():
    r = 0.016 #Discount rate
    life = 100 #Lifespan [years]
    A = r*(1+r)**life/((1+r)**life-1) #Annuity factor

    mfg = 25 #Maintenance interval gates (years)
    mfps = 10 #Maintenance interval power supply (years)

    cfg = 250000 #Maintenance cost gate / unit
    cfps = 10000 #Maintenance cost power supply / unit

    ufg = 3 #Failure gate units
    ufps = 1 #Failure power supply units
```

Figure 82: Example case input values maintenance cost (weir 1)

Figure 82 shows the function definition and input values. The annuity factor is calculated in the same figure, this parameter is used for the calculation of the maintenance cost.

```
#Calculation

MG = life//mfg #amount of maintenance performed for the gates over the life time
MPS = life//mfps #amount of maintenance performed for the power supply over the life time

pwMfg = np.zeros(MG) #list of present worth factors for the maintenance of gates
pwMfps = np.zeros(MPS) # list of present wort factors for the maintenance of power supply

for a in np.arange(len(pwMfg)):
    pwMfg[a] = 1/(1+r)**(mfg*(a+1))
for b in np.arange(len(pwMfps)):
    pwMfps[b] = 1/(1+r)**(mfps*(b+1))

mcMfg = sum(cfg*ufg*pwMfg)*A #Equivalent annual cost for the maintenance of gate
mcMfps = sum(cfps*ufps*pwMfps)*A #Equivaent annual cost for the maintenance of power supply

Maintenance_cost = mcMfg+mcMfps
```

Figure 83: Example case maintenance cost calculation (weir 1)

The equivalent annual maintenance cost is calculated in figure 83. First the amount of maintenance performed over the weirs lifespan is calculated by dividing the life time using a floor division with the maintenance interval. This is done for both weir components. The present worth factor for each weir component is calculated for each time maintenance is performed for that component. This is done by first creating an array of zeros with the length of the amount of maintenance performed for each weir component. So if the life span is 100 years and a weir component is maintained every 40 years. This means maintenance is performed twice over the weirs life span. So the length of the array of zeros is two. A loop is written for each weir component that calculates the present worth factor and replaces the zeros in the arrays. So now the arrays consist of present worth factors that corresponds with the time of maintenance. The equivalent annual maintenance cost for each component is calculated by summing the present worth factors and multiplying them by the amount of units and maintenance cost for each component and the annuity factor. The equivalent annual maintenance costs per component are summed.

```
d = dict()
d['EAC gates [€/year]'] = [mcMfg]
d['EAC power supply [€/year]'] = [mcMfps]
d['EAC total [€/year]'] = [Maintenance_cost]

return d
```

Figure 84: Example case Python output (weir 1)

Figure 84 shows the output of the Python script, it gives the equivalent annual maintenance costs for the gates, power supply and the sum of both the gates and power supply.

The script for weir 2 is identical except for some input values.

```
#Weir 2
def Weir2():
    r = 0.016 #Discount rate
    life = 100 #Lifespan [years]
    A = r*(1+r)**life/((1+r)**life-1) #Annuity factor

    mfg = 25 #Maintenance interval gates (years)
    mfps = 10 #Maintenance interval power supply (years)

    cfg = 250000 #Maintenance cost gate / unit
    cfps = 10000 #Maintenance cost power supply / unit

    ufg = 4 #Failure gate units
    ufps = 1 #Failure power supply units

    #Calculation
    MG = life//mfg
    MPS = life//mfps

    pwMfg = np.zeros(MG) #List of present worth factors for the maintenance of gates
    pwMfps = np.zeros(MPS) # List of present wort factors for the maintenance of power supply

    for a in np.arange(len(pwMfg)):
        pwMfg[a] = 1/(1+r)**(mfg*(a+1))
    for b in np.arange(len(pwMfps)):
        pwMfps[b] = 1/(1+r)**(mfps*(b+1))

    mcMfg = sum(cfg*ufg*pwMfg)*A #Equivalent annual cost for the maintenance of gate
    mcMfps = sum(cfps*ufps*pwMfps)*A #Equivaent annual cost for the maintenance of power supply

    Maintenance_cost = mcMfg+mcMfps

    d = dict()
    d['EAC gates [€/year]'] = [mcMfg]
    d['EAC power supply [€/year]'] = [mcMfps]
    d['EAC total [€/year]'] = [Maintenance_cost]

    return d
```

Figure 85 Example case weir 2 script

Appendix D: Fault tree analysis

This appendix shows the fault trees from chapter 9 with all the failure mechanisms. In chapter 2 the weir functions were introduced. For these functions a functional analysis was performed based on the report for the preliminary designs of the next weir in Grave (Rijkswaterstaat, 2021b). The functional analysis can be found in chapter 8. In the same chapter the functional requirements were determined using the functional analysis. From the functional requirements the functional failure criteria were determined and further elaborated to determine the top undesired event for each function for each weir alternative as presented in the tables below. The top undesired events serve as the top events of the fault trees.

Table 31: Top undesired event for each function (lift gate alternative)

Functions	**I.D.**	**TUE**
Retention of water	TUE 1.L	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.L	At least one of the headgates of the weir fails to open.
Ship passage	TUE 3	At least one of the headgates of the weir fails to open.

Table 32: Top undesired event for each function (radial gate alternative)

Functions	**I.D.**	**TUE**
Retention of water	TUE 1.R	At least one of the flow-through openings of the weir cannot be closed.
Discharge of water	TUE 2.R	At least one of the headgates of the weir fails to open.

For TUE 1.L and TUE 1.R a key detail is left out because of the short description of the events. If a component needs repairs, for example the headgate. Dewatering structures are placed to temporarily retain water. Technically this would mean that during repairs that flow-through opening is closed, however as long as the weir cannot close the opening by itself it is considered failure.

The top undesired event TUE 2.L and TUE 3 can be described by the same fault tree, because the description of both events are the same. So in total there are 4 unique fault trees (two for the lift gate alternative and two for the radial gate alternative).

The failure rates in the coming paragraphs are based on RAMS-analyses by (Iv-Infra, 2010a) and the Rijkswaterstaat database (Rijkswaterstaat, 2016). The failure rates are assumed to be based on a preventive maintenance strategy with a moderate maintenance plan. The failure events in the fault trees are independent of each other.

D.1 Failure water retention, lift gate alternative (TUE 1.L)

The failure of the water retention function for the lift gate alternative is covered in this paragraph, with TUE 1.L as the top event of the fault tree. This means that the weir fails if one or more control flap gates or headgates cannot be opened. The figure below shows the fault tree for this undesired event.

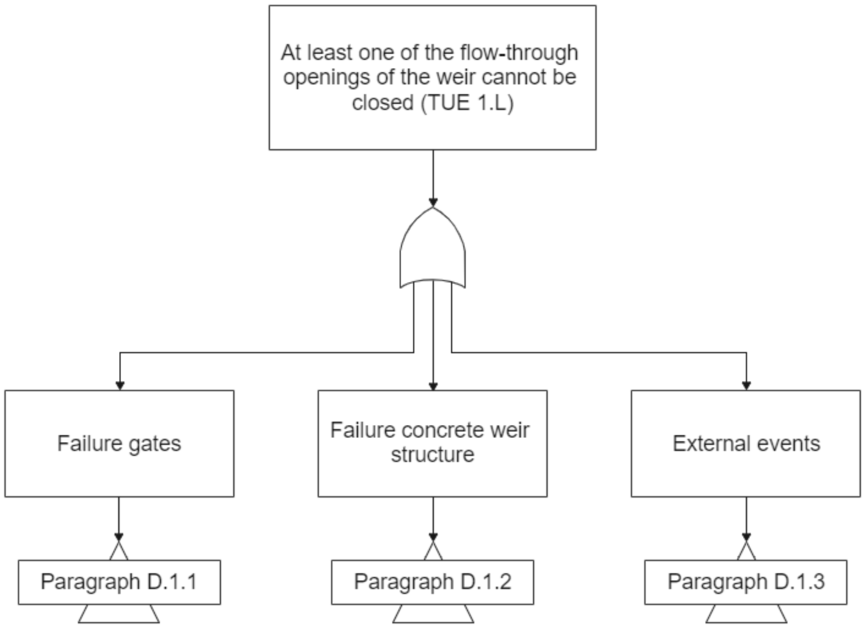

Figure 86: Failure water retention function, lift gate alternative (TUE 1.L)

Each failure event is explained in the following paragraphs.

D.1.1 Failure gates TUE 1.L

The event “Failure gates” takes the events that lead to the gates not being able to close (figure 87). The lift gate alternative consists of two gates. If either one of the gates fail it will lead to failure of the system. The failure of the power supply is also taken into account, if there is no power none of the gates can be operated.

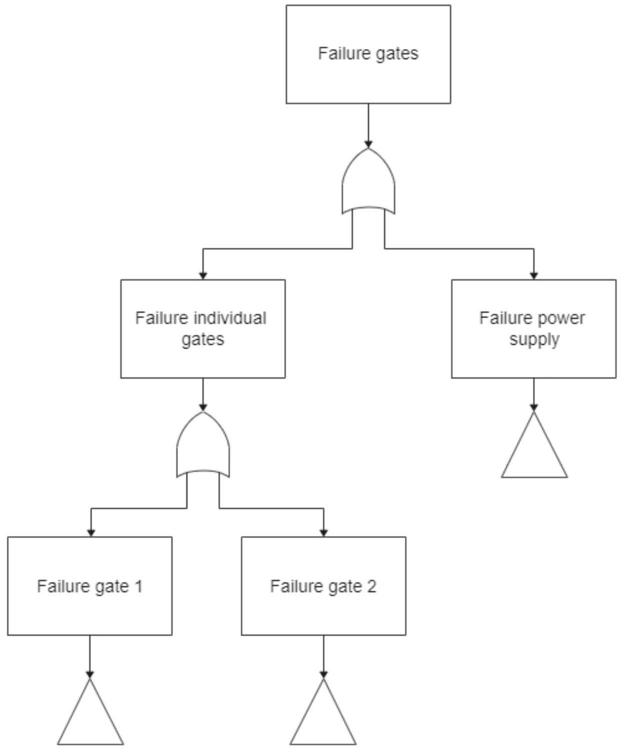

Figure 87: Failure gates TUE 1.L

Failure individual gates

The two gates are identical so only one fault tree will be presented for the individual gates. The failure of each gate consists of the steel structure failing, the movement works failing (hydraulic cylinders) or the hydraulic aggregates.

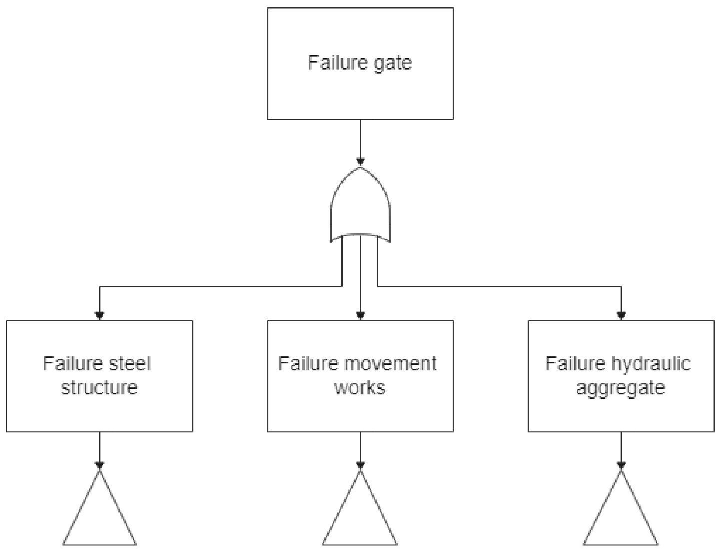

Figure 88: Failure individual gate TUE 1.L

Failure steel structure

The figure below shows the failure of the steel weir structure for the lift gate module. The lift gate module has two headgates, with two control flap gates attached to each headgate. If structural failure occurs to any of these components repairs have to be performed and the gates cannot operate.

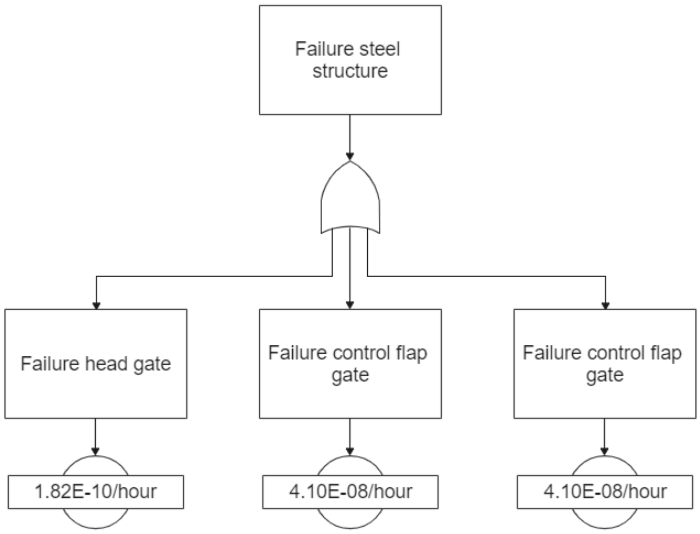

Figure 89: Failure of the steel structure TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Failure steel control flap gate (lift gate module)	4.10E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a). Constructief falen klep
Failure steel lift gate	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a). Constructief falen stuwschuif

Object/failure mechanism repairs	MTTR [hours]	Source
Failure steel control flap gate (lift gate module)	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen
Failure steel lift gate	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen

Failure movement works

For the lift gate module each control flap gate has three hydraulic cylinders and each lift gate has two hydraulic cylinders. If the movement works fail the gates cannot open or close.

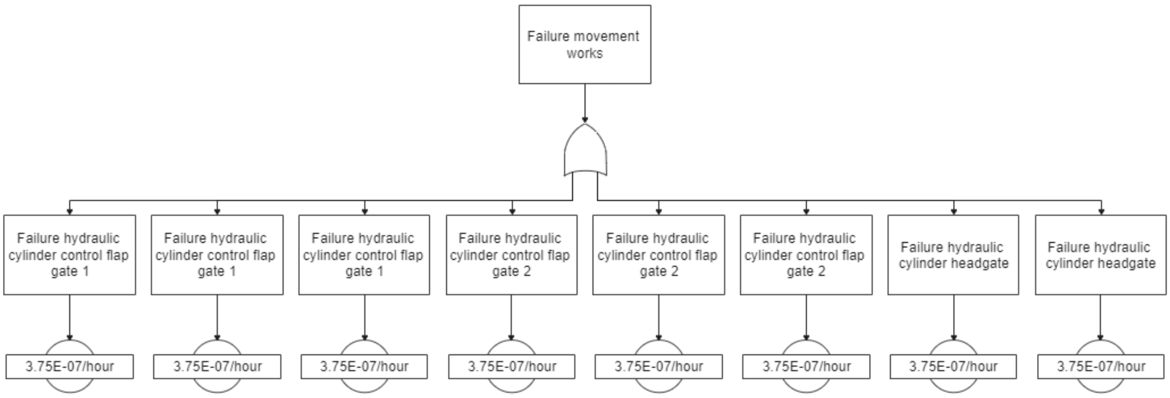

Figure 90: Failure movement works TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Failure hydraulic cylinder (flap gate, lift alternative)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert
Failure hydraulic cylinder (lift gate)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert

Object/failure mechanism	MTTR [hours]	Source
Failure hydraulic cylinder (flap gate, lift alternative)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt
Failure hydraulic cylinder (lift gate)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt

Failure hydraulic aggregate

For the failure of the hydraulic aggregate only the pump/motor combination is considered (figure 91). Each headgate has two hydraulic aggregates, one on each side. And each hydraulic aggregate is provided with two pumps and electromotors. One of the benefits of using this set up is that in the case that one of the pumps or electromotors stops working the other set can take over and perform at half the speed (Rijkswaterstaat, 2021b). As mentioned in chapter 7, hydraulic aggregates provide pressure in the hydraulic cylinders for both the headgates and the control flap gates by pumping oil. If the hydraulic aggregates fail the hydraulic cylinders do not move.

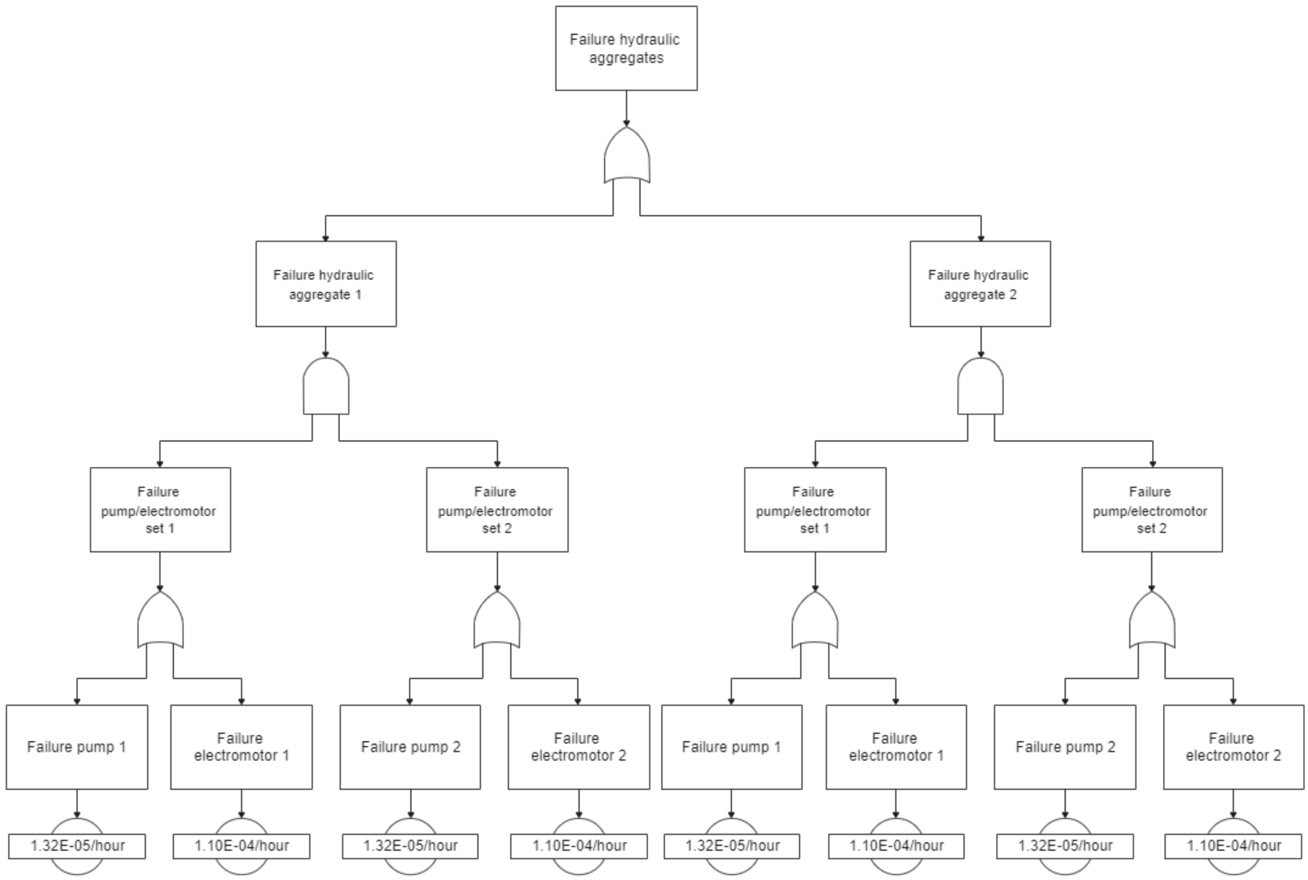

Figure 91: Failure hydraulic aggregates TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Failure pump	1.32E-05	RWS faaldatabase (T-BOOK 6th edition) Pomp, hydraulisch; start niet (stand-by)
Failure electrical motor	1.10E-04	RWS faaldatabase (Egg-SSRE 8875) Motor, elektrische motor; stopt voortijdig (stand-by)

Object/failure mechanism repairs	MTTR [hours]	Source
Failure pump	168	RAMS-analysis weir Belfeld (Iv-infra, 2010d) Failure hydraulic aggregate
Failure electrical motor	168	RAMS-analysis weir Roermond (Iv-Infra, 2010a). Falen elektromotor

Failure power supply

The power supply failure mechanism occurs when there is no power available. If there is no power none of the gates can be operated. The weir having no power occurs when both the power grid shuts down and the emergency power supply fails. The emergency power supply is only switched on once the power grid shuts down, this is also known as cold standby. The only formula for cold standby that was found is based on two identical components. Since the events "power grid shutdown" and "Failure emergency power supply" are not identical, the cold standby is approximated with an 'and-gate' in figure 92.

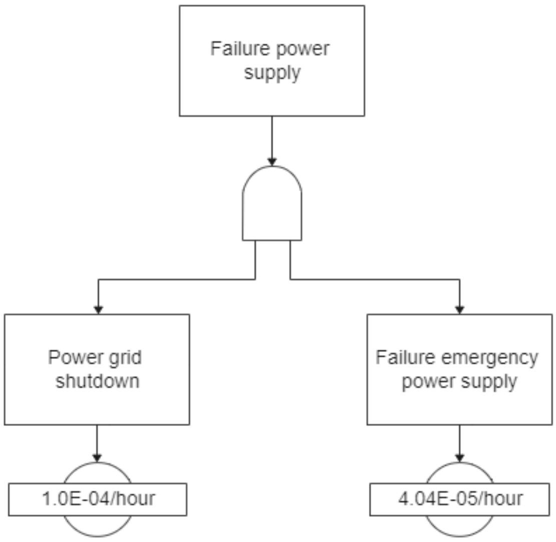

Figure 92: Failure power supply TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Power grid shutdown	1.0E-04	RWS faaldatabase (VDEN-86) Openbaar elektriciteitsnet; valt uit (in bedrijf)
Failure emergency power supply	4.04E-05	RAMS-analysis weir Lith (Iv-Infra, 2010a). Generator diesel; Start niet (stand-by)

Object/failure mechanism repairs	MTTR [hours]	Source
Power grid shutdown	1.5	RAMS-analysis weir Lith (Iv-Infra, 2010a). Uitvallen energienet
Failure emergency power supply	24	RAMS-analysis weir Lith (Iv-Infra, 2010a). Falen noodstroomvoorziening

D.1.2 Failure concrete weir structure TUE 1.L

The structural failure of the weir consists of the failure of the lifting tower structures. The concrete structures are the main load carriers of the weir and facilitate the gates and MEI. Even though they do not serve any specific weir function, they facilitate weir components that serve the weir functions.

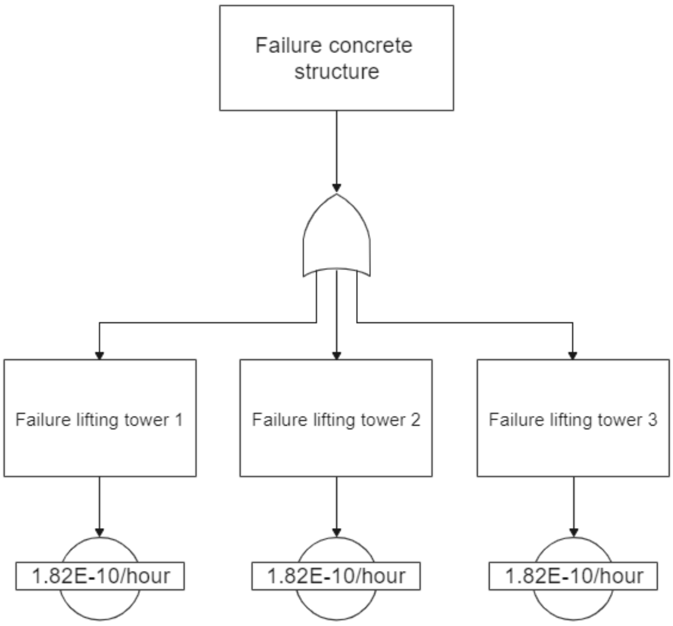

Figure 93: Failure concrete weir structure TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Failure lifting tower	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a). Falen hoofddraagconstructie

Object/failure mechanism repairs	MTTR [hours]	Source
Failure lifting tower	4380	RAMS-analysis weir Linne (Iv-Infra, 2010a). Falen hoofddraagconstructie

D.1.3 External events TUE 1.L

There are three external events that are taken into account. Ship collision, ice formation and fire in the installation rooms. The fault tree corresponding with external events is illustrated in figure 94. A significant ship collision will severely damage the weir gates. Ice formation can also lead to significant damage to weir gates and the weir must be opened up completely. In this case the weir cannot retain water. Fire in the installation rooms can lead to severe damage to the electrical installations. These events can lead to weir gates not being operable or retain water.

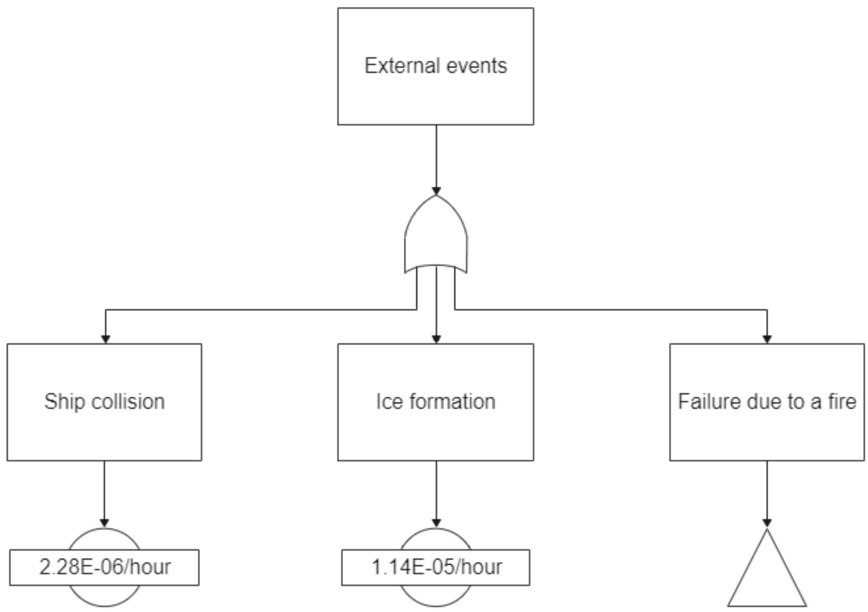

Figure 94: External events TUE 1.L

The calculation of the failure rate due to ship collision is done in appendix B. Significant ice formation is assumed to occur once every 10 years and lasts for two weeks (Iv-Infra, 2010a). The failure rate for fires in installation rooms in river piers is slightly larger than for fires in installation rooms in land piers, because the river piers facilitate two gates while the land piers only facilitate one gate. Since the river piers facilitate more gates there is more equipment that can catch on fire.

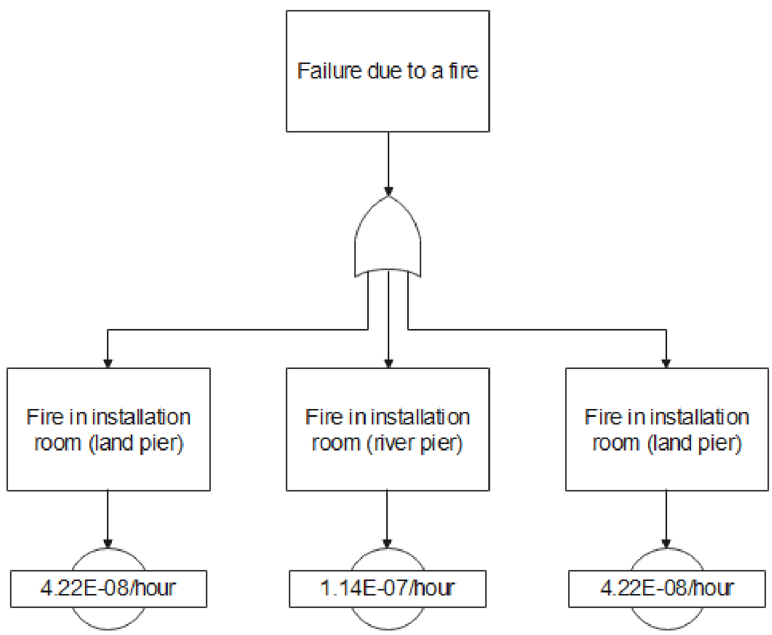

Figure 95: Failure due to a fire TUE 1.L

Object/failure mechanism	Failure rate [1/hour]	Source
Ship collision	2.28E-06	Appendix B
Ice formation	1.14E-05	RAMS-analysis weir Lith (Iv-Infra, 2010a). Ijsgang
Fire in installation room (abutment)	4.22E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in landheftoren
Fire in installation room (in river)	1.14E-07	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in rivierheftoren

Object/failure mechanism repairs	MTTR [hours]	Source
Ship collision	6570	Reparatie stuw Linne na aanvaring (Rijkswaterstaat, 2020b)
Ice formation	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Ijsgang
Fire in installation room (abutment)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningsruimte
Fire in installation room (in river)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningstuimte

D.2 Failure discharge of water and ship passage (TUE 2.L and TUE 3)

In figure 96 the fault tree for TUE 2.L and TUE 3 (At least one of the headgates of the weir fails to open) is shown. There are two differences between the fault trees for TUE 1.L and the fault tree for TUE 2.L and TUE 3. The first difference between these top undesired events and TUE 1.L lies in the gates. While TUE 1.L takes both the headgates and control flap gates into account, the TUE 2.L and TUE 3 focus solely on the headgates. The differences are in the individual gates, specifically the failure of the steel structure and failure of the movement works. The other difference is in the external events. Ice formation is not a concern, since the weir already has to open. So in the next paragraph only the these failure mechanisms are shown as the other failure mechanisms are the same. The failure of the concrete weir structure is the same between TUE 1.L and TUE 2.L/3.

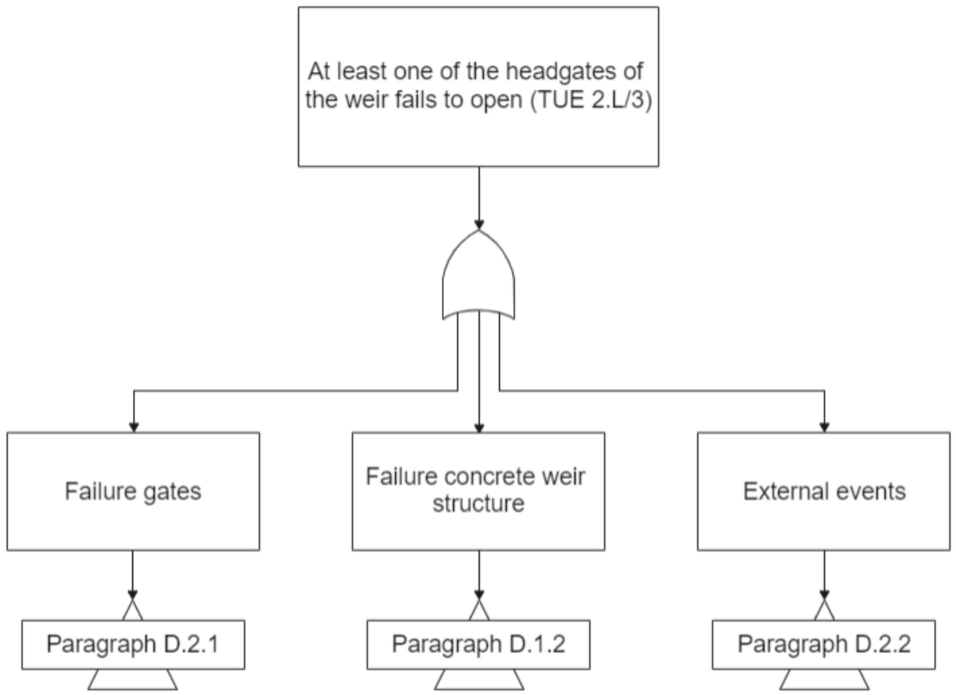

Figure 96: Failure discharge of water function and ship passage function, lift gate alternative (TUE 2.L and TUE 3)

D.2.1 Failure gates TUE 2.L and TUE 3

As mentioned in the previous paragraph, the only difference between the TUE 1.L, and TUE 2.L and TUE 3 lies in the difference in the failure of the steel structure and the failure of the movement works. Only the headgates are taken into account for the TUE 2.L and TUE 3.

Failure steel structure

The figure below shows the failure of the steel weir structure for the lift gate module. Only the headgate is taken into account. If structural failure occurs to the headgate repairs have to be performed and the gates cannot operate.

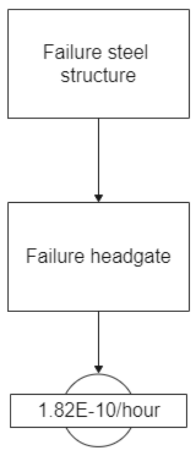

Figure 97: Failure of the steel structure TUE 2.L and TUE 3

Object/failure mechanism	Failure rate [1/hour]	Source
Failure steel lift gate	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a). Constructief falen stuwschuif

Object/failure mechanism repairs	MTTR [hours]	Source
Failure steel lift gate	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen

Failure movement works

For the lift gate module each control flap gate has three hydraulic cylinders and each lift gate has two hydraulic cylinders. If the movement works fail the gates cannot open or close.

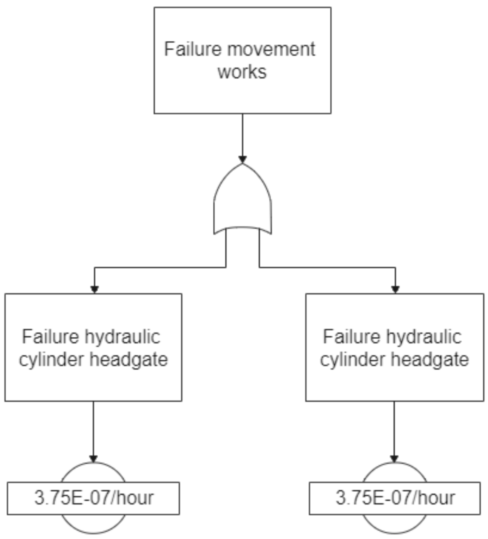

Figure 98: Failure movement works TUE 2.L and TUE 3

Object/failure mechanism	Failure rate [1/hour]	Source
Failure hydraulic cylinder (lift gate)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert

Object/failure mechanism	MTTR [hours]	Source
Failure hydraulic cylinder (lift gate)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt

D.2.2 External events TUE 2.L and TUE 3

As explained in paragraph D.2 ice formation is not a concern for these functions. There are only two external events that are taken into account. Ship collision and fire in the installation rooms. The fault tree corresponding with the failure due to external events is illustrated in the figure below.

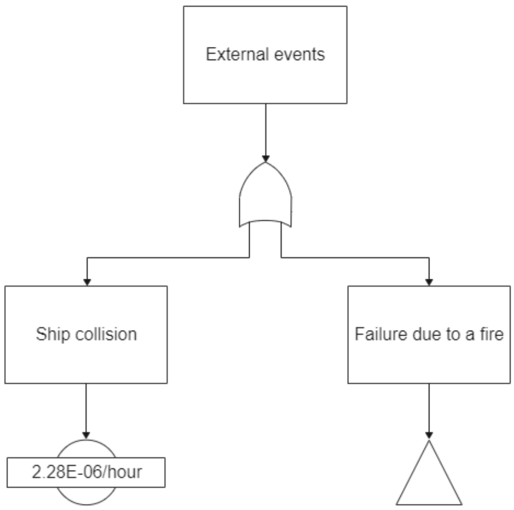

Figure 99: External events TUE 2.L and TUE 3

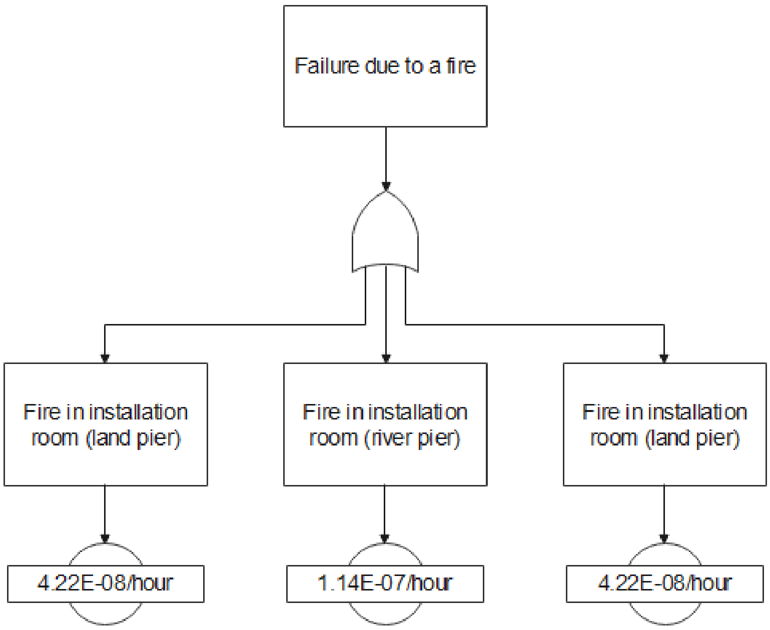

Figure 100: Failure due to a fire TUE 2.L and TUE 3

Object/failure mechanism	Failure rate [1/hour]	Source
Ship collision	2.28E-06	Appendix B
Fire in installation room (abutment)	4.22E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a).

		Brand in landheftoren
Fire in installation room (in river)	1.14E-07	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in rivierheftoren

Object/failure mechanism repairs	MTTR [hours]	Source
Ship collision	6570	Reparatie stuw Linne na aanvaring (Rijkswaterstaat, 2020b)
Fire in installation room (abutment)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningsruimte
Fire in installation room (in river)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningstuimte

D.3 Retention of water, radial gate alternative TUE 1.R

The failure of the water retention function for the radial gate variant is covered in this paragraph, with TUE 1.R as the top event of the fault tree. The top undesired event goes: “At least one of the flow-through openings of the weir cannot be closed.”. This means that the weir fails if one or more control flap gates or headgates cannot be operated. The figure below shows the fault tree for this undesired event.

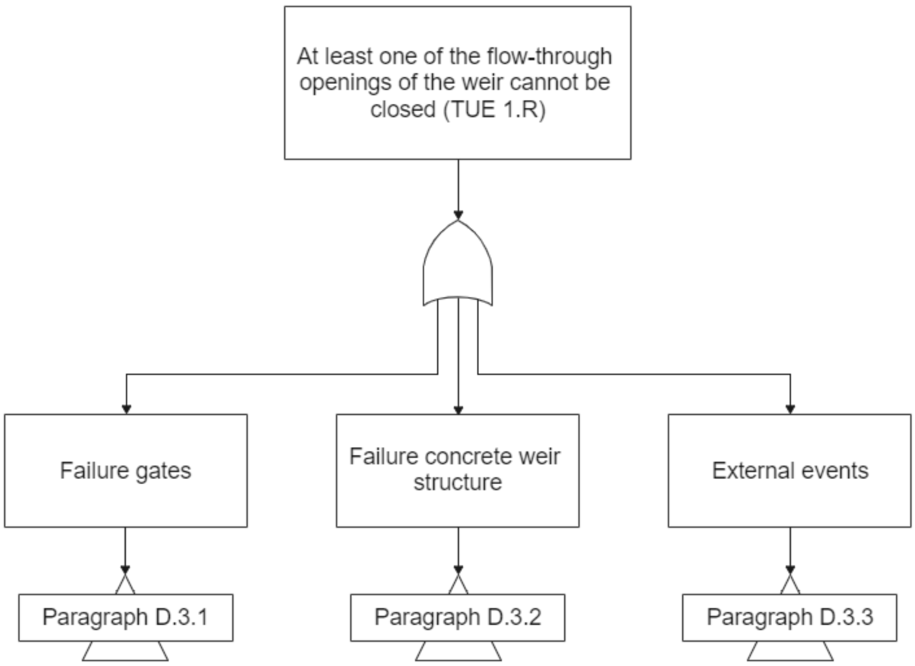

Figure 101: Failure water retention function, radial gate alternative (TUE 1.R)

D.3.1 Failure gates TUE 1.R

The event “Failure gates” takes the events that lead to the gates not being able to close. The radial gate alternative consists of four gates. If at least one of the four gates fail it will lead to failure of the system, this is denoted with an “OR-gate”. The failure of the power supply is also taken into account, if there is no power none of the gates can be operated.

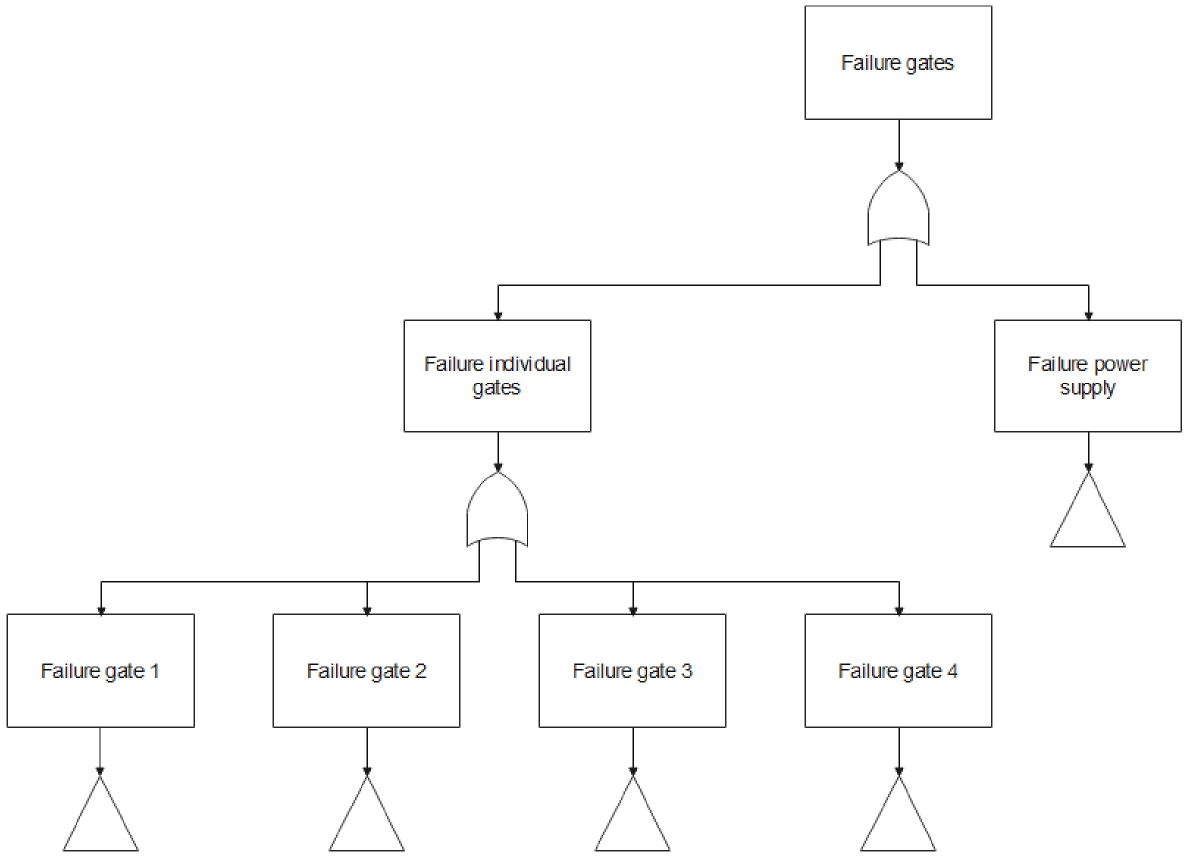

Figure 102: Failure gates TUE 1.R

Failure individual gates

The four individual gates are identical so only one fault tree will be presented for the individual gates. The failure of each gate consists of the steel structure failing, the movement works failing (hydraulic cylinders) or the hydraulic aggregates (figure 103).

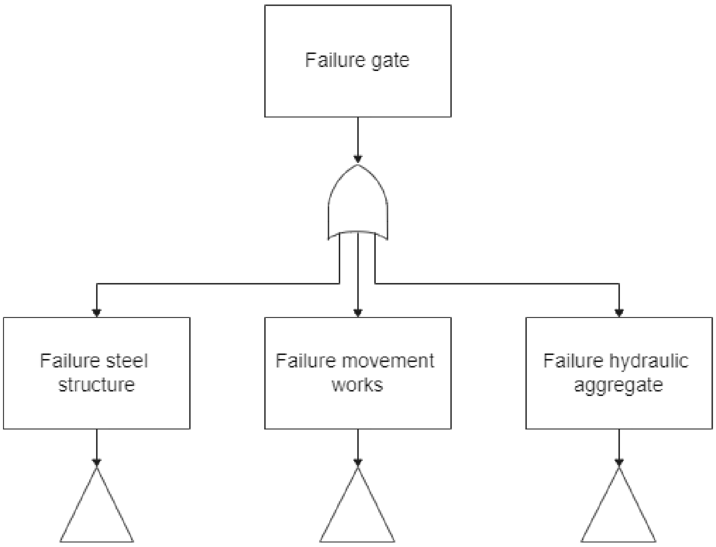

Figure 103: Failure individual gate TUE 1.R

Failure steel structure

The figure below shows the failure of the steel weir structure for the radial gate module. The radial gate module has four headgates, with one control flap gate attached to each headgate. If structural failure occurs to any of these components repairs have to be performed and the gates cannot operate.

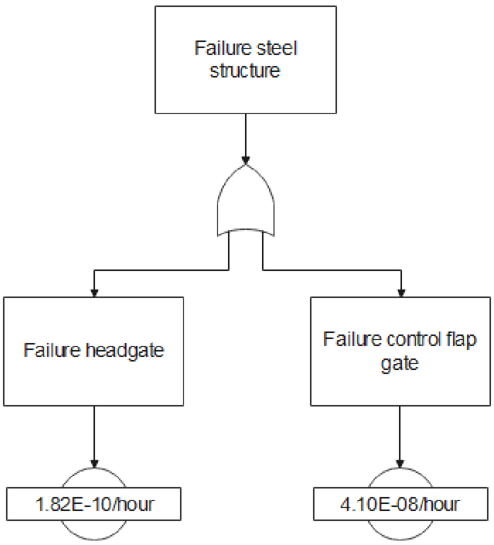

Figure 104: Failure of the steel structure TUE 1.R

Object/failure mechanism	Failure rate [1/hour]	Source
Failure steel control flap gate (radial gate module)	4.10E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a). Constructief falen klep
Failure steel radial gate	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a).

		Constructief falen stuwschuif

Object/failure mechanism repairs	MTTR [hours]	Source
Failure steel control flap gate (radial gate module)	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen
Failure steel radial gate	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen

Failure movement works

For the radial gate module each control flap gate has two hydraulic cylinders and each headgate has two hydraulic cylinders. If the movement works fail the gates cannot open or close.

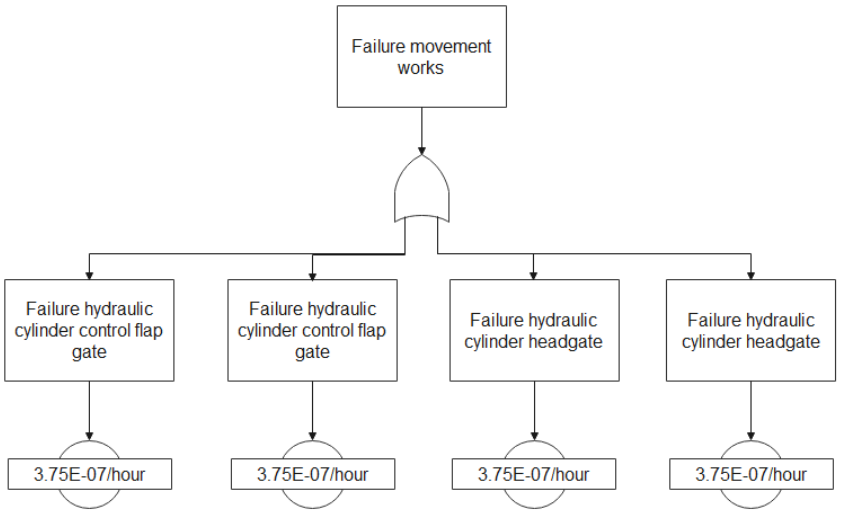

Figure 105: Failure movement works TUE 1.R

Object/failure mechanism	Failure rate [1/hour]	Source
Failure hydraulic cylinder (flap gate, radial alternative)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert
Failure hydraulic cylinder (radial gate)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert

Object/failure mechanism	MTTR [hour]	Source
Failure hydraulic cylinder (flap gate, radial alternative)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt
Failure hydraulic cylinder (radial gate)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt

Failure hydraulic aggregate

The hydraulic aggregates for the lift gate alternative and the radial gate alternative are the same. Thus the failure mechanisms are the same in both cases. The fault tree for the failure mechanism can be found in paragraph D.1.1.

Failure power supply

The power supply failure mechanism occurs when there is no power available. This is the same failure mechanism from paragraph D.1.1. There is no difference in the power supply between the lift gate alternative and radial gate alternative.

D.3.2 Failure concrete weir structure TUE 1.R

The structural failure of the weir consists of the failure of the pier structures. The concrete structures are the main load carriers of the weir and facilitate the gates and MEI. Even though they do not serve any specific weir function, they facilitate weir components that serve the weir functions.

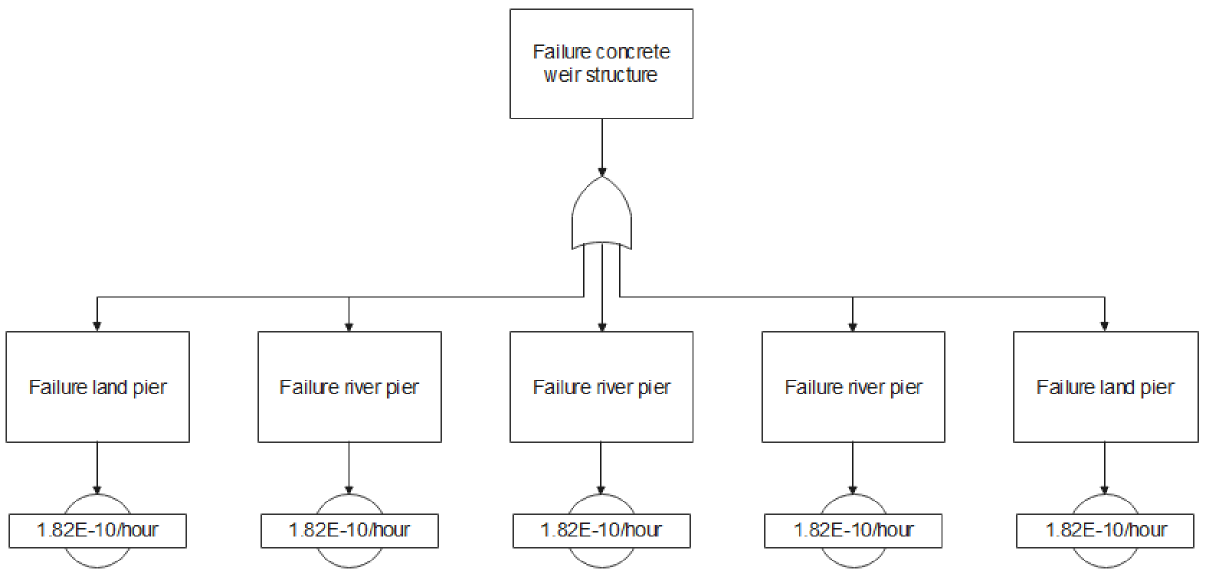

Figure 106: Failure concrete weir structure TUE 1.R

Object/failure mechanism	Failure rate [1/hour]	Source
Failure pier	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a). Falen hoofddraagconstructie

Object/failure mechanism repairs	MTTR [hours]	Source
Failure pier	4380	RAMS-analysis weir Linne (Iv-Infra, 2010a). Falen hoofddraagconstructie

D.3.3 External events TUE 1.R

The external events for the radial gate alternative are the same as the lift gate alternative from paragraph D.1.3. It also takes three external events: ship collision, ice formation and failure due to a fire. The only difference is in the 'failure due to a fire' failure mechanism, there are five piers for the radial gate alternative instead of three (figure 108).

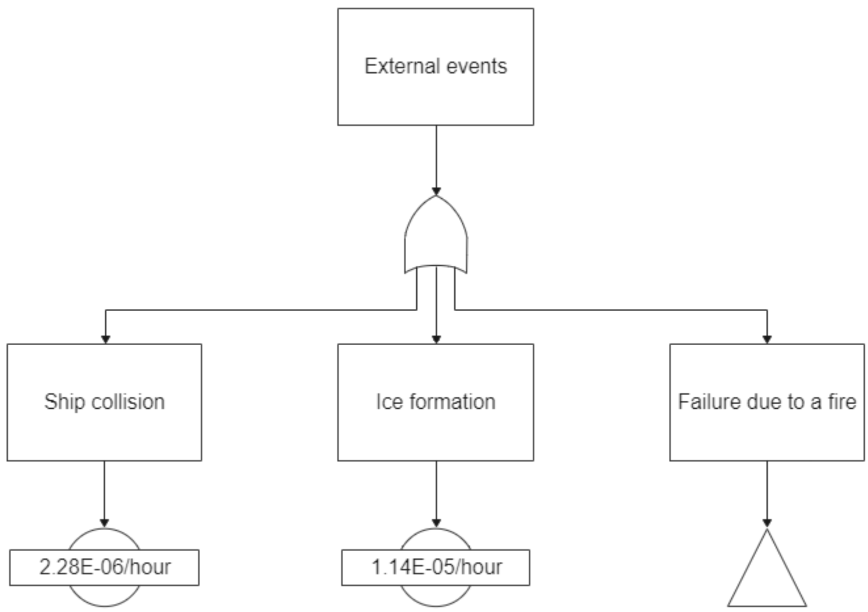

Figure 107: External events TUE 1.R

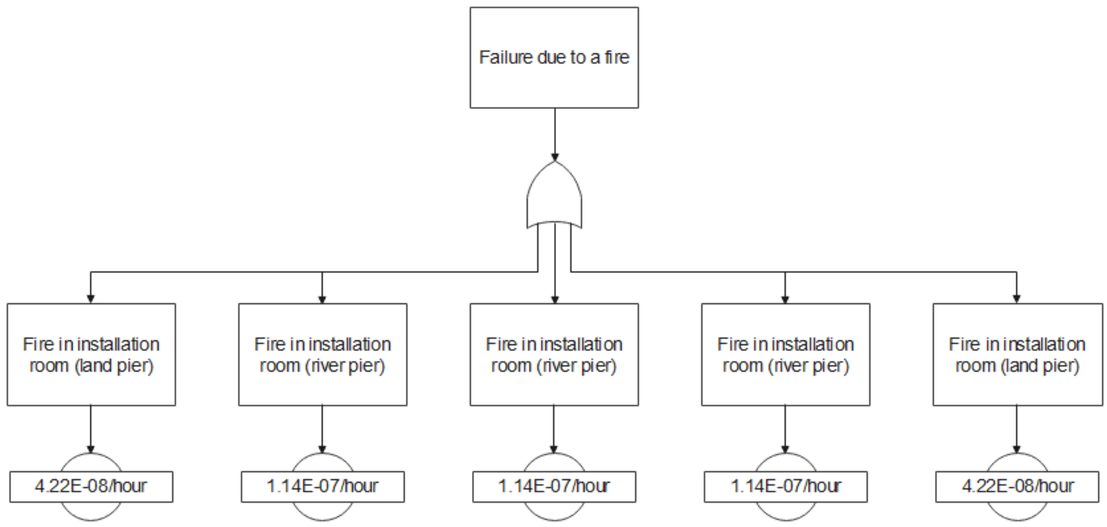

Figure 108: Failure due to a fire TUE 1.R

Object/failure mechanism	Failure rate [1/hour]	Source
Ship collision	2.28E-06	Appendix B
Ice formation	1.14E-05	RAMS-analysis weir Lith (Iv-Infra, 2010a). Ijsgang
Fire in installation room (abutment)	4.22E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in landheftoren
Fire in installation room (in river)	1.14E-07	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in rivierheftoren

Object/failure mechanism repairs	MTTR [hours]	Source
Ship collision	6570	Reparatie stuw Linne na aanvaring (Rijkswaterstaat, 2020b)
Ice formation	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Ijsgang
Fire in installation room (abutment)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningsruimte
Fire in installation room (in river)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningstuimte

D.4 Discharge of water, radial gate alternative TUE 2.R

In the figure below the fault tree for TUE 2.R (At least one of the headgates of the weir fails to open) is shown. There are two differences between the fault trees for TUE 1.R and the fault tree for TUE 2.R. The first difference between TUE 2.R and TUE 1.R lies in the gates. While TUE 1.R takes both the headgates and control flap gates into account, the TUE 2.R focus solely on the headgates. This is because for TUE 2.R the weir has to be opened up and only the headgates have to be operable. The differences are in the individual gates, specifically the failure of the steel structure and failure of the movement works. The other difference is in the external events. Ice formation is not a concern for TUE 2.R, since the weir already has to open. So in the next paragraph only the these failure mechanisms are shown as the other failure mechanisms are the same. The failure of the concrete weir structure is the same between the TUE 1.R and TUE 2.R.

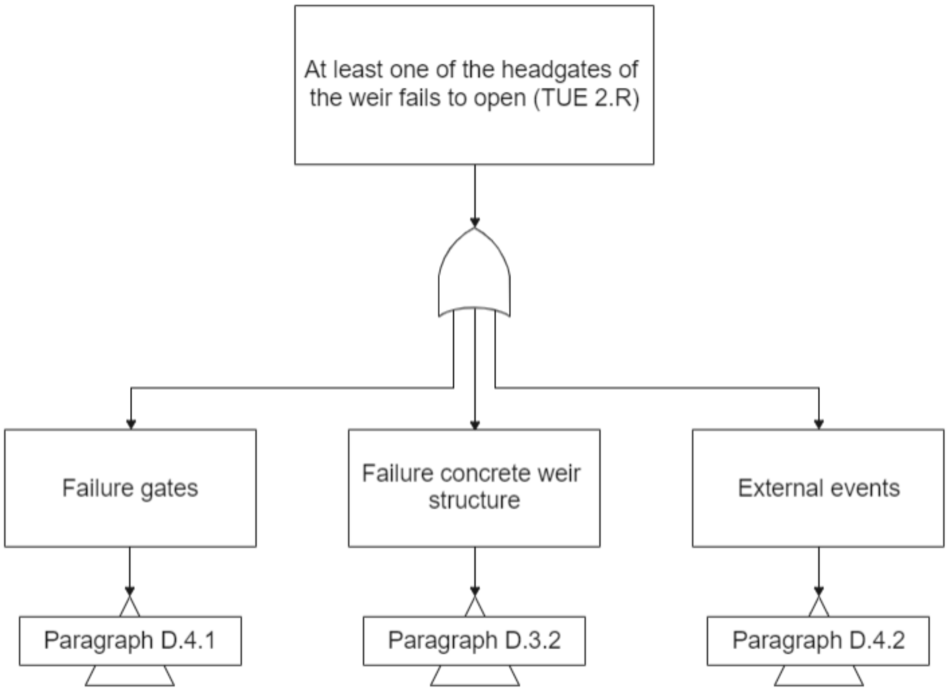

Figure 109: Failure discharge of water function, radial gate alternative (TUE 2.R)

D.4.1 Failure gates TUE 2.R

As mentioned in the previous paragraph the only difference between TUE 1.R and 2.R lies in the failure of the steel structure and the failure of the movement works and that is that only the headgates are taken into account for the TUE 2.R.

Failure steel structure

Figure 110 shows the failure of the steel weir structure for the lift gate module. Only the headgate is taken into account. If structural failure occurs to the headgate repairs have to be performed and the gates cannot operate.

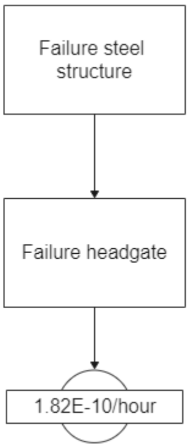

Figure 110: Failure of the steel structure TUE 2.R

Object/failure mechanism	Failure rate [1/hour]	Source
Failure steel radial gate	1.82E-10	RAMS-analysis weir Lith (Iv-Infra, 2010a). Constructief falen stuwschuif

Object/failure mechanism repairs	MTTR [hours]	Source
Failure steel radial gate	672	RAMS-analysis weir Roermond (Iv-infra, 2010c) Stuw schuif; constructief falen

Failure movement works

For the lift gate module each control flap gate has three hydraulic cylinders and each lift gate has two hydraulic cylinders. If the movement works fail the gates cannot open or close.

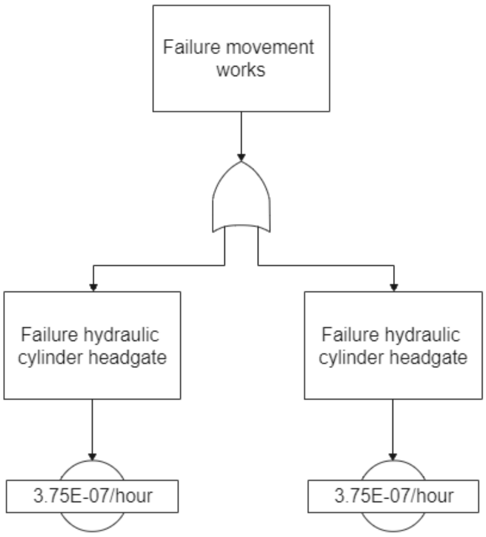

Figure 111: Failure movement works TUE 2.R

Object/failure mechanism	Failure rate [1/hour]	Source
Failure hydraulic cylinder (radial headgate)	3.75E-07	RWS faaldatabase (Wels, KEMA-40050). Cilinder, hydraulische cilinder; blokkeert

Object/failure mechanism	MTTR [hours]	Source
Failure hydraulic cylinder (radial headgate)	168	RAMS-analysis weir Linne (Iv-infra, 2010b) Tandwiel kast faalt

D.4.2 External events TUE 2.R

The ice formation is not a concern for these functions, so only two external events are taken into account. Ship collision and fire in the installation rooms. The fault tree corresponding with the failure due to external events is illustrated in the figure below. The fault tree for failure due to a fire is illustrated in figure 113.

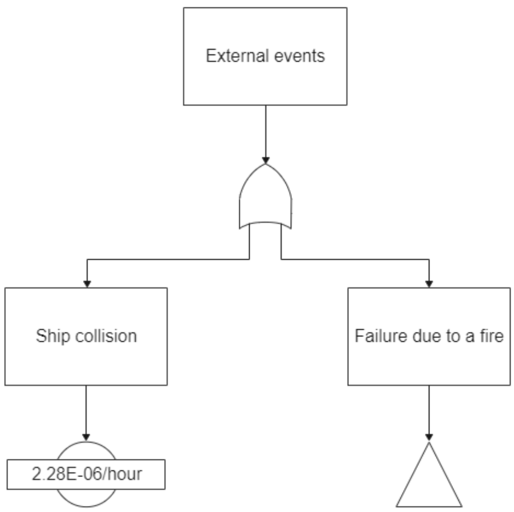

Figure 112: External events TUE 2.R

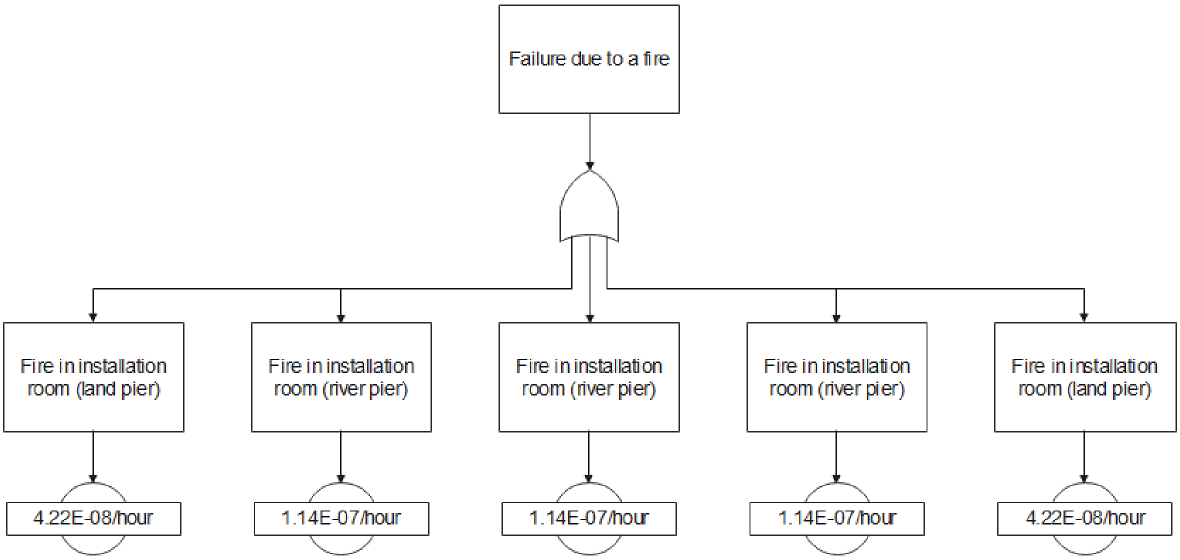

Figure 113: Failure due to a fire TUE 2.R

Object/failure mechanism	Failure rate [1/hour]	Source
Ship collision	2.28E-06	Appendix B
Fire in installation room (abutment)	4.22E-08	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in landheftoren
Fire in installation room (in river)	1.14E-07	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in rivierheftoren

Object/failure mechanism repairs	MTTR [hours]	Source
Ship collision	6570	Reparatie stuw Linne na aanvaring (Rijkswaterstaat, 2020b)
Fire in installation room (abutment)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningsruimte
Fire in installation room (in river)	336	RAMS-analysis weir Lith (Iv-Infra, 2010a). Brand in bedieningstuimte

Appendix E: Input values

This chapter is on the input values that were used in the model. Each paragraph goes over the input the input values that were used to determine the availability (paragraph E.1), the cost due to maintenance (paragraph E.2), the cost due to weir failure (paragraph E.3) and the scheduled downtime (paragraph E.4).

E.1 Availability

The availability is calculated with the time to failure (inverse of the failure rate) and the time to repair (MTTR). The MTTR and failure rate for each failure mechanism are listed in the table below.

For certain components the failure rate differs between corrective maintenance and preventive maintenance. In the case of corrective maintenance no maintenance is performed until the system fails, in which case the failing components are either repaired or replaced. In the case of preventive maintenance components are replaced before they fail, or maintenance measures are performed to extend the components life span (for example the gates). The components that have their life span extended by maintenance have a lower failure rate under preventive maintenance than under corrective maintenance, since under corrective maintenance no life extending maintenance is performed. These components have a higher failure rate under corrective maintenance.

Under corrective maintenance no maintenance is performed unless failure occurs, however for the failure of the concrete structure preventive maintenance must be performed even under corrective maintenance. The reason being that the consequences of failure of the concrete structure is extremely severe. Failure of the concrete structure must be avoided and thus the concrete structure cannot be correctively maintained, but must be maintained preventively.

Certain failure mechanisms are external events such as ship collision. Those events cannot be prevented.

Table 33: Input values to calculate availability

Failure mechanism	Repair measure	MTTR [hours]	Failure rate (preventive) [1/hour]	Failure rate (corrective) [1/hour]
Failure headgates	Replacing headgate	672	1.82E-10	1.14E-06
Failure control flap gates	Replacing control flap gate	672	4.10E-08	1.14E-06
Failure movement works	Replacing hydraulic cylinder	168	3.75E-07	5.71E-06
Failure walls piers, lifting towers	Restoring concrete damage to pier/lifting tower	4380	1.82E-10	1.82E-10
Failure emergency power supply	Replacing emergency power supply	24	4.04E-05	4.04E-05
Power grid shutdown	Wait for power grid to get back up	1.5	1.00E-04	1.00E-04
Failure pump (hydraulic aggregate)	Replacing pump	168	1.32E-05	1.32E-05
Failure electric motor (hydraulic aggregate)	Replacing electric motor	168	1.10E-04	1.10E-04
Fire installation rooms (land)	Replacing electrical installations	336	4.22E-08	4.22E-08

Fire installation rooms (river)	Replacing electrical installations	336	1.14E-07	1.14E-07
Ship collision	Replace and repair weir components affected	6570	2.28E-06	2.28E-06
Ice formation	-	336	1.14E-05	1.14E-05

E.2 Costs due to maintenance

Under preventive maintenance the movement works and hydraulic aggregates are replaced and the steel weir structure is conserved. Damage to the concrete structure (lifting towers/piers) are restored under both preventive and corrective maintenance.

Replacement hydraulic cylinders

The replacement cost of a hydraulic cylinder is based on the replacement cost of the electromechanical drive of the weir in Lith. The replacement of the electromechanical drive for all gates costs about € 2,000,000. The weir in Lith has three gates so that is about € 650,000 per gate. With an estimate that a gate needs about 4 hydraulic cylinders (2 for the headgate and 2 for the control flap gate), the replacement of a single hydraulic cylinder comes out to about € 170,000.

Restore concrete damage

The cost for restoring concrete damage to the concrete lifting tower or pier is based on the cost of renovating the concrete lifting towers of the weir in Sambeek. The cost of renovation to all three lifting towers was € 750,000. So the cost of renovating a single concrete lifting tower/pier is assumed to be € 250,000.

Replacement steel weir structure

The conservation cost of the headgate is € 144,000 and the conservation cost of the control flap gate is € 74,000. These costs are the maintenance costs of the gates for the weir in Lith (Nebest, 2010). The headgates of the lift gate alternative are twice as large as the headgates of the radial gate alternative, so the conservation cost for the lift gate alternative is assumed to be twice as large (€ 288,000).

Replacement hydraulic aggregate

The hydraulic aggregate consists of a pump and a electromotor. The replacement cost of an electromotor is € 20,000, which is based on the weir in Sambeek. No replacement cost could be found for the pump, so the replacement cost of an electromotor was assumed. The replacement costs of electromotors and pumps are proportional to the amount of fluid that has to be pumped. Which in turn is proportional to the size of the gates. The lift gates are twice as large as the radial gates. So for the replacement costs of the individual electromotor and pump for the lift gate alternative € 20,000 is assumed. The replacement costs of the individual electromotor and pump for the radial gate alternative are assumed to be € 10,000. The hydraulic aggregates for both weir alternatives consists of two pumps and two electromotors.

Two tables are presented, the first table (table 34) are on the costs of maintenance under preventive maintenance, and the second table (table 45) are the costs of maintenance under corrective maintenance.

The maintenance frequencies are also presented in the tables below, these are based on the maintenance plans of the weir in Lith (Nebest, 2010).

Table 34: Costs of maintenance measures preventive maintenance

	Cost/unit [€/unit]		Frequency [1/year] (moderate)
Movement works			
Replace hydraulic cylinders	170,000	(Rijkswaterstaat, 2014)	1/40
Lifting tower/pier			
Concrete renovation concrete structure	250,000	(Rijkswaterstaat, 2014)	1/30
Steel weir structure			
Conserve headgates (radial gate)	144,000	(Nebest, 2010)	1/15
Conserve headgates (lift gate)	288,000		1/15
Conserve control flap gates	74,000	(Nebest, 2010)	1/15
Hydraulic aggregates			
Replace hydraulic aggregate (lift gate)	80,000	Based on replacement pump and electromotor	1/25
Replace hydraulic aggregate (radial gate)	40,000	Based on replacement pump and electromotor	1/25

Table 35: Costs of maintenance measures corrective maintenance

	Cost/unit [€/unit]		Frequency [1/year] (moderate)	Frequency [1/year] (intensive)
Lifting tower/pier				
Restore concrete damage	250,000	(Rijkswaterstaat, 2014)	1/30	1/10

E.3 Costs due to weir failure

Replacement hydraulic cylinders

The replacement cost of a hydraulic cylinder was covered in paragraph E.2.

Replacement steel weir structure

For the replacement cost of the headgate and the replacement cost of the control flap gate the conservation cost of each component was taken and tripled (the replacement costs are higher than the conservation costs, but replacement costs could not be found). The conservation costs were determined in the previous paragraph.

Replacement hydraulic aggregate

The replacement costs of an hydraulic aggregate was covered in paragraph E.2.

External events

For the repair cost of a ship collisions it is assumed that in the event of a ship collision a whole gate needs to be replaced (the headgate, control flap gates and hydraulic cylinders). For the lift gate alternative the costs are the sum of the replacement costs of one headgate, two control flap gates and eight hydraulic cylinders (each headgate has two hydraulic cylinders and each control flap gate has three hydraulic cylinders). For the radial gate alternative the costs are the sum of the replacement costs of one headgate, one control flap gates and four hydraulic cylinders. (each headgate has two hydraulic cylinders and each control flap gate for the radial gate alternative has two hydraulic cylinders).

The repair costs due to a fire in the installation rooms is based on the replacement costs of the hydraulic aggregate. Each hydraulic aggregate has two pumps and two electro motors. An abutment only has one hydraulic aggregate, because it only operates one gate. A river pier has two hydraulic aggregates, because it operates two gates.

Table 36: Repair costs for weir components

	Cost/unit [€/unit]
Movement works	
Replace hydraulic cylinders	170,000
Steel weir structure	
Replace headgates (lift gate)	900,000
Replace headgates (radial gate)	450,000
Replace control flap gates	225,000
Hydraulic aggregate	
Replace pump (lift gate)	20,000
Replace pump (radial gate)	10,000
Replace electromotor (lift gate)	20,000
Replace electromotor (radial gate)	10,000
External events	
Ship collision (lift gate)	2,710,000
Ship collision (radial gate)	1,805,000
Fire in installation room (river pier)	160,000
Fire in installation room (abutment)	80,000

E.4 Scheduled downtime

The scheduled downtime is determined with the maintenance interval and maintenance time of each maintainable component. The next paragraph goes over these parameters for both weir alternatives.

Maintenance gates

According to the maintenance plans of the weir in Lith the gates are maintained about every 15 years, depending on the damage on the gate surface (Nebest, 2010). This goes for both the headgates and control flap gates. The replacement time of an individual headgate or control flap gates is about 672 hours according to table 33. The maintenance time for an entire gate (headgate with control flap gate) is assumed to be half of the replacement time of a single headgate, so 336 hours.

There is a difference for the maintenance times of the lift gate alternative and the radial gate alternative. Since a lift gate (50 m span) has twice the span of a single radial (25 m span). So the maintenance time for a lift gate is assumed to be twice as long as the maintenance time for a radial gate (672 hours).

Maintenance movement works

The movement works consist of hydraulic cylinders, which are supposed to be replaced every 40 years. The 40 years are based on the replacement interval of the electromechanical drive of the weir in Lith (Nebest, 2010).

The downtime for lubricating the lifting chains of the weir in Lith are 2 weeks per gate (Iv-Infra, 2010a). A large part of the maintenance time is the time it takes to prepare dewatering structures to create a workable environment at the weir gate. For the maintenance time of replacing hydraulic cylinders it is assumed that replacing the hydraulic cylinders of one gate of the radial gate alternative takes two weeks. Replacing the hydraulic cylinders of one gate of the lift gate alternative is assumed to be three weeks, since this alternative has larger gates.

Maintenance concrete structures

The maintenance of the concrete structure consists of restoring concrete damage to the piers/lifting towers. It is assumed that it takes 1 week to restore concrete damage to one lifting tower/pier.

Maintenance hydraulic aggregate

One hydraulic aggregate consists of two pumps and two electromotor, this is the case for both the lift gate alternative and the radial gate alternative. It is assumed that the maintenance time of a hydraulic aggregate is as long as the repair time of one pump and one electromotor, so 336 hours.

Table 37: Maintenance plan moderate

Maintenance object	**Maintenance measure**	**Interval [years]**	**MT [hours]**
Gates (headgates with control flap gates), radial gate	Conservation gate	15	336
Gates (headgates with control flap gates), lift gate	Conservation gate	15	672
Movement works, radial gate	Replacing hydraulic cylinders of one gate	40	336
Movement works, lift gate	Replacing hydraulic cylinders of one gate	40	504
Piers, lifting towers	Restoring concrete	30	168

	damage to piers and lifting towers		
Hydraulic aggregate	Replacing hydraulic aggregate	25	336

Appendix F: Python script maintenance strategy assessment tool

The calculations for the results in chapter 9 are shown in this appendix. The calculations are done in the same manner as explained in the research methodology. Screenshots of the Python script are presented as figures and explained. The explanation for the calculations is only given for the lift gate weir alternative (paragraph F.1), since the script for both weir alternatives follow the same calculations and structure. The only difference is in the input values and the structure of the fault trees. For the radial gate alternative only the screenshots are illustrated (paragraph F.2).

F.1 Python script lift gate alternative

```
#Lift gate weir alternative
def Weir1():

    r = 0.016 #Discount rate
    life = 100 #Lifespan [years]
    A = r*(1+r)**life/((1+r)**life-1) #Annuity factor
```

Figure 114: Function definition (lift alternative)

Figure 114 shows the function definition for the maintenance strategy assessment tool. The annuity factor is calculated in the same figure, this parameter is used for the calculation of the maintenance cost, which is done further down the script (figure 127).

```
#-----------------------Input units based on moderate maintenance plan-------------------------------------
#Maintenance interval in years
Failure_wall_lifting_tower_interval = 30
Failure_control_flap_gate_interval = 15
Failure_lift_gate_interval = 15
Failure_hydraulic_cylinder_flap_gate_interval = 40
Failure_hydraulic_cylinder_lift_gate_interval = 40
Failure_hydraulic_aggregate_interval = 25

#Failure rate/hour
Failure_wall_lifting_tower_rate = 1.82*10**-10
Failure_control_flap_gate_rate = 4.10*10**-8
Failure_lift_gate_rate = 1.82*10**-10
Ship_collision_rate = 2.28*10**-6
Ice_formation_rate = 1.14*10**-5
Failure_hydraulic_cylinder_flap_gate_rate = 3.75*10**-7
Failure_emergency_power_supply_rate = 4.04*10**-5
Power_grid_shutdown_rate = 10**-4
Fire_in_installation_room_land_rate = 4.22*10**-8
Fire_in_installation_room_river_rate = 1.14*10**-7
Failure_hydraulic_cylinder_lift_gate_rate = 3.75*10**-7
Failure_pump_lift_gate_rate = 1.32*10**-5
Failure_electrical_motor_lift_gate_rate = 1.10*10**-4

#TTR (hours)
Failure_wall_lifting_tower_TTR = 4380
Failure_control_flap_gate_TTR = 672
Failure_lift_gate_TTR = 672
Ship_collision_TTR = 6570
Ice_formation_TTR = 336
Failure_hydraulic_cylinder_flap_gate_TTR = 168
Failure_emergency_power_supply_TTR = 24
Power_grid_shutdown_TTR = 1.5
Fire_in_installation_room_land_TTR = 336
Fire_in_installation_room_river_TTR = 336
Failure_hydraulic_cylinder_lift_gate_TTR = 168
Failure_pump_lift_gate_TTR = 168
Failure_electrical_motor_lift_gate_TTR = 168

#Maintenance costs
Failure_wall_lifting_tower_Mcost = 250000
Failure_control_flap_gate_Mcost = 74000
Failure_lift_gate_Mcost = 288000
Failure_hydraulic_cylinder_flap_gate_Mcost = 170000
Failure_hydraulic_cylinder_lift_gate_Mcost = 170000
Failure_hydraulic_aggregate_Mcost = 80000
```

Figure 115: Input values based on a preventive maintenance strategy (1/2) (lift alternative)

```
#Repair costs
Failure_control_flap_gate_Rcost = 225000
Failure_lift_gate_Rcost = 900000
Ship_collision_Rcost = 2710000
Failure_hydraulic_cylinder_flap_gate_Rcost = 170000
Fire_in_installation_room_land_Rcost = 80000
Fire_in_installation_room_river_Rcost = 160000
Failure_hydraulic_cylinder_lift_gate_Rcost = 170000
Failure_hydraulic_aggregate_Rcost = 80000
Failure_pump_lift_gate_Rcost = 2000
Failure_electrical_motor_lift_gate_Rcost = 2000

#Units
Failure_wall_lifting_tower_units = 3
Failure_control_flap_gate_units = 4
Failure_lift_gate_units = 2
Ship_collision_units = 1
Failure_hydraulic_cylinder_flap_gate_units = 12
Failure_emergency_power_supply_units = 1
Power_grid_shutdown_units = 1
Fire_in_installation_room_land_units = 2
Fire_in_installation_room_river_units = 1
Failure_hydraulic_cylinder_lift_gate_units = 4
Failure_hydraulic_aggregate_units = 4
Failure_pump_lift_gate_units = 8
Failure_electrical_motor_lift_gate_units = 8

#Maintenance duration [hours]
MT_wall_lifting_tower = 168
MT_gate = 672
MT_hydraulic_cylinder = 504
MT_hydraulic_aggregate = 336
```

Figure 116: Input values based on a preventive maintenance strategy (2/2) (lift alternative)

The input values for the lift alternative are shown in figures 115 and 116. The failure rates and maintenance intervals are based on the moderate maintenance plan. These are the input values that were presented in appendix E. With the exception of the units. The units can be deduced from chapter 7.

```
#failure rate for corrective maintenance
Cor_Failure_wall_lifting_tower_rate = Failure_wall_lifting_tower_rate
Cor_Failure_control_flap_gate_rate = 1/(100*8760)
Cor_Failure_lift_gate_rate = 1/(100*8760)
Cor_Failure_hydraulic_cylinder_flap_gate_rate = 1/(40*8760)
Cor_Failure_hydraulic_cylinder_lift_gate_rate = 1/(40*8760)
Cor_Failure_pump_lift_gate_rate = Failure_pump_lift_gate_rate
Cor_Failure_electrical_motor_lift_gate_rate = Failure_electrical_motor_lift_gate_rate
```

Figure 117: Failure rates for a corrective maintenance strategy (lift alternative)

As explained in the research methodology, under both preventive maintenance and corrective maintenance components can still fail. The difference is that in the case of preventive maintenance the components are inspected in replaced according to a schedule, while under corrective maintenance the components are not inspected and are only replaced once the weir fails to fulfill one of its functions. This means that for components that are inspected and replaced under a schedule the failure rate is less than in the case that components are inspected. The failure rates presented in figure 117 come from appendix E.

```
#Non availability due to failure for each failure event (under preventive maintenance strategy)
Prev_NonAvailability_wall_lifting_tower = 1-((1/Failure_wall_lifting_tower_rate)/
                                    (Failure_wall_lifting_tower_TTR+1/Failure_wall_lifting_tower_rate))
Prev_NonAvailability_control_flap_gate = 1-((1/Failure_control_flap_gate_rate)/
                                    (Failure_control_flap_gate_TTR+1/Failure_control_flap_gate_rate))
Prev_NonAvailability_lift_gate = 1-((1/Failure_lift_gate_rate)/
                            (Failure_lift_gate_TTR+1/Failure_lift_gate_rate))
Prev_NonAvailability_Ship_collision = 1-((1/Ship_collision_rate)/
                                 (Ship_collision_TTR+1/Ship_collision_rate))
Prev_NonAvailability_Ice_formation = 1-((1/Ice_formation_rate)/
                                 (Ice_formation_TTR+1/Ice_formation_rate))
Prev_NonAvailability_hydraulic_cylinder_flap_gate = 1-((1/Failure_hydraulic_cylinder_flap_gate_rate)/
                                              (Failure_hydraulic_cylinder_flap_gate_TTR+1/
                                               Failure_hydraulic_cylinder_flap_gate_rate))
Prev_NonAvailability_emergency_power_supply = 1-((1/Failure_emergency_power_supply_rate)/
                                         (Failure_emergency_power_supply_TTR+1/Failure_emergency_power_supply_rate))
Prev_NonAvailability_Power_grid_shutdown = 1-((1/Power_grid_shutdown_rate)/
                                      (Power_grid_shutdown_TTR+1/Power_grid_shutdown_rate))
Prev_NonAvailability_Fire_in_installation_room_land = 1-((1/Fire_in_installation_room_land_rate)/
                                            (Fire_in_installation_room_land_TTR+1/Fire_in_installation_room_land_rate))
Prev_NonAvailability_Fire_in_installation_room_river = 1-((1/Fire_in_installation_room_river_rate)/
                                            (Fire_in_installation_room_river_TTR+1/Fire_in_installation_room_river_rate))
Prev_NonAvailability_hydraulic_cylinder_lift_gate = 1-((1/Failure_hydraulic_cylinder_lift_gate_rate)/
                                                  (Failure_hydraulic_cylinder_lift_gate_TTR+1/
                                                   Failure_hydraulic_cylinder_lift_gate_rate))
Prev_NonAvailability_Failure_pump_lift_gate = 1-((1/Failure_pump_lift_gate_rate)/
                                            (Failure_pump_lift_gate_TTR+1/Failure_pump_lift_gate_rate))
Prev_NonAvailability_Failure_electrical_motor_lift_gate = 1-((1/Failure_electrical_motor_lift_gate_rate)/
                                            (Failure_electrical_motor_lift_gate_TTR+1/
                                             Failure_electrical_motor_lift_gate_rate))
Prev_NonAvailability_hydraulic_aggregate = ((1-(1-Prev_NonAvailability_Failure_pump_lift_gate)*
                                           (1-Prev_NonAvailability_Failure_electrical_motor_lift_gate))**2)
```

Figure 118: Non-availability of each failure event under preventive maintenance (lift alternative)

In figure 118 the non-availability of each failure mechanism is calculated under preventive maintenance. This is done using the formula for availability presented in the research methodology and taking its inverse (NA = 1-A).

```
#Non availability due to failure for each failure event (under corrective maintenance strategy)
Cor_NonAvailability_wall_lifting_tower = 1-((1/Cor_Failure_wall_lifting_tower_rate)/
                                     (Failure_wall_lifting_tower_TTR+1/Cor_Failure_wall_lifting_tower_rate))
Cor_NonAvailability_control_flap_gate = 1-((1/Cor_Failure_control_flap_gate_rate)/
                                    (Failure_control_flap_gate_TTR+1/Cor_Failure_control_flap_gate_rate))
Cor_NonAvailability_lift_gate = 1-((1/Cor_Failure_lift_gate_rate)/
                           (Failure_lift_gate_TTR+1/Cor_Failure_lift_gate_rate))
Cor_NonAvailability_hydraulic_cylinder_flap_gate = 1-((1/Cor_Failure_hydraulic_cylinder_flap_gate_rate)/
                                             (Failure_hydraulic_cylinder_flap_gate_TTR+1/
                                              Cor_Failure_hydraulic_cylinder_flap_gate_rate))
Cor_NonAvailability_hydraulic_cylinder_lift_gate = 1-((1/Cor_Failure_hydraulic_cylinder_lift_gate_rate)/
                                                (Failure_hydraulic_cylinder_lift_gate_TTR+1/
                                                 Cor_Failure_hydraulic_cylinder_lift_gate_rate))
Cor_NonAvailability_Failure_pump_lift_gate = 1-((1/Cor_Failure_pump_lift_gate_rate)/
                                        (Failure_pump_lift_gate_TTR+1/Cor_Failure_pump_lift_gate_rate))
Cor_NonAvailability_Failure_electrical_motor_lift_gate = 1-((1/Cor_Failure_electrical_motor_lift_gate_rate)/
                                        (Failure_electrical_motor_lift_gate_TTR+1/
                                         Cor_Failure_electrical_motor_lift_gate_rate))
Cor_NonAvailability_hydraulic_aggregate = ((1-(1-Cor_NonAvailability_Failure_pump_lift_gate)*
                                        (1-Cor_NonAvailability_Failure_electrical_motor_lift_gate))**2)
```

Figure 119: Non-availability of each failure event under corrective maintenance (lift alternative)

In figure 119 the non-availability for each failure mechanism is calculated under corrective maintenance plan. Components that are not maintained have a larger failure rate, which leads to a smaller availability and thus a larger non-availability.

```
### Non availability under preventive maintenance strategy ##############################################################

### TUE 1.L (water retention function)####################################################################################

#Failure gates
Failure_steel_weir_structure_TUE1L_prev = (1-(1-Prev_NonAvailability_control_flap_gate)**2*
                                          (1-Prev_NonAvailability_lift_gate))

Failure_movement_works_flap_gate_prev =(1-(1-Prev_NonAvailability_hydraulic_cylinder_flap_gate)**6)

Failure_movement_works_lift_gate_prev = (1-(1-Prev_NonAvailability_hydraulic_cylinder_lift_gate)**2)

Failure_movement_works_TUE1L_prev = (1-(1-Failure_movement_works_flap_gate_prev)
                                    *(1-Failure_movement_works_lift_gate_prev))

Failure_hydraulic_aggregate_prev = (1-(1-Prev_NonAvailability_hydraulic_aggregate)**2)


Failure_gate_TUE1L_prev = (1-(1-Failure_steel_weir_structure_TUE1L_prev)*
                              (1-Failure_movement_works_TUE1L_prev)*
                        (1-Failure_hydraulic_aggregate_prev))

Failure_individual_gates_TUE1L_prev = (1-(1-Failure_gate_TUE1L_prev)**2)

Failure_power_supply_prev = ((Prev_NonAvailability_emergency_power_supply)*
                                (Prev_NonAvailability_Power_grid_shutdown))

Failure_gates_TUE1L_prev = (1-(1-Failure_individual_gates_TUE1L_prev)*
                               (1-Failure_power_supply_prev))

#Failure concrete weir structure
Failure_concrete_weir_structure_prev = (1-(1-Prev_NonAvailability_wall_lifting_tower)**Failure_wall_lifting_tower_units)

#External events
External_events_TUE1L = (1-(1-Prev_NonAvailability_Ship_collision)*
                        (1-Prev_NonAvailability_Ice_formation)*
                   (1-Prev_NonAvailability_Fire_in_installation_room_land)**Fire_in_installation_room_land_units*
                   (1-Prev_NonAvailability_Fire_in_installation_room_river)**Fire_in_installation_room_river_units)

#Nonavailability TUE 1.L
NonAvailability_TUE1L_prev = (1-(1-Failure_gates_TUE1L_prev)*
                              (1-Failure_concrete_weir_structure_prev)*
                              (1-External_events_TUE1L))
```

Figure 120: Non-availability calculation TUE 1.L preventive maintenance (lift alternative)

The non-availability of top undesired event TUE 1.L “At least one of the flow-through openings of the weir cannot be closed” is calculated under preventive maintenance in figure 120. The fault tree structure from appendix D was used.

```
### Non availability under corrective maintenance strategy ##############################################################
### TUE 1.L (water retention function)####################################################################################

#Failure gates
Failure_steel_weir_structure_TUE1L_cor = (1-(1-Cor_NonAvailability_control_flap_gate)**2*
                                         (1-Cor_NonAvailability_lift_gate))

Failure_movement_works_flap_gate_cor =(1-(1-Cor_NonAvailability_hydraulic_cylinder_flap_gate)**6)

Failure_movement_works_lift_gate_cor = (1-(1-Cor_NonAvailability_hydraulic_cylinder_lift_gate)**2)

Failure_movement_works_TUE1L_cor = (1-(1-Failure_movement_works_flap_gate_cor)*
                                     (1-Failure_movement_works_lift_gate_cor))

Failure_hydraulic_aggregate_cor = (1-(1-Cor_NonAvailability_hydraulic_aggregate)**2)


Failure_gate_TUE1L_cor = (1-(1-Failure_steel_weir_structure_TUE1L_cor)*
                           (1-Failure_movement_works_TUE1L_cor)*
                          (1-Failure_hydraulic_aggregate_cor))

Failure_individual_gates_TUE1L_cor = (1-(1-Failure_gate_TUE1L_cor)**2)

Failure_power_supply_cor = (Prev_NonAvailability_emergency_power_supply*
                             Prev_NonAvailability_Power_grid_shutdown)

Failure_gates_TUE1L_cor = (1-(1-Failure_individual_gates_TUE1L_cor)*
                            (1-Failure_power_supply_prev))


#Nonavailability TUE 1.L
NonAvailability_TUE1L_cor = (1-(1-Failure_gates_TUE1L_cor)*
                            (1-Failure_concrete_weir_structure_prev)*
                            (1-External_events_TUE1L))
```

Figure 121: Non-availability calculation TUE 1.L corrective maintenance (lift alternative)

The non-availability of the same top undesired event is calculated under corrective maintenance in figure 121.

```
### TUE 2.L and TUE 3 (discharge and ship passage functions)#########################################################

#Failure gates
Failure_steel_weir_structure_TUE2L_prev = Prev_NonAvailability_lift_gate

Failure_movement_works_TUE2L_prev = Failure_movement_works_lift_gate_prev

Failure_gate_TUE2L_prev = (1-(1-Failure_steel_weir_structure_TUE2L_prev)*
                                (1-Failure_movement_works_TUE2L_prev)*
                          (1-Failure_hydraulic_aggregate_prev))

Failure_individual_gates_TUE2L_prev = (1-(1-Failure_gate_TUE2L_prev)**Failure_lift_gate_units)

Failure_gates_TUE2L_prev = (1-(1-Failure_individual_gates_TUE2L_prev)*
                                 (1-Failure_power_supply_prev))

#External events
External_events_TUE2L = (1-(1-Prev_NonAvailability_Ship_collision)*
                    (1-Prev_NonAvailability_Fire_in_installation_room_land)**Fire_in_installation_room_land_units*
                    (1-Prev_NonAvailability_Fire_in_installation_room_river)**Fire_in_installation_room_river_units)

#Nonavailability TUE 2.L and TUE 3
NonAvailability_TUE2L_prev = (1-(1-Failure_gates_TUE2L_prev)*
                                (1-Failure_concrete_weir_structure_prev)*
                                (1-External_events_TUE2L))
```

Figure 122: Non-availability calculation TUE 2.L and TUE 3 preventive maintenance (lift alternative)

The non-availability of top undesired events TUE 2.L and TUE 3 “At least one of the headgates of the weir fails to open” is calculated under preventive maintenance in figure 122. The fault tree structure from appendix D was used.

```
### TUE 2.L and TUE 3 (discharge and ship passage functions)#############################################################

#Failure gates
Failure_steel_weir_structure_TUE2L_cor = (Cor_NonAvailability_lift_gate)

Failure_movement_works_TUE2L_cor = Failure_movement_works_lift_gate_cor

Failure_gate_TUE2L_cor = (1-(1-Failure_steel_weir_structure_TUE2L_cor)*
                          (1-Failure_movement_works_TUE2L_cor)*
                         (1-Failure_hydraulic_aggregate_cor))

Failure_individual_gates_TUE2L_cor = (1-(1-Failure_gate_TUE2L_cor)**Failure_lift_gate_units)

Failure_gates_TUE2L_cor = (1-(1-Failure_individual_gates_TUE2L_cor)*
                           (1-Failure_power_supply_prev))

#Nonavailability TUE 2.L and TUE 3
NonAvailability_TUE2L_cor = (1-(1-Failure_gates_TUE2L_cor)*
                          (1-Failure_concrete_weir_structure_prev)*
                          (1-External_events_TUE2L))
```

Figure 123: Non-availability calculation TUE 2.L and TUE 3 corrective maintenance (lift alternative)

The non-availability of the same top undesired events is calculated under corrective maintenance in figure 123.

```
### Expected repair cost for each failure event [€/year] (under preventive maintenance strategy) ########################
PERC_control_flap_gate = (365*24*Failure_control_flap_gate_rate*Failure_control_flap_gate_units*
                          Failure_control_flap_gate_Rcost)
PERC_lift_gate = 365*24*Failure_lift_gate_rate*Failure_lift_gate_units*Failure_lift_gate_Rcost
PERC_Ship_collision = 365*24*Ship_collision_rate*Ship_collision_units*Ship_collision_Rcost
PERC_hydraulic_cylinder_flap_gate = (365*24*Failure_hydraulic_cylinder_flap_gate_rate*
                                    Failure_hydraulic_cylinder_flap_gate_units*Failure_hydraulic_cylinder_flap_gate_Rcost)
PERC_Fire_in_installation_room_land = (365*24*Fire_in_installation_room_land_rate*Fire_in_installation_room_land_units*
                                      Fire_in_installation_room_land_Rcost)
PERC_Fire_in_installation_room_river = (365*24*Fire_in_installation_room_river_rate*Fire_in_installation_room_river_units*
                                       Fire_in_installation_room_river_Rcost)
PERC_hydraulic_cylinder_lift_gate = (365*24*Failure_hydraulic_cylinder_lift_gate_rate*
                                        Failure_hydraulic_cylinder_lift_gate_units*
                                        Failure_hydraulic_cylinder_lift_gate_Rcost)

#Failure rate hydraulic aggregate (under preventive maintenance strategy)
Prev_Availability_Failure_pump_lift_gate = 1-Prev_NonAvailability_Failure_pump_lift_gate
Prev_Availability_Failure_electrical_motor_lift_gate = 1-Prev_NonAvailability_Failure_electrical_motor_lift_gate

Prev_Availability_hydraulic_aggregate_pump_works = (1-(1-((1)*
                                                    (Prev_Availability_Failure_electrical_motor_lift_gate)))*
                                                    (1-((Prev_Availability_Failure_pump_lift_gate)*
                                                    (Prev_Availability_Failure_electrical_motor_lift_gate))))
Prev_Availability_hydraulic_aggregate_pump_fails = (1-(1-((0)*
                                                    (Prev_Availability_Failure_electrical_motor_lift_gate)))*
                                                    (1-((Prev_Availability_Failure_pump_lift_gate)*
                                                    (Prev_Availability_Failure_electrical_motor_lift_gate))))
Prev_Availability_hydraulic_aggregate_electromotor_works = (1-(1-((Prev_Availability_Failure_pump_lift_gate)*
                                                            (1)))*
                                                            (1-((Prev_Availability_Failure_pump_lift_gate)*
                                                            (Prev_Availability_Failure_electrical_motor_lift_gate))))
Prev_Availability_hydraulic_aggregate_electromotor_fails = (1-(1-((Prev_Availability_Failure_pump_lift_gate)*
                                                            (0)))*
                                                            (1-((Prev_Availability_Failure_pump_lift_gate)*
                                                            (Prev_Availability_Failure_electrical_motor_lift_gate))))

Prev_MIF_pump = (Prev_Availability_hydraulic_aggregate_pump_works-
             Prev_Availability_hydraulic_aggregate_pump_fails)
Prev_MIF_electromotor = (Prev_Availability_hydraulic_aggregate_electromotor_works-
                     Prev_Availability_hydraulic_aggregate_electromotor_fails)

Prev_W_pump = (Prev_Availability_Failure_pump_lift_gate*
               Failure_pump_lift_gate_rate)
Prev_W_electromotor = (Prev_Availability_Failure_electrical_motor_lift_gate*
                       Failure_electrical_motor_lift_gate_rate)

Prev_Failure_rate_hydraulic_aggregate = ((Prev_MIF_pump*Prev_W_pump)*2+
                                         (Prev_MIF_electromotor*Prev_W_electromotor)*2)

#Repair cost hydraulic aggregate (preventive)
PERC_hydraulic_aggregate = (365*24*Prev_Failure_rate_hydraulic_aggregate*
                                        Failure_hydraulic_aggregate_units*
                                        Failure_hydraulic_aggregate_Rcost)
```

Figure 124: Expected annual repair cost under preventive maintenance (lift alternative)

The expected annual corrective cost for each failure mechanism is calculated under preventive maintenance (figure 124). The failure rate (hourly rate) is multiplied with the cost of failure and the amount of components (units) for each failure mechanism. This leads to an hourly expected cost which is multiplied by the amount of hours in a year.

The hydraulic aggregate consists of two pumps and two electromotors, it fails only if at least one of the pump/electromotor sets fails. Therefore the failure rate of the hydraulic aggregate has to be determined. The procedure to determine the failure rate of a system is explained in the IEC standard (IEC, 2016) and is based on three steps. The first step is to determine the Birnbaum importance factor for each basic component (single pump or electromotor).

The Birnbaum importance factor or otherwise called the marginal importance factor describes the impact of a component on a systems probability of success or failure, similar as the Fussel-Vesely importance factor (IEC, 2016). It provides the basis for estimating the equivalent failure rate (and therefore the reliability) of a repaired system. It is based on the partial derivative of the probability of success (or failure) of the system with regards to the probability of success (or failure) of the considered block B_i. The Birnbaum importance factor is basically given by the following Formula:

$$MIF_S(B_i) = \frac{\partial P_S}{\partial P_{b_i}}.$$

It is symmetrical with regards to success or failure. The following formula is equivalent to the previous formula:

$$MIF_S(B_i) = P_{S|b_i} - P_{S|b_i{}^c}.$$

Where $P_{S|bi}$ is the probability (reliability/availability) of the system given that component B_i functions and $P_{S|bic}$ is the probability (reliability/availability) of the system given that component B_i does not function.

The steps to determine the failure rate of a system (in this case the hydraulic aggregate) are as follows:

1) Calculation of Birnbaum importance factor for each component:

$$MIF_S(B_i) = A_{S|B_i} - A_{S|B_i{}^c}.$$

2) Calculation of the unconditional failure intensities w_i of each component B_i:

$$w_i = \lambda_i * A_{B_i}.$$

3) Calculation of the failure rate of the system:

$$w_s = \sum_i MIF_S(B_i) * w_i.$$

Where B_i stands for each component in the system, S stands for the system, A is the availability, and λ_i is the failure rate of each component. The object tree of the hydraulic aggregate is shown in figure 125, this is based on the fault tree for the hydraulic aggregate from appendix D. The object tree was used to determine the availability of the system (hydraulic aggregate).

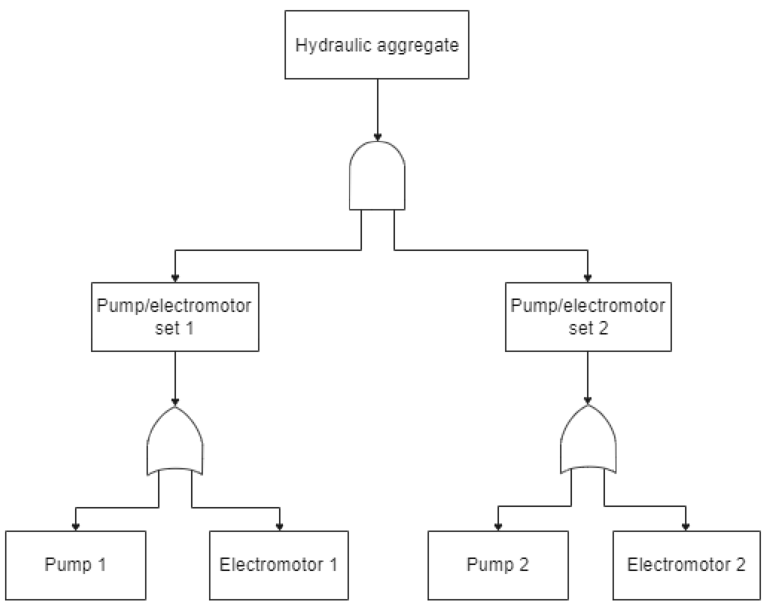

Figure 125: Object tree hydraulic aggregate

The calculation of the expected annual corrective cost under corrective maintenance is presented in figure 126.

```
### Expected repair cost for each failure event [€/year] (under corrective maintenance strategy) #####################
CERC_control_flap_gate = (365*24*Cor_Failure_control_flap_gate_rate*Failure_control_flap_gate_units*
                          Failure_control_flap_gate_Rcost)
CERC_lift_gate = 365*24*Cor_Failure_lift_gate_rate*Failure_lift_gate_units*Failure_lift_gate_Rcost
CERC_hydraulic_cylinder_flap_gate = (365*24*Cor_Failure_hydraulic_cylinder_flap_gate_rate*
                                     Failure_hydraulic_cylinder_flap_gate_units*Failure_hydraulic_cylinder_flap_gate_Rcost)
CERC_hydraulic_cylinder_lift_gate = (365*24*Cor_Failure_hydraulic_cylinder_lift_gate_rate*
                                         Failure_hydraulic_cylinder_lift_gate_units*
                                         Failure_hydraulic_cylinder_lift_gate_Rcost)

#Failure rate hydraulic aggregate (under corrective maintenance strategy)
Cor_Availability_Failure_pump_lift_gate = 1-Cor_NonAvailability_Failure_pump_lift_gate
Cor_Availability_Failure_electrical_motor_lift_gate = 1-Cor_NonAvailability_Failure_electrical_motor_lift_gate

Cor_Availability_hydraulic_aggregate_pump_works = (1-(1-((1)*
                                                     (Cor_Availability_Failure_electrical_motor_lift_gate)))*
                                                     (1-((Cor_Availability_Failure_pump_lift_gate)*
                                                     (Cor_Availability_Failure_electrical_motor_lift_gate)))
Cor_Availability_hydraulic_aggregate_pump_fails = (1-(1-((0)*
                                                     (Cor_Availability_Failure_electrical_motor_lift_gate)))*
                                                     (1-((Cor_Availability_Failure_pump_lift_gate)*
                                                     (Cor_Availability_Failure_electrical_motor_lift_gate)))
Cor_Availability_hydraulic_aggregate_electromotor_works = (1-(1-((Cor_Availability_Failure_pump_lift_gate)*
                                                             (1)))*
                                                             (1-((Cor_Availability_Failure_pump_lift_gate)*
                                                             (Cor_Availability_Failure_electrical_motor_lift_gate)))
Cor_Availability_hydraulic_aggregate_electromotor_fails = (1-(1-((Cor_Availability_Failure_pump_lift_gate)*
                                                             (0)))*
                                                             (1-((Cor_Availability_Failure_pump_lift_gate)*
                                                             (Cor_Availability_Failure_electrical_motor_lift_gate)))

Cor_MIF_pump = (Cor_Availability_hydraulic_aggregate_pump_works-
            Cor_Availability_hydraulic_aggregate_pump_fails)
Cor_MIF_electromotor = (Cor_Availability_hydraulic_aggregate_electromotor_works-
                    Cor_Availability_hydraulic_aggregate_electromotor_fails)

Cor_W_pump = (Cor_Availability_Failure_pump_lift_gate*
              Cor_Failure_pump_lift_gate_rate)
Cor_W_electromotor = (Cor_Availability_Failure_electrical_motor_lift_gate*
                      Cor_Failure_electrical_motor_lift_gate_rate)

Cor_Failure_rate_hydraulic_aggregate = ((Cor_MIF_pump*Prev_W_pump)*2+
                                        (Cor_MIF_electromotor*Cor_W_electromotor)*2)

#Repair cost hydraulic aggregate (corrective)
CERC_hydraulic_aggregate = (365*24*Cor_Failure_rate_hydraulic_aggregate*
                                        Failure_hydraulic_aggregate_units*
                                        Failure_hydraulic_aggregate_Rcost)

#Total expected repair Cost (under preventive maintenance strategy) [€/year]
CERC = (CERC_control_flap_gate+
       CERC_lift_gate+
       PERC_Ship_collision+
       CERC_hydraulic_cylinder_flap_gate+
       PERC_Fire_in_installation_room_land+
       PERC_Fire_in_installation_room_river+
       CERC_hydraulic_cylinder_lift_gate+
       CERC_hydraulic_aggregate)
```

Figure 126: Expected annual corrective cost under corrective maintenance (lift alternative)

```
### Equivalent annual maintenance cost #################################################
#Amount of maintenance performed over lifespan
Maintenance_wall_lifting_tower = life//Failure_wall_lifting_tower_interval
Maintenance_control_flap_gate = life//Failure_control_flap_gate_interval
Maintenance_lift_gate = life//Failure_lift_gate_interval
Maintenance_hydraulic_cylinder_flap_gate = life//Failure_hydraulic_cylinder_flap_gate_interval
Maintenance_hydraulic_cylinder_lift_gate = life//Failure_hydraulic_cylinder_lift_gate_interval
Maintenance_hydraulic_aggregate = life//Failure_hydraulic_aggregate_interval

#List of present worth factors
PWF_wall_lifting_tower = np.zeros(Maintenance_wall_lifting_tower)
PWF_control_flap_gate = np.zeros(Maintenance_control_flap_gate)
PWF_lift_gate = np.zeros(Maintenance_lift_gate)
PWF_hydraulic_cylinder_flap_gate = np.zeros(Maintenance_hydraulic_cylinder_flap_gate)
PWF_hydraulic_cylinder_lift_gate = np.zeros(Maintenance_hydraulic_cylinder_lift_gate)
PWF_hydraulic_aggregate = np.zeros(Maintenance_hydraulic_aggregate)

for a in np.arange(len(PWF_wall_lifting_tower)):
    PWF_wall_lifting_tower[a] = 1/(1+r)**(Failure_wall_lifting_tower_interval*(a+1))
for b in np.arange(len(PWF_control_flap_gate)):
    PWF_control_flap_gate[b] = 1/(1+r)**(Failure_control_flap_gate_interval*(b+1))
for c in np.arange(len(PWF_lift_gate)):
    PWF_lift_gate[c] = 1/(1+r)**(Failure_lift_gate_interval*(c+1))
for d in np.arange(len(PWF_hydraulic_cylinder_flap_gate)):
    PWF_hydraulic_cylinder_flap_gate[d] = 1/(1+r)**(Failure_hydraulic_cylinder_flap_gate_interval*(d+1))
for e in np.arange(len(PWF_hydraulic_cylinder_lift_gate)):
    PWF_hydraulic_cylinder_lift_gate[e] = 1/(1+r)**(Failure_hydraulic_cylinder_lift_gate_interval*(e+1))
for f in np.arange(len(PWF_hydraulic_aggregate)):
    PWF_hydraulic_aggregate[f] = 1/(1+r)**(Failure_hydraulic_aggregate_interval*(f+1))

#Equivalent annual maintenance cost of each component [€/year]
EAC_wall_lifting_tower = sum(Failure_wall_lifting_tower_Mcost*Failure_wall_lifting_tower_units*PWF_wall_lifting_tower)*A
EAC_control_flap_gate = sum(Failure_control_flap_gate_Mcost*Failure_control_flap_gate_units*PWF_control_flap_gate)*A
EAC_lift_gate = sum(Failure_lift_gate_Mcost*Failure_lift_gate_units*PWF_lift_gate)*A
EAC_hydraulic_cylinder_flap_gate = sum(Failure_hydraulic_cylinder_flap_gate_Mcost*
                                       Failure_hydraulic_cylinder_flap_gate_units*
                                       PWF_hydraulic_cylinder_flap_gate)*A
EAC_hydraulic_cylinder_lift_gate = sum(Failure_hydraulic_cylinder_lift_gate_Mcost*
                                           Failure_hydraulic_cylinder_lift_gate_units*
                                           PWF_hydraulic_cylinder_lift_gate)*A
EAC_hydraulic_aggregate = sum(Failure_hydraulic_aggregate_Mcost*
                                           Failure_hydraulic_aggregate_units*
                                           PWF_hydraulic_aggregate)*A

#Total equivalent annual maintenance cost (under preventive maintenance strategy) [€/year]
Preventive_Maintenance_cost = (EAC_wall_lifting_tower+
                          EAC_control_flap_gate+
                          EAC_lift_gate+
                          EAC_hydraulic_cylinder_flap_gate+
                          EAC_hydraulic_cylinder_lift_gate+
                          EAC_hydraulic_aggregate)
#Total equivalent annual maintenance cost (under corrective maintenance strategy) [€/year]
Corrective_Maintenance_cost = EAC_wall_lifting_tower
```

Figure 127: Equivalent annual maintenance cost (lift alternative)

The equivalent annual maintenance cost is determined (figure 127). First the amount of maintenance performed over the weirs lifespan is calculated by dividing the life time using a floor division with the maintenance interval. This is done for each weir component. The present worth factor of each weir component is calculated for each time maintenance is performed for that component. This is done by first creating an array of zeros with the length of the amount of maintenance performed for each weir component. So if the life span is 100 years and a weir component is maintained every 40 years. This means maintenance is performed twice over the weirs life span. So the length of the array of zeros is two. A loop is written for each weir component that calculates the present worth factor and replaces the zeros in the arrays with the respective present worth factor. So now the arrays consist of present worth factors that corresponds with the time of maintenance. The equivalent annual maintenance cost for each component is calculated by summing the present worth factors and multiplying them by the amount of units, the maintenance cost per unit and the annuity factor. The equivalent annual maintenance costs per component are summed up.

Figure 128 shows the calculations for the planned downtime for both maintenance strategies. This is done by multiplying the amount of maintenance performed per object with the amount of units per object and the maintenance time. The sum of each component gives the total planned downtime.

```
#Planned downtime (under preventive maintenance strategy)
PPDT = (Maintenance_wall_lifting_tower*MT_wall_lifting_tower*Failure_wall_lifting_tower_units+
       Maintenance_lift_gate*MT_gate*Failure_lift_gate_units+
       Maintenance_hydraulic_cylinder_lift_gate*MT_hydraulic_cylinder*Failure_lift_gate_units+
       Maintenance_hydraulic_aggregate*MT_hydraulic_aggregate*Failure_hydraulic_aggregate_units)

#Planned downtime (under corrective maintenance strategy)
CPDT = Maintenance_wall_lifting_tower*MT_wall_lifting_tower*Failure_wall_lifting_tower_units
```

Figure 128: Planned downtime (lift alternative)

Figure 129 shows the output of the Python script. The availability is determined by taking the inverse of the non-availability of each top undesired event and maintenance strategy (corrective and preventive). The unexpected downtime is determined by multiplying the non-availability of each top undesired event with the life time of the weir (depicted by the parameter 'life' which is 100 years, see figure 114) and then multiplied by the amount of hours in a year. The other parameters were already determined in the previous sections.

```
d = dict()
d['Availability TUE 1.L (corrective, preventive)'] = [1-NonAvailability_TUE1L_cor,
                                                      1-NonAvailability_TUE1L_prev]
d['Availability TUE 2.L and TUE 3 (corrective, preventive)'] = [1-NonAvailability_TUE2L_cor,
                                                      1-NonAvailability_TUE2L_prev]
d['Unexpected downtime TUE 1.L (corrective, preventive) [hours]'] = [(NonAvailability_TUE1L_cor)*life*8760,
                                                                 (NonAvailability_TUE1L_prev)*life*8760]
d['Unexpected downtime TUE 2.L (corrective, preventive) [hours]'] = [(NonAvailability_TUE2L_cor)*life*8760,
                                                                 (NonAvailability_TUE2L_prev)*life*8760]
d['Planned downtime (corrective, preventive) [hours]'] = [CPDT, PPDT]
d['Expected repair cost (corrective, preventive) [€/year]'] = [CERC, PERC]
d['Equivalent maintenance cost (corrective, preventive) [€/year]'] = [Corrective_Maintenance_cost,
                                                                      Preventive_Maintenance_cost]

return d
```

Figure 129: Output Python script (lift alternative)

F.2 Python script radial gate alternative

For the radial gate alternative only screenshots are shown as explained in the introduction of this appendix. This is done because the script for the radial gate alternative follows the same calculations and structure as the script for the lift gate alternative. The only difference is in the input values and the fault trees.

```python
#Radial gate weir alternative
def Weir2():

    r = 0.016 #Discount rate
    life = 100 #Lifespan [years]
    A = r*(1+r)**life/((1+r)**life-1) #Annuity factor
```

Figure 130: Function definition (radial alternative)

```python
#-----------------------------------------Input units -----------------------------------------
#Maintenance interval in years
Failure_wall_pier_interval = 30
Failure_control_flap_gate_interval = 15
Failure_radial_gate_interval = 15
Failure_hydraulic_cylinder_flap_gate_interval = 40
Failure_hydraulic_cylinder_radial_gate_interval = 40
Failure_hydraulic_aggregate_interval = 25

#Failure rate/hour under preventive maintenance
Failure_wall_pier_rate = 1.82*10**-10
Failure_control_flap_gate_rate = 4.10*10**-8
Failure_radial_gate_rate = 1.82*10**-10
Ship_collision_rate = 2.28*10**-6
Ice_formation_rate = 1.14*10**-5
Failure_hydraulic_cylinder_flap_gate_rate = 3.75*10**-7
Failure_emergency_power_supply_rate = 4.04*10**-5
Power_grid_shutdown_rate = 10**-4
Fire_in_installation_room_land_rate = 4.22*10**-8
Fire_in_installation_room_river_rate = 1.14*10**-7
Failure_hydraulic_cylinder_radial_gate_rate = 3.75*10**-7
Failure_pump_radial_gate_rate = 1.32*10**-5
Failure_electrical_motor_radial_gate_rate = 1.10*10**-4

#Failure rate/hour under corrective maintenance
Cor_Failure_wall_pier_rate = Failure_wall_pier_rate
Cor_Failure_control_flap_gate_rate = 1/(100*8760)
Cor_Failure_radial_gate_rate = 1/(100*8760)
Cor_Failure_hydraulic_cylinder_flap_gate_rate = 1/(20*8760)
Cor_Failure_hydraulic_cylinder_radial_gate_rate = 1/(20*8760)
Cor_Failure_pump_radial_gate_rate = Failure_pump_radial_gate_rate
Cor_Failure_electrical_motor_radial_gate_rate = Failure_electrical_motor_radial_gate_rate

#Time to repair (MTTR) (hours)
Failure_wall_pier_TTR = 4380
Failure_control_flap_gate_TTR = 672
Failure_radial_gate_TTR = 672
Ship_collision_TTR = 6570
Ice_formation_TTR = 336
Failure_hydraulic_cylinder_flap_gate_TTR = 168
Failure_emergency_power_supply_TTR = 24
Power_grid_shutdown_TTR = 1.5
Fire_in_installation_room_land_TTR = 336
Fire_in_installation_room_river_TTR = 336
Failure_hydraulic_cylinder_radial_gate_TTR = 168
Failure_pump_radial_gate_TTR = 168
Failure_electrical_motor_radial_gate_TTR = 168

#Maintenance costs per unit
Failure_wall_pier_Mcost = 250000
Failure_control_flap_gate_Mcost = 74000
Failure_radial_gate_Mcost = 144000
Failure_hydraulic_cylinder_flap_gate_Mcost = 170000
Failure_hydraulic_cylinder_radial_gate_Mcost = 170000
Failure_hydraulic_aggregate_Mcost = 40000
```

Figure 131: Input values (failure rates are based on preventive maintenance) (1/2) (radial alternative)

```
#Repair costs per unit
Failure_control_flap_gate_Rcost = 225000
Failure_radial_gate_Rcost = 450000
Ship_collision_Rcost = 1805000
Failure_hydraulic_cylinder_flap_gate_Rcost = 170000
Fire_in_installation_room_land_Rcost = 40000
Fire_in_installation_room_river_Rcost = 80000
Failure_hydraulic_cylinder_radial_gate_Rcost = 170000
Failure_hydraulic_aggregate_Rcost = 80000
Failure_pump_radial_gate_Rcost = 10000
Failure_electrical_motor_radial_gate_Rcost = 10000

#Units
Failure_wall_pier_units = 5
Failure_control_flap_gate_units = 4
Failure_radial_gate_units = 4
Ship_collision_units = 1
Failure_hydraulic_cylinder_flap_gate_units = 8
Failure_emergency_power_supply_units = 1
Power_grid_shutdown_units = 1
Fire_in_installation_room_land_units = 2
Fire_in_installation_room_river_units = 3
Failure_hydraulic_cylinder_radial_gate_units = 8
Failure_hydraulic_aggregate_units = 8
Failure_pump_radial_gate_units = 16
Failure_electrical_motor_radial_gate_units = 16

#Maintenance duration [hours]
MT_wall_pier = 168
MT_gate = 336
MT_hydraulic_cylinder =  336
MT_hydraulic_aggregate = 336
```

Figure 132: Input values (failure rates are based on preventive maintenance) (2/2) (radial alternative)

```
#Non availability of each failure event (under preventive maintenance strategy)
Prev_NonAvailability_wall_pier = 1-((1/Failure_wall_pier_rate)/
                                   (Failure_wall_pier_TTR+1/Failure_wall_pier_rate))
Prev_NonAvailability_control_flap_gate = 1-((1/Failure_control_flap_gate_rate)/
                                   (Failure_control_flap_gate_TTR+1/Failure_control_flap_gate_rate))
Prev_NonAvailability_radial_gate = 1-((1/Failure_radial_gate_rate)/
                                   (Failure_radial_gate_TTR+1/Failure_radial_gate_rate))
Prev_NonAvailability_Ship_collision = 1-((1/Ship_collision_rate)/
                                   (Ship_collision_TTR+1/Ship_collision_rate))
Prev_NonAvailability_Ice_formation = 1-((1/Ice_formation_rate)/
                                   (Ice_formation_TTR+1/Ice_formation_rate))
Prev_NonAvailability_hydraulic_cylinder_flap_gate = 1-((1/Failure_hydraulic_cylinder_flap_gate_rate)/
                                   (Failure_hydraulic_cylinder_flap_gate_TTR+1/
                                    Failure_hydraulic_cylinder_flap_gate_rate))
Prev_NonAvailability_emergency_power_supply = 1-((1/Failure_emergency_power_supply_rate)/
                                   (Failure_emergency_power_supply_TTR+1/Failure_emergency_power_supply_rate))
Prev_NonAvailability_Power_grid_shutdown = 1-((1/Power_grid_shutdown_rate)/
                                   (Power_grid_shutdown_TTR+1/Power_grid_shutdown_rate))
Prev_NonAvailability_Fire_in_installation_room_land = 1-((1/Fire_in_installation_room_land_rate)/
                                   (Fire_in_installation_room_land_TTR+1/Fire_in_installation_room_land_rate))
Prev_NonAvailability_Fire_in_installation_room_river = 1-((1/Fire_in_installation_room_river_rate)/
                                   (Fire_in_installation_room_river_TTR+1/Fire_in_installation_room_river_rate))
Prev_NonAvailability_hydraulic_cylinder_radial_gate = 1-((1/Failure_hydraulic_cylinder_radial_gate_rate)/
                                   (Failure_hydraulic_cylinder_radial_gate_TTR+1/
                                    Failure_hydraulic_cylinder_radial_gate_rate))
Prev_NonAvailability_Failure_pump_radial_gate = 1-((1/Failure_pump_radial_gate_rate)/
                                   (Failure_pump_radial_gate_TTR+1/Failure_pump_radial_gate_rate))
Prev_NonAvailability_Failure_electrical_motor_radial_gate = 1-((1/Failure_electrical_motor_radial_gate_rate)/
                                   (Failure_electrical_motor_radial_gate_TTR+1/
                                    Failure_electrical_motor_radial_gate_rate))
Prev_NonAvailability_hydraulic_aggregate = ((1-(1-Prev_NonAvailability_Failure_pump_radial_gate)*
                                   (1-Prev_NonAvailability_Failure_electrical_motor_radial_gate))**2)
```

Figure 133: Non-availability of each failure event preventive maintenance (radial alternative)

```
#Non availability of each failure event (under corrective maintenance strategy)
Cor_NonAvailability_wall_pier = 1-((1/Cor_Failure_wall_pier_rate)/
                                       (Failure_wall_pier_TTR+1/Cor_Failure_wall_pier_rate))
Cor_NonAvailability_control_flap_gate = 1-((1/Cor_Failure_control_flap_gate_rate)/
                                      (Failure_control_flap_gate_TTR+1/Cor_Failure_control_flap_gate_rate))
Cor_NonAvailability_radial_gate = 1-((1/Cor_Failure_radial_gate_rate)/
                              (Failure_radial_gate_TTR+1/Cor_Failure_radial_gate_rate))
Cor_NonAvailability_hydraulic_cylinder_flap_gate = 1-((1/Cor_Failure_hydraulic_cylinder_flap_gate_rate)/
                                                  (Failure_hydraulic_cylinder_flap_gate_TTR+1/
                                                   Cor_Failure_hydraulic_cylinder_flap_gate_rate))
Cor_NonAvailability_hydraulic_cylinder_radial_gate = 1-((1/Cor_Failure_hydraulic_cylinder_radial_gate_rate)/
                                                      (Failure_hydraulic_cylinder_radial_gate_TTR+1/
                                                       Cor_Failure_hydraulic_cylinder_radial_gate_rate))
Cor_NonAvailability_Failure_pump_radial_gate = 1-((1/Cor_Failure_pump_radial_gate_rate)/
                                               (Failure_pump_radial_gate_TTR+1/Cor_Failure_pump_radial_gate_rate))
Cor_NonAvailability_Failure_electrical_motor_radial_gate = 1-((1/Cor_Failure_electrical_motor_radial_gate_rate)/
                                               (Failure_electrical_motor_radial_gate_TTR+1/
                                                Cor_Failure_electrical_motor_radial_gate_rate))
Cor_NonAvailability_hydraulic_aggregate = ((1-(1-Cor_NonAvailability_Failure_pump_radial_gate)*
                                          (1-Cor_NonAvailability_Failure_electrical_motor_radial_gate))**2)
```

Figure 134: Non-availability of each failure event corrective maintenance (radial alternative)

```
### Availability under preventive maintenance strategy ###############################################################
### TUE 1.R (water retention function) #####################################################################################


#Failure gates
Failure_steel_weir_structure_TUE1R_prev = (1-(1-Prev_NonAvailability_control_flap_gate)*
                                               (1-Prev_NonAvailability_radial_gate))

Failure_movement_works_flap_gate_prev =(1-(1-Prev_NonAvailability_hydraulic_cylinder_flap_gate)**2)

Failure_movement_works_radial_gate_prev = (1-(1-Prev_NonAvailability_hydraulic_cylinder_radial_gate)**2)

Failure_movement_works_TUE1R_prev = (1-(1-Failure_movement_works_flap_gate_prev)*
                                         (1-Failure_movement_works_radial_gate_prev))

Failure_hydraulic_aggregate_prev = (1-(1-Prev_NonAvailability_hydraulic_aggregate)**2)

Failure_gate_TUE1R_prev = (1-(1-Failure_steel_weir_structure_TUE1R_prev)*
                             (1-Failure_movement_works_TUE1R_prev)*
                           (1-Failure_hydraulic_aggregate_prev))

Failure_individual_gates_TUE1R_prev = (1-(1-Failure_gate_TUE1R_prev)**4)

Failure_power_supply_prev = ((Prev_NonAvailability_emergency_power_supply)*
                                   (Prev_NonAvailability_Power_grid_shutdown))

Failure_gates_TUE1R_prev = (1-(1-Failure_individual_gates_TUE1R_prev)*
                              (1-Failure_power_supply_prev))

#Failure concrete weir structure
Failure_concrete_weir_structure_prev = (1-(1-Prev_NonAvailability_wall_pier)**Failure_wall_pier_units)

#External events
External_events_TUE1R = (1-(1-Prev_NonAvailability_Ship_collision)*
                           (1-Prev_NonAvailability_Ice_formation)*
                      (1-Prev_NonAvailability_Fire_in_installation_room_land)**Fire_in_installation_room_land_units*
                      (1-Prev_NonAvailability_Fire_in_installation_room_river)**Fire_in_installation_room_river_units)

#Non availability TUE 1.R
NonAvailability_TUE1R_prev = (1-(1-Failure_gates_TUE1R_prev)*
                             (1-Failure_concrete_weir_structure_prev)*
                              (1-External_events_TUE1R))
```

Figure 135: Non-availability calculation TUE 1.R preventive maintenance (radial alternative)

```
### TUE 2.R (discharge function) ######################################################################################

#Failure gates
Failure_steel_weir_structure_TUE2R_prev = (Prev_NonAvailability_radial_gate)

Failure_movement_works_radial_gate_prev = (1-(1-Prev_NonAvailability_hydraulic_cylinder_radial_gate)**2)

Failure_movement_works_TUE2R_prev = Failure_movement_works_radial_gate_prev

Failure_hydraulic_aggregate_prev = (1-(1-Prev_NonAvailability_hydraulic_aggregate)**2)

Failure_gate_TUE2R_prev = (1-(1-Failure_steel_weir_structure_TUE2R_prev)*
                            (1-Failure_movement_works_TUE2R_prev)*
                          (1-Failure_hydraulic_aggregate_prev))

Failure_individual_gates_TUE2R_prev = (1-(1-Failure_gate_TUE2R_prev)**4)

Failure_power_supply_prev = ((Prev_NonAvailability_emergency_power_supply)*
                                  (Prev_NonAvailability_Power_grid_shutdown))

Failure_gates_TUE2R_prev = (1-(1-Failure_individual_gates_TUE2R_prev)*
                             (1-Failure_power_supply_prev))

#External events
External_events_TUE2R = (1-(1-Prev_NonAvailability_Ship_collision)*
                    (1-Prev_NonAvailability_Fire_in_installation_room_land)**Fire_in_installation_room_land_units*
                    (1-Prev_NonAvailability_Fire_in_installation_room_river)**Fire_in_installation_room_river_units)


#Non availability TUE 2.R
NonAvailability_TUE2R_prev = (1-(1-Failure_gates_TUE2R_prev)*
                               (1-Failure_concrete_weir_structure_prev)*
                               (1-External_events_TUE2R))
```

Figure 136: Non-availability calculation TUE 2.R preventive maintenance (radial alternative)

```
### Availability under corrective maintenance strategy ################################################################

### TUE 1.R (water retention function)#################################################################################


#Failure gates
Failure_steel_weir_structure_TUE1R_cor = (1-(1-Cor_NonAvailability_control_flap_gate)*
                                          (1-Cor_NonAvailability_radial_gate))

Failure_movement_works_flap_gate_cor =(1-(1-Cor_NonAvailability_hydraulic_cylinder_flap_gate)**2)

Failure_movement_works_radial_gate_cor = (1-(1-Cor_NonAvailability_hydraulic_cylinder_radial_gate)**2)

Failure_movement_works_TUE1R_cor = (1-(1-Failure_movement_works_flap_gate_cor)*
                                    (1-Failure_movement_works_radial_gate_cor))

Failure_hydraulic_aggregate_cor = (1-(1-Cor_NonAvailability_hydraulic_aggregate)**2)

Failure_gate_TUE1R_cor = (1-(1-Failure_steel_weir_structure_TUE1R_cor)*
                           (1-Failure_movement_works_TUE1R_cor)*
                          (1-Failure_hydraulic_aggregate_cor))

Failure_individual_gates_TUE1R_cor = (1-(1-Failure_gate_TUE1R_cor)**4)

Failure_power_supply_prev = ((Prev_NonAvailability_emergency_power_supply)*
                              (Prev_NonAvailability_Power_grid_shutdown))

Failure_gates_TUE1R_cor = (1-(1-Failure_individual_gates_TUE1R_cor)*
                            (1-Failure_power_supply_prev))

#Non availability TUE 1.R
NonAvailability_TUE1R_cor = (1-(1-Failure_gates_TUE1R_cor)*
                             (1-Failure_concrete_weir_structure_prev)*
                             (1-External_events_TUE1R))
```

Figure 137: Non-availability calculation TUE 1.R corrective maintenance (radial alternative)

```python
### TUE 2.R (discharge function)##########################################################################################

#Failure gates
Failure_steel_weir_structure_TUE2R_cor = (Cor_NonAvailability_radial_gate)

Failure_movement_works_radial_gate_cor = (1-(1-Cor_NonAvailability_hydraulic_cylinder_radial_gate)**2)

Failure_movement_works_TUE2R_cor = Failure_movement_works_radial_gate_cor

Failure_hydraulic_aggregate_cor = (1-(1-Cor_NonAvailability_hydraulic_aggregate)**2)

Failure_gate_TUE2R_cor = (1-(1-Failure_steel_weir_structure_TUE2R_cor)*
                          (1-Failure_movement_works_TUE2R_cor)*
                         (1-Failure_hydraulic_aggregate_cor))

Failure_individual_gates_TUE2R_cor = (1-(1-Failure_gate_TUE2R_cor)**4)

Failure_power_supply_prev = ((Prev_NonAvailability_emergency_power_supply)*
                                 (Prev_NonAvailability_Power_grid_shutdown))

Failure_gates_TUE2R_cor = (1-(1-Failure_individual_gates_TUE2R_cor)*
                           (1-Failure_power_supply_prev))


#Non availability TUE 2.R
NonAvailability_TUE2R_cor = (1-(1-Failure_gates_TUE2R_cor)*
                          (1-Failure_concrete_weir_structure_prev)*
                          (1-External_events_TUE2R))
```

Figure 138: Non-availability calculation TUE 2.R corrective maintenance (radial alternative)

```
### Expected repair cost (under preventive maintenance strategy) ######################################################
PERC_control_flap_gate = (365*24*Failure_control_flap_gate_rate*Failure_control_flap_gate_units*
                         Failure_control_flap_gate_Rcost)
PERC_radial_gate = 365*24*Failure_radial_gate_rate*Failure_radial_gate_units*Failure_radial_gate_Rcost
PERC_Ship_collision = 365*24*Ship_collision_rate*Ship_collision_units*Ship_collision_Rcost
PERC_hydraulic_cylinder_flap_gate = (365*24*Failure_hydraulic_cylinder_flap_gate_rate*
                                    Failure_hydraulic_cylinder_flap_gate_units*Failure_hydraulic_cylinder_flap_gate_Rcost)
PERC_Fire_in_installation_room_land = (365*24*Fire_in_installation_room_land_rate*Fire_in_installation_room_land_units*
                                 Fire_in_installation_room_land_Rcost)
PERC_Fire_in_installation_room_river = (365*24*Fire_in_installation_room_river_rate*Fire_in_installation_room_river_units*
                                 Fire_in_installation_room_river_Rcost)
PERC_hydraulic_cylinder_radial_gate = (365*24*Failure_hydraulic_cylinder_radial_gate_rate*
                                        Failure_hydraulic_cylinder_radial_gate_units*
                                        Failure_hydraulic_cylinder_radial_gate_Rcost)


#Failure rate hydraulic aggregate (under preventive maintenance strategy)
Prev_Availability_Failure_pump_radial_gate = 1-Prev_NonAvailability_Failure_pump_radial_gate
Prev_Availability_Failure_electrical_motor_radial_gate = 1-Prev_NonAvailability_Failure_electrical_motor_radial_gate

Prev_Availability_hydraulic_aggregate_pump_works = (1-(1-((1)*
                                                    (Prev_Availability_Failure_electrical_motor_radial_gate)))*
                                                    (1-((Prev_Availability_Failure_pump_radial_gate)*
                                                    (Prev_Availability_Failure_electrical_motor_radial_gate)))
Prev_Availability_hydraulic_aggregate_pump_fails = (1-(1-((0)*
                                                    (Prev_Availability_Failure_electrical_motor_radial_gate)))*
                                                    (1-((Prev_Availability_Failure_pump_radial_gate)*
                                                    (Prev_Availability_Failure_electrical_motor_radial_gate)))
Prev_Availability_hydraulic_aggregate_electromotor_works = (1-(1-((Prev_Availability_Failure_pump_radial_gate)*
                                                            (1)))*
                                                            (1-((Prev_Availability_Failure_pump_radial_gate)*
                                                            (Prev_Availability_Failure_electrical_motor_radial_gate)))
Prev_Availability_hydraulic_aggregate_electromotor_fails = (1-(1-((Prev_Availability_Failure_pump_radial_gate)*
                                                            (0)))*
                                                            (1-((Prev_Availability_Failure_pump_radial_gate)*
                                                            (Prev_Availability_Failure_electrical_motor_radial_gate)))

Prev_MIF_pump = (Prev_Availability_hydraulic_aggregate_pump_works-
            Prev_Availability_hydraulic_aggregate_pump_fails)
Prev_MIF_electromotor = (Prev_Availability_hydraulic_aggregate_electromotor_works-
                    Prev_Availability_hydraulic_aggregate_electromotor_fails)

Prev_W_pump = (Prev_Availability_Failure_pump_radial_gate*
               Failure_pump_radial_gate_rate)
Prev_W_electromotor = (Prev_Availability_Failure_electrical_motor_radial_gate*
                       Failure_electrical_motor_radial_gate_rate)

Prev_Failure_rate_hydraulic_aggregate = ((Prev_MIF_pump*Prev_W_pump)*2+
                                         (Prev_MIF_electromotor*Prev_W_electromotor)*2)

#Repair cost hydraulic aggregate (preventive)
PERC_hydraulic_aggregate = (365*24*Prev_Failure_rate_hydraulic_aggregate*
                            Failure_hydraulic_aggregate_units*
                            Failure_hydraulic_aggregate_Rcost)

#Expected repair cost (under preventive maintenance strategy) [€/year]
PERC = (PERC_control_flap_gate+
       PERC_radial_gate+
       PERC_Ship_collision+
       PERC_hydraulic_cylinder_flap_gate+
       PERC_Fire_in_installation_room_land+
       PERC_Fire_in_installation_room_river+
       PERC_hydraulic_cylinder_radial_gate+
       PERC_hydraulic_aggregate)
```

Figure 139: Expected repair cost under preventive maintenance (radial alternative)

```
### Expected repair cost (under corrective maintenance strategy) #####################################################
CERC_control_flap_gate = (365*24*Cor_Failure_control_flap_gate_rate*Failure_control_flap_gate_units*
                         Failure_control_flap_gate_Rcost)
CERC_radial_gate = 365*24*Cor_Failure_radial_gate_rate*Failure_radial_gate_units*Failure_radial_gate_Rcost
CERC_hydraulic_cylinder_flap_gate = (365*24*Cor_Failure_hydraulic_cylinder_flap_gate_rate*
                                    Failure_hydraulic_cylinder_flap_gate_units*Failure_hydraulic_cylinder_flap_gate_Rcost)
CERC_hydraulic_cylinder_radial_gate = (365*24*Cor_Failure_hydraulic_cylinder_radial_gate_rate*
                                        Failure_hydraulic_cylinder_radial_gate_units*
                                        Failure_hydraulic_cylinder_radial_gate_Rcost)

#Failure rate hydraulic aggregate (under corrective maintenance strategy)
Cor_Availability_Failure_pump_radial_gate = 1-Cor_NonAvailability_Failure_pump_radial_gate
Cor_Availability_Failure_electrical_motor_radial_gate = 1-Cor_NonAvailability_Failure_electrical_motor_radial_gate

Cor_Availability_hydraulic_aggregate_pump_works = (1-(1-((1)*
                                                    (Cor_Availability_Failure_electrical_motor_radial_gate)))*
                                                    (1-((Cor_Availability_Failure_pump_radial_gate)*
                                                    (Cor_Availability_Failure_electrical_motor_radial_gate)))
Cor_Availability_hydraulic_aggregate_pump_fails = (1-(1-((0)*
                                                    (Cor_Availability_Failure_electrical_motor_radial_gate)))*
                                                    (1-((Cor_Availability_Failure_pump_radial_gate)*
                                                    (Cor_Availability_Failure_electrical_motor_radial_gate)))
Cor_Availability_hydraulic_aggregate_electromotor_works = (1-(1-((Cor_Availability_Failure_pump_radial_gate)*
                                                            (1)))*
                                                            (1-((Cor_Availability_Failure_pump_radial_gate)*
                                                            (Cor_Availability_Failure_electrical_motor_radial_gate)))
Cor_Availability_hydraulic_aggregate_electromotor_fails = (1-(1-((Cor_Availability_Failure_pump_radial_gate)*
                                                            (0)))*
                                                            (1-((Cor_Availability_Failure_pump_radial_gate)*
                                                            (Cor_Availability_Failure_electrical_motor_radial_gate)))

Cor_MIF_pump = (Cor_Availability_hydraulic_aggregate_pump_works-
            Cor_Availability_hydraulic_aggregate_pump_fails)
Cor_MIF_electromotor = (Cor_Availability_hydraulic_aggregate_electromotor_works-
                    Cor_Availability_hydraulic_aggregate_electromotor_fails)

Cor_W_pump = (Cor_Availability_Failure_pump_radial_gate*
               Failure_pump_radial_gate_rate)
Cor_W_electromotor = (Cor_Availability_Failure_electrical_motor_radial_gate*
                       Failure_electrical_motor_radial_gate_rate)

Cor_Failure_rate_hydraulic_aggregate = ((Cor_MIF_pump*Prev_W_pump)*2+
                                         (Cor_MIF_electromotor*Cor_W_electromotor)*2)

#Repair cost hydraulic aggregate (corrective)
CERC_hydraulic_aggregate = (365*24*Prev_Failure_rate_hydraulic_aggregate*
                             Failure_hydraulic_aggregate_units*
                             Failure_hydraulic_aggregate_Rcost)

#Expected repair Cost (under corrective maintenance strategy) [€/year]
CERC = (CERC_control_flap_gate+
       CERC_radial_gate+
       PERC_Ship_collision+
       CERC_hydraulic_cylinder_flap_gate+
       PERC_Fire_in_installation_room_land+
       PERC_Fire_in_installation_room_river+
       CERC_hydraulic_cylinder_radial_gate+
       CERC_hydraulic_aggregate)
```

Figure 140: Expected repair cost under corrective maintenance (radial alternative)

```python
### Equivalent annual maintenance cost  ################################################################################
#Amount of maintenance performed over lifespan
Maintenance_wall_pier = life//Failure_wall_pier_interval
Maintenance_control_flap_gate = life//Failure_control_flap_gate_interval
Maintenance_radial_gate = life//Failure_radial_gate_interval
Maintenance_hydraulic_cylinder_flap_gate = life//Failure_hydraulic_cylinder_flap_gate_interval
Maintenance_hydraulic_cylinder_radial_gate = life//Failure_hydraulic_cylinder_radial_gate_interval
Maintenance_hydraulic_aggregate = life//Failure_hydraulic_aggregate_interval

#List of present worth factors
PWF_wall_pier = np.zeros(Maintenance_wall_pier)
PWF_control_flap_gate = np.zeros(Maintenance_control_flap_gate)
PWF_radial_gate = np.zeros(Maintenance_radial_gate)
PWF_hydraulic_cylinder_flap_gate = np.zeros(Maintenance_hydraulic_cylinder_flap_gate)
PWF_hydraulic_cylinder_radial_gate = np.zeros(Maintenance_hydraulic_cylinder_radial_gate)
PWF_hydraulic_aggregate = np.zeros(Maintenance_hydraulic_aggregate)

for a in np.arange(len(PWF_wall_pier)):
    PWF_wall_pier[a] = 1/(1+r)**(Failure_wall_pier_interval*(a+1))
for b in np.arange(len(PWF_control_flap_gate)):
    PWF_control_flap_gate[b] = 1/(1+r)**(Failure_control_flap_gate_interval*(b+1))
for c in np.arange(len(PWF_radial_gate)):
    PWF_radial_gate[c] = 1/(1+r)**(Failure_radial_gate_interval*(c+1))
for d in np.arange(len(PWF_hydraulic_cylinder_flap_gate)):
    PWF_hydraulic_cylinder_flap_gate[d] = 1/(1+r)**(Failure_hydraulic_cylinder_flap_gate_interval*(d+1))
for e in np.arange(len(PWF_hydraulic_cylinder_radial_gate)):
    PWF_hydraulic_cylinder_radial_gate[e] = 1/(1+r)**(Failure_hydraulic_cylinder_radial_gate_interval*(e+1))
for f in np.arange(len(PWF_hydraulic_aggregate)):
    PWF_hydraulic_aggregate[f] = 1/(1+r)**(Failure_hydraulic_aggregate_interval*(f+1))

#Equivalent annual maintenance cost of each component  [€/year]
EAC_wall_pier = sum(Failure_wall_pier_Mcost*Failure_wall_pier_units*PWF_wall_pier)*A
EAC_control_flap_gate = sum(Failure_control_flap_gate_Mcost*Failure_control_flap_gate_units*PWF_control_flap_gate)*A
EAC_radial_gate = sum(Failure_radial_gate_Mcost*Failure_radial_gate_units*PWF_radial_gate)*A
EAC_hydraulic_cylinder_flap_gate = sum(Failure_hydraulic_cylinder_flap_gate_Mcost*
                                       Failure_hydraulic_cylinder_flap_gate_units*
                                       PWF_hydraulic_cylinder_flap_gate)*A
EAC_hydraulic_cylinder_radial_gate = sum(Failure_hydraulic_cylinder_radial_gate_Mcost*
                                           Failure_hydraulic_cylinder_radial_gate_units*
                                           PWF_hydraulic_cylinder_radial_gate)*A
EAC_hydraulic_aggregate = sum(Failure_hydraulic_aggregate_Mcost*
                                           (Failure_hydraulic_aggregate_units)*
                                           PWF_hydraulic_aggregate)*A

#Total equivalent annual maintenance cost (under preventive maintenance strategy)
Preventive_Maintenance_cost = (EAC_wall_pier+
                              EAC_control_flap_gate+
                              EAC_radial_gate+
                              EAC_hydraulic_cylinder_flap_gate+
                              EAC_hydraulic_cylinder_radial_gate+
                              EAC_hydraulic_aggregate)

#Total equivalent annual maintenance cost (under corrective maintenance strategy)
Corrective_Maintenance_cost = EAC_wall_pier
```

Figure 141: Equivalent annual maintenance cost (radial alternative)

```python
#Planned downtime (under preventive maintenance strategy)
PPDT = (Maintenance_wall_pier*MT_wall_pier*Failure_wall_pier_units+
        Maintenance_radial_gate*MT_gate*Failure_radial_gate_units+
        Maintenance_hydraulic_cylinder_radial_gate*MT_hydraulic_cylinder*Failure_radial_gate_units+
        Maintenance_hydraulic_aggregate*MT_hydraulic_aggregate*Failure_hydraulic_aggregate_units)

#Planned downtime (under preventive maintenance strategy)
CPDT = Maintenance_wall_pier*MT_wall_pier*Failure_wall_pier_units
```

Figure 142: Planned downtime (radial alternative)

```
d = dict()
d['Availability TUE 1.R (corrective, preventive)'] = [1-NonAvailability_TUE1R_cor,
                                                     1-NonAvailability_TUE1R_prev]
d['Availability TUE 2.R (corrective, preventive)'] = [1-NonAvailability_TUE2R_cor,
                                                     1-NonAvailability_TUE2R_prev]
d['Unexpected downtime TUE 1.R (corrective, preventive) [hours]'] = [(NonAvailability_TUE1R_cor)*life*8760,
                                                                (NonAvailability_TUE1R_prev)*life*8760]
d['Unexpected downtime TUE 2.R (corrective, preventive) [hours]'] = [(NonAvailability_TUE2R_cor)*life*8760,
                                                                (NonAvailability_TUE2R_prev)*life*8760]
d['Planned downtime (corrective, preventive) [hours]'] = [CPDT, PPDT]
d['Expected repair cost (corrective, preventive) [€/year]'] = [CERC, PERC]
d['Equivalent maintenance cost (corrective, preventive) [€/year]'] = [Corrective_Maintenance_cost,
                                                                      Preventive_Maintenance_cost]

return d
```

Figure 143: Output Python script (radial alternative)