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Comparison of Human Reliability Analysis Method

Applied on the Volkerak sluice complex in the Netherlands

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Author:

Ilse Hogenboom

Supervisor:

Anders S. Kristensen

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Author:

IHogenboom

Ilse Hogenboom

AALBORG UNIVERSITY
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Abstract:

The executive agency of the Ministry of Infrastructure and Water, called Rijkswaterstaat, has the mission to develop and maintain the road network, the water network and the water systems in the Netherlands. The aim is to create procedures that facilitates the safety of the people operating and using these systems and to reduce the risk of an error being made. With the use of various methods, the risk is aimed to be as low as possible. However, to reduce the risk in these systems, it requires a combination of man and machine. Within Rijkswaterstaat, there was a method created to establish the reliability of the man in storm surge barriers, called OPSCHEP model. This method was based on a Human Reliability Analysis (HRA) method called THERP. The OPSCHEP model was only appropriate to use on storm surge barriers within the Netherlands. When this model was applied on other objects, this lead to conservative results. Therefore, Rijkswaterstaat is looking for another HRA method that would be appropriate to use on other objects. In this research, the HRA methods are applied on the Volkerak sluice complex in the Netherlands. As this is one of the largest sluice complex in Europe and therefore, important for the economics in the Netherlands. This leads to the following problem formulation:

Which HRA method is most suitable to be applied for a task performed by the operator on the Volkerak complex?

Three HRA methods were investigated: THERP, SPAR-H, and CREAM. Before the methods could be used, a task analysis for the operator at the Volkerak sluice needed to be identified. In this task analysis, the steps and actions were identified that the operators execute when ships want to pass the sluice from the south side to the north side. With the use of the three methods, each action that the operator executes there is a certain probability that could lead to an error. An error is defined as a significant delay in the process of the ships going from the south side to the north side of the sluice. In each of these actions, factors could influence the performance of the operator, which are included in the three HRA methods. The probabilities of these methods are compared to the results from experts. Based on these results and the review of the three methods, a suitable HRA method was identified to be used for the operator of the Volkerak complex.

The results identified that the CREAM method was the most suitable for Rijkswaterstaat to use on the Volkerak sluice complex. As the method was easy to use and the results showed more than just the probability of a human error. Also, the comparison of the results showed that CREAM is a good method to use.

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Preface

The research presented in this report is within the context of the Master Thesis for the Msc. Risk and Safety Management at Aalborg University Esbjerg. This report strives to achieve the objectives of the Master Thesis and to improve the skills obtained from the different studies and courses.

The scope of this research is to identify the best suited Human Reliability Analysis method for the Volkerak sluice complex in the Netherlands. This research has been done in collaboration with Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water. Different Human Reliability Analysis method are discussed to calculate the probability of a human error in the actions that the operator performs for the sluice to function. The main objective is to determine which method could be used on sluices in general. This report is aimed towards professionals and students who are interested in Human Reliability Analysis methods and applying them.

As Ilse Hogenboom has a Bachelor in Psychology, and with the current education, the perspective taken in this research is to focus on the actions that a person takes. Ilse's background will contribute to both the interpretation and the findings of the Human Reliability Analysis methods.

There are a few guidelines for reading this report:

- There are blank pages in report, which are left blank purposely.
- The glossary is used throughout the entire report, if not then it is pointed out differently. This can be found in the beginning of the report.
- Acronyms are used throughout the report, the first time there are used an abbreviation will be given using (). E.g., Human Reliability Analysis (HRA). The acronyms list will be presented in the beginning of the report.
- Several forms of references are used in the report. There is a reference to a source, table, figure and appendix.
    - A reference to a source is indicated with [ ]. E.g., "this gives the possibility to optimize the lifecycle cost [1]". The reference can be found in the bibliography, in the end of the report.
    - A reference to a table and figure are similar. This is indicated in the text with Figure X or Table X. Below the figure or table, the number and title is indicated. An overview list of the figures and tables is given in the end of the report.
    - A reference to the appendix is put behind the relevant text with (see Appendix X). This will be indicated with a number, which can be found in the end of the report to refer to the right document.

I would like to acknowledge the participation and help from Gwen Kleijn van Willigen from Rijkswaterstaat. She helped in supervising during this research, accessing the information needed and other contacts when needed. Also, John Romeijn, Mike Arnouts and Rene Krijgh for helping in accessing information of the Volkerak complex. All the experts that helped in providing different insights for this topic: Gerben Hesilinga, Alexander Bakker, and Pieter van Gelder. My supervisor, Anders Schmidt Kristensen from AAU Esbjerg, provided comments, considerations and feedback to improve this research.

Acronyms

CFP	Cognitive Failure Probability
COCOM	COntextual COntrol Model
CPC	Common Performance Conditions
CREAM	Cognitive Reliability and Error Analysis Method
FMECA	Failure Mode Error & Criticality Analysis
FTA	Fault Tree Analysis
GPO	"Grote Projecten en Onderhoud", translated into Major Projects and Maintenance
HAZOP	Hazard and Operability Study
HEART	Human Error Assessment and Reduction Technique
HEP	Human Error Probability
HRA	Human Reliability Analysis
HTA	Hierarchical Task Analysis
MMI	Man-Machine Interface
NARA	Nuclear Action Reliability Assessment
NGT	Nominal Group Technique
NHEP	Nominal Human Error Probability
NRC	Nuclear Regulatory Commission
OPSCHEP	Development of storm surge barrier Europoort Project Software for the Calculation of Human Error Probabilities
PRA	Performance Risk Analysis
ProBO	Probabilistic Management and Maintenance
PSF	Performance Shaping Factor
RAMSSHEEP	Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics and Politics
RCM	Reliability Centered Maintenance
SPAR-H	Standardized Plant Analysis Risk Human Reliability Assessment
SRK	Skill-, Rule- and Knowledge based
THERP	Technique for Human Error Rate Prediction
VWM	"Verkeer en Water Management", translated into Traffic and Water Management

Glossary

Human Error in locking process = the actions that are performed by the operator in the locking process, that lead to a significant delay in the locking process.

Leveling of water = this is the process of letting water in the lock or out of the lock to have the same water level.

Lock = the space in a sluice, in which the ships will move up on move down of the water level. This is defined by the doors in the beginning and the end of the lock.

Locking process = the actions that are part of moving ships from the south/north of the sluice to the north/south of the sluice.

Operator = the person who executed all the actions to perform the locking process.

Sailing Master = the person responsible for the ship and who sails it.

Significant delay = this is more than 15 minutes.

Sluice = an object that makes it possible for ships to pass a difference in water level.

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1 Introduction

The Netherlands is a country that deals with a lot of water, both from the sea and the rivers. It must protect itself from the water, but also maintain the shipping route as the rivers are an important part of the economics of the country. A lot of goods are transported through the main rivers in the Netherlands, not only for national purposes but also international [2]. However, as the Netherlands is below sea level, different measures were taken to protect the land from the water. A combination of dikes, dams and storm surge barriers were build, some part of the famous “Deltawerken” [2]. Several dams were built within the main shipping route. A sluice was built into the dam, to cross the dam from one water system to the next. In the Netherlands, there are several sluices, one of the most important sluices is the Volkerak complex. Annually 185,000 ships pass the sluice which connects the shipping route between Amsterdam and Germany, and Antwerp and Rotterdam [2]. For the economical aspect of the Netherlands, there is a high priority in a good flow of ships on passing the Volkerak complex.

Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water, operates and maintains the Volkerak complex, amongst other objects in the Netherlands. The operation is based on Performance Risk Analysis (PRA). As such, the performance of the systems is determined by the RAMSSHEEP criteria, RAMSSHEEP stands for Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economics and Politics [1]. Requirements are connected to each aspect. If the requirements are not fulfilled, performance risks will be connected to the systems. Rijkswaterstaat maps the performance risks through qualitative and/or quantitative risk analysis, depending on the type of object. During the development and construction phase, choices are made that could influence the expected performance and maintenance cost of the object which is based on the Reliability Centered Maintenance (RCM) model, this gives the possibility to optimize the lifecycle cost [1]. Whenever the requirements, the expected performance and maintenance cost, are not in balance, another look will be given and changes need to be made.

Asset management is based on PRA, which is used in all objects of Rijkswaterstaat, also the Volkerak complex. To determine the performance threats, there are four areas which are considered [1]:

- Hardware defaults.
- Software defaults.
- Failure due to human factors.
- Failure due to external risks.

In this research, the focus is on failure due to human factors. To determine the probability of that failure, a Human Reliability Analysis (HRA) method should be implemented [1]. The failure of human factors could eventually have major consequences. A human error could lead to an interruption in functioning of a sluice which creates an economical loss. However, when operations talk about a failure of human factors, there is a certain negativity about it, as blame is perceived to be put onto an individual in that operation [3]. There is a certain sensitivity in this topic. On the other hand, it would be better to talk about the failure of human factors as this could only improve the operation and reduce failures. To indicate what the probability of a human factor leading to a failure in an operation is, calculations could be made based on HRA methods. Mostly in HRA, a failure of the human factor is not described as a shortcoming of an individual, but rather as a combination of both contextual and situational factors that influence the human's performance, either positively or negatively [3]. These are called Performance Shaping Factors (PSF), such as training, experience, culture, communication, management and procedures [4].

A HRA method was developed for the storm surge barriers in the Netherlands. The model does not provide realistic results for other objects within Rijkswaterstaat, mainly due to the difference in frequency of use [1]. Therefore, this research will focus on HRA methods that could potentially be realistic for sluices in the Netherlands.

1.1 Reason for Choosing

Rijkswaterstaat aims to uniform methods for the objects in the Netherlands. There is a HRA method for the failure of human factors on storm surge barriers, it is also deemed necessary to find a HRA method that is suitable for sluices. The Volkerak complex was selected as it is the largest sluice complex of Europe with a high frequency in usage and large economical value. Therefore, the Volkerak complex has the most value for the new HRA method.

To determine which of the HRA methods are used in this research, the most commonly known HRA methods were compared from the HSE Review of Human reliability assessment methods [5]. The comparison can be seen in Appendix A. According to this comparison, the following methods were selected: THERP, SPAR-H, and CREAM.

Also in this research, various tools learned in the Master Risk and Safety Management can be applied. The courses Risk Management, Risk Analysis, Risk Communication, Applied Statistics and Probability Theory, and Health and Safety Management are applied in this research. Another perspective is taken by looking closely to the human factors that can influence the safety performance.

1.2 Problem Analysis

Before the problem can be formulated, an understanding of the stakeholders is necessary. It is relevant to identify the stakeholders and to see their involvement in this research. Afterwards, a thorough problem description and setting the context will be necessary before understanding the problems that are formulated.

1.2.1 Stakeholder Analysis

The objective of this stakeholder analysis is to identify all stakeholders that are influenced by a change in the procedure for operating the Volkerak complex. The scope has been taken intern and extern of Rijkswaterstaat. One of the major stakeholder for the Volkerak complex is Rijkswaterstaat. Rijkswaterstaat is the executive agency of the Ministry of Infrastructure and Water. Their main mission is to manage and develop the main road network, the main water network and the main water systems. The only system that is discussed in this research is the water network. Rijkswaterstaat cooperates to promote safety, mobility and the quality of life in the Netherlands [6]. The agency works together with other companies and citizens to increase the safety of the infrastructure. Within Rijkswaterstaat, there are several departments. The two departments that are relevant for this research are Major Projects and Maintenance, abbreviated GPO, and Traffic and Water Management, abbreviated (VWM). GPO manages, develops and maintains the major projects, like road work, sluices and storm surge barriers. VWM manages the operation of the three major systems.

Rijkswaterstaat's responsibility is safely operating the sluice and is not liable for the behavior of the sailing master as they follow the safety traffic behavior rules equivalent to the road. Another responsibility of Rijkswaterstaat is to prevent incidents from happening. This is done through[7]:

- Selection based on proper education and competencies of personnel.
- Ensuring that the workplace is appropriate for safety critical actions.
- Correct functioning of equipment.
- Ensuring that the protocol, procedures and guidelines of the object are complete and understandable.
- Ensuring that employees are not overloaded with tasks.

However, Rijkswaterstaat and the operator are not responsible for extra safety measures on the ships and determining if the ship can pass the sluice or other objects. To conclude, Rijkswaterstaat ensures that the protocol, procedures and guidelines are safe when followed. This applies for both the operator and the captain of the ship. Rijkswaterstaat provides optimal safety within a certain scope.

Within Rijkswaterstaat there are several parties involved when it comes to the Volkerak complex. These stakeholders of Rijkswaterstaat are identified according to the expected impact of the implementation of a new HRA method, see Figure 1. The stakeholders can be divided into three groups: stakeholders relevant for the Volkerak complex, stakeholders of sluices in general and Rijkswaterstaat in general. The operator of the sluice is part of the stakeholders in the Volkerak complex. The stakeholders of the sluices, are the users and the sluices itself. The stakeholders for Rijkswaterstaat are the asset manager, performance manager, Steunpunt ProBO and the public image.

Figure 1. Stakeholder Analysis due to change in HRA method [Made by Ilse Hogenboom].

- *Sluices*. As the method will apply for these objects, therefore they are described as a stakeholder. The changes can affect the sluices in the way that they are maintained and operated and all changes need to be considered.
- *Asset Manager*. The new HRA method needs to be adopted. The effort and benefit of this method should be balanced as described in the PRA perspective of Rijkswaterstaat. As such, maintenance and operations can be influenced by the performance.
- *Performance Manager*. These are the people that are eventually implementing the method and should be taught the new method.
- *Steunpunt ProBO*. This is a group of employees that determines the methods that are going to be used and give advice about them. Therefore, these group of employees needs to be considered when changing methods as they are also the ones that explain them.
- *Image of Rijkswaterstaat.* A change in method can lead to a hypothetical change in performance and distrust in the media. It is important that the image that Rijkswaterstaat has, is maintained.
- *Operator of sluice.* The training and procedures could be different if the method supports new training.
- *Users of the sluices, like ships*. The new method can change the number of ships that are allowed in the lock. This can affect the waiting times for ships.

1.2.2 Problem Description

As mentioned before, the Volkerak complex is an important passage for the transport industry. Many ships pass this point to transport goods, nationally and international. Therefore, it is in the interest of Rijkswaterstaat to have a well-functioning sluice, otherwise the Netherlands suffers economically.

Currently at Rijkswaterstaat, there is a HRA method that is used for storm surge barriers, this is the OPSCHEP-model. OPSCHEP stands for the Development of storm surge barrier Europoort Project Software for the Calculation of Human Error Probabilities [8]. The aim of the model is to quantify human errors. The model categorizes the human errors in execution error and neglect error. The error that are found in the hazard identification will be categorized in one of the two failure categories. The model also refers to the possibility of correcting the error that has been made. Through the categorization of the failures a certain probability can be attached to failure. The OPSCHEP model is based on the THERP model, this will be explained in the following chapters.

After the OPSCHEP model was applied on the storm surge barriers, Rijkswaterstaat wanted to see if the model could also be used for other objects within the agency. However, the results did not correlate with the reality, it was conservative [1]. The results were from a research of the OPSCHEP model on a bridge. The model, however, is created for storm surge barriers that is not operated as often as a bridge. This is an explanation for the conservative results [1]. Therefore, a new method should be introduced to estimate the probability of a human factor failing in a frequently operated object, such as a sluice.

1.2.3 Setting the context

As mentioned before, Rijkswaterstaat does not have an accurate HRA method to estimate the probability of a human failure in operating the sluices in the Netherlands. Therefore, in this research, three methods will be used to see if a realistic probability can be estimated. These probabilities will be compared with the results from expert judgment, this is to see if the probabilities from the methods match the reality.

These methods are used in the scenario that an operator transports ships from the south side of the lock of to the north side of the lock of one of the sluices of the Volkerak complex. All the actions that the operator will execute are taken into consideration. This will be done in a task analysis. For each action, different factors could be of influence on the performance. Which could increase the likelihood of a failure on the operator side. The effect of the relevant performing shaping factors will be calculated. In this research, a failure is described as a significant delay in the locking process of ships due to actions of the operator. Eventually, the Human Error Probability (HEP) will be calculated for each of the action and the overall performance to determine the overall reliability of the operator.

1.3 Problem Formulation

In result of the problem analysis, the main concern within Rijkswaterstaat is to find a HRA method that is suitable for the sluices in the Netherlands. As it is now, the budget approach for sluices is based on a method that is conservative and not realistic. Therefore, a new method is required to make a better and realistic estimation of the reliability of human factors. This new method can result to a change in budget and create a better view of where the improvements should be implemented.

This leads to the following problem formulation:

Which HRA method is most suitable to be applied for a task performed by the operator on the Volkerak complex?

Before the problem formulation can be answered, several research questions are proposed:

- Is there are operating procedure for the Volkerak complex and how does it look like?
- What are the steps that are taken in a HRA analysis?
- What is the theory behind THERP, SPAR-H, and CREAM, and how do they differ?
- Is there a difference in the expert judgement and the HRA methods in this scenario?
- Can these conclusions be generalized to sluices in general?

1.4 Delimitations

There are some delimitations that have been constructed at the beginning of this research. These are:

- Only one lock is being looked at from the Volkerak complex.
- Three methods are used to compare.
- Focus is on the human factors, not the technical aspect.
- Focus is on human factors failure of the operator, not the captain of the ship.
- Focus is on the factors that influence the human failure and not the consequences of it.

There is only one lock chosen in this research. The Volkerak complex is a combination of four locks and a bridge. Three locks are for the ships and one lock if for recreation vessels. Over one of the three locks, a moveable bridge is placed. This will not be included in the research. However, one lock is chosen as this can be generalized to other locks in the Netherlands. The Volkerak complex is chosen due to the high demand of ships passing the complex.

The three methods that are chosen are from different generations in HRA methods. Therefore, a variation of methods is represented. Only methods of the first two generation are chosen, as third generation methods are not publicly available. In Appendix A, the comparison for the chosen methods is shown.

This research only focusses on the human factors that could fail and not the technical aspect of the sluice. This is relevant for the methods that are used and to identify if the probability of a failure in human factors can be predicted. Throughout the research, the assumption is made that there are no technical failures.

The only focus is the operator of the sluice and not the captain of the ship, as this out of the scope of this research. The captain of a ship does not work for Rijkswaterstaat and is therefore not in their control. The point of view that is taken is from the operator and their human factors that are of influence on a failure. The assumption is made that the sailing master follows the instruction of the operator correctly.

Whenever a failure has happened, certain consequences are tied to it. In this research, the focus is not on the consequences but to estimate the probability of a failure of the human factor happening. Some consequences are taken into consideration in this research, as it is part of a failure but it is not the focus.

1.5 Outline of the Report

To answer the questions that are formulated in the problem formulation, several perspectives should be considered. The following chapters discuss these perspectives and the relevance to the problem formulation.

Chapter 2 describes the operations of the Volkerak complex. The operation procedures and emergency procedures of the locking process are discussed. Also, a bow-tie identifies the causes and consequences of one of the hazards of the locking process of the Volkerak complex.

Chapter 3 deals with the background information of the HRA methods. A general description will be given of how a HRA method is used. The steps are discussed of the task analysis, human error identification and the quantification of human failures. Fault Tree Analysis (FTA) is included to describe the context.

Chapter 4 discusses the HRA methods that are used during this research. This includes THERP, SPAR-H, CREAM, and an expert judgment method. The information is discussed that is necessary to use these methods.

Chapter 5 presents the task analysis and error identification. For each of the actions performed, errors are identified that can occur. These task identifications and error identifications are taken from the operator's perspective. The FTA is put into the context of the locking process.

Chapter 6 describes the application of the three methods and the expert judgment on the task analysis that is made in chapter 5. The results will be shown for the probability of a human error occurring. In the end of the chapter, an overview will be given of the results.

Chapter 7 discusses the findings from the previous chapters, and the strengths and limitations of this research will be discussed.

Chapter 8 concludes on the earlier chapters and compares this with the questions that have been defined in the problem formulation.

Chapter 9 establish the practical relevance of this research and recommendations that can be made for further research.

2 The Volkerak Complex

There are many sluices in the Netherlands that have the function of passing ships through a dam. In this research, the focus is on the Volkerak complex. The Volkerak complex is placed in between two storm surge barriers; the Oosterschelderkering and the Haringsvlietsluizen. The Volkerak complex contains a sluice that manages the water level, a sluice that manages the shipping, which has three shipping locks, a lock managing the recreation vessels and a moveable bridge over one of the three shipping locks [9]. The complex manages the water level and can drain the high water of the Haringvliet and Hollandsch Diep to the Volkerak lake, in order to prevent flooding's in parts of South-Holland [2]. The Volkerak complex is located near a town called Willemstad, in Figure 2 the location of the sluice is pointed out in a red circle.

Figure 2. Location of the Volkerak Complex [Made from Google Maps].

The location of the Volkerak complex is on a shipping route. Not only cargo ships pass the sluice, also recreation vessels pass the sluice. Therefore, there are four locks in the sluice, three for cargo ships and one for the recreating vessels. It is one of the busiest sluice complexes in Europe. Around 150,000 cargo ships and 35,000 recreation vessels annually pass the Volkerak complex [2]. Therefore, the sluice is open 24 hours per day to regulate the ships passing the sluice. The focus of this research is to look at the sluices that manage the shipping and not the water level. The shipping locks of the Volkerak complex is shown in Figure 3. The locks can be very crowded with ships. The three locks for the shipping are 330 meters long and 24 meters wide [2]. The smaller lock for recreation vessels is 135 meters long and 16 meters wide [2]. The ships that are placed inside the lock need to follow certain safety regulations, like having a distance from the stop line, and with hazardous material on the ship, have at least a ten-meter distance between ships [7]. These regulations are not relevant for this research. However, these regulations are important for the operator of the sluice as this needs to be managed by him/her.

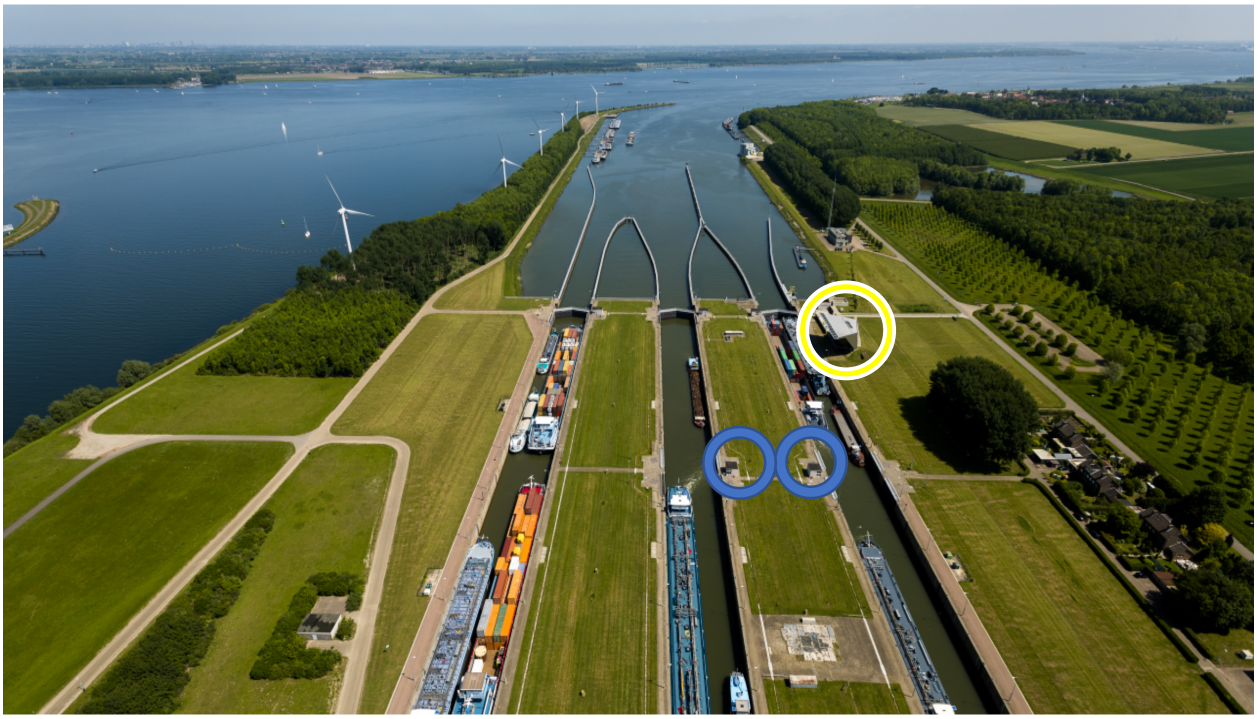

Figure 3. The Volkerak Complex [10].

2.1 Working of a sluice

In discussing the functioning of a sluice, all locks follow the same procedure. However, in this research the focus will be on lock one, which is the most right lock in Figure 3.

There are different modes in which the sluice can be operated [9]:

- *Central operation*. This is the regular operation place. In Figure 3 the central point, marked with a yellow circle, is the building close to lock one. From here all the operations are executed for all the locks and bridge.
- *Local operation*. Whenever it is not possible to work from the central point. It is also possible to operate the lock locally. From small buildings, marked with a blue circle in Figure 3, the operator can operate one set of doors within each lock.
- *Hand operation*. If it is not possible to operate the locks from the central or local point, it is possible to make the locks function by directly controlling the hydraulic pumps.
- *Emergency operation*. Whenever an incident has happened, the lock will go into an emergency operation. All operations will stop.
- *Maintenance operation*. If one of the locks needs to have maintenance work done, the lock will be out of function. The lock will then go into a maintenance operation, in which the lock can only be operated locally.

Operators

There are four operators working during the day shifts, in the night shift there are only three due to low demand of the ships [9]. Two of the operators are responsible for opening and closing the doors and levelling the water. One of the operators is responsible for communicating with the ships that arrive at the sluice and integrating them into the workflow. The last operator is responsible for the opening and closing the bridge and managing the recreation sluice [9]. All the operators go through intensive training. The training period is minimal four months and can continue for six months. All the operators need to have a level of stress resistance however this is not tested. During the training period, all the necessary competencies will be tested and will determine if you can continue as operator.

Lock doors

A sluice is built to let the ships pass from one water system into another, between which has a difference in water level. When ships enter the lock, the doors will close and water will be let in or let out of the lock to overcome the water level difference. This process is called leveling. In lock one and two, there are three sets of doors: one set in front, one set in the back and one set in de middle. The middle doors are placed so the leveling process can be divided and the process will go faster as the lock does not have to fill up entirely. In each door, there are three openings which can be opened or closed to let the water into or out of the lock. Each set of doors have doors for each tide, which are used depended on which side the water is higher [9].

What is automatic and manually in the process of the locks?

During the process of operating the lock, some of the actions are automatic and others are controlled by the operator. From the moment that ships can enter the lock, there is a green light that is manually turned on. This is indication for the ships to enter the lock. Once the lock is full, the light will be manually put on red and the doors starts closing. The doors are also closed with a push on a button, a hydraulic pump will start closing the doors, shown in Figure 4. After the doors are properly closed, then the next step can be put in motion, which is leveling. This can either be done by letting water out of the lock or letting water in the lock. The leveling can only be activated when the step of closing the door is done. This is a safety lock on the system. After the leveling is finished, the doors will open. The doors open manually, these only open when the leveling is done, which is another safety lock. Once the doors are all the way open, automatically the green light will be turned on in the lock. Now the ships inside can sail out of the lock. After

Figure 4. Picture of the lock doors and the hydraulic system [Made by Ilse Hogenboom].

all the ships have left the lock the green light can be turned red manually and the red light for incoming ships will be turned to green [9].

Equipment for the Operators

To operate the lock, there is certain equipment that the operators use. Cameras are placed all around the Volkerak complex. This is to check if the ships sail correctly in the lock and to see if the doors are clear before closing. Whenever there is bad vision or a malfunction in the cameras, there is a radar that the operator can use to continue the operation. Besides the vision, the operators also use a radio phone in which the operators can communicate with the ships. Relevant information is communicated, such as the place the ship should wait in the lock or the waiting time. There is also a system in which the operator can map the ships place in the lock, called IVS-90. This is done in an efficient and safe way, to minimize the waiting time of the ships. In IVS-90, all the numbers are saved like the number of ships that pass the sluice and the characteristics of the ships, as well as the total transfer time [9].

2.2 Operator Procedure at the Sluice at the Volkerak Complex

There is an object specific operation protocol for the Volkerak complex [11], [12]. First the protocol that is used by the operator will be discussed, afterwards the special circumstances will be discussed according to the general protocol for sluices in the Netherlands and at the end the functioning of the stop and emergency stop button will be discussed according to the general protocol for sluices in the Netherlands.

2.2.1 Protocol of Operating a Sluice at the Volkerak Complex

As mentioned before, there are four operators during a shift in the daytime. In this research, each of the operator has a number and will be addressed to this number and the description throughout the report [9]:

- Operator 1: This is the operator who is responsible for the operations of the doors, including levelling and in- and out coming ships at the south side of all three locks.
- Operator 2: This is the operator who is responsible for the operations of the doors, including levelling and in- and out coming ships at the north side of all three locks.
- Operator 3: This is the operator who is responsible for the operations of the bridge and the recreation lock.
- Operator 4: This is the operator who is responsible for the communication with the arriving ships and arrangement of the workflow.

The protocol for the process of using the lock are put into steps. This is an ongoing process and follows a cycle which repeats continuously. Operator one and two each have several steps when one ship sails from the south to the north. When the ship has arrived in the north of the lock operator two starts with a new locking process to the south. The steps explained below is the locking process of a ship moving from the south to the north of the sluice and back:

1. Collecting information from the ships. Executed by operator four, responsible for collecting information about the measurements of a ship arriving at the south of the sluice.
2. Communication with the ships. Executed by operator one (southbound), responsible for the doors on the south side.
3. Ships entering the lock. Executed by operator one (southbound).
4. Closing the lock doors. Executed by operator one (southbound).
5. Levelling the water. Executed by operator two (northbound), responsible for the doors on the north side.
6. Opening the lock doors. Executed by operator two (northbound).
7. Letting the ships out of the lock. Executed by operator two (northbound).
8. Communication with the ships. Executed by operator two (northbound), responsible for the doors on the north side.
9. Ships entering the lock. Executed by operator two (northbound).
10. Closing the lock doors. Executed by operator two (northbound).
11. Levelling the water. Executed by operator one (southbound), responsible for the doors on the south side.
12. Opening the lock doors. Executed by operator one (southbound).
13. Letting the ships out of the lock. Executed by operator one (southbound).

The first step and second step is to start the locking process. Communication needs to take place with operator 4 to see which ships want to enter the lock, what the measurements of the ship are and if there is hazardous material on board. This also includes: creating a lock plan and communicating with ships. It is relevant to know the characteristics of the ship, this influences the lock plan. The plan needs to be as efficient as possible. This will reduce the waiting time for the ships and a better flow. The location of the ship inside the lock will be communicated [11].

The third step is when the operator has checked that the lock is empty, to put the light on green for the new ships to enter the lock. Operator one should check when all the ships are inside, so the doors can be closed [11].

The fourth step is the process of closing the door. The lights will be turned to red by operator one as the operator checks if there are no ships around the doors. If everything is safe, operator one will close the doors. Turning the lights and closing the doors are a manual action performed by the operator. When the doors are closed, operator two will take over the locking process [11].

The fifth step is for operator two to start levelling the water when the doors are closed. This is again a manual action performed by operator two [11].

The sixth step, is to see if the water level is equal, which can have a difference of 5 cm maximum. The doors are opened while the windows for levelling the water are closing. This is executed simultaneously. [11].

The seventh step is letting the ships out of the lock. Operator two will check if the outgoing light will automatically turn to green when the doors are completely opened. The ships will leave the lock the same way they came in. Afterwards, the operator needs to check if the lock is empty [11].

This process continues itself during the shift. As shown in the steps, other ships arrive and operator two (northbound) will (re)start the steps. In this research, the ships are moved from the south side to the north side of the lock. However, to give a complete picture the steps are mentioned for when the cycle is complete.

2.2.2 Stop and Emergency Stop Button

The process described above in an ongoing cycle, which should not be stopped unless necessary. It can be stopped with a stop button or an emergency stop button. With the stop button, the current movement of the sluice process is stopped. The button is positioned at the Man-Machine Interface (MMI). When the danger is gone, the process can be restarted with a start button [7]. Additionally, with the emergency stop button the current movement can be stopped abruptly. This button must only be used in immediate danger or when the stop button does not function. The location of the emergency stop button is on a fixed spot which is reachable. After the use of the emergency stop button, it must be reset before the usual process can continue. This will only be done when the danger is gone [7].

2.2.3 Special Circumstances in Operating a Sluice

These are circumstances which cause deviations from the standard procedure above, like [7]:

- Incidents.
- Rijkswaterstaat safety behavior rules: “I stop every action that does not feel safe”.
- General instructions due to weather conditions.
- Special transport.
- Failure of camera footage.
- Technical failure, maintenance work or emergency operation.

Whenever an incident is close to or in the lock, the operator should stay at the workplace, unless he/she is directly in danger. The procedure according to the emergency protocol should be followed. Whenever the emergency stop button has been pushed, the system should be reset before the process can be restarted. This may only happen when the threat has passed. What has happened should be reported in the digital journal and an event rapport must be written for the miss or near miss [7].

“I stop every action that does not feel safe” is a human behavior rule of Rijkswaterstaat, regarding safety. Every action that does not feel safe can and should be stopped by the operator. This is done so the manager does not need to be contacted whether an action should be stopped. However, afterwards the manager should be notified that the action is stopped and why. The manager can say that the action is not allowed to be stopped, then the responsibility lies with the manager in case of an accident [7].

There are different procedures to follow due to weather conditions. These weather conditions are: wind, fog, rain and ice, darkness, sun, and extreme high/low water. When certain limits are exceeded the protocol for these circumstances needs to be followed. Current actions are to be put on hold and the event should be reported at the central station. The ships that are currently around the sluice need to be notified and follow the instructions. These are general instructions for each of the weather conditions [7].

Whenever there is special transport that needs to pass the sluice, the manager should be notified and the operator needs to follow the instructions of the manager [7].

Whenever there is a failure in the cameras, the current actions need to be stopped. The manager need to be informed. Perhaps current actions can be continued with the help of other measures. The cameras are important for safely operating the sluice and for quick passage of the ships [7].

When maintenance or emergency operations need to be performed, the sluice must stop functioning in that area and needs to be handed over to maintenance personnel. Whenever there is a technical failure, the ships and the central station need to be informed about the failure. After maintenance or recovery, there will be a trial, before the sluices continues normal operation [7].

2.3 Bow-tie analysis

A simplified bow-tie analysis identifies the causes and consequences of a particular event, see Figure 5. In this research, the causes and consequences are identified for a significant delay in the locking process. There could be technical failure, but also human failures. Both could have an influence on the delay in the locking process. The consequences could lead to major economic losses.

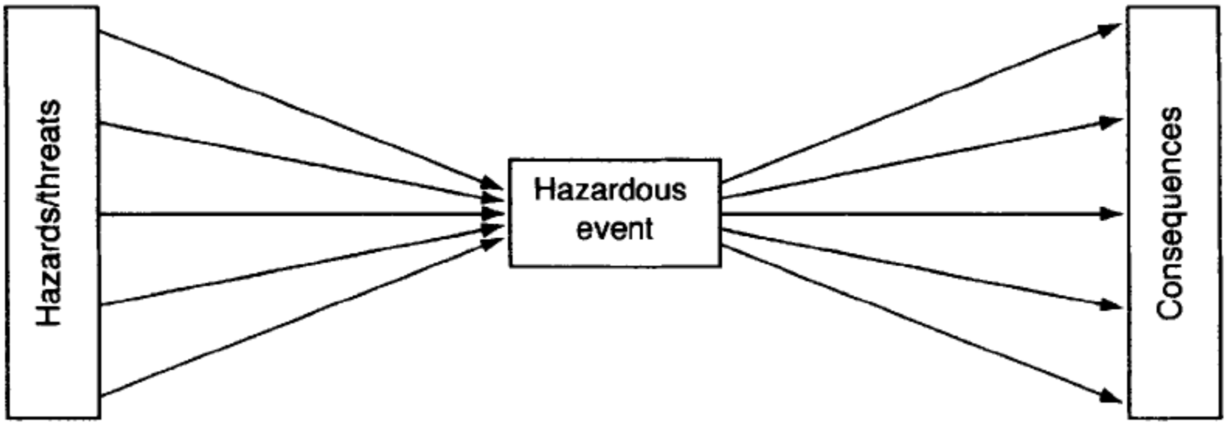

Figure 5. A simplified bow-tie analysis [13].

Causes	**Hazardous Event**	**Consequences**
System failure, like computers.		A line of ships waiting.
A mechanical failure, like the doors are not responding to a commando.		Delay for the ships and their transport.
No attention for the action by the operator.	A significant delay in the locking process.	Economical loss for the ships.
Distracting factors in the surroundings of the operator.		Stress for the sailing master on delivering on time.
Tiredness of the operator.		Collision due to stress of the delay.
More reckless behavior due to pressure of the operator.		

Table 1. Bow-tie Analysis [Made by Ilse Hogenboom].

As shown in Table 1, the causes can be divided into two categories: technical failure and human failure. Whenever, the MMI system is not correct and this is not identified by the operator it could lead to the hazardous event. One of the major consequences of the delay in the locking process is economic losses for the Netherlands and the shipping business. The transport will not be on time and a collision of ships could be near the sluice. This could lead to dangerous situations and more reckless behavior of the operator but also the captains. A higher probability of accidents can occur of this reckless behavior, many ships are on a deadline and therefore in a hurry.

3 Human Reliability Analysis

Humans are part of all phases of technical systems, during the design, construction, maintenance, operating and improving phases. As humans are an important part of a system, it is more likely that an error can occur. Humans are more complex than technical systems, and therefore more unpredictable in making errors [14]. In certain situations, it is more reliable to use a technical system than a human. In repetitive tasks, it would be more reliable to use a technical system, as the attention span from a human is low and this will lead to errors [15]. However, a human can adapt itself and could correct errors that have been made. Humans use their intelligence when executing a task. To minimize the amount of human errors, a human should be assigned for a task in which their strength can be used [15]. To indicate how these errors can be reduced, first an estimation should be given on what the probability is of them occurring.

To estimate the reliability of humans in certain task Human Reliability Analysis (HRA) was created. This is a method that works in a systematic way to identify and evaluate possible errors that are made by operators, maintenance and other personnel that work on a system [14]. With HRA a quantification of possible human error is made, it also supports preventive and mitigating measures and it improves the value of risk assessment as the human elements is included. In general, most HRA methods use three distinct phases [3]:

1. *Task Analysis*. Here the overall task is subdivided to smaller actions for further analysis. The subdivision varies between HRA methods and has no general standard for it.
2. *Human Error Identification*. The performance shaping factors (PSF) are identified. The factors that are identified varies between HRA method, the number of factors could differ from 1 to 50 PSF.
3. *Quantification of human error.* The quantification indicates how likely it is for a human error to occur in a specific task. The human error probability (HEP) is calculated in this phase. There is not standard for calculating. It could be based on the PSF, expert estimation, simulations or Bayesian approach.

Both quantitative and qualitative methods are used in HRA phases. The qualitative methods are used in identifying the task analysis, in which the task is subdivided into smaller actions. Also, the identification of PSF is part of a qualitative method. The quantitative part of the HRA phases is the calculations of HEP. HEP calculates the probability of a human error occurring for a specific task [14]. This is done by dividing the number of errors by the number of times the task has been performed [14], [15].

3.1 Task Analysis

This is the first phases of a HRA method, a detailed examination of activities related to the execution of a certain task. There are several task analysis methods, but overall the methods have the same basis [14]:

- A breakdown of the task into smaller and simpler steps.
- The identification of communication between persons in these steps.
- A description of the dependencies between the steps.
- Classification of the different task types.
- Identification of cues and feedback of each step.

The main objective is to divide the task into smaller steps and to identify the human activities, both physical and cognitive process, with each of the steps.

3.2 Human Error Identification

In the second phase, a human error identification will be analyzed, this includes the identification, description and analysis of possible action that could lead to an error in performing a task [14]. For the analysis of human reliability, these methods should only focus on the human aspect of error and not on the technical side. In the analysis of the human error identification, the performance shaping factors and the classification of the errors should be included to create an overview of the contributors to the error.

3.2.1 Performance Shaping Factors

A human error is related to the task that is performed. The task can be divided into smaller actions. An error can be triggered by a combination of multiple factors, like the conditions of the environment but also the personal factors. The influence of factors on the performance is called Performance Shaping Factor (PSF). An error could be that the action has not been executed correctly, this could be an incomplete, wrong direction, over completion, wrong execution, wrong object, etc. However, it could also be that the error is with the human. For example, lack of instruction, lack of attention, inadequately with remembering procedure, miscommunication, lack of knowledge, etc. These are typical errors that are made by humans and are shaping the performance [14]. Human error is not just shortcomings of a human, but a combination of situational and contextual factors that are shaping the humans performance [3]. The factors that could influence a human's performance, can be divided into three groups [14]:

- *Internal*. The characteristics of human performing the task, such as training, experience, motivation, and health.
- *External*. The factors that are not internal for the human performing the task, such as complexity of the task, work environment, and management and organizational factors.
- *Stressors*. These are factors that induce stress for both mental and physique, such as speed of the task, work load, and fatigue.

To each of the PSF a multiplying factor is associated, this is dependent on the method that is used. The multiplier is used to identify the probability of a human error occurring. The Human Error Probability (HEP) gives an indication of how likely it is to have a human error in the task that is performed. The HEP helps identify which task and even subtask needs more attention to improve and reduce the number of human errors [14]. Each multiplier for the PSF and the formula for calculating the HEP of the task is dependent on the method.

3.2.2 Classification of errors

Whenever an error is made with a certain action, a classification system can identify the origin of the error. The classification system depends on the task that needs to be executed. In general, there are three classification systems that are used [14], [15]:

1. **Rasmussen's Skill-, Rule- and Knowledge (SRK) based classification** [16]**.** There are three categories in this classification, which will lead to different types of errors, see Figure 6.

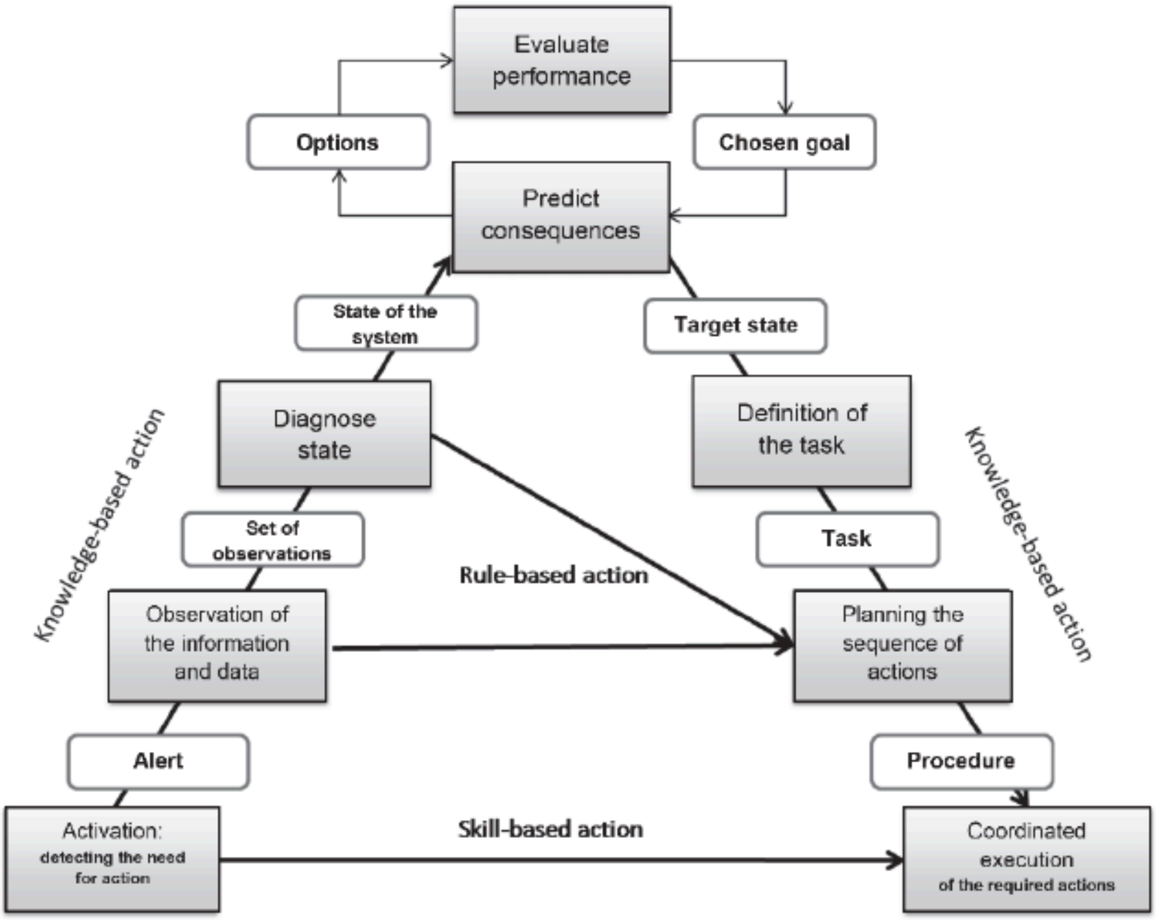

Figure 6. Classification by Rasmussen's SRK model [16].

   a. *Skill based.* These are automatic actions, like writing and cycling, they require little to no cognitive effort. This depends on the operators practice in performing the action. The error probability for these types of actions is between 1/200 and 1/20,000.
   b. *Rule based.* These are actions that are performed with the use of procedures. The level of practice is lower in comparison to the skill based actions. In these cases, the procedures are not recalled, or performed correctly. The error probability for these types of action is between 1/20 and 1/2,000.
   c. *Knowledge based.* In these actions, there is a requirement of problem solving and decision making. There are no procedures or rules written for these types of actions. First, the situation should be observed, the information should be interpreted and a decision should be made. The error probability for these types of actions is between 1/2 and 1/200.

2. **Reason's classification** [17]**.** The SRK method of Rasmussen was improved by Reason. A categorization was used to identify the faults of a human being, an error with good intention or a violation, see Figure 7.

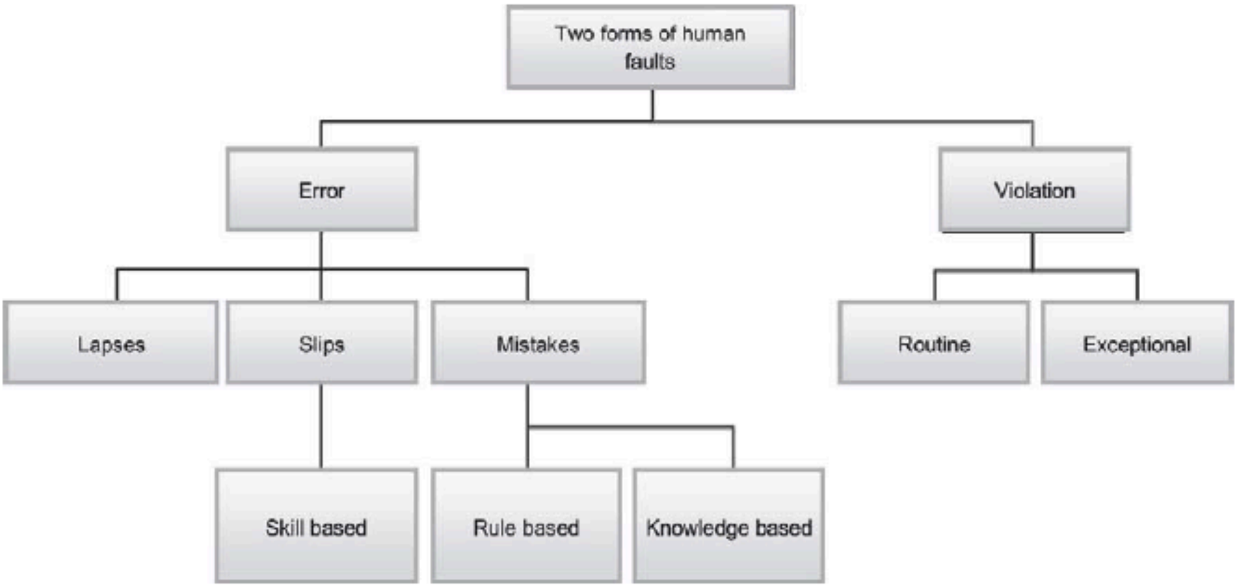

Figure 7. Classification by Reason [17].

   a. Whenever an error was made with good intention, three types of errors could occur:
      i. *Lapses.* This is an error due to distraction of forgetfulness. A lapse could be dangerous and hard to contain, like not closing the valve because someone interrupted.
      ii. *Slips.* This is an error with correct intention, but executed poorly. The consequences of such an error can be minor or severe, like pressing the wrong button or not closing the valve properly.
      iii. *Mistakes.* A correct implementation of the wrong action. An example is pressing the wrong button correctly. An error like this could be prevented with training.
   b. Whenever an error was made due to a violation, four types of errors could occur:
      i. *Routine violations.* A systematic behavior opposite to the rule or procedure. Like a pedestrian crossing on the not protected crossing paths.
      ii. *Exceptional violations.* These are violations of the procedure for a particular situation, like an emergency.
      iii. *Situation-specific violations.* These violations of the procedure occur when there is a restriction due to the environment, in a physical or organizational way.
      iv. *Acts of sabotage.* The cause of these violations could range from vandalism to terrorism. Sabotage is not considered in HRA methods.

   Violations are intentional and are usually not reported, as they are forbidden and not mentioned.

3. **Error of Omission and Commission classification by Swain and Guttman** [18]**.** There are two categories according to Swain and Guttman, see Figure 8.

a. *Error of Omission.* The error occurred due to not fulfilling of the requirements or lack of time, this could be intentional or unintentional. The error could be compared to Reasons' lapses.

b. *Error of Commission.* The action is executed incorrectly. The commission error could lead to poor execution or wrong execution.

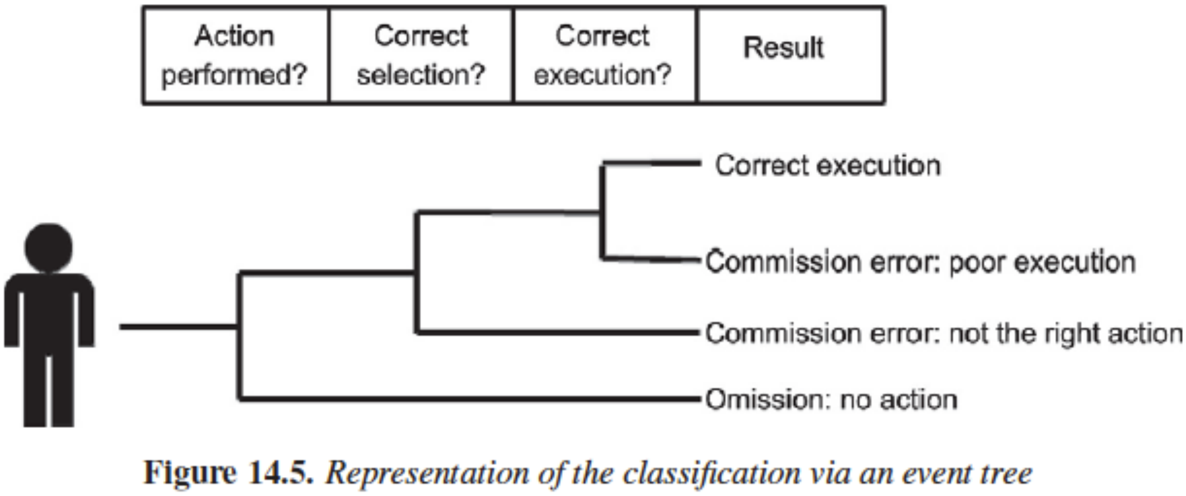

Figure 8. Classification of Commission and Omission [18].

This classification uses an event tree, and therefore are easier to use for quantitative analysis. The THERP method uses this model to identify the errors.

3.3 Quantification of Human Error

There are multiple HRA methods that are used nowadays. These methods are classified into four categories [5], [14], [15]:

- *1st Generation.* The first HRA methods that were developed, integrated the quantitative risk analysis with human actions and errors. The tasks are broken into single actions and the PSF are identified. However, these methods do not consider the cognitive aspect, error of commission, context and organizational factors when looking at the PSF. The 1st generation HRA methods that are used in this research are: Technique for Human Error Rate Prediction (THERP) and Standardized Plant Analysis Risk Human Reliability Assessment (SPAR-H).
- *2nd Generation*. In this generation, the error of commission, context and cognitive processes are considered in the human error prediction. It is more complex, as it focusses more on the cognitive aspect of human reliability where the first generation HRA only focusses on the behavioral aspect of human reliability. There is more psychology involved in the second generation. The 2nd generation HRA method that is used for this research is: Cognitive Reliability and Error Analysis Method (CREAM).
- *3rd Generation*. This is the combination of the first and second generation HRA. Here is, for example Human Error Assessment and Reduction Technique (HEART), the first generation method has been

revised and is therefore now a 3rd generation method under the name NARA (Nuclear Action Reliability Assessment).

- *Expert judgement methods.* Whenever there is no data or methods to use, the expert judgment method is a good method. As the information is based on experts from the field. This will give insights, which the researcher might not have thought of. The judgement of an expert can be biased. Also, a session for an expert judgement is time consuming. Experts consider how likely it is that an error occur for an action. This method is also suitable when other HRA methods are not appropriate for certain industries. An example is the Nominal Group Technique (NGT), in which experts discuss their estimations on a certain topic and the mean of the scores is calculated.

3.4 Fault Tree Analysis

After the HEP is defined, with the use of the three methods: THERP, SPAR-H, and CREAM, a context should be given to the probability. The consequences of human error on defined failure mode (delay) is not a 1:1 relation. A Fault Tree Analysis (FTA) provides a context.

A fault tree shows the relation between the top event, like the initiating event in a bow-tie, and the components of the system. The tree represents a diagram that explains the relation between the top event and the components of the system. So, from the top event, possible causes need to be identified to create the fault tree. In the fault tree, there are different symbols that are used (shown in Figure 9). The rectangle represents the basic events, or the steps that are performed of the task. The circle presents the lowest level of the fault tree, which are the actions that are performed. Then there are AND- and OR-gates. The And-gate is that the event below needs to happen before the other events can happen. On the other hand, with an OR-gate there is one of the events that needs to happen for the other to happen [19].

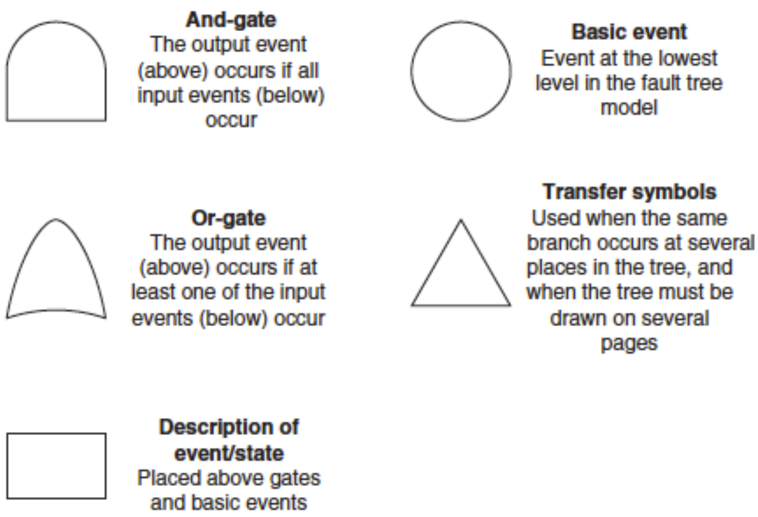

Figure 9. Symbols Fault Tree Analysis [19].

4 Human Reliability Assessment Methods

There are several HRA methods, in this research three methods have been selected and compared to an expert judgment method. As mentioned before, the three HRA methods are: THERP, SPAR-H, and CREAM. These three methods will first be explained, with background information and what information is necessary to use the method. Afterwards, the expert judgment method will be discussed. In later chapters the application of the methods will be shown.

4.1 Technique for Human Error Rate Prediction (THERP)

As mentioned before, this is a first generation HRA method. The method is developed by Swain and Guttman in 1983. The purpose of this method was for the nuclear and military industry, later the method was also used in the oil and gas industry. Most of the applications of THERP are involved in estimating the probability that a system-required task is executed correctly, sometimes within a specified time limit [18]. The HRA method, OPSCHEP model, created for Rijkswaterstaat is based on THERP.

In various of systems, human activities are necessary to continue the work in maintenance, testing, calibration and other operations, like coping with abnormal events [20]. As such, humans are considered part of a machine system. The man-machine interface, refers to the interaction between the man and the machine, is explained by THERP in Figure 10.

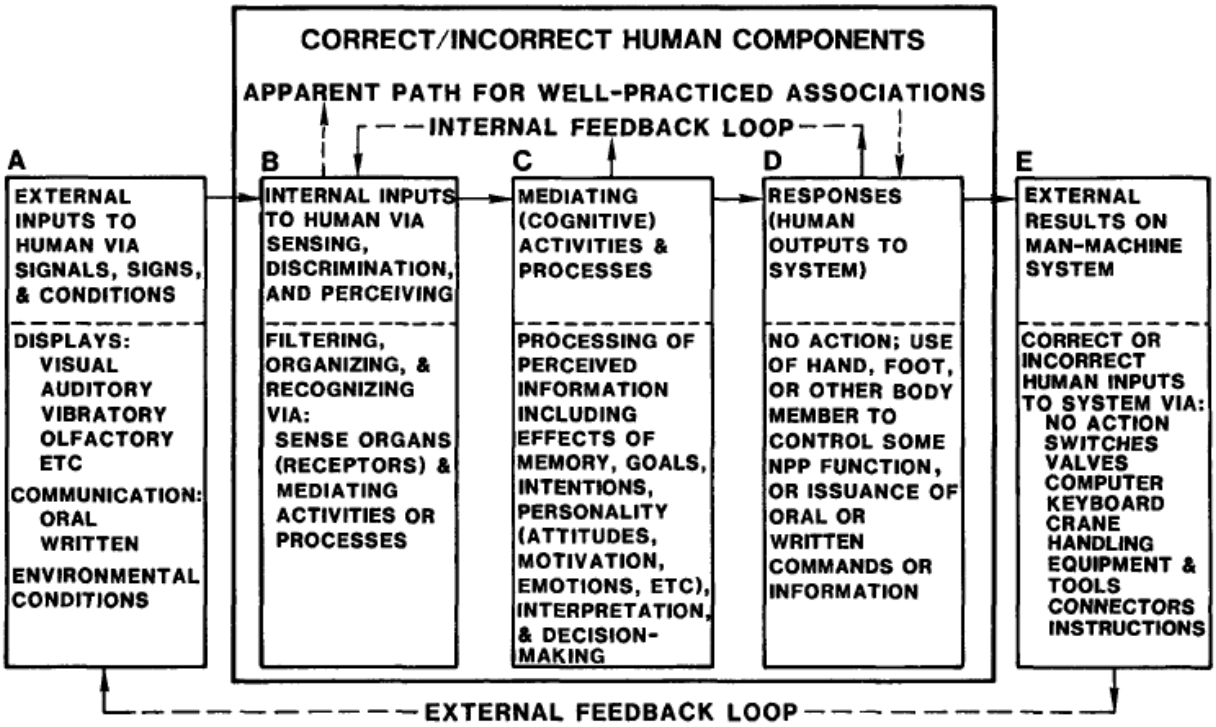

Figure 10. Man-Machine Interface by THERP [19].

Box A includes all the information that the operator perceives. This includes stimuli that can be heard or seen, but also the environment that the operator works in. The stimuli that is perceived in Box A will be send to Box B. Here the operator needs to be selective in what information should be processed. The operator filters, organizes and recognize various stimuli, and perceives what is relevant and should be further processed. The operators who have a lot of experience can proceed to Box D, however the operators who do not master these skills yet, will continue to Box C. All the perceived information in Box B, will be considered in Box C. How this information is considered depends on the skills that the operator has, personality and decision making tools. Whenever the information is considered, the actions will be determined and the operator continues to Box D. In here, the different actions are considered. Eventually, the operator continues to Box E, the actions are executed [20]. This process is considered by THERP for each action an operator executes. During this process, there are different factors that could be of influence on the performance.

According to THERP, the factors that influence the human performance are PSF. These models are about identifying whether the performance is highly reliable, unreliable or in between. THERP has divided the PSF into three categories [20]:

1. *External PSF*. These are the factors that influence the performance from outside of the operator. This can be subdivided into:
    a. Situational characteristics. Here can be thought of the quality of the environment, work hours/work breaks, and organizational structure.
    b. Task and equipment characteristics. These are PSF specific for the task. This can be the complexity of the equipment, the frequency of using the equipment/task, and decision making.
    c. Job and task instructions. This is the communication about procedures and work methods.
2. *Internal PSF.* These are the factors from inside the operators, like the training, personality, attitudes, knowledge, stress and physical conditions.
3. *Stressors.* These are the stressors, mentally and physically.
    a. Psychological stressors. These factors can be considered; task speed, conflicts of motives about job performance, distractions, and task load.
    b. Physiological stressors. Such as, temperature, noise, fatigue, vibration, movement restriction, and lack of physical exercise.

Event Tree

The basic tool of THERP is an event tree. The limbs represent a binary decision, a successful or unsuccessful performance. To each of the limb a conditional probability can be assigned, in which the sum of the branches should be 1.0. Figure 11 shows an example of the format of that event tree, in each of the limbs a description should be given of the human action that takes place. Eventually, a conditional probability will be given for each of the success and failures [20]. However, in this research, a fault tree is used to represent the relation between the steps and actions. The description of an event tree is included to show a representation of the method, but this is not used in this research.

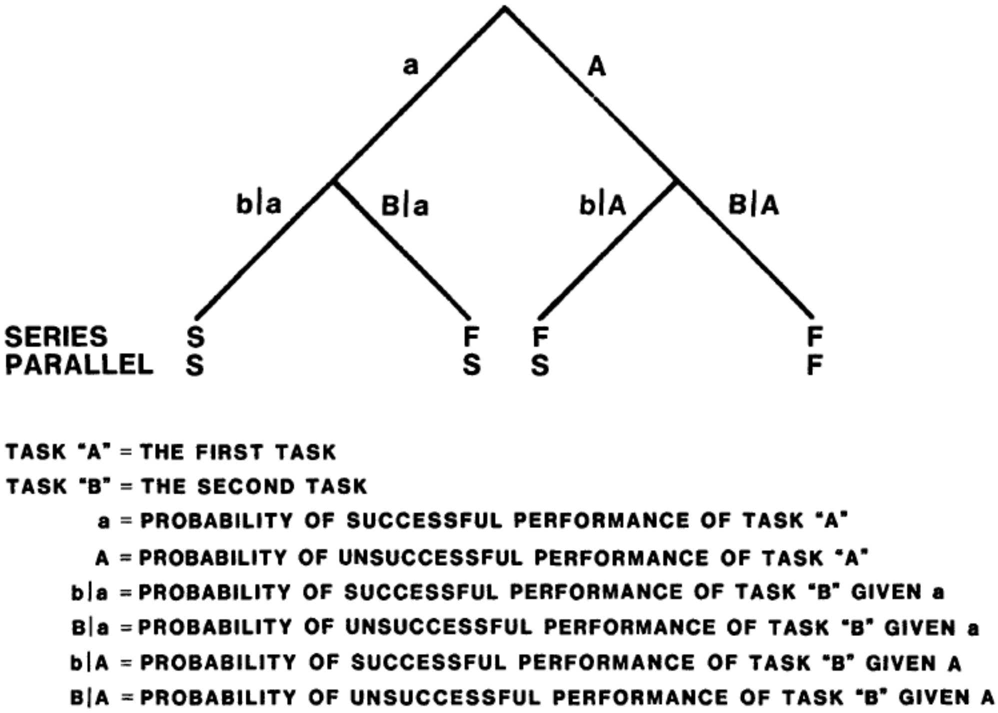

Figure 11. An Example of an Event Tree of THERP [19].

Search schemes are used in THERP to identify which tables are used to calculate the HEP. There are five phases in the search scheme (see Appendix B). The first step is to ask whether the action is abnormal, this research is about an abnormal event as there is a high failure probability for the actions that are discussed. The next step is to include a screening of diagnosis and rule based actions. The question is whether to continue with a sensitivity analysis. In this case, the answer is NO. As mentioned before, the three methods should be executed as equally as possible and therefore will the sensitivity not be included. The next question is if a nominal diagnosis is required, in this case the answer is YES. As these HEPs will be more realistic than the HEPs from the screening. Afterwards a post-event staffing table is included. When it is decided that it is a rule based action, these paths include table 20-1, 20-2, 20-2, 20-4. The actions that are executed are rule based. This was the first scheme, now the second scheme will be used. In each action, the question will be asked, whether the error is commission or omission, as mentioned in chapter 3. From here, several tables can be used to calculated the nominal HEP, like 20-5, 20-6, 20-7, 20-8, till 20-12. Depending on the path that is followed which tables are used in the calculations. Eventually the step will be made to the third scheme, in which the PSF will be discussed and calculated with the use of table 20-15, 20-16, 20-4, 20-17, 20-18, and 20-19. The path continues to the question if uncertainty bounds are used, in this case the answer is NO. This again is due to the factors that the HRA methods that are used should be as equally as possible. This will continue to the question whether recovery factors are used, to which the answer is also NO. Again, it is because the other methods do not use this. The last scheme is used, which is the Sensitivity Analysis, however this is also not used in this research. This is the end of the path for the search scheme. This is the path that is used throughout the research [18]. The next step is to display the results in an event tree or fault tree. This will make a representation of the path that is followed in the actions and the associated HEP with the action. With each branch and action a HEP can be calculated. The nominal HEP that is determined in the table that are used, are based on data that has been gathered [18]

The tables that are used to identified the multiplier of HEP for each PSF will be included in the Appendix B. Table 20-16 for the PSF stress/experience will be discussed to explain how the table should be read.

		Modifiers for Nominal HEPs*	
	Stress Level	Skilled**	Novice**
Item		(a)	(b)
(1)	Very low (Very low task load)	x2	x2
	Optimum (Optimum task load):		
(2)	Step-by-step†	x1	x1
(3)	Dynamic†	x1	x2
	Moderately high (Heavy task load):		
(4)	Step-by-step†	x2	x4
(5)	Dynamic†	x5	x10
	Extremely High (Threat stress)		
(6)	Step-by-step†	x5	x10
(7)	Dynamic† Diagnosis††	.25 (EF = 5)	.50 (EF = 5)
		These are the actual HEPs to use with dynamic tasks or diagnosis-- they are NOT modifiers.	

Figure 12. HEP for stress for THERP [19].

In Figure 12, skilled can be described as a person with 6 months or more of experience. Novice is a person with less than 6 months of experience on the job. The level of stress can be divided into four categories [20]:

1. Very low. Described as insufficient arousal to keep alert.
2. Optimum. This is subdivided into step-by-step and dynamic. This is due to the form of task, as in step-by-step is routine task and dynamic task has a higher degree of man-machine interface. This is the facilitative level.
3. Moderately high, which is moderately disruptive. This category is also subdivided into step-by-step and dynamic task described in the category of Optimum stress level.
4. Extremely high, which is very disruptive. This will give an emotional reaction to the task situation and is determined as threatening stress. The same as for the stress level of optimum and moderately high, it is subdivided into step-by-step and dynamic tasks.

The information that has been collected from the tables are included in to the fault tree, to determine what the probability is of a human error. It also could have been implemented into an event tree, however as mentioned before in this research a fault tree is used [20]. Either the table gives information about the HEP or about the multiplying factor, with the combination of this information the final HEP can be calculated.

Process of THERP

- Define the system failures of interest.
- List and analyze the related human operations
- Estimate the relevant error probabilities.
- Estimate the effects of human error on the system failure events.
- Possible changes can be recommended to the system and recalculate the system failure probabilities.

Pros and Cons of THERP

This method was created for the nuclear power plant industry, but it is a generic tool and can be used for different industries. It is a well applied method for highly procedural activities. A disadvantaged of THERP is that the method does not include the cognitive side of the human performance. To perform a HRA with the THERP method requires some expertise, most often training is needed before applying the THERP method into practice [5].

4.2 Standardized Plant Analysis Risk Human Reliability Assessment (SPAR-H)

This first generation HRA method was developed to support plant specific models for the Nuclear Regulatory Commission (NRC), and similar organization [21]. In 1994, the S stood for Simplified, and in 1999 the model was renamed as Standardized. The basic elements of this model come from literature based on information processing models of human performance. This includes the representation of perception and perceptual elements, memory, working memory, sensory memory, and long term memory. Also, stimulus-response models have been included to understand human behavior, this contains the process of receiving stimuli and responding to it. The inflow of information, task demands and environmental and situational factors influence the perception of a human. SPAR-H model believes that the HRA analyst should understand aspects of

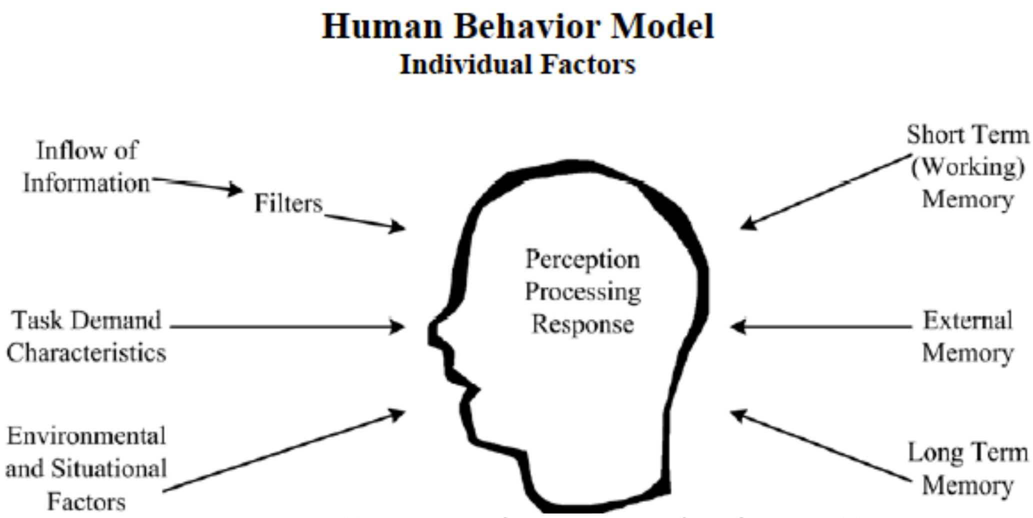

Figure 13. Human Performance Model from SPAR-H [21].

diagnosis and planning as well as the likelihood of the success of operators to carry out the action according to the procedures [22]. The distinction between diagnosis, information processing, and action, stimulus-response, is the basis of this model. Diagnosis tasks are the process before the action, like interpreting and thinking of the inflow information and processing it to an action. However, action tasks are plainly executing the action according to procedure or as conclusion of the diagnosis task. Therefore, two worksheets (see Appendix C) are created for the separate calculations.

Performing Shaping Factors

In Figure 13, a representation is given of the Human Performance Model of SPAR-H. These factors above, are the basis of the PSF within the SPAR-H model. The inflow of information to the operator can appear auditory, visual or kinesthetic. However, every human has a filter and distinguishes between what is relevant. This has an influence on the perception and eventually the action of the operator. Also, the role of experience, training, learning and beliefs has an influence upon perception. These factors can influence the response and therefore, the performance of the operator. The information and behavior model can be translated into eight PSF, used in the quantification process [22]:

1. *Available time*. This is the time that is available for an operator to diagnosis and act upon an abnormal event.
2. *Stress and stressors.* Stress has a positive or negative motivating factor on the performance. In this model, stress is used as an undesirable condition that withhold the operator from completing the task. This includes, physical stress, workload and mental stress. Environmental factors are used as stressors, like poor ventilation, radiation, or noise.
3. *Complexity.* This is the difficulty of performing the task in the given context. This is the interaction between the task and the environments in which it is performed. The more complex a task is, the greater the chance of human error.
4. *Experience and training.* The number of years of experience and if the operator has been part of training will influence the performance.
5. *Procedures.* This includes whether there is a procedure to follow and if it is followed under the correct circumstances.
6. *Ergonomics and human-machine interface (HMI).* Refers to the displays, layout, quality and quantity of information available from the instrumentation that is used. This is the relation between the machine and human, to see if the instructions are clear and up-to-date.
7. *Fitness for duty*. Is the operator, mentally and physically, fit to perform the task?
8. *Work processes*. This includes the aspect of doing work, like the organizational structure, safety culture, communication, and management.

Defining the Performing Shaping Factors and their multipliers

The PSF's has different levels and the multipliers depend on that level. In Table 2 are the levels and multipliers identified, this will be used for later analysis. Every PSF will be defined on the level of action, according to the SPAR-H Handbook [22].

PSF	Level	Definition	Multiplier
Available time	Inadequate Time	If the operator cannot execute the action in the time available.	P (Failure) = 1.0
	Time required	There is just enough time to execute the action.	10
	Nominal time	There is minimal extra time to execute the action.	1
	Time available ≥ 5x time required	There is extra time to execute the action, with a ratio of 5:1.	.1
	Time available ≥ 50x time required	There is extra time to execute the action, with a ratio of 50:1.	.01
Stress/stressors	Extreme	Level of disruptive stress, which results in deteriorate performance.	5
	High	A higher level of stress than the nominal level.	2
	Nominal	The level of stress that results is a good performance.	1
Complexity	Highly complex	Very difficult to execute.	5
	Moderately complex	Somewhat difficult to execute.	2
	Nominal	Not difficult to perform.	1
Experience/training	Low	Less than 6 months of training and/or experience.	3
	Nominal	More than 6 months of training and/or experience.	1
	High	A demonstrated master.	.5
Procedures	Not available	To perform the task, relevant procedures are not available.	50
	Incomplete	Relevant information is missing in the procedure.	20
	Available, but poor	Procedure is available, but does not contain correct information.	5
	Nominal	Procedures are available and improve performance.	1
Ergonomics/MMI	Missing/misleading	The current instrumentation fails to support the diagnosis and actions.	50
	Poor	The design of the work place does not improve performance.	10

	Nominal	The design of the work place is correct for the performance.	1
	Good	The design of the work place enhances the performance.	.5
Fitness for Duty	Unfit	Due to physically or mentally incapability, the operator cannot perform the task.	P(Failure) = 1
	Degraded fitness	The operator can carry out the task, but performance is negatively influences by it.	5
	Nominal	The operator can carry out the task, and there is no influence on the performance.	1
Work Processes	Poor	Performance is negatively influence by the work process at the work place.	2
	Nominal	The work place is not influence in the performance.	1
	Good	The work place is positively influencing the performance.	.8

Table 2. Levels and Multipliers of PSF SPAR-H [Made by Ilse Hogenboom].

Calculating the Human Error Probability

When all the levels and multipliers are identified for each of the tasks, the process starts of calculating the HEP. First, the task should be identified as a diagnosis or action task. Afterwards, all the PSF and the appropriate levels are identified. The multipliers of the PSFs are multiplied. When a task has ≥ 3 PSF, the adjustment factor need to be used. This can be done with the formula in Figure 14. NHEP stands for Nominal Human Error Probability, which depends on whether the task is diagnosis or action. If the task is diagnosis the NHEP will be .01, if the task is an action the NHEP will be .001. The PSF composite is calculated through multiplying all the multipliers of the PSF with each other. This number is the adjusted HEP for a task with ≥ 3 PSF. However, when a task does not have ≥ 3 PSF, then the HEP is calculated through multiplying the factor of the task, either diagnosis or action, with the multiplication of the PSF [22]. This is the final step before determining the HEP.

$$HEP = \frac{NHEP \cdot PSF_{composite}}{NHEP \cdot \left(PSF_{composite} - 1\right) + 1}$$

Figure 14. Equation for HEP in SPAR-H model [21].

The Process of SPAR-H

Figure 15 presents the process of the SPAR-H method. First, the task should be determined whether it is diagnosis, action or both. This will influence the worksheet that is used to determine the HEP. From that point, the PSF can be determined. With this information, the HEP can be calculated and the errors can be taken out of the process. The last phase is to determine if there is dependency in the errors. Then the last HEP can be determined with the associated PSF [22].

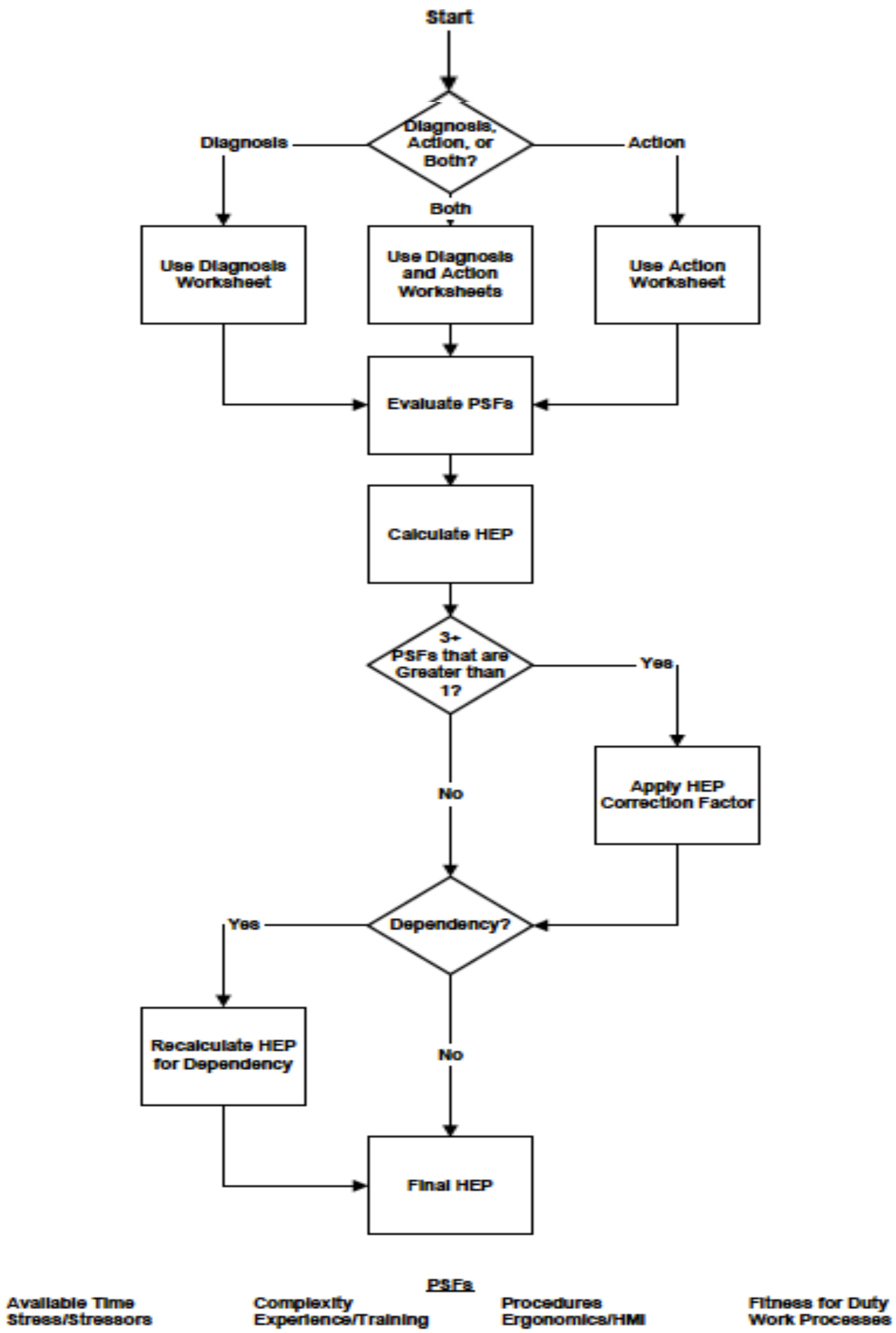

Figure 15. Phases of SPAR-H [21].

Pros and Cons of SPAR-H

Most HRA methods only describe PSF as a negative aspect of human performance, SPAR-H also includes the potential beneficial aspects of PSF on human performance. It also reports the dependency of a negative influence on human error and the reflection on the HEP. However, the positive influence is not explicitly integrated into the method [22].

The SPAR-H spreadsheet simplifies the estimation procedure. The procedure to use the spreadsheet differs slightly, dependent whether the analyst wants to build a SPAR-H model, perform event analysis, or perform a more detailed HRA. The aim is to create an event tree containing the diagnosis and action tasks [5], [21], [23]. SPAR-H is a simple underlying model, which makes it easy to use and provides more traceable results. The eight PSF cover most situations where a detailed analysis is not required. There is no guidance in exploring the PSF more in detail, which could be a con for the method [5].

4.3 Cognitive Reliability and Error Analysis Method (CREAM)

This is a second generation HRA method, as such the method also focusses on the cognitive aspect of human activity and the effect on their performance. The cognitive aspect is used in CREAM to organize the categories that define potential causes and effect in human actions. CREAM believes that traditional human factor models do not account adequately for how the context and the actions are linked and mutually dependent. Therefore, in this model the context in which the action takes place is relevant [24].

The basic principle of the model is a description of competence and control as two separate aspects of the performance. Competence is described as the human capability to perform the task, and control is described how the task is performed with the competence of the human. The competence and control that an operator has, will determine the reliability of the performance. [24]. The competence and control also returns in the Contextual Control Model (COCOM), which is the basis of CREAM. According to this model, cognition is not only about processing input and producing a reaction, but also a loop of reviewing goals and intentions. Figure 16 shows the loop, which is used during the cognition process. Competence can be divided into: observation, interpretation, planning and execution. According to CREAM, control can be divided into four control models:

1. *Scrambled control*. In this case, task demand is high, the situation is unfamiliar and can change rapidly. In extreme cases, this can lead to a state of panic.
2. *Opportunistic control*. The operator does no planning, this could be because the context is not clear or because of time constrains.
3. *Tactical control.* The performance is based on a procedure and is planned.
4. *Strategic control.* Operator looks further, with a wider horizon and considers the global context.

To describe the classification scheme of PSF according to CREAM and to use the high level of performance prediction, the competence and control modes that have been discussed above should be included [24].

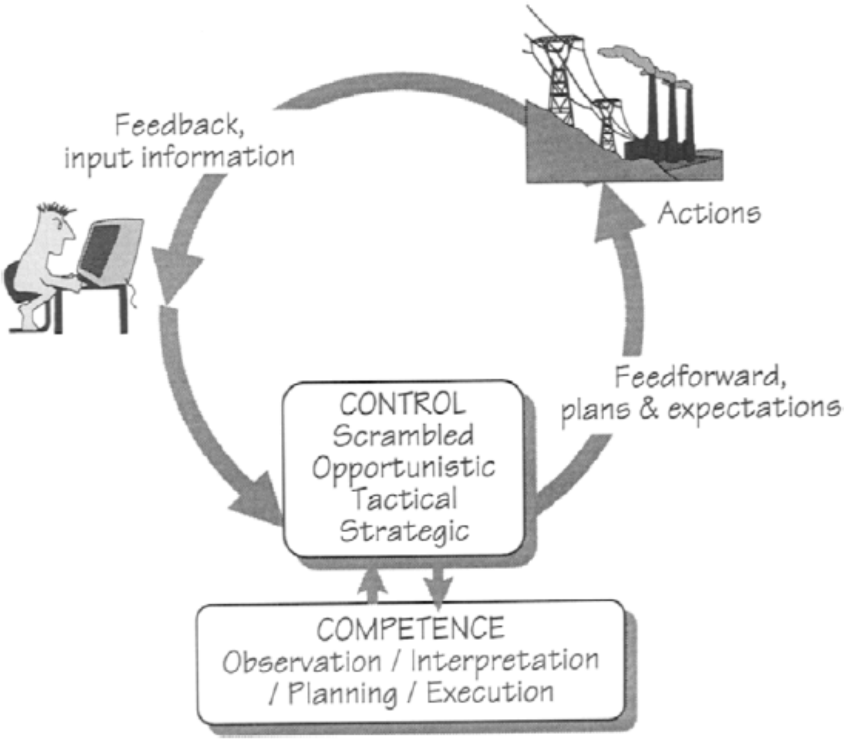

Figure 16. The Contextual Control Model of Cognition [23].

Performing Shaping Factors (PSF)

The classifications scheme should be able to identify possible erroneous actions as possible causes. A distinction in the scheme is made between effects, phenotypes, and causes, genotypes. The effects, phenotypes, refer to the observable factors, both human and technical, of the system. The causes, genotypes, are the categories that can be used to describe the effects. A cause, genotype, can be the internal process of a human before leading up to the effect, phenotype [24]. For the performance reliability, it needs to be considered how the possible erroneous actions and possible causes can be accomplished so that both the cognition and the context can be obtained in the performance conditions [25]. This can be combined in a small set of nine Common Performance Conditions (CPC), also described as PSF:

1. *Adequacy of organization.* Described as the adequacy of the role and responsibility of the operators.
2. *Working conditions.* The physical working conditions, like glare on screens, noise, and interruptions.
3. *Adequacy of Man-Machine Interface and operational support.* Is the Man-Machine Interface generally used? Is everything computerized?
4. *Availability of procedures/plans*. Whether the procedure/plans include the operating and emergency procedures and if the operators are familiar with it.
5. *Number of simultaneous goals.* The number of tasks that the operator must execute at the same time.
6. *Available time.* The time available to execute a task.
7. *Time of day.* The time of the day the task is performed. This is related to night shift, and to see if the circadian rhythm of the operator is correct.

8. *Adequacy of training and experience*. The level of training and experience, to see if the operator is familiar with the procedures that are performed.
9. *Quality of crew collaboration.* The quality of the collaboration between crew members, both professionally and unprofessionally. To see if there is a level of trust and the social climate between the crew members.

Defining the Performing Shaping Factors and their calculation

There are certain levels in the CPC and the expected effect it has on the performance reliability [25], displayed in Table 3. According to CREAM, with the definition of the CPC and the expected effect on the performance reliability, the analyst should be able to identify the levels of the CPC in the overall task [24].

Common Performance Conditions (CPC)	**Level**	**Expected effect on the performance reliability**
Adequacy of organization	Very efficient	Improved
	Efficient	Not significant
	Inefficient	Reduced
	Deficient	Reduced
Working conditions	Advantageous	Improved
	Compatible	Not significant
	Incompatible	Reduced
Adequacy of MMI and operational support	Supportive	Improved
	Adequate	Not significant
	Tolerable	Not significant
	Inappropriate	Reduced
Availability of procedures	Appropriate	Improved
	Acceptable	Not significant
	Inappropriate	Reduced
Number of simultaneous goals	Fewer than capacity	Not significant
	Matching current capacity	Not significant
	More than capacity	Reduced
Available time	Adequate	Improved
	Temporarily inadequate	Not significant
	Continuously inadequate	Reduced
Time of the day	Day-time (adjusted)	Not significant
	Night-time (unadjusted)	Reduced
Adequacy of training and experience	Adequate, high experience	Improved
	Adequate, limit experience	Not significant
	Inadequate	Reduced
Quality of crew collaboration	Very efficient	Improved

	Efficient	Not significant
	Inefficient	Not significant
	Deficient	Reduced

Table 3. Characteristics of the Common Performance Conditions (CPC) [Made by Ilse Hogenboom].

Quantification Method and Calculating HEP

There are two methods that can be used to quantify the predictions. Either the basic method can be used, in which the frequency of the effects, improved, not significant and reduced, are summed up and an interval of failure probability is assigned to the sum of the effects. However, for this research the extended method is used. In this method, the cognitive activity needs to be assigned to the task that is performed [26]. The cognitive activities and definition are shown in Figure 17.

Cognitive Activity	General Definition
Co-ordinate	Bring system states and/or control configurations into the specific relation required to carry out a task or task step. Allocate or select resources in preparation for a task/job, calibrate equipment, etc.
Communicate	Pass on or receive person-to-person information needed for system operation by either verbal, electronic or mechanical means. Communication is an essential part of management.
Compare	Examine the qualities of two or more entities (measurements) with the aim of discovering similarities or differences. The comparison may require calculation.
Diagnose	Recognise or determine the nature or cause of a condition by means of reasoning about signs or symptoms or by the performance of appropriate tests. "Diagnose" is more thorough than "identify".
Evaluate	Appraise or assess an actual or hypothetical situation, based on available information without requiring special operations. Related terms are "inspect" and "check".
Execute	Perform a previously specified action or plan. Execution comprises actions such as open/close, start/stop, fill/drain, etc.
Identify	Establish the identity of a plant state or sub-system (component) state. This may involve specific operations to retrieve information and investigate details. "Identify" is more thorough than "evaluate".
Maintain	Sustain a specific operational state. (This is different from *maintenance* that is generally an off-line activity.)
Monitor	Keep track of system states over time, or follow the development of a set of parameters.
Observe	Look for or read specific measurement values or system indications.
Plan	Formulate or organise a set of actions by which a goal will be successfully achieved. Plans may be short-term or long-term.
Record	Write down or log system events, measurements, etc..
Regulate	Alter speed or direction of a control (system) in order to attain a goal. Adjust or position components or subsystems to reach a target state.
Scan	Quick or speedy review of displays or other information source(s) to obtain a general impression of the state of a system / sub-system.
Verify	Confirm the correctness of a system condition or measurement, either by inspection or test. This also includes checking the feedback from prior operations.

Figure 17. Cognitive Activity of the Extended Model of CREAM [26].

These cognitive activities can then be divided over the four-cognitive competence: Observation, Interpretation, Planning and Execution. With this information, a cognitive demand profile can be made. It will show with each task what the demands are of the competence [26]. In combination with the cognitive demand profile, various cognitive function failures can be determined based on the four-cognitive competence. The next step is to assign Cognitive Failure Probability (CFP) to each cognitive function failure. In Figure 18, the failure types of the cognitive function failure are described and the nominal values with the lower and upper bound are defined. With these values the overall Human Error Probability (HEP) can be calculated [26].

Cognitive function	Generic failure type	Lower bound (.5)	Basic value	Upper bound (.95)
Observation	O1. Wrong object observed	3.0E-4	1.0E-3	3.0E-3
	O2. Wrong identification	2.0E-2	7.0E-2	1.7E-2
	O3. Observation not made	2.0E-2	7.0E-2	1.7E-2
Interpretation	I1. Faulty diagnosis	9.0E-2	2.0E-1	6.0E-1
	I2. Decision error	1.0E-3	1.0E-2	1.0E-1
	I3. Delayed interpretation	1.0E-3	1.0E-2	1.0E-1
Planning	P1. Priority error	1.0E-3	1.0E-2	1.0E-1
	P2. Inadequate plan	1.0E-3	1.0E-2	1.0E-1
Execution	E1. Action of wrong type	1.0E-3	3.0E-3	9.0E-3
	E2. Action at wrong time	1.0E-3	3.0E-3	9.0E-3
	E3. Action on wrong object	5.0E-5	5.0E-4	5.0E-3
	E4. Action out of sequence	1.0E-3	3.0E-3	9.0E-3
	E5. Missed action	2.5E-2	3.0E-2	4.0E-2

Figure 18. CFP of the Cognitive Function Failures [26].

CREAM states that the effects are dependent on the context. Therefore, the COCOM should be coupled with the effects of the CPCs. Table 3 shows the effects of the CPC on the performance reliability. However, to incorporate these effects with the COCOM, for each CPC the cognitive function should be identified and the relations to the cognitive functions determined, see Figure 19. Whenever the effect is to be predicted as "not significant" the weighted factor will be 1, this means that the basic CFP will not change. So first, the CPC should be identified and determined. If the task analysis shows that there is a cognitive function involved, the appropriate effect in Figure 19 should be determined. The overall weighted factor for a task is calculated by multiplying the chosen levels of PSF with each other. This weighted factor should be multiplied with the failure type that has been identified in Figure 18.

CPC name	Level	COCOM function			
		OBS	INT	PLAN	EXE
Adequacy of organisation	Very efficient	1.0	1.0	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.2	1.2
	Deficient	1.0	1.0	2.0	2.0
Working conditions	Advantageous	0.8	0.8	1.0	0.8
	Compatible	1.0	1.0	1.0	1.0
	Incompatible	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive	0.5	1.0	1.0	0.5
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	1.0	1.0	1.0	1.0
	Inappropriate	5.0	1.0	1.0	5.0
Availability of procedures / plans	Appropriate	0.8	1.0	0.5	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Inappropriate	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity	1.0	1.0	1.0	1.0
	Matching current capacity	1.0	1.0	1.0	1.0
	More than capacity	2.0	2.0	5.0	2.0
Available time	Adequate	0.5	0.5	0.5	0.5
	Temporarily inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Day-time (adjusted)	1.0	1.0	1.0	1.0
	Night-time (unadjusted)	1.2	1.2	1.2	1.2
Adequacy of training and preparation	Adequate, high experience	0.8	0.5	0.5	0.8
	Adequate, low experience.	1.0	1.0	1.0	1.0
	Inadequate.	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient	0.5	0.5	0.5	0.5
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.0	1.0
	Deficient	2.0	2.0	2.0	5.0

Figure 19. Weighted factors for CREAM [26].

The Process of CREAM

1. Making a task analysis, in each step the cognitive function should be identified.
2. Determine the level of CPC in each step.
3. Determine the cognitive failure type.
4. For each step of a task the CFP can be identified.
5. Calculate the HEP for each step of a task.
6. Calculate the overall HEP for the task.

Pros and Cons of CREAM

CREAM can be used in a comprehensive and complex setting. However, the method can be used with the use of the handbook of Hollnagel from 1998. This method is aimed to be used by psychologists who understand the underlying concept of cognition of a human [5], [14]. It is a qualitative and quantitative method, that has a clear structured way to error identification and quantification. CREAM is a method that is not yet familiar in the HRA methods, but it can be used in major hazards sectors.

4.4 Expert Judgment Method

In some cases, using a method to estimate the reliability of a human is not good enough. An expert can give more insight on the probabilities of the reliability of a human in certain cases. An expert has developed tools to make evaluations, therefore, the judgment of an expert can help to estimate the probability of human reliability. There is however, a certain level of uncertainty on the expert judgment. The combination of multiple experts should minimize the uncertainty with the use of calculations [27].

For this research, the Nominal Group Technique (NGT) is going to be used [28]. This method is chosen, because of there is a level of interaction between the experts, there is no training needed, anonymity of the experts and the limited amount of time and resources that is put into the preparations of the method. The method follows six stages [28]:

1. Presenting the experts with the initial statement for the research.
2. The experts reflect individually on the statement and write their responses down.
3. The session leader will ask, randomly, someone to explain their responses to the statement. This will be written down on a board for everyone to see. All the experts will be asked to explain their response. This will be discussed in the group for everyone to understand what the other expert meant.
4. The list of responses will be reviewed and every response will be indicated with a number.
5. All the experts establish the relevant importance of the responses.
6. All the responses and the importance of the responses is combined to see which one is higher in rank according to the group of experts.

The NGT method provides a list of ideas for the statement and quantifies the desirability of the topic. This method is relevant for this research, because the experts can express their ideas on the matter and later can rank all the ideas together. This will give a nice view of what are important performing shaping factors on the operator of the sluice. Also, this is the opportunity to discuss the probability of a human failure in each of the steps of operating a sluice. Eventually the results of the expert session will be compared with the results of the HRA methods.

5 Task Analysis & Error Identification

Before the methods can be applied, the context should be described step by step. This will be done in the task analysis. All the actions of the locking process are described and including which action is executed by which operator. Also, the errors that could be made in these steps are identified and categorized. A Fault Tree Analysis will identify the dependency of the actions and steps to the failure definition, which is a significant delay of the locking process.

5.1 Task Analysis

According to the Hierarchical Task Analysis (HTA), there is a goal to performing a specified task. HTA follows a top-down process. The task is divided into sub goals and these are decomposed. The main steps are [14]:

1. Plan and prepare.
2. Determine the overall goal of the task.
3. Determine the task sub goals.
4. Decompose each sub goal.
5. Analyze plans.
6. Report the analysis.

This research will follow this process, however step 1 and 6 are discussed explicitly.

Determine the overall goal of the task

The goal of the task is to move a ship from the south to the north of the sluice. This is the operational goal of the sluice. To perform this task, the operator must perform each subtask to reach the main goal. It is relevant to determine what the sub goals are of the task and what the hazardous points are in the process. To each of the sub goals the operator will be assigned who is responsible in the sub goals. To reach the overall goal of the task, operator 1, 2 and 4 are working together.

Determine the task sub goals

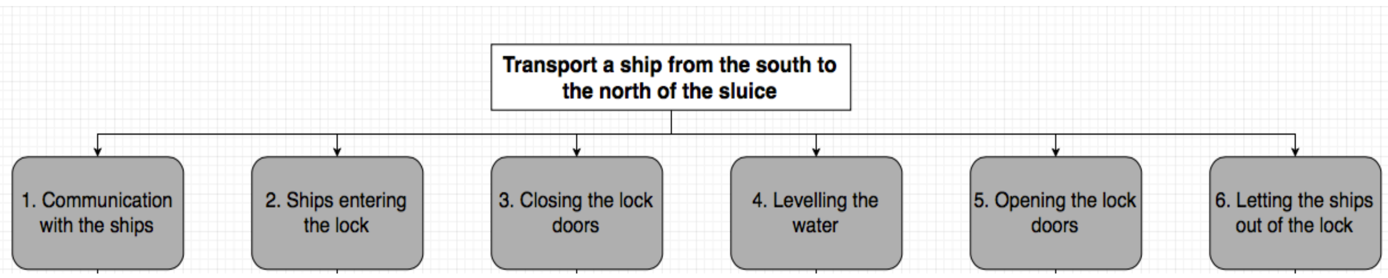

Figure 20. Sub goals of the task [Made by Ilse Hogenboom].

As shown in Figure 20, the overall goal of the task is divided into six sub goals:

1. *Communication with the ships*. Operator 4 will obtain the information from the ships and will pass the information on to operator 1, as he/she is handing the south side of the sluice. This is done through the computer system. This is a collaboration of two operators.

2. *Ships entering the lock*. Operator 1 is responsible for the ships entering the lock from the south.
3. *Closing the lock doors*. Operator 1 is responsible for closing the door at the south end of the sluice.
4. *Levelling the water*. Operator 2 is responsible for levelling the water, as this is done at the north of the lock. This is also the point where operator 1 communicate the information to operator 2. This will go through the computer system with the relevant information.
5. *Opening the lock doors.* The ships will leave the lock at the north side, therefore operator 2 is responsible for opening the doors on the north side.
6. *Letting the ships out of the lock.* This is also at the north side of the lock, and operator 2 is responsible for letting the ships out of the lock.

Decompose each sub goal

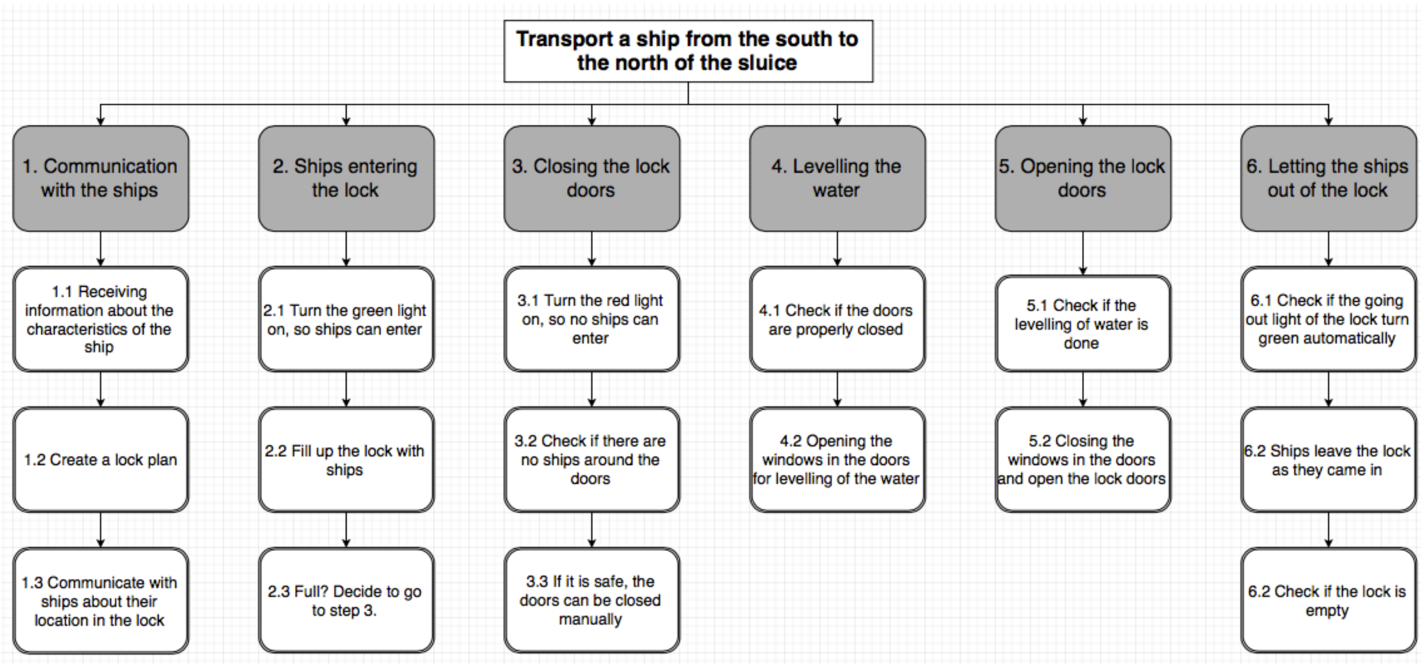

Figure 21. Task Analysis Transporting a ship from the south to the north of the sluice [Made by Ilse Hogenboom].

As seen in Figure 21, each sub goal is decomposed into smaller sub-sub goal, called actions. This is an act that the operator performs. For each of the actions, the operator who is responsible is described, a note is added and whether the action is relevant for a delay in the locking process.

Step 1: Communication with the ships

Action	Operator	Note	Relevant for delay
1.1 Receiving information about the characteristics of the ship.	Operator 1 and 4	This will be done through the computer system.	Yes.
1.2 Create a lock plan.	Operator 1	In IVS-90, the systems that is used.	Yes.

1.3 Communicate with ships about their location in the lock.	Operator 1	Through the radio phone.	Yes.

Table 4. Actions of Step 1 [Made by Ilse Hogenboom].

Step 2: Ships entering the lock

Action	**Operator**	**Note**	**Relevant for delay**
2.1 Turn the green light on, so ships can enter	Operator 1	The lights will be turned on manually in the computer system.	No, because the sailing master will give a signal to turn them on.
2.2 Fill up the lock with ships	Operator 1	The ships will enter the lock as agreed in step 1.3.	No, this is out of the hands of the operator.
2.3 Full? Decide to go to step 3.	Operator 1	Decide to close the door.	Yes.

Table 5. Action of Step 2 [Made by Ilse Hogenboom].

Step 3: Closing the lock doors.

Action	**Operator**	**Note**	**Relevant for delay**
3.1 Turn the red light on, so no ship can enter.	Operator 1	This will be turned on manually in the computer system.	No, the relevant ships are inside and will not influence the delay.
3.2 Check if there are no ships around the doors.	Operator 1	Cameras and the radar can be used to check this.	No, as the sailing master will make sure that the ships is not damaged.
3.3 If it is safe, the doors can close manually.	Operator 1	The doors will close through the computer system when the operator decides it is safe.	Yes.

Table 6. Actions of Step 3 [Made by Ilse Hogenboom].

Step 4: Levelling the water.

Action	**Operator**	**Note**	**Relevant for delay**
4.1 Check if the doors are properly closed.	Operator 2	This is done with the computer system and the cameras. This is also the point in transferring the	Yes.

		responsibility to operator 2.	
4.2 Open the windows in the doors for levelling of the water	Operator 2	As mentioned before, depending on which side the water level is higher on who performs the action. In this case operator 2 will start the levelling process.	Yes.

Table 7. Actions of Step 4 [Made by Ilse Hogenboom].

Step 5: Opening the lock doors.

Action	**Operator**	**Note**	**Relevant for delay**
5.1 Check if the levelling of water is done.	Operator 2	This process is mainly automatically; however, it should be checked before continuing to the next step.	No, the sailing master will otherwise give a signal.
5.2 Closing the windows in the doors and open the lock doors.	Operator 2	Whenever the system measures the water on both sides equally, the windows will close automatically. This can be interrupted by the operator if necessary. The doors open will the levelling process is almost finihsed. This is done manually.	Yes.

Table 8. Actions of Step 5 [Made by Ilse Hogenboom].

Step 6: Letting the ships out of the lock.

Action	**Operator**	**Note**	**Relevant for delay**
6.1 Check if the shipping light of the lock turns green automatically.	Operator 2	This process is automatically, the operator only needs to check if it happens.	No, this is an automatically process.
6.2 Ships leave the lock as they came in.	Operator 2	Observe if it is going correctly and safe, use the cameras for this.	No, the operator has no control over this.
6.3 Check if the lock is empty.	Operator 2	Use the cameras to see if the lock is empty.	No, the ships have left and otherwise, the next ships will

			give a signal that it is empty.

Table 9. Actions of Step 6 [Made by Ilse Hogenboom].

Analyze plan

To reach the goal of the task, the steps are followed in chronical order. The actions are carried out before the next step can be carried out. So, step 1 is performed, with every action in it before the operator can move on to step 2. This will continue till the end of the task and the goal have been achieved.

5.2 Error Identification

Before an error identification can be made, a definition is needed of what an error is in this research. During the locking process the operators can make errors, however it is only seen as an error in this research when it leads to a significant delay in the locking process. The time that a locking process takes is dependent on several factors, like the number of ships and the weight of the ships. The operator at the Volkerak complex states that the locking process takes between 20-30 minutes, this is the time when the ships enter from the south and leave the lock at the north. A significant delay can be seen when the error leads to a delay of more than 15 minutes. With this base, an error identification can be made and these definitions will also be used for the quantification.

- **Locking process**: ships entering the lock from the south and leave from the north. This contains all the steps shown in Figure 21.
- **Error**: a significant delay in the locking process, this is a delay of more than 15 minutes.

As mentioned in chapter 3, there are three methods for identifying errors. In this research, two of those methods are used to identify the errors:

1. Reason's classification.
2. Error of Omission and Commission classification by Swain and Guttman.

These methods are chosen, as Reason's classification is a follow-up on Rasmussen classification. Therefore, for each of the steps the errors are identified according to Reason's classification [17] and the classification by Swain and Guttman [18]. Table 10 presents the identification of the errors, according to the two methods.

Action	**Error**	**Reason's**	**Swain and Guttman**
1.1 Receiving information about the characteristics of the ship.	Not filling in the correct information in the system.	Slips	Commission error: poor execution.
1.2 Create a lock plan.	Overruling the system, which leads to an inadequate plan.	Exceptional Violation	Commission error: poor execution.
	Wrong information in the system.	Slips	Commission error: poor execution.
1.3 Communicate with ships about their location in the lock.	Telling wrong information.	Slips	Commission error: poor execution.

	Communication problems, due to different language.	Poor execution	Commission error: poor execution.
2.1 Turn the green light on, so ships can enter	Forgetting to turn on the light.	Slips	Omission: no action.
	Wrong light turned on.	Mistake	Commission error: not the right action.
2.2 Fill up the lock with ships	None		
2.3 Full? Decide to go to step 3.	Forget to check if the lock is full.	Slips	Omission: no action.
3.1 Turn the red light on, so no ship can enter.	Forgetting to turn on the light.	Slips	Omission: no action.
	Wrong light turned on.	Mistake	Commission error: not the right action.
3.2 Check if there are no ships around the doors.	Looking in the wrong screen.	Mistake	Commission error: not the right action.
3.3 If it is safe, the doors can close manually.	Pressing the wrong button.	Mistake	Commission error: not the right action.
	Forgetting to see if it is safe.	Slips	Omission: no action.
4.1 Check if the doors are properly closed.	Forgetting to check if they are closed.	Slips	Omission: no action.
4.2 Open the windows in the doors for levelling of the water	Pressing the wrong button	Mistake	Commission error: not the right action.
5.1 Check if the levelling of water is done.	Forgetting to check on the screen.	Slips	Omission: no action.
5.2 Closing the windows in the doors and open the lock doors.	Pressing the wrong button.	Mistake	Commission error: not the right action.
6.1 Check if the going out light of the lock turns green automatically.	Forgetting to check it on the screen and cameras.	Slips	Omission: no action.
6.2 Ships leave the lock as they came in.	None		
6.3 Check if the lock is empty.	Forgetting to check if the lock is empty.	Slips	Omission: no action.

Table 10. Error Identification for the locking process [Made by Ilse Hogenboom].

Many of the errors are due to lapses or execution of the wrong action, however two of the actions does not contain errors on the side of the operator. These actions can lead to an error, due to the sailing master. This will not be put into consideration in this research. The error identification is the basis for the further analysis of this research.

5.3 Fault Tree Analysis

This fault tree will identify whether all the steps and actions are needed for a significant delay to occur. From the main event, the significant delay, each step and action is discussed in whether the step and action alone will lead to a significant delay. This is presented in Table 4, Table 5, Table 6, Table 7, Table 8, and Table 9. The actions that are relevant for delay are used in further analysis, the other actions are not used. In each of the actions, only human failure is taken into consideration. Therefore, Step Six: “Letting the ships out of the lock” is not included in the analysis as in these actions only checking of the technique is considered. This would not lead to a significant delay. Figure 22 shows which of the actions have an influence on the significant delay in the locking process. The other actions have no influence on the significant delay and will not be considered in further analysis. All the actions have an OR-gate to the main event, because all the actions could lead individually to a delay.

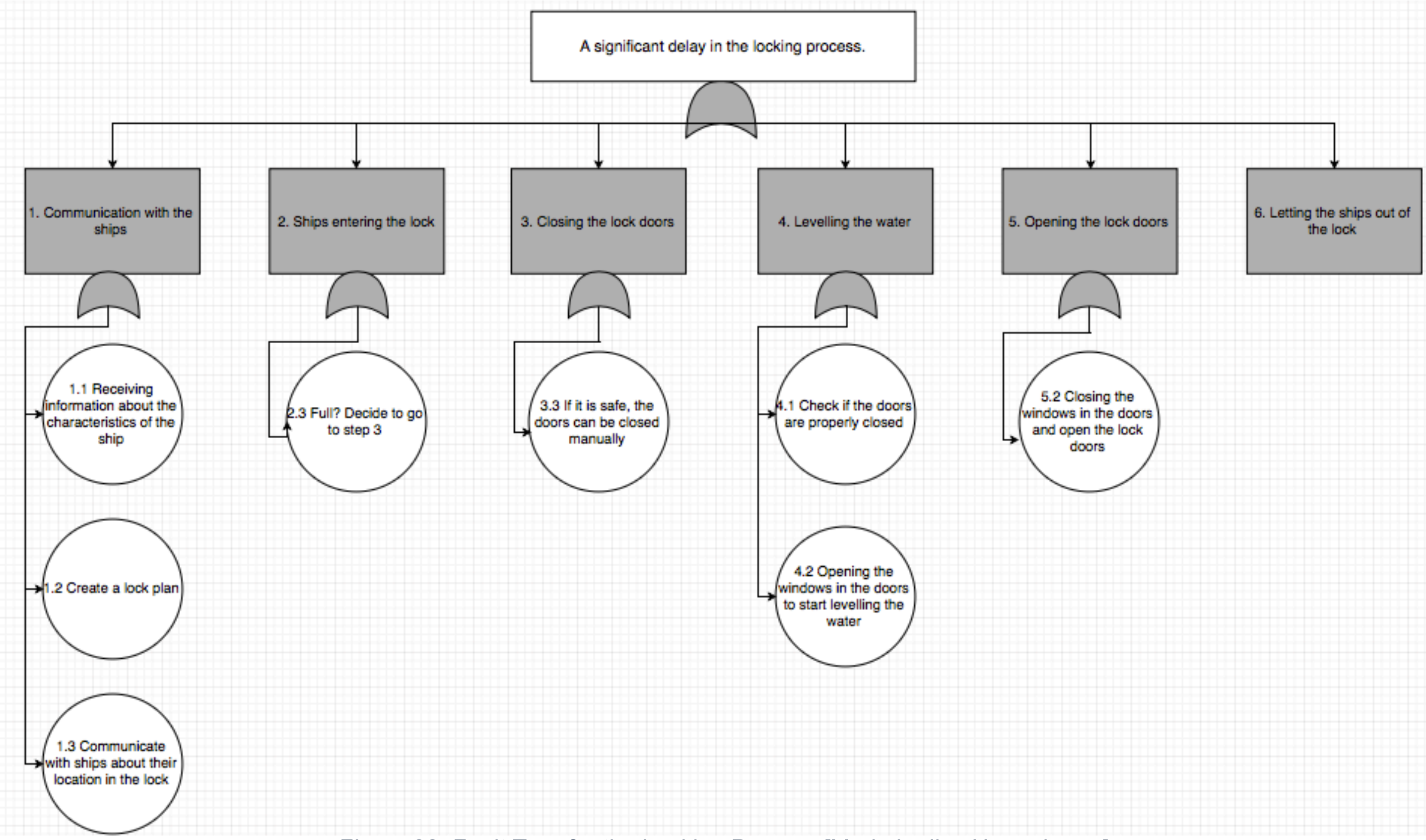

Figure 22. Fault Tree for the Locking Process [Made by Ilse Hogenboom].

6 Quantification

In this chapter, the quantification of the methods will be presented. For each of the methods the probability will be calculated for a human error in an action. This will be according to the method description in chapter 4. All the calculations of each method have been done as equally as possible, whenever in one method the stress level is not significant as performing shaping factor, this will be applied in all the different methods. In all the methods dependency and recovery factors are not included, this is because some methods do not account for that and as the similarity between the methods should be as large as possible. This chapter also includes the results from the expert session. In the end, an overview will be given of the probabilities of all the methods in the fault tree. This is to give context to the HEP and to compare results. A review of the use of the methods is described in later chapters.

6.1 THERP

With the use of search schemes, various HEP and multipliers are identified with the THERP method. These schemes are presented and the associated tables are attached in Appendix B. With this information, all the actions have an associated HEP or multiplier and the calculations can be done. Below, the factors are identified for Step 1: "Communication with the ships", the other steps can be found in Appendix D.

Step 1: Communication with the ships.

Action	Error Type?	Table	HEP (Error Factor)	Explanation
1.1 Receiving information about the characteristics of the ship.	Commission	20-1	.1 (5)	Initial screening of for diagnosis within 20 minutes.
		20-2	.05 (10)	Errors without recovery factor
		20-3	.01 (10)	Same as 20-1
		20-9	.001 (3)	Many screens in which a wrong choice can be made.
		20-10	Negligible	No reading of digits
		20-11	.001 (3)	Action is read from a display.
		20-15		Nominal HEP is used.
		20-16	Modifier is x1	Optimum level of stress and step-by-step action.
		Dependency	Zero	
1.2 Create a lock plan.	Commission	20-1	.1 (5)	Initial screening of for diagnosis within 20 minutes.
		20-2	.05 (10)	Errors without recovery factor
		20-3	.01 (10)	Same as 20-1

		20-9	.001 (3)	Many screens in which a wrong choice can be made.
		20-10	Negligible	No reading of digits.
		20-11	.001 (3)	Action is read from a display.
		20-15		Nominal HEP is used.
		20-16	Modifier is x1	Optimum level of stress and step-by-step action.
		Dependency	Zero	
1.3 Communicate with ships about their location in the lock.	Commission	20-1	.1 (5)	Initial screening of for diagnosis within 20 minutes.
		20-2	.05 (10)	Errors without recovery factor
		20-3	.01 (10)	Same as 20-1
		20-9	.001 (3)	Many screens in which a wrong choice can be made.
		20-10	Negligible	No reading of digits
		20-11	.001 (3)	Action is read from a display.
		20-15		Nominal HEP is used.
		20-16	Modifier is x1	Optimum level of stress and step-by-step action.
		Dependency	Zero	

Table 11. Identification of Multipliers and HEP of Step 1 THERP [Made by Ilse Hogenboom].

Before the results can be integrated into a fault tree, the HEP per action should be determined. This is done by multiplying each HEP or multiplier with each other. The results are shown in Table 12.

Step	Action	Calculation	HEP per action	HEP per step
1.	1.1	.1*.05*.01*.001*.001*1	.00000000005	.00000000015 =Negligible
	1.2	.1*.05*.01*.001*.001*1	.00000000005	
	1.3	.1*.05*.01*.001*.001*1	.00000000005	
2.	2.3	.1*.05*.01*.003*1	.00000015	.00000015 =Negligible
3.	3.3	.1*.05*.01*.003*1	.00000015	.00000015 =Negligible
4.	4.1	.1*.05*.01*.003*1	.00000015	.00000015005 =Negligible
	4.2	.1*.05*.01*.001*.001*1	.00000000005	
5.	5.2	.1*.05*.01*.001*.001*1	.00000000005	.00000000005 =Negligible

Table 12. Calculations THERP [Made by Ilse Hogenboom].

Fault Tree Analysis

The HEP that are calculated for each action can be integrated into the FTA that has been created in Figure 22. This is shown in Figure 24. This will give an overall probability for a human error in a locking process. Because there is a certain amount of overlap in adding the probabilities together, the Fault Tree Plus program from Isograph is used. This is a program used by the employees of Rijkswaterstaat for Fault Tree Analysis. It uses minimal cut sets to calculate the probability, this is to minimize the number of actions that are relevant for the significant delay. The program uses Boolean Algebra to calculate the probability without the overlap of each action that could lead to a significant delay. The addition law is used, which uses the formula in Figure 23. This is basic probability theory that the program uses. So, with this program it takes out the overlap that different action can lead to different significant delay [29].

$$P(A+B) = P(A) + P(B) - P(A) \cdot P(B)$$

Figure 23. Addition Law of Boolean Algebra [29].

In Figure 24, the result is presented for the Fault Tree Analysis for THERP. For this method, there is a very small probability of a significant delay due to a human error in one or more of the actions that the operator executes. This probability is considered negligible.

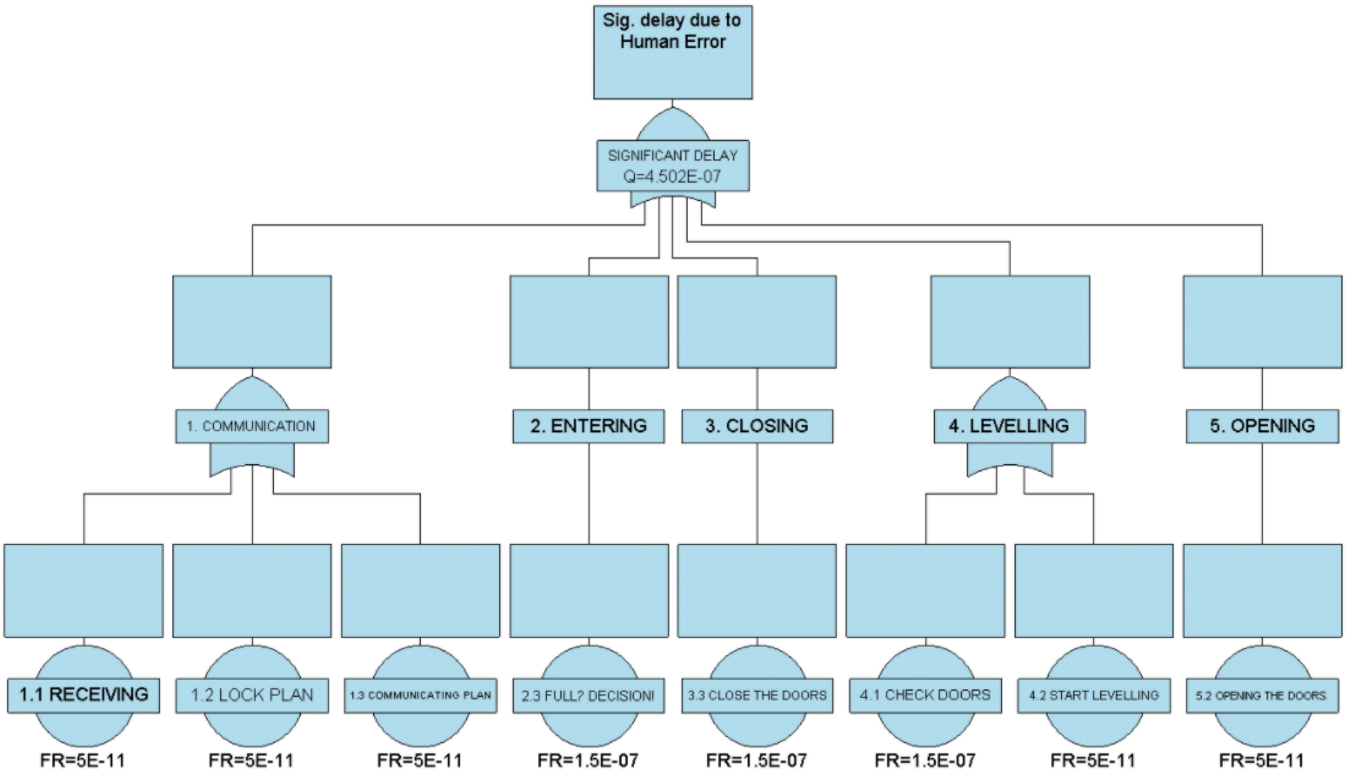

Figure 24. Fault Tree Analysis for THERP [Made by Ilse Hogenboom].

6.2 SPAR-H

For the SPAR-H method, there are several factors that need to be identified before calculating the Human Error Probability (HEP), which are:

- If the task is diagnosis or action task.
- PSF.

- The level of PSF.
- An explanation for the chosen level of PSF.
- The multiplier.

These factors need to be identified for each steps of the locking process. In Table 13, the above-mentioned factors are identified for "Step 1: Communication with the ship" of the locking process. The other steps are enclosed in Appendix D.

Step 1: Communication with the ship.

Action	Operator	What kind of task is it?	PSF	Level	Explanation	Multiplier
1.1 Receiving information about the characteristics of the ship.	Operator 1 and 4.	Diagnosis.	Available time	Time available ≥ 5x	Ships enter information in before arriving to the sluice.	.1
			Stressors	Nominal		1
			Complexity	Moderately	The communication between two operators.	2
			Experience	High	All the operators have more than 6 months' experience.	.5
			Procedures	Nominal		1
			HMI	Nominal		1
			Fitness for duty	Degraded fitness	Tiredness negatively influences the performance.	5
			Work processes	Nominal		1
1.2 Create a lock plan.	Operator 1.	Action.	Available time	Time available ≥ 5x	Information is available and can be entered in earlier.	.1
			Stressors	Nominal		1
			Complexity	Moderately	Insight skills for planning.	2
			Experience	High	All the operators have more than 6 months' experience.	.5
			Procedures	Nominal		1
			HMI	Nominal		1

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			Fitness for duty	Degraded fitness	Tiredness negatively influences the performance.	5
			Work processes	Nominal		1
1.3 Communicate with ships about their location in the lock.	Operator 1.	Action.	Available time	Nominal		1
			Stressors	Nominal		1
			Complexity	Nominal		1
			Experience	High	All the operators have more than 6 months' experience.	.5
			Procedures	Nominal		1
			HMI	Nominal		
			Fitness for duty	Degraded fitness	Tiredness negatively influences the performance.	5
			Work processes	Nominal		1

Table 13. PSF Identification of Step 1 for SPAR-H [Made by Ilse Hogenboom].

For all the actions, it is determined whether it is an actions or diagnosis task and the adjustment factor. The HEP is determined for each subtask.

Step	**Action**	**Action or Diagnosis?**	**Composite PSF**	**Adjustment factor**	**HEP per subtask**	**HEP per step**
1	1.1	Diagnosis = .01	.1*2*.5*5= .5	.005	.005	.008
	1.2	Action = .001	.1*2*.5*5= .5	.0005	.0005	
	1.3	Action = .001	.5*5= 2.5		.0025	
2	2.3	Diagnosis = .01	.1*.5*5= .25	.0025	.0025	.0025
3	3.3	Action = .001	.5*5= 2.5		.0025	.0025
4	4.1	Diagnosis = .01	.1*.5*5= .25	.0025	.0025	.005
	4.2	Action = .001	.5*5= 2.5		.0025	
5	5.2	Action = .001	.1*.5*5= .25	.00025	.00025	.00025

Table 14. HEP values per subtask and step of SPAR-H [Made by Ilse Hogenboom].

Fault Tree Analysis

As described in chapter 6.1, the Fault Tree Plus from Isograph is used to calculate the HEP for significant delay. The overall HEP for the SPAR-H is .0181 with the use of this method, see Figure 25. This means that there is a 1.8% chance that a human error leads to a significant delay in the locking process. This is approximately 1 out of the 50 locking processes.

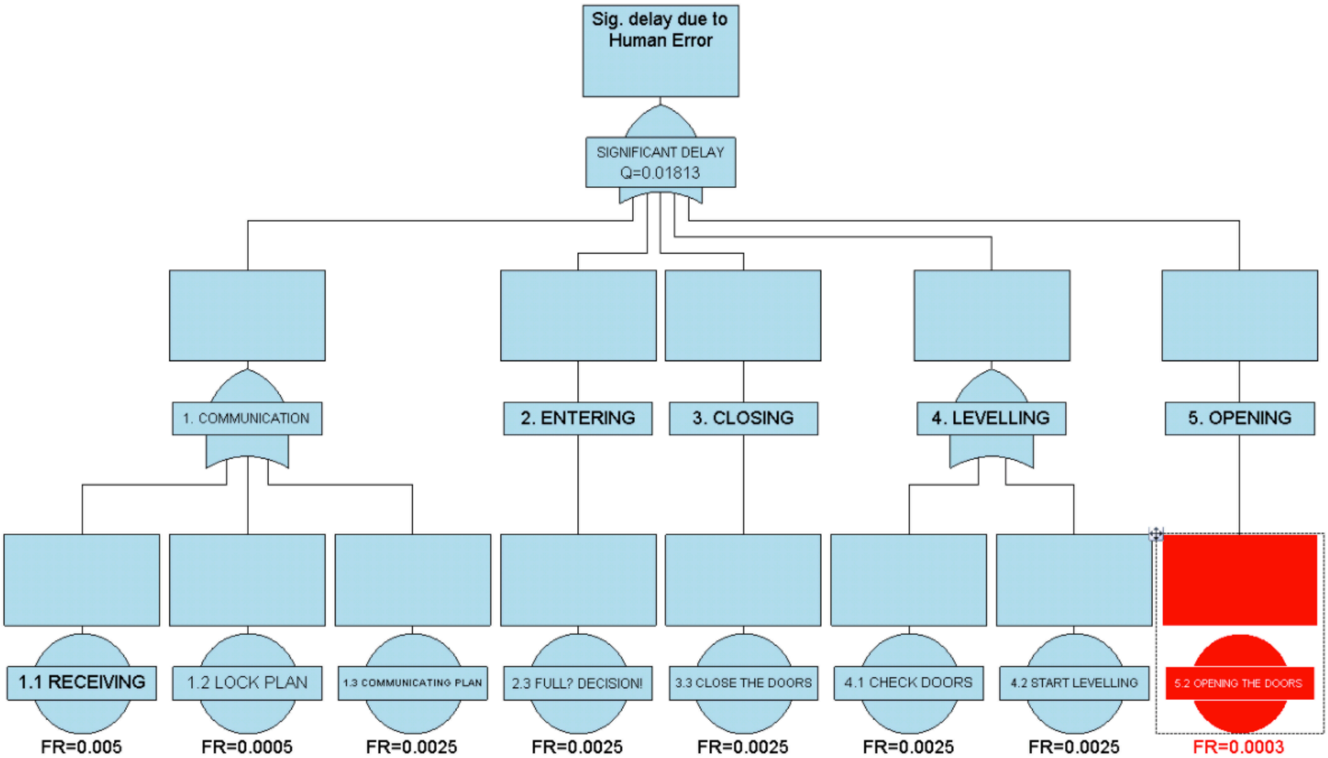

Figure 25. Fault Tree Analysis of SPAR-H [Made by Ilse Hogenboom].

6.3 CREAM

According to the method CREAM, in each action or subtask, the following should be identified before calculating the HEP:

- Cognitive activity.
- Cognitive function.
- Failure Type.
- Nominal Cognitive Failure Probability (CFP).

These factors should be identified for all the steps in the locking process. Step 1: “Communication with the ships”, is identified in Table 15. The factors have identified according to the description in Figure 17 and Figure 18. The other steps are enclosed in the Appendix D.

Step 1: Communication with the ships.

Action	Operator	Cognitive Activity	Cognitive Function	Failure type	Nominal CFP

1.1 Receiving information about the characteristics of the ship.	Operator 1 and 4	Record	Interpretation	I3. Delayed interpretation.	.01
1.2 Create a lock plan.	Operator 1	Plan	Planning	P2. Inadequate plan.	.01
1.3 Communicate with ships about their location in the lock.	Operator 1	Communicate	Execution	E1. Action of wrong type.	.003
				E4. Action out of sequence.	.003

Table 15. Cognitive Factors identified for step 1 according to CREAM [Made by Ilse Hogenboom].

Afterwards, the CPC levels are identified for the overall task. As mentioned in chapter 4.3, the CPC levels are identified according to the definition of the CPC and the effect on the performance reliability, whether it is improved, not significant or reduced.

- **Adequacy of organization**: efficient. The organization does not influence the performance of the operators, so therefore it is not significant.
- **Working conditions**: compatible. The working conditions are compatible for what the operators have been taught during their training and therefore will not significantly change their performance.
- **Adequacy of MMI**: adequate. All the systems necessary are available, and the same for each operator. It is up-to-date on what is necessary to performance, however it could be more supportive. Therefore, it does not significantly improve the performance reliability.
- **Procedures**: acceptable. The necessary procedures are available, but not always followed. Therefore, it does not have a significant effect on the performance reliability.
- **Simultaneous goals**: more than capacity. The operator needs to monitor three locks at one time, in which he must communicate, plan and operator the locks. Therefore, this will reduce the performance reliability.
- **Available time**: adequate. As many of the task give space for the operator to anticipate on this next action. Whenever the ships are entering the lock, this gives the operator time to work on the next task. Therefore, this will improve the performance reliability.
- **Time of the day**: day-time. In this scenario, there are four operators present and therefore the operation takes places during the day. The performance reliability will not change due to the time of the day.
- **Adequacy of training**: adequate, high experience. All operators have had extensive training of at least four months and are working in this position for several years. Therefore, the performance reliability will improve.
- **Crew collaboration quality**: very efficient. The operators know each other and can work together efficiently. Therefore, this will improve the performance.

With the levels of the CPC the weighted factors can be calculated, this done by multiplying each CPC level with the error type that has been defined in Table 15. The calculations can be found in the Appendix D. In Table 16, the calculations for each subtask has been done. The nominal CFP is multiplied with the weighted factors, which will lead to an adjusted CFP for each sub task. When the adjusted CFP have been added to each step the adjusted CFP has been identified for each step.

Step	**Action**	**Error Mode**	**Nominal CFP**	**Weighted Factor**	**Adjusted CFP per subtask**	**Adjusted CFP per step**
1	1.1	I3. Delayed Interpretation.	.01	.25	.0025	.0112
	1.2	P2. Inadequate plan.	.01	.625	.00625	
	1.3	E1 Action of wrong type.	.003	.4	.0012	
		E4. Action out of sequence.	.003	.4	.0012	
2	2.3	I3. Delayed information.	.01	.25	.0025	.0025
3	3.3	E2. Action at wrong time.	.003	.4	.0012	.0012
4	4.1	I2. Decision error.	.01	.25	.0025	.0037
	4.2	E2. Action at wrong time.	.003	.4	.0012	
5	5.2	E2. Action at wrong time.	.003	.4	.0012	.0012

Table 16. Calculating HEP for CREAM [Made by Ilse Hogenboom].

Fault Tree Analysis

As described in chapter 6.1, the Fault Tree Plus from Isograph is used to calculate the HEP for significant delay. The overall HEP for the CREAM is .0196 with the use of this method, see Figure 26. This means that there is a 1.9% chance that a human error leads to a significant delay in the locking process. This is almost 1 in the 50 locking processes.

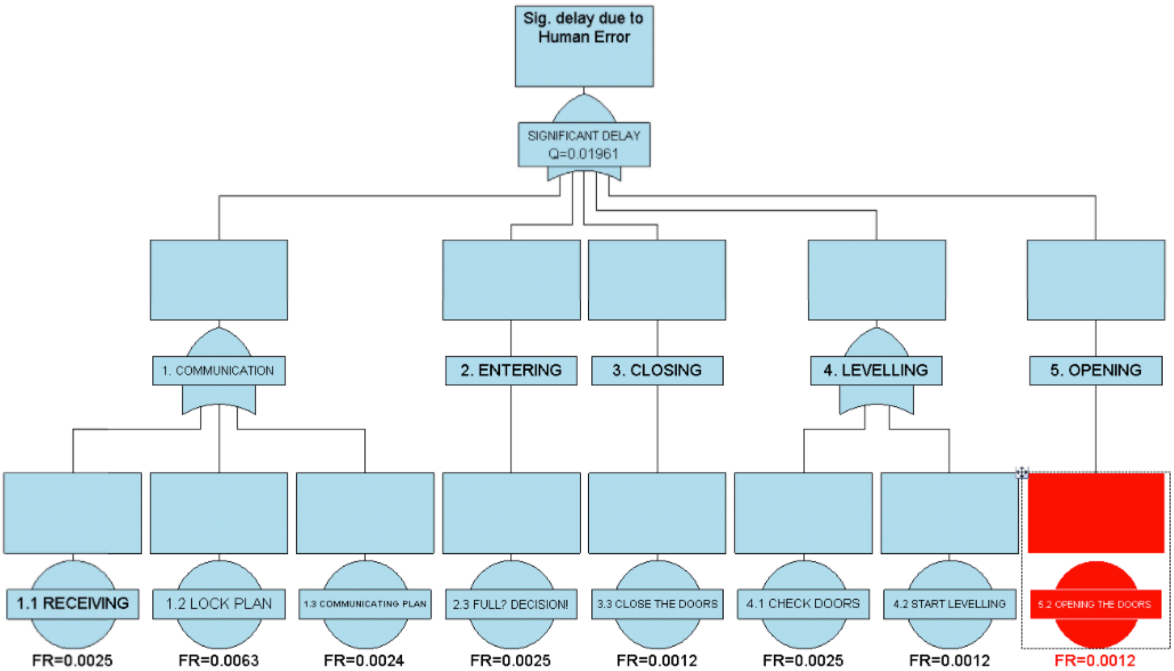

Figure 26. Fault Tree Analysis of CREAM [Made by Ilse Hogenboom].

6.4 Expert Judgement Method

To apply the expert Judgement Method, the Nominal Group Technique (NGT), an expert session was organized on the 8th of December 2017. Several experts where invited to join this session and to discuss this topic. The expert session was held at the Volkerak complex in Willemstad. The experts that were included in the session, are an operator of the Volkerak complex, management of the Volkerak complex, an expert in human reliability methods and an expert in risk analysis. All the experts were given the questionnaire shown in Appendix D. First the context was set for the experts, in which everyone could understand the basic principle of the locking process. Afterwards, the experts where asked to fill in the first part of the questionnaire individually. In here, the experts where asked to give an estimate of a human error of the operator during the locking process. This contains:

- A percentage of how likely it is that an error, a significant delay, is made in the entire locking process. This percentage is given in the case of one locking process, so once from south to north of the lock.
- A percentage of how likely it is that an error, a significant delay, is made in the six steps of the locking process.
- What are the most important/relevant factors that could lead to a human error, a significant delay?

After part 1 was filled in, the results were discussed with all the experts. The discussion could lead to a change in answers to the questions in the first part. After the discussion, the experts were asked to rank the results that were discussed. They were asked to give a top 3 of most relevant answers. This was the end of part 1 of the questionnaire. Part 2 has the same structure, first were asked to give the percentage of how likely it is that an error, a significant delay, is made in the action of the locking process. Afterwards, the results were discussed and ranked. All the results can be found in Appendix D. Based on the ranking of the experts, a value was associated with each rank to calculate a weighted average. For the value that was ranked as the most important, was given a value of 3, the second most important value had a 2 and the last one 1. With this information, the weighted average of each action for every expert was calculated. With the weighted average, the overall average was calculated for each action as the ranking of the experts is equally. The results are shown in Table 17.

Step	Action	Average probability experts	
1	1.1	.0032	.0073
	1.2	.001	
	1.3	.0031	
2	2.3	.0002	.0002
3	3.3	.0002	.0002
4	4.1	.0025	.0027
	4.2	.0002	
5	5.2	.0014	.0014
Total		.0118	

Table 17. Results Expert Session [Made by Ilse Hogenboom].

Fault Tree Analysis

As described in chapter 6.1, the Fault Tree Plus from Isograph is used to calculate the HEP for significant delay. The overall HEP for the Expert Judgment Method is .0117 with the use of this method, see Figure 27

This means there is a 1.2% chance that a human error leads to a significant delay. This is almost 1 in the 100 locking processes.

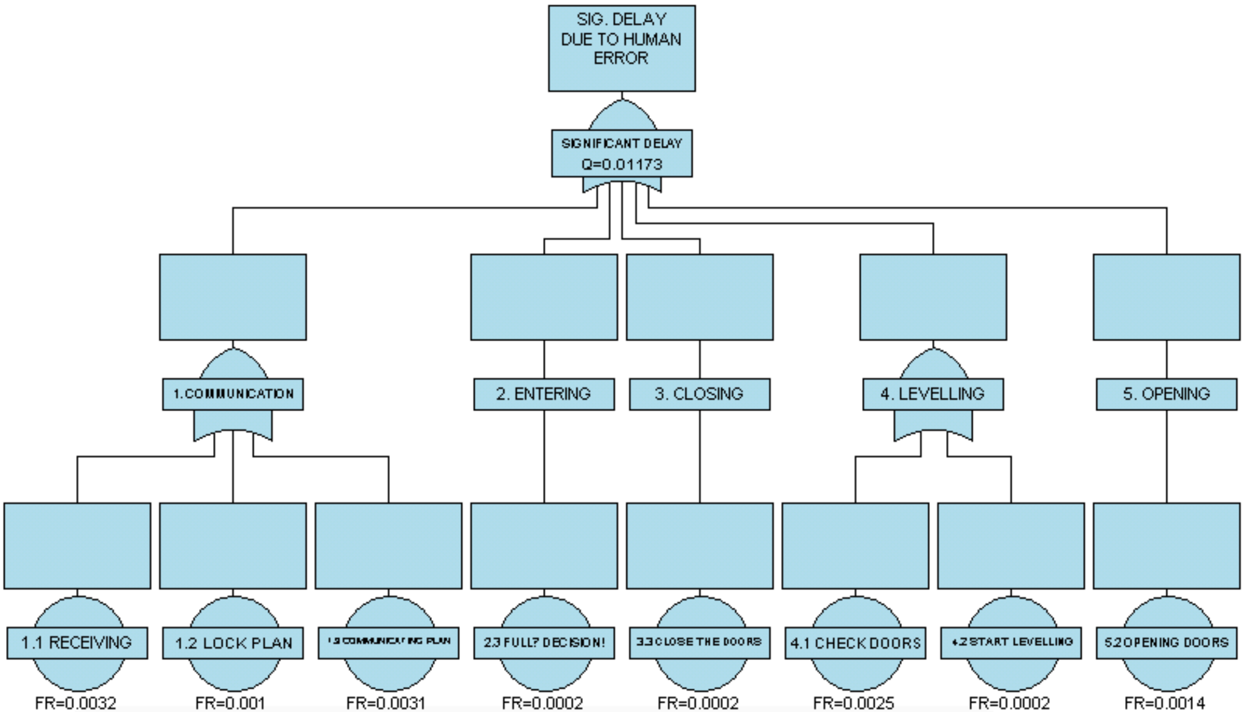

Figure 27. Fault Tree Analysis of Expert Judgment [Made by Ilse Hogenboom].

6.5 Overview

To put this information into context, a fault tree is used to make a visual representation of the results. Table 18 gives an overview of all the results of the methods. This is to compare each method and to see the differences without the use of a fault tree and with the use of a fault tree. However, as seen in the table, the differences between the overall HEP are small.

Step	Action	THERP		SPAR-H		CREAM		Experts	
1	1.1	.00000000005	Negligible	.005	.008	.0025	.0112	.0032	.0073
	1.2	.00000000005		.0005		.0063		.001	
	1.3	.00000000005		.0025		.0012 + .0012		.0031	
2	2.3	.00000015	Negligible	.0025	.0025	.0025	.0025	.0002	.0002
3	3.3	.00000015	Negligible	.0025	.0025	.0012	.0012	.0002	.0002
4	4.1	.00000015	Negligible	.0025	.005	.0025	.0037	.0025	.0027
	4.2	.00000000005		.0025		.0012		.0002	
5	5.2	.00000000005	Negligible	.0003	.0003	.0012	.0012	.0014	.0014
Total without FTA		Negligible		.0183		.0198		.0118	
Total with FTA		Negligible		.0181		.0196		.0117	

Table 18. Overview of results HEP all methods [Made by Ilse Hogenboom].

7 Discussion

This chapter discusses the results from the previous chapters. Also, a summary will be given to refresh the context of this research. The strengths and limitations of this research will be discussed at the end of the chapter.

7.1 Summary

The Volkerak complex is managed and by the executive agency of the Ministry of Infrastructure and Water, called Rijkswaterstaat. This includes the responsibility of risk management, in which the performance of the object is effectively managed. The probability of failure is also an aspect that is included, however there is no universal method to measure the probability of human failure for the sluices. There is Human Reliability Analysis (HRA) method for the storm surge barriers, however this is not appropriate for the sluices in the Netherlands. Therefore, Rijkswaterstaat wants to test different HRA methods, THERP, SPAR-H, CREAM and expert judgment, to see which is most appropriate to apply on the sluices in the Netherlands. The Volkerak complex is used, because this is the largest sluice complex in the Netherlands. These HRA methods, THERP, SPAR-H, and CREAM, and compared to the results from an expert judgment method. This is done, to see which method represents reality the best. A task analysis is executed, to identify various of error types and to see which Performing Shaping Factor (PSF) can influence the performance. The main fault to human error is considered whenever there is a significant delay in the locking process of the sluice. With this information, Human Error Probabilities (HEP) can be calculated to give an estimation of how reliable an operator is. However, not all actions that are executed by the operator of the sluice are equally responsible to a significant delay. Therefore, a fault tree provides information on which action is more critical than others. In the comparison to the results of the expert judgment method, it shows that SPAR-H and CREAM have similar overall HEP. On the other hand, the results from THERP are so small that they are considered negligible.

7.2 Results

As mentioned above, the results should be brought into context to make valuable conclusions. The first method that is discussed is THERP, then SPAR-H and as last CREAM. All the results will be compared to the results from expert judgment, and in context with the fault tree. The perspective is taken that the HEPs from the Expert Judgment is the more realistic results.

7.2.1 THERP

The results from THERP are considered negligible, as the probability of an error is so small that it is not realistic. When the HEP from THERP are compared to the HEP from the expert judgment session, it shows that the probabilities are far apart. Therefore, the conclusion can be made that THERP does not show realistic probabilities for human errors. This could be because THERP is most often used in actions that are executed in a low frequency, like in the nuclear sector. However, the actions at the Volkerak complex are executed frequently on a day. This is an explanation for the HEP. It is difficult to make a good prediction of the reliability of the human actions with this method for the Volkerak complex and other sluices, because it is expected that other sluices also executed these actions more frequent on a day. Therefore, the reliability of THERP for the use of sluices is low. With this method, no reliable conclusion can be drawn for the operators at the Volkerak complex.

7.2.2 SPAR-H

To have a good idea what the comparison is between the SPAR-H HEP and Expert Judgments HEP, they are presented in the Table 19 below. In here, the difference is pointed out, whenever the HEP from SPAR-H is larger than the HEP from Expert Judgment, that will be indicated with a "+". When the HEP from SPAR-H is smaller than the HEP from Expert Judgment, that will be indicated with a "-".

Step	Action	SPAR-H	Expert Judgment	Difference
1.	1.1	.005	.0032	+ .0018
	1.2	.0005	.001	-.0005
	1.3	.0025	.0031	-.0006
2.	2.3	.0025	.0002	+ .0023
3.	3.3	.0025	.0002	+.0023
4.	4.1	.0025	.0025	0
	4.2	.0025	.0002	+.0023
5.	5.2	.0003	.0014	-.0011

Table 19. Comparison Table SPAR-H and Expert Judgement [Made by Ilse Hogenboom].

As mentioned before, only the actions are used in the analysis that are relevant for the significant delay. The table shows that there are some small differences between the two HEPs. Action 4.1 shows an identical result with the expert judgment result, which is special. However, this could fluctuate when different experts are used. SPAR-H is mainly higher in the probability for a human error in the actions. This can be explained by not included the factor that operators can recover their actions. However, in general are the differences between SPAR-H and Expert Judgment small.

7.2.3 CREAM

To compare the HEP from CREAM and Expert Judgment, the same method is used as in the SPAR-H method. In here, the difference is pointed out, whenever the HEP from CREAM is larger than the HEP from Expert Judgment, that will be indicated with a "+". When the HEP from CREAM is smaller than the HEP from Expert Judgment, that will be indicated with a "-". The differences are shown in Table 20.

Step	Action	CREAM	Expert Judgment	Difference
1.	1.1	.0025	.0032	-.0007
	1.2	.0063	.001	+.0053
	1.3	.0012 + .0012	.0031	-.0007

2.	2.3	.0025	.0002	+.0023
3.	3.3	.0012	.0002	+.001
4.	4.1	.0025	.0025	0
	4.2	.0012	.0002	+.001
5.	5.2	.0012	.0014	-.0002

Table 20. Comparison HEP between CREAM and Expert Judgment [Made by Ilse Hogenboom].

In the comparison between CREAM and Expert Judgment, most differences are smaller. Also, here on action 4.1 the method is identical with the expert judgment results. Another observation from the comparison is that CREAM is more often larger than smaller when looked at the HEPs from the Expert Judgment. CREAM estimates the probability for a human error higher than the Expert Judgment.

7.2.4 Comparison of Methods

As the aim for this research is to find the most appropriate HRA method, a comparison to the SPAR-H and CREAM method is necessary, as THERP was negligible. This will give an overview of the difference between the Expert judgement method and the comparison between the differences of the two methods. This will indicate whether the method is larger or smaller than the HEP of the Expert Judgment. This is shown in Table 21.

Step	Action	Differences Table SPAR-H	Difference Table CREAM
1	1.1	+ .0018	-.0007
	1.2	-.0005	+.0053
	1.3	-.0006	-.0007
2	2.3	+ .0023	+.0023
3	3.3	+.0023	+.001
4	4.1	0	0
	4.2	+.0023	+.001
5	5.2	-.0011	-.0002

Table 21. Comparison between the two difference tables [Made by Ilse Hogenboom].

When looked at the table, some of the actions have the same differences to the expert judgment, like action 2.3 and 4.1. Other actions have an opposite difference compared to the expert judgment results, like action 1.1 and 1.2. This is due to the calculations of the methods. However, when looked at which estimation of the HEP of both methods, CREAM and SPAR-H are very close together. So, more factors should be taken into consideration when making the decision in which methods is more suitable.

	THERP	SPAR-H	CREAM	Expert Judgment
Total without FTA	Negligible	.0183	.0198	.0118
Total with FTA	Negligible	.0181	.0196	.0117

Table 22. Comparison between overall HEP [Made by Ilse Hogenboom].

As shown in Table 22, the differences between just adding the HEP for each action and the FTA program are small. However, it can be stated that SPAR-H is better at predicting the human reliability than CREAM as the value is closer to the Expert Judgment value. The value states that there is a probability of .0181 for SPAR-H that a human error in one or more of the actions leads to a significant delay of the locking process. The value for CREAM states that there is a probability of .0196 that a human error in one or more of the actions leads to a significant delay of the locking process. The value of the expert judgment states that there is a probability of .0117 that a human error in one or more of the actions leads to a significant delay of the locking process. So, for each of the action the likelihood of a human error occurring is taken into consideration when calculating the overall HEP in the Fault Tree software. As the Fault Tree is described as an OR-gate. Which means that a human error in one or more of the actions could lead to a significant delay in the locking process. However, the end conclusion is not only based on the results of the analysis. It is also based on the use of the methods, which is presented in the review of the methods in the next paragraph.

7.2.5 Review of the Methods for Rijkswaterstaat

Rijkswaterstaat is looking for a method which is appropriate for their company, something that is easy to use, less intensive and uniform applicable. Those are the three aspects that has been considered when reviewing the methods. First, THERP will be discussed, afterwards SPAR-H and CREAM, and in the end **Error! Reference source not found.** will be presented with the information to compare.

THERP

In the beginning, the expectation would be that the results of THERP could be equal to the results of the OPSCHEP model. Not only the results should be similar but also the way the method is used. However, this was not the case. As mentioned before, the results from the OPSCHEP model was conservative and the THERP results were very low. Based on the result alone was THERP not suitable for the Volkerak complex for the Rijkswaterstaat standard. Also, the method was not easy to use. The probabilities were based on the nuclear industry which might not be realistic for a sluice. The way the handbook was writing did not help with using the method. It was writing in a difficult and unorganized way. THERP was not intensive to use, to understand the method that was the most intensive part. However, after that it was not so time consuming to calculated the HEP. THERP should lead to the same results, when the method is used by someone else. This is due to the well-formulated definitions. Another positive aspect of THERP is that, recovery factors and dependency are included in the method. On the other hand, there is not correction factor for when there are several PSF used. Even though, this was not included in the research, these are important aspects to consider for using the method further on.

SPAR-H

At first, this method complied with every aspect that Rijkswaterstaat has put on the methods. In the description, it stated that the method should be easy to use for someone who is not familiar with HRA methods. When using this method, this was confirmed. It was well writing in the handbook, with clear definitions for the levels of the PSF's. SPAR-H also has an adjustment factor, to correct the HEP when more than 3 PSF are used.

This is an important aspect to contain the amount of PSF, otherwise the HEP are so high or low based on the PSF. Because the handbook was well writing, the method was less intensive to use. Most of the time when into, deciding on which level the PSF for the operator was. It would be expected that the method is uniform applicable. This is again due to the well written handbook. SPAR-H does not contain the aspect of recovery factors. This could have a significant influence on the human reliability. The method could improve on that aspect. On the other hand, SPAR-H also includes the aspect of a positive influence of a PSF. This is to reduce the HEP by having a positive influence due to for example high experience.

CREAM

In the CREAM method, the cognitive aspect is taking into consideration when calculating the HEP. Based on the task is performed, the cognitive activity is decided and with that the failure type and the nominal CFP is determined. And together with the weighted PSF factor for the action, the overall HEP for the action is determined. This method is like the SPAR-H method, well written and therefore easy to use. There are no requirements to have training for this method or to have knowledge about the cognition. This is well explained in the handbook. This method is a bit more intensive to use than the SPAR-H method, as a lot more factors need to be defined. However, a lot more information is given in the method, like what is the action that leads to an error. There is a lack in definition for the CPC, the handbook states that the information given should be sufficient to define the levels. This could be improved, because this could lead to variability in the results. The method also does not include recovery factors and adjustment factor. However, this does include dependency but this is not used in this research. Overall, the method has some shortcomings but it also gives more than the other methods.

Overview

	THERP	**SPAR-H**	**CREAM**
Easy to use	NO, due to complicated handbook.	YES	YES
Intensive	YES	NO	NO, but more than SPAR-H.
Uniform applicable	YES	YES	YES
Include dependency factor	YES	YES	YES
Include recovery factor	YES	NO	NO
Include adjustment factor for PSF	NO	YES	NO
Output more than input	NO	NO	YES, as more useful information comes out of the model than has been put in.

Table 23. Review of the three HRA Methods [Made by Ilse Hogenboom].

Error! Reference source not found. shows review of the three HRA methods. It could be debated, whether SPAR-H or CREAM is the better method. However, this research will conclude that CREAM is the better method for Rijkswaterstaat, as more information comes out of the model than has been put in to it.

7.3 Strengths

There are some strengths aspects for this research:

- Accessible information of the Volkerak complex. It was easy to receive information that was necessary to analyze the tasks of the operators at the sluice.
- Handbook of the three HRA methods. It was possible to access this information, this made it easier to perform the analysis and to understand the method.
- SPAR-H and CREAM were easy to use method, in comparison to THERP. There is no professional needed to perform the analysis. On the other hand, THERP was more difficult to use due to the writing style and structure of the handbook.
- Different HRA methods were used to find the most suitable method. This made the research more valuable and a good comparison can be made between the methods in background information and use. This also includes the expert judgment method.
- In the end, a method was identified to seem the most suitable for the Volkerak complex to use to analyze the probability of a human error.

7.4 Limitations

There are also some limitations for this research:

- THERP seems not appropriate for actions that are executed frequently. The results from THERP are negligible. The assumption is that THERP is only used for actions that are limited performed.
- There was only one expert session. More expert session would make the results more reliable.
- The expert judgment results were used as basis, however there were no actual statistics used. Therefore, the results are based on an estimation of experts which could influence the reliability of the conclusions.

8 Conclusion

In this research, the focus was on the Volkerak complex in Willemstad. There are various operators at work, making sure the sluices operate as fast and efficient as possible. To execute this, they use the operating procedure that looks like the actions described in Figure 21. As there are humans at work, it is possible that failures are made. To ensure the reliability of the humans, a research had started to find out which method can estimate this reliability the best. To find the methods, first a Human Reliability Analysis method description should be given. This contains a task analysis, error identification and a quantification of those errors. The quantification can be executed by various of methods. In this research, THERP, SPAR-H, and CREAM are used to perform the quantification. A description of these methods is given in Chapter 4. To ensure the quantification shows a result that is realistic to practice, a comparison is made with an expert judgment method. In here, experts are used to estimate the probability of human error made in the various actions. This is also the difference with a HRA method, which is performed based on theories and not practice. The comparison shows that the results from the SPAR-H and CREAM method had a minimal of difference. However, this research was not only based on the results of the analysis but also on the use of the methods. As CREAM provides more information after the analysis and the differences in results were minimal, the most suitable method for the Volkerak sluice complex is CREAM. It should also be suitable to generalize to other sluices as the actions are similar.

To conclude, this research showed that the CREAM method is most suitable to be applied for task performed by the operator on the Volkerak complex. The overall Human Error Probability that could lead to a significant delay due to the operator is .0196.

9 Practical Relevance and Recommendations

As mentioned before, the performances of humans always include a probability of an error. However, it is possible to include this when making a risk analysis. This can be done with the use of Human Reliability Analysis (HRA) methods. The aim for this research was not only to find an appropriate HRA method for the Volkerak complex, but also to raise awareness for the human aspect in risk analysis. Most of the risk analysis includes human factors at the surface and discusses technical aspects into depth. However, a risk analysis should include everything aspect to ratio of its importance. This also includes the software and external aspects. For Rijkswaterstaat, it is interesting to see if this method can be standardized for every sluice in the Netherlands. This is to include the human factor in risk analysis and eventually to reduce the human failure in operating the sluices.

This research has used several HRA methods for the operators at the Volkerak complex. With this knowledge, further research can be done. Therefore, it is recommended:

- To discuss improvement of procedures based on HRA methods for the operators.
- To apply CREAM on other sluices in the Netherlands, to see if it is possible to generalize the method.
- To research CREAM on other object in the Netherlands. The aim is to provide a method that is useable for all objects within Rijkswaterstaat.

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