Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Justin Gargadennec

Human Reliability Analysis of a safety operator on an autonomous passenger ferry

Master's thesis in Marine Technology
Supervisor: Ingrid Bouwer Utne
Co-supervisor: Øyvind Smogeli
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ABSTRACT

As the company Zeabuz tries to develop their own autonomous passenger ferry, the problem of the human reliability with respect to the system arose. The major concern of this master thesis is to find out whether the human operator is able to take over after a system failure and what are the factors that influence their performance. It focuses on the regular and abnormal operations, and aims to demonstrate whether the operator is reliable no matter where they operate from.

A Human Reliability Analysis was performed, using the SPAR-H method, considering two cases: an operator operating onboard the ferry and one from a remote control room, onshore. The different tasks and failure are identified and the Nominal Human Error Probabilities (NHEP) and Performance Shaping Factors (PSF) are assigned to calculate the final Human Error Probabilities (HEP). It is found that the reliability of the operator decreases when operating from the control room and gives details on where to improve, the passengers' management and the manual takeover see their failure probabilities double or more when not operating onboard the ferry.

Based on the results, it is then suggested to implement a passenger control system and add more training for the operators who may have to drive the ferry during operations. It is also advised to reevaluate the probabilities when modifying the system and the organization, in order to check the improvements of the changes.

SAMMENDRAG

Når selskapet Zeabuz forsøker å utvikle sin egen autonome passasjerferge, oppsto problemet med den menneskelige påliteligheten med hensyn til systemet. Den største bekymringen for denne masteroppgaven er å finne ut om den menneskelige operatøren er i stand til å overta etter en systemfeil og hva er faktorene som påvirker deres ytelse. Den fokuserer på de vanlige og unormale operasjonene, og har som mål å demonstrere om operatøren er pålitelig uansett hvor de opererer fra.

En menneskelig pålitelighetsanalyse ble utført, ved hjelp av SPAR-H-metoden, med tanke på to tilfeller: en operatør som opererer om bord på fergen og en fra et fjernstyringsrom på land. De forskjellige oppgavene og feilen blir identifisert, og de nominelle menneskelige feilsannsynlighetene (NHEP) og ytelsesformingsfaktorene (PSF) er tildelt for å beregne de endelige menneskelige feilsannsynlighetene (HEP). Det er funnet at operatørens pålitelighet reduseres når den opererer fra kontrollrommet og gir detaljer om hvor man kan forbedre, passasjerenes ledelse og den manuelle overtakelsen ser at feilsannsynlighetene deres er doble eller mer når de ikke opererer ombord på fergen.

Basert på resultatene foreslås det så å implementere et passasjerkontrollsystem og legge til mer opplæring for operatørene som eventuelt skal kjøre fergen under operasjoner. Det anbefales også å revurdere sannsynlighetene ved endring av systemet og organisasjonen, for å sjekke forbedringene av endringene..

PREFACE

This master thesis was written between January and June 2023 and represents the final work done for the degree of Master of Science in the Department of Marine Technology, specialization in Safety and Assets Management, at the Norwegian University of Science and Technology (NTNU).

Trondheim, 11th of June 2023

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I want to express my gratitude to all the people that supported me during this period: to my roommates for being a constant source of entertainment, to my volleyball team, H3A, for experiencing incredible moments, to my parents for supporting me from far away, to Marie for being amazing.

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ABBREVIATIONS

AI Artificial Intelligence

ATHEANA A Technique for Human Error ANAlysis

CREAM Cognitive Reliability and Error Analysis Method

DP Dynamic positioning

ESD Event Sequence Diagram

GNSS Global Navigation Satellite System

H-SIA Human-System Interaction in Autonomy

HEP Human Error Probability

HRA Human Reliability Analysis

HTA Hierarchical Task Analysis

IMO International Maritime Organization

INS Inertial Nabigation System

IR InfraRed

LIDAR LIght Detection And Ranging

MASS Maritime Autonomous Surface Ship

MRC Minimum Risk Condition

MRM Minimum Risk Maneuvre

MTO Man-Technology-Organization

NHEP Nominal Human Error Probability

NTNU Norges teknisk-naturvitenskapelige universitet

ORM Online Risk Model

PSF	Performance Shaping Factor
RGB	Red Green Blue
RTK	Real-Time Kinematic
SPAR-H	Standardized Plant Analysis Risk-Human Reliability Analysis
TA	Task Analysis
THERP	Technique for Human Error Rate Prediction
TTA	Tabular Task Analysis
USV	Unmanned Surface Vehicle

CHAPTER

ONE

INTRODUCTION

1.1 Background of the project

Autonomous ferries offer a flexible, cost-effective, and sustainable solution to the challenges of crossing bodies of water. They can change their route, require less construction and maintenance, and have a smaller environmental footprint compared to traditional bridges. As the technology evolves, autonomous ferries have the potential to transform transportation across waterways.

In this context, Zeabus, a team of researchers from Norges teknisk-naturvitenskapelige universitet (NTNU) in Trondheim, built the world's first autonomous urban ferry prototype as part of their study on autonomous vessels. Their plan is to launch their own autonomous ferry in 2023, but current regulations require a safety operator onboard during operation. The team aims to eliminate the need for an onboard operator and operate the ferry 24/7 using a fully autonomous system or a remote control room. However, to achieve this goal, the system must be capable of making decisions similar to a human operator. One of the major challenges identified by the researchers is the potential for the autonomous system to fail, which would require intervention from the operator. Thus, they must examine the relationship between the system and the human operator to ensure effective cooperation.

The ferry used for trial operations and on which this thesis based its data was developed by NTNU, milliAmpere 2, with a capacity of up to 12 passengers (Figure 1.1.1). The objective of this project was to facilitate the transportation of passengers across the harbor canal in Trondheim by summer 2022 and, in doing so, gain valuable experience in all aspects of autonomous ferry operations. In order to ensure a safe operation, the project was divided into two distinct phases. The first phase had been planned for the second quarter of 2022 and had included tests and trials, without passengers. Based on the learnings and inputs from this first phase, the second phase was scheduled for summer 2022 with the intention of transporting passengers across the canal as part of the mobility services in Trondheim. Prior to commencing passenger transportation, necessary shoreside infrastructure had been put in place to ensure the safe embarkation and disembarkation of the ferry passengers. Passenger safety and handling had been paramount for the operation, and the assessment of manning levels had taken these factors into consideration. During operations with passengers, there had been a safety operator onboard the ferry to supervise the operation, including passenger handling, and with the ability to take control of the ferry if necessary. Before the commencement of passenger operation in 2022, the entire system had undergone thorough assurance activities, extensive testing, and the necessary certification processes to ensure passenger safety and build trust. The majority of these activities had taken place in 2021. Although the concept of a remote support center (RSC) had been explored as part of the operations, it had not been implemented in the actual operation, as a safety operator had been present onboard at all times. The purpose of exploring the RSC concept had been to develop the roles and responsibilities for a future RSC in the operation of autonomous ferries.

Figure 1.1.1: MilliAmpere2

The ferry is scheduled to traverse the harbor channel in Trondheim, transporting passengers from Ravnkloa on the downtown side to Vestre Kanalkai on the Brattøra side, as depicted in Figure 1.1.2. The distance of the crossing is approximately 85 meters, with varying depths ranging from 3 meters to 6 meters. Under normal service speed, the crossing is anticipated to take around 1 minute. During typical operation, the environmental conditions include a tidal range of 3.2 meters, a maximum current speed of 1.5 meters per second, a maximum wave height of 0.5 meters, and a maximum wind speed of 10 meters per second. In the event of severe weather, the ferry operation will be temporarily suspended to ensure the safety of passengers.

The main parameters and characteristics of the ferry are:

- Max 12 persons

Figure 1.1.2: Area of operations of the ferry

- Design speed max 7 knots, operation speed max 5 knots
- Propulsion: 4 x 10 kW thrusters
- Electrical, battery charging with induction transfer from shore
- Length: 8.5 meters; beam 3.5 meters
- Dynamic positioning (DP) automation system by Marine Technologies LLC
- Sensors: radar, IR cameras, RGB cameras, LIDARs and RTK GNSS/INS based navigation
- HMI display

1.2 Objective

The overall objective of this master thesis is to investigate the human reliability related to the operation of the autonomous passenger ferry milliAmpere2. A major challenge is to move the safety operator from the ferry to the remote control center and get permission to operate from the Norwegian Maritime Authority (NMA). Hence, this thesis identifies and analyses potential hazards related to the safety operator's tasks and responsibilities during the voyage, and assesses the human error probabilities of failures whether the tasks are performed onboard or remotely.

The goal is to determine what are the changes to bring to allow the operator to operate from a remote control room with the same level of success.

1.3 Scope of work

Based on the objective, the work during the MSc thesis will embrace the whole ferry operations, gathering two categories: the normal functioning conditions and the abnormal ones, during which the operator has to take decisions. Therefore, a human reliability analysis will be performed on the operator's tasks and will consider whether the operator is onboard or in a control room on shore. The emergency situations are not going to be considered as they have been studied in Tørressen 2021.

CHAPTER

TWO

THEORY

2.1 Autonomy

Maritime Autonomous Surface Ships (MASS) have been increasing in number in recent years. According to the International Maritime Organization (IMO), MASS are "a kind of ships, to a varying degree, which can operate independently of human interaction" (IMO 2018). Unmanned surface vehicles (USVs), which include autonomous ferries, are a specific type of MASS that operate without a crew (IMO 2018).

USVs have been in use since World War II, initially for military purposes as guided vessels. Nowadays, they are used for various purposes, including passenger transport, research, and maritime exploration. Autonomous ships are designed to operate on a predetermined route using a system that guides the vessel and avoids any potential problems. The system makes decisions based on information received from sensors and analyzed by algorithms programmed by engineers. Criteria such as position, speed, environmental conditions, and the presence of other ships are evaluated by the system before any action is taken (IMO 2018).

The level of autonomy of the system can vary depending on the type of ferry and the crew requirements. Developing such vessels is relatively new, and existing regulations are not yet adapted to them. The system running the ferry must be able to replace the captain or crew with the same efficiency and safety standards described in the regulations for manned vehicles. Studies have been conducted to determine how to consider autonomous ships from a legal standpoint, as the sensors and system may be more precise than human capacity in many respects, but human judgment remains more trustworthy in most cases (IMO 2018). These levels have been defined by the IMO (Committee 2021) and are presented in Table 2.1.1.

Autonomous ships offer significant potential benefits, such as increased safety and

Ship with automated processes and decision support	Seafarers are on board to operate and control shipboard systems and functions
Remotely controlled ship with seafarers on board	The ship is controlled and operated from another location Seafarers are available on board to take control and to operate the shipboard systems and functions.
Remotely controlled ship without seafarers on board	The ship is controlled and operated from another location. There are no seafarers on board
Fully autonomous ship	The operating system of the ship is able to make decisions and determine actions by itself

Table 2.1.1: Levels of autonomy, defined by IMO

improved efficiency, but they also present challenges that need to be addressed, such as regulatory and legal issues, cybersecurity concerns, and public perception (United Nations Conference on Trade and Development 2020).

2.2 Human Reliability Analysis

2.2.1 Purpose

The purpose of human reliability analysis (HRA) is to assess the likelihood of human error in complex systems and develop strategies to prevent or mitigate those errors. HRA is widely used in domains such as nuclear power plants, aviation, and healthcare to identify potential sources of error and to improve safety (Swain and Guttman 1983; C. Wu et al. 2018; Li et al. 2019; Jin et al. 2018). The key goal of HRA is to ensure that human error is minimized in order to prevent accidents and enhance overall system performance (Kirwan and Ainsworth 1992).

2.2.2 Background

Several approaches have been proposed for HRA, including cognitive task analysis, human error identification and classification, and probabilistic risk assessment (Reason 1990; Dekker 2011). Cognitive task analysis involves studying the mental processes and decision-making strategies that individuals use when performing a task, in order to identify potential sources of error. This approach can be useful in identifying human factors that could lead to errors, such as workload, stress, or lack of training (Kirwan and Ainsworth 1992).

Human error identification and classification is another approach to HRA, which involves categorizing errors based on their underlying causes. This approach can help identify specific types of human errors that are common in a given domain, and can also help identify the underlying factors that contribute to those errors. For example, errors in healthcare may be classified as diagnostic errors, medication errors, or communication errors (Hollnagel 2004).

Probabilistic risk assessment is a quantitative approach to HRA that involves estimating the probability of human error based on statistical data and mathematical models. This approach can be useful in assessing the overall risk associated with a system, and can also help prioritize strategies for reducing the likelihood of human error (Swain and Guttmann 1989).

One important aspect of HRA is the use of performance shaping factors (PSFs), which are factors that can influence the likelihood of human error. PSFs can include environmental factors (such as noise or lighting), individual factors (such as fatigue or stress), and organizational factors (such as training or communication protocols). By identifying and addressing PSFs, it is possible to reduce the probability of human error (Kirwan 1996).

There have been several studies on the effectiveness of HRA in various domains. For example, in the field of aviation, HRA has been used to identify potential sources of error in cockpit design and crew resource management (Jin et al. 2018). In the nuclear industry, HRA has been used to assess the safety of nuclear power plants and to develop accident response plans (Swain and Guttman 1983). In healthcare, HRA has been used to improve patient safety and to reduce medical errors (Hollnagel 2004).

In conclusion, human reliability analysis is an important method for assessing the probability of human error in complex systems. By identifying potential sources of error and addressing performance shaping factors, it is possible to improve safety and reduce the risk of accidents. The approaches used in HRA can vary depending on the domain and specific context, but the ultimate goal remains the same - to minimize the risk of human error and enhance system performance.

2.2.3 Use

In this section, several examples will be presented to illustrate how HRA is used in the context of autonomous vessels and the issues related to its development and utilization.

One example of the complexity of HRA is discussed in Orzáez et al. 2019. The paper explains that for every task that is analyzed, there is a need to conduct or consult reviews to ensure the most appropriate method is used. However, there is often a lack of data, which creates difficulties in developing HRA models. To address this issue, Yang et al. 2013 modified the Cognitive Reliability and Error Analysis Method (CREAM) to make the quantification of human failure easier by implementing new ways of estimating probabilities.

Another challenge related to HRA in autonomous vessels is the unpredictability of human-AI interactions, as discussed in Veitch and Andreas Alsos 2022. The paper provides a review of human-AI interactions in autonomous vessels to address the increasing number of autonomous vessels using Artificial Intelligence (AI) to overtake human guidance, especially during collision scenarios. Hogenboom et al. 2020 also address this issue by discussing the importance of considering the human factor in the design of Dynamic Positioning (DP) systems, as the design of the system can significantly influence the probability of human error.

The challenges of remote control of unmanned ships are also discussed in Man et al. 2015 and Wahlström et al. 2015. Man et al. 2015 focuses on the gaps created by changes in the framework, which can lead to a modification of the operators' awareness. Wahlström et al. 2015 highlights some of the most important human factor challenges to consider, such as the overwhelming amount of system information, the delay between monitoring and control, and the need for more specific human understanding.

There have been recent breakthroughs in the assessment of human error probabilities in autonomous vessels, as demonstrated in Zhang et al. 2020. The paper developed a new model to assess human error probabilities when dealing with autonomous systems using THERP as the main method and tested it on an autonomous ship in China. Abilio Ramos et al. 2019 presents a Hierarchical Task Analysis (HTA) for collision avoidance, showing that humans can reduce the risks by overtaking the autonomous systems, leading to an HRA of the system. Ramos et al. 2020 also presents a Task Analysis (TA) joint with an Event Sequence Diagram (ESD) to form a method called Human-System Interaction in Autonomy (H-SIA) used for a collision scenario. Tørressen 2021 presents an HRA of a safety operator operating onboard an autonomous passenger ferry and analyzes the different tasks when responding to an emergency situation. The findings lead to the conclusion that the operator's role should be kept to a minimum. As the operator's contribution is limited to facilitating passenger assistance, their responsibilities should be restricted solely to that aspect. By reducing the number of tasks assigned to the operator, more time can be allocated to each task. Consequently, the reliability of performing this smaller set of tasks increases, ensuring a higher level of efficiency and effectiveness.

Human reliability assessment (HRA) is a tool that has been extensively used in several industries to evaluate the safety and reliability of various systems and procedures. In the nuclear power industry, HRA is mandated by the U.S. Nuclear Regulatory Commission (NRC) to evaluate the safety and reliability of nuclear power plants. The purpose of HRA is to identify potential human errors that could cause an accident or failure and evaluate the effectiveness of the plant's safety systems and procedures. It also assesses the training and qualifications of plant personnel and identifies areas for improvement.

Similarly, the aviation industry uses HRA to evaluate the safety and reliability of aircraft systems and procedures. The Federal Aviation Administration (FAA) requires HRA as part of the certification process for new aircraft to identify potential human errors that could cause an accident or incident. The evaluation also helps to determine the effectiveness of crew training and procedures, as well as evaluate the design of cockpit interfaces and displays to ensure they are intuitive and easy to use.

HRA is also used in the transportation industry to evaluate the safety and reliability of trains, ships, and other forms of transportation. For example, the International Maritime Organization (IMO) requires shipowners and operators to perform HRA as part of the design and operation of ships to identify potential human errors that could lead to an accident or incident. Additionally, HRA is used to evaluate the design of control systems and interfaces to ensure they are easy to use and understand.

Lastly, HRA is used in the oil and gas industry to evaluate the safety and reliability of drilling and production operations. The U.S. Bureau of Safety and

Environmental Enforcement (BSEE) requires offshore operators to perform HRA as part of their safety management systems. HRA is used to identify potential human errors that could cause an accident or incident, evaluate the effectiveness of safety procedures and equipment, and assess the training and qualifications of personnel to ensure they are prepared to respond to emergencies.

In summary, these examples demonstrate the importance and complexity of HRA in the development of autonomous vessels, and the need for ongoing research to develop effective HRA models and address human factors related to the use of autonomous systems in marine transportation.

2.3 The SPAR-H method

2.3.1 Description of the method

HRA methods are designed to identify potential sources of human error and estimate the likelihood of errors occurring during a specific task or activity. By understanding the factors that contribute to human error, HRA can inform the development of procedures, training programs, and system design to minimize the risk of accidents and improve overall performance. There are several HRA methods available, ranging from quantitative to qualitative approaches, each with their own strengths and limitations. Understanding these methods is essential for ensuring safe and efficient operations in complex systems where human performance is critical. One of these methods is the SPAR-H method.

The NUREG/CR-6883 INL/EXT-05-99509 report (D. Gertman et al. 2004) provides a comprehensive overview of the SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis) method, which is a systematic approach to HRA (Human Reliability Analysis) used to identify and assess the likelihood of human errors in complex systems. The report describes the method's key steps and discusses its strengths, limitations, and applications.

The SPAR-H method involves several steps, including task analysis, PSF identification, PSF assessment, HEP calculation, and error reduction strategies. The task analysis involves breaking down the task into its component parts to identify potential sources of human error. The PSF identification step involves identifying internal and external factors that can affect human performance, including factors such as fatigue, stress, distractions, and equipment reliability. In the PSF assessment step, the impact of each PSF on human performance is assessed based on expert judgment and experience, and weighting factors are assigned to each PSF based on its influence on human performance. The HEP calculation step involves calculating the probability of human error based on the PSF weighting factors and the specific task being performed. Finally, in the error reduction step, strategies for reducing the likelihood of human error are identified, which may include changes to task design, improvements to equipment or procedures, or training and education programs for personnel.

The SPAR-H method is a flexible approach that can be adapted to a wide range of tasks and environments. It has several strengths, including its ability to identify and assess the impact of multiple PSFs on human performance, its ability to calculate quantitative HEPs, and its flexibility in adapting to a wide range of tasks and environments. However, the method has limitations, including its reliance on expert judgment, its difficulty in assessing complex tasks with multiple steps, and its limited applicability to non-nuclear industries.

Overall, the SPAR-H method is a powerful tool for assessing and managing the risk of human error in complex systems, particularly in the nuclear industry, where the consequences of human error can be catastrophic. By identifying potential sources of error and developing strategies for reducing their likelihood, the SPAR-H method can help improve safety and reduce the risk of catastrophic events. It has been chosen to use this method for this thesis for different advantages: it provides a standardized framework that ensures consistency in the analysis process and results, it places significant emphasis on the PSFs, and it is designed to be integrated with system analysis which enables the integration of human error probabilities into larger risk models, considering the interactions between human performance and other system components.

2.3.2 Application

A study conducted in Park et al. 2019 was to develop an approach for addressing human and organizational factors in multi-unit Human Reliability Analysis (HRA) using the Standardized Plant Analysis Risk HRA (SPAR-H) method. The proposed approach is applicable to level 1, 2, and 3 Probabilistic Safety Assessments (PSAs). The study began by identifying six multi-unit task types based on previous research that categorized human and organizational factors relevant to multi-unit HRA. Subsequently, a task analysis was conducted for each of the six task types, incorporating HRA event tree analysis suggested by the Technique for Human Error Rate Prediction (THERP) and timeline analysis techniques. To evaluate the suitability of the existing SPAR-H method for multi-unit task types, a qualitative and quantitative analysis was performed, identifying the challenges associated with its application. The study also examined the applicability of the dependence assessment approach proposed in the existing SPAR-H method in the context of multi-unit situations. Finally, addressing the challenges identified in the previous steps, the study proposed methods for analyzing the six multi-unit task types and evaluating the interdependence between operator actions. Concrete examples were provided to illustrate these methods. The anticipated outcome of this research is to enhance the estimation and calculation of human error probabilities in multi-unit PSAs.

In Nazari et al. 2018, the primary objective of is to assess the Human Error Probability (HEP) associated with operator intervention in initiating the Feed & Bleed (F&B) recovery procedure during a Total Loss of Feedwater (TLFW) accident in a typical VVER-1000 Nuclear Power Plant (NPP). The F&B strategy is crucial for preventing core damage in the event of a loss of Ultimate Heat Sink (UHS) accident. In addition to the proper functioning of multiple safety systems, the role of human factors is significant in avoiding severe scenarios. The research employs the Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) Method to quantitatively assess the HEP of operator interference during the TLFW accident. One of the factors influencing human performance is the available time for operators to intervene and restore natural circulation to remove residual heat following a reactor scram. This time is computed using the RELAP5 Mod 3.2 best estimate code. The findings indicate a strong dependence between the operators' diagnosis and action HEPs, resulting in a combined HEP value that is associated with a high level of risk and unacceptable uncertainty. Consequently, it is concluded that the accident management procedure should be redesigned to eliminate the dependency between diagnosis and action.

The significance of emergency preparedness in ensuring successful emergency responses at sea cannot be overstated. Regular emergency drills are conducted to maintain acceptable levels of preparedness. However, it is important to recognize that emergency drill operations themselves carry significant risks, and there is insufficient evidence indicating that these risks are adequately considered during drill planning. Human error stands out as a major contributor to accidents during emergency drill procedures. Consequently, a key question arises: how can the overall risk, including human errors, be accurately evaluated during an emergency drill? Ahn et al. 2022 introduces a novel hybrid approach that combines the Standardized Plant Analysis Risk Human Reliability Analysis (SPAR-H) method with a fuzzy multiple attributive group decision-making method. This approach offers a framework for evaluating specific scenarios associated with human errors and identifying the factors that influence human performance. Estimated human error probabilities are employed to assess human reliability, utilizing a new approach based on a system reliability block diagram. To illustrate the method, the rescue boat drill procedure for a man overboard is selected as an example. The research findings present the probability of each human error and its contributing factors for each task involved in the drill. Consequently, an overall reliability value of 6.06E-01 is obtained for the rescue boat drill operation.

Human reliability analysis plays a crucial role in predicting the performance of ship crews during critical shipboard operations that entail high risks. In particular, crew members working on tanker ships must exercise extra vigilance due to the hazardous nature of the cargo they handle. Elidolu et al. 2023 focuses on conducting a detailed human reliability analysis, step by step, for cargo discharging operations in crude oil tankers. To achieve this objective, the research utilizes a combination of the Standardized Plant Analysis Risk Human Reliability Analysis (SPAR-H) method and the Evidential Reasoning (ER) approach. By extending SPAR-H with ER, the study systematically predicts the probability of human errors. SPAR-H serves as a robust tool for calculating human error probability, while ER incorporates the opinions of multiple raters to support decision-making. The research findings indicate an overall human reliability value of 6.52E-01 for cargo discharging operations in crude oil tankers. In addition to its practical implications for maritime crude oil transportation, the proposed approach demonstrates how a comprehensive understanding of human reliability can be obtained.

CHAPTER

THREE

METHODOLOGY

3.1 Research methodology

The HRA that is being performed takes support on the trial operations led by NTNU on the *MilliAmpere2* ferry, for the functioning of the ferry and the operator's job, during the summer 2022. It aims to help Zeabuz develop their own ferry and try it during the summer 2023. In order to perform this HRA, meetings and discussion have been held with Zeabuz members, in order to determine and agree on which tasks should be included and which should not. These meetings occurred twice monthly, to maintain updates and add precision to the work. A field trip on the ferry was done during the trial operations, but most of the data was provided from discussions with Zeabuz, to ensure qualitative data. A SPAR-H method has been used, as described in Section 2.3.1. The different steps of this method are described in Figure 3.1.1

3.2 Task Analysis

A hierarchical task analysis has been conducted to give details about the operator's tasks when the ferry is running in normal operations and will embrace scenarios of abnormal situations. The main tasks are described below:

Task 1: Charging

In normal operations, this task is done automatically when the system detects the good conditions to charge.

In case of problem, the operator should connect the cable manually.

Task 2: Passenger Handling

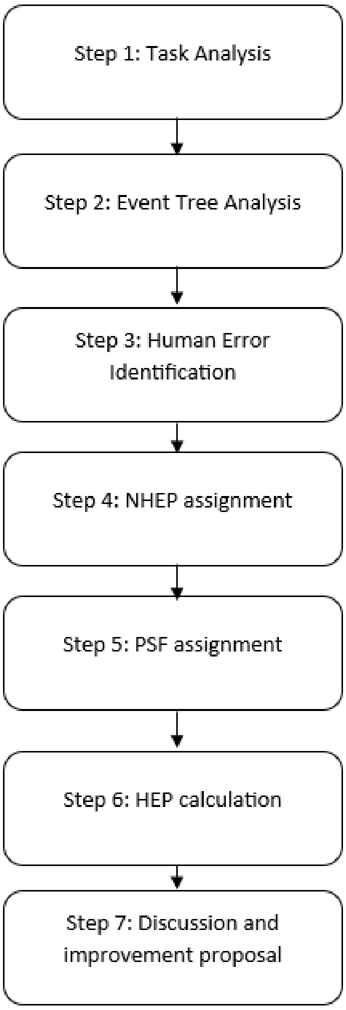

Figure 3.1.1: Steps for the SPAR-H analysis

When the ferry is at quay, the operator must handle the passengers going in and out of the ferry. He has to control manually the gates that allow passenger to cross the ramp and be sure there are no more than 12 people onboard before leaving.

In case of malfunction of the system, the operator has to control manually the ramp that gives access to the dock.

Task 3: Departure

Once the passengers are onboard, the autonomous system will perform a predeparture check. The operator needs to be sure that the check is passed and then has to initiate manually the departure sequence by pushing a green button on the dashboard.

Task 4: Transit

During the transit, the autonomous system is in charge of everything and the operator needs to supervise and look out for any failure in the system.

In case an unexpected situation happens, the operator should switch the system to an emergency state, called Minimum Risk Condition, the specific case of manual takeover is called Minimum Risk Maneuver. There are 4 buttons the operator can push to decide towards which state the system will transition to:

- Return to quay (MRC 2)
- Stay on Dynamic Positioning (MRC 3)
- Joystick control (MRM)
- Cut power (MRC 4)

In all the MRC states, the autonomous system is still running, and the operator has to keep supervising and run some control checks before restarting the system or contacting some help. If the system runs down and the operator has to activate the joystick control mode, he then has to lead the ferry to the nearest quay. To do so, he has to keep control of four elements at the same time:

- Vision of the path
- Speed of the ferry
- Heading of the ferry
- Safety of the passengers

These tasks have to be done successfully and simultaneously to ensure the integrity of the ferry and the passengers until the ferry is at quay and safe to disembark the passengers.

Task 5: Docking/Mooring During docking, the system is in charge of everything, if no problems occur. If the system is unable to perform the docking, the operator has to switch into MRM mode and dock the ferry. He then has to perform the same actions as described in Task 4:

Elements to keep under control:

- Vision of the path
- Speed of the ferry
- Heading of the ferry
- Safety of the passengers

These tasks are the one the operator should perform during regular operations to ensure a safe and successful travel. They are summed up in Figure 3.2.1

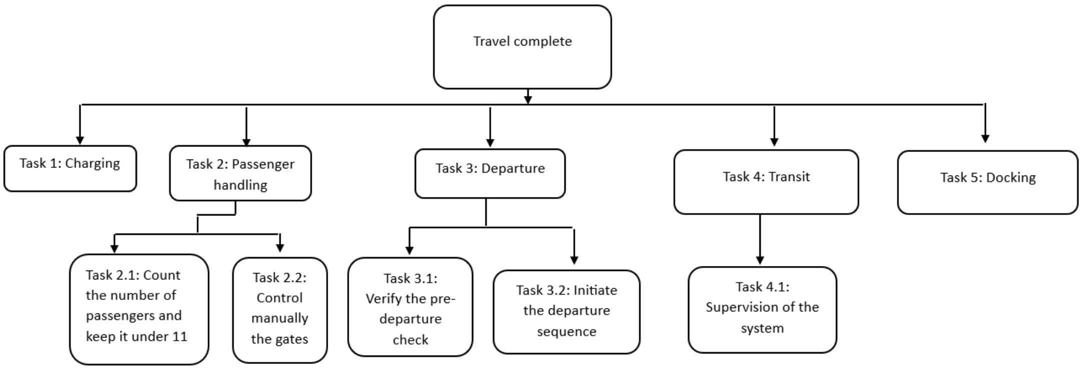

Figure 3.2.1: Task Analysis for the regular operations

3.3 Event Tree

In order to develop the Event Tree, the initial situation is assumed to be "Ferry at quay, ramp down". The sequence of events is represented in Figure 3.3.1.

The Tree is designed with arrows from three different colors: the green arrows symbolize a successful task performed either by the system or the human when involved, the blue arrows symbolize a failure of the autonomous system that can't be controlled by the operator and the red arrows symbolize a failure of the operator. The block from which the arrow is leaving refers to the task concerned by the color of the arrow, and it points to the task that need to be performed next.

The events on the main line refer to the tasks and subtasks that are described in Section 3.2 and can be found in Figure 3.2.1. Based on the scope of the work, the emergency situations are not considered. Therefore, the possible end events are either "Travel complete successfully", "Ferry at quay waiting for next departure" or "Contact emergency support and wait for help".

The first end event, "Travel complete successfully", is reached if the ferry crosses from one quay to the other without any human or material casualties. It happens if everything goes well or if the operator manages to fix problems occurring because of system failure. Before departing, to keep on track of this end event, the operator should, if necessary, connect manually the ferry to charge, limit the number of passengers to 11 and be sure the predeparture check is passed. During the crossing, the operator should perform successfully the manual takeover in case the system fails to perform its tasks.

The second end event, "Contact emergency support and wait for help", is reached if the ferry does not complete the travel. This can happen at every step of the travel: if the ferry is not charged or charging, if the number of passengers exceeds 12, if the predeparture check can't be validated, if the autonomous system fails and the operator has to drop the anchor and shut down everything or if the ramp and gates can't open.

The last end event is "Ferry at quay, waiting for next departure". This event is reached in case the operator decides to transition to the MRC2 state and the system is able to lead the ferry that way. In that case, if the nearest quay is the arrival quay, the event can turn into "Travel complete". If the nearest quay is the departure one, the ferry is back at step 1.

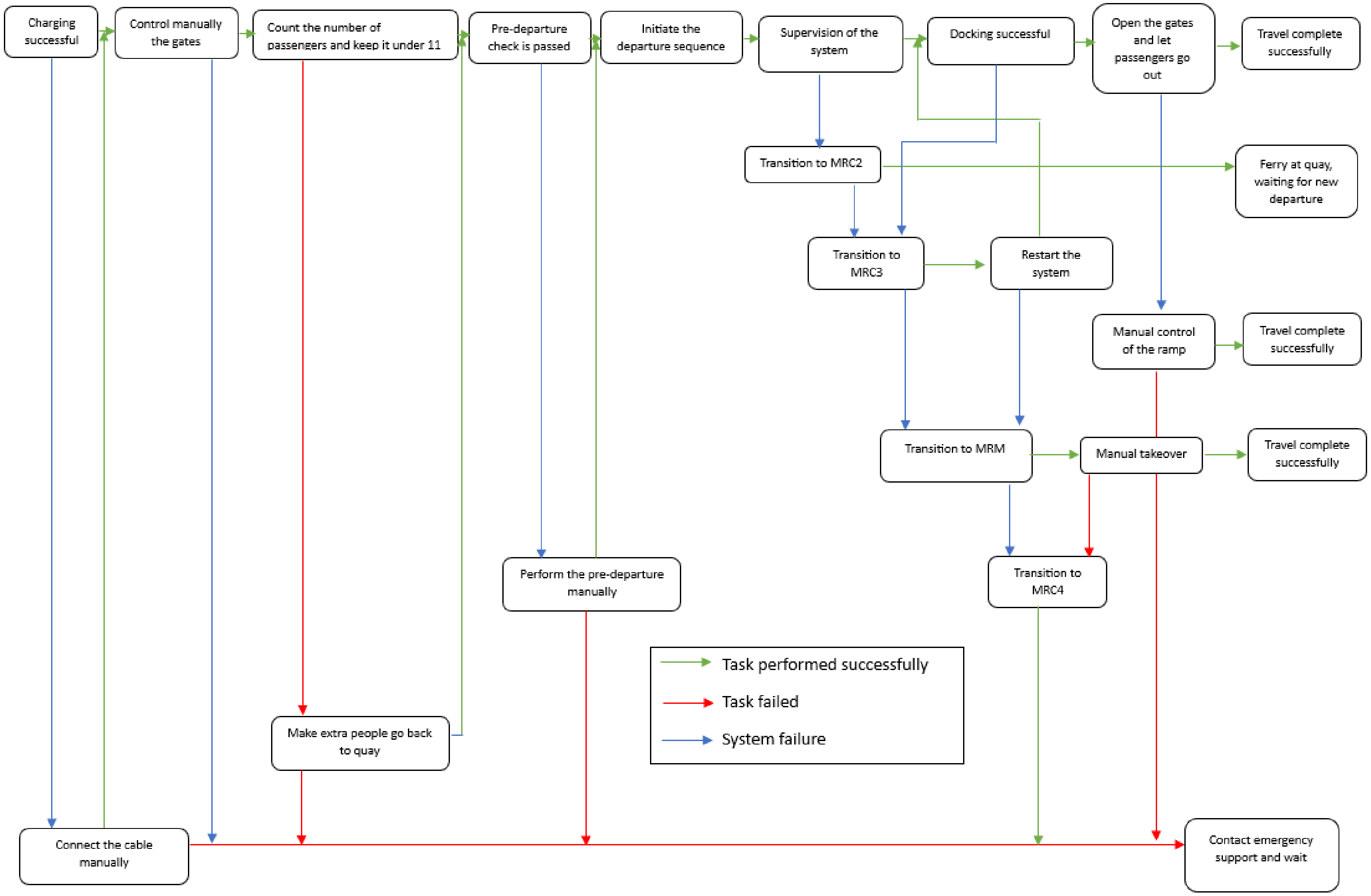

Figure 3.3.1: Event Tree representation of one travel

3.4 Identification of human errors

In order to assess the probabilities, the human errors need to be identified first. As explained in Section 3.3, the red arrows in Figure 3.3.1 represent a task failed by the operator. The possible errors, based on the tasks performed, can be found in Table 3.4.1. They consider only failures in which neither the system nor any equipment is involved. These tasks have been identified from the ConOps made by Zeabuz, after analyze of the trial operation performed with *MilliAmpere2*.

Task	Human failure
Connect the cable manually	The operator can't find the charging cable
	The operator can't connect the charging cable
Number of passenger under 11	The operator can't limit the number of passengers
Make extra people leave	The operator doesn't manage to talk with the passengers and make them leave
Perform the predeparture check	The operator doesn't detect an error message on the HMI display
	The operator decides to leave without enough battery
Manual takeover	Bad management of the ferry speed
	Bad management of the vision around the ferry
	Bad management of the direction

Table 3.4.1: Identification of operator's possible errors

3.5 Assign NHEPs

The Nominal Human Error Probability (NHEP) is the value given for the probability of failure before considering the different shaping factors. In the SPAR-H method, there are two categories that define the NHEP: Diagnosis and Action (D. Gertman et al. 2004). 'Diagnosis' should be attributed to a task in which the operator or crew must exert cognitive effort to observe and interpret available information, discern its implications, consider potential causes, and make decisions accordingly. 'Action' should be attributed when performing one or more activities, such as executing steps or tasks as directed by a diagnosis, operating rules, or written procedures. The SPAR-H handbook assess NHEP for these two categories: 0.01 for Diagnosis and 0.001 for Action.

3.6 Assign PSFs

Many, if not most, HRA approaches incorporate PSF information to estimate HEPs. Generally, PSF analysis enhances the level of realism in HRA analysis. The level and detail of PSF analysis should be tailored to identify potential influences and assess them. The current generation of HRA methods, often referred to as second-generation HRA, also incorporates PSF information in various forms when calculating HEPs. When assigning the PSF level, the analyst evaluates the complexity of the diagnosis or action required for a specific scenario or range of scenarios from the perspective of the operator, rather than the analyst's holistic view of complexity.

The different PSFs considered by the SPAR-H method are: Available Time, Stress/Stressors, Complexity, Experience/Training, Procedures, Ergonomics/HMI, Fitness for Duty and Work Processes.

- **Available Time**: The term "available time" pertains to the duration allocated for an operator or crew to diagnose and respond to an abnormal event. Insufficient time can impede the operator's cognitive clarity and hinder the exploration of alternatives. Moreover, it can impact the operator's overall performance. Multipliers vary to some extent depending on whether the task involves diagnosis or action.

- **Stress/Stressors**: Stress, encompassing both negative and positive motivational influences on human performance, has been broadly defined and utilized. In the context of SPAR-H, stress refers to the degree of unfavorable conditions and circumstances that impede an operator's ease in completing a task. It encompasses mental stress, excessive workload, and physical strain induced by challenging environmental factors. This includes factors like narrowed attention or muscle tension, as well as general apprehension or nervousness related to the significance of an event. Environmental stressors, such as excessive heat, noise, poor ventilation, or radiation, can induce stress in individuals and impact their mental and physical performance. It's crucial to note that the impact of stress on performance follows a curvilinear pattern: moderate levels of stress can enhance performance to some extent, considered nominal, while high and extreme levels of stress have a negative effect on human performance . Various measures have been used to assess stress, including galvanic skin response (GSR), heart rate (HR), blood volume pulse (BVP), self-report inventories, and chemical markers. For instance, reduced levels of s-IgA, an immune response marker found in saliva, have been linked to increased health risks in individuals. When employing SPAR-H, physical measures are not readily available to the analyst. Therefore, assigning a specific stress level requires interpretation based on operational knowledge and human factors to estimate the expected stress level for a given scenario or context.

- **Complexity**: Complexity refers to the level of difficulty associated with performing a task within a specific context. It takes into account both the nature of the task itself and the environment in which it is performed. The more challenging a task is, the higher the probability of human error. Likewise, tasks that are more ambiguous also carry a greater risk of human error. Complexity also encompasses the mental effort required, such as mental calculations, memory demands, understanding the underlying system model, and relying on knowledge rather than training or practice. Physical effort can also contribute to complexity, particularly when intricate patterns of movement are involved.

  Figure 3.6.1 provides an overview of typical factors that contribute to complexity. References such as Braarud and Kirwan 2011, Electric Power Research Institute 1992, D. I. Gertman and Blackman 1994 and Division of Risk Analysis and Applications, Office of Nuclear Regulatory Research 2000 identify these complexity factors. SPAR-H analysts may find it helpful to consult these factors when assessing the complexity Probability Shaping Factor (PSF). It is important to acknowledge that a single complexity factor can have varying degrees of influence on human-system interaction. For instance, mental calculations required of operators can range from minimal to overwhelming, depending on the specific event's aspects. The same applies to combinations of factors. Therefore, determining the specific complexity level associated with a Human Error Probability (HEP) is at the discretion of the analyst. Currently, there is no algorithm for inferring influence levels based on the combination of selected factors.

For analysts differentiating between rule-based and knowledge-based diagnosis, rule-based scenarios generally involve lower complexity and often receive positive ratings regarding procedures. On the other hand, knowledge-based diagnosis and decision-making typically entail higher complexity and are often associated with more negative ratings on procedures, including incomplete or misleading guidance.

In general, tasks with higher complexity require greater skill and understanding to be successfully accomplished. Complex tasks usually involve multiple variables, and concurrently diagnosing multiple events and executing multiple actions simultaneously is more complex than handling single events.

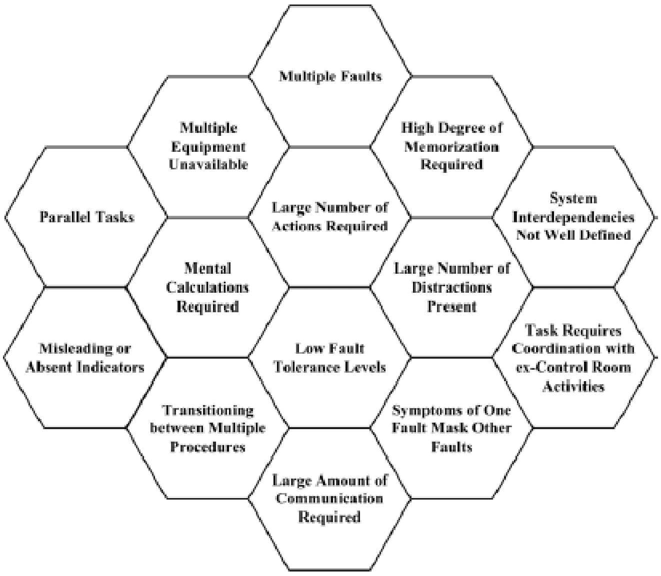

Figure 3.6.1: Factors that contribute to the complexity, from D. Gertman et al. 2004

- **Experience/Training**: This PSF pertains to the expertise and training of the operator(s) engaged in the task. This includes considering factors such as the individual or crew's years of experience, whether they have received training on the specific accident type, the elapsed time since training, and their familiarity with the systems involved in the task and scenario. Additionally, the novelty or uniqueness of the scenario is taken into account, evaluating whether the crew or individual has encountered a similar situation in either a training or operational context. Examples where training may be inadequate to include lacking guidance on bypassing engineered safety functions, monitoring reactor conditions during reactivity changes, and monitoring plant operation during apparently normal and stable conditions to facilitate early detection of abnormalities.

- **Procedures**: This PSF relates to the presence and utilization of formal operating procedures for the tasks being considered. Event investigations often reveal issues where procedures provide incorrect or insufficient information regarding specific control sequences. Another common problem is the ambiguity of procedural steps. The levels of PSF vary depending on whether the activity involves diagnosis or action. In situations where multiple transitions between procedures are necessary to support a task or group of tasks, SPAR-H recommends that the analyst adjust the PSF for complexity accordingly. If the procedures themselves are problematic or inadequate, the HRA analyst should evaluate the procedures and determine whether they should be assigned an "inadequate" or "poor" rating.

- **Ergonomics/HMI**: Ergonomics encompasses various factors such as equipment, displays, controls, layout, the quality and quantity of information provided by instrumentation, and the interaction between the operator/crew and the equipment during task execution. It includes aspects of human-machine interaction (HMI), and the adequacy or inadequacy of computer software is also considered within this PSF. Instances of poor ergonomics can be observed in panel design layout, annunciator designs, and labeling.

  Regarding panel design layout, investigations conducted at U.S. commercial nuclear facilities have revealed that when essential plant indications are not consolidated in one designated location, it becomes challenging for operators to effectively monitor all the necessary indications for proper plant control. If there is evidence of this issue, a negative PSF value is assigned.

  Poor annunciator designs can involve situations where there is only a single acknowledge circuit for all alarms, increasing the likelihood that an alarm may go unnoticed before it is cleared. Another problem arises when annunciators have alarm set points positioned too close to the affected parameter, making it difficult for operators or crews to react and take appropriate mitigating actions.

  Examples of poor labeling include temporary, informal, or illegible labels, as well as instances where multiple names are given to the same equipment. The ergonomics of the plant, also known as the human-machine interface (HMI) or human engineering aspects, are considered. Job performance aids can also fall under the umbrella of ergonomics. However, in SPAR-H, if a job performance deficiency is related to a procedure, it is preferable to evaluate it under the procedures PSF rather than the ergonomics PSF. For instance, if a procedure does not align with the equipment being used, the equipment procedure deficiency should be noted in the procedures PSF rather than the ergonomics PSF.

- **Fitness for Duty**: Fitness for duty pertains to assessing whether the individual responsible for performing a task is physically and mentally capable of carrying it out effectively at the given time. Various factors can influence fitness, including fatigue, illness, drug use (both legal and illegal substances), overconfidence, personal issues, and distractions. Fitness for duty encompasses elements associated with individuals that are distinct from their training, experience, or stress levels.

- **Work Processes**:Work processes encompass various aspects of conducting work, including inter-organizational dynamics, safety culture, work planning, communication, and management support and policies. The manner in which work is planned, communicated, and executed can significantly impact individual and crew performance. Poor planning and communication can result in a lack of clarity regarding work requirements. Work processes involve considerations of coordination, command, and control, as well as management, organizational, or supervisory factors that can influence performance.

  Event investigations have highlighted issues related to inadequate information exchange during shift turnovers, as well as communication challenges with maintenance crews and auxiliary operators. Measurable indicators may include rework volume, risk assessment of items in the utility's corrective action program backlog, enforcement actions, turnover rates, and performance efficiencies. The role of the shift supervisor is crucial in work processes, and instances where they become overly involved in event specifics instead of maintaining a leadership position in the control room indicate a breakdown in work processes.

  Work practices also encompass conditions that adversely affect quality and problems associated with a safety-conscious work environment. This includes instances of management retaliation against allegations concerning the investigated failure event. For example, the analyst must assess whether utility management actions against maintenance staff have any relevance to a specific control room or maintenance action being evaluated. If evidence suggests such a connection, a negative level for the work practices PSF is assigned.

  Furthermore, SPAR-H acknowledges the potential for conflicts and indecisiveness between different groups within an organization, such as engineering and operations, or between operators and management, as work process issues. Communication challenges or non-adherence to enforcement actions or notices between regulators and licensees are also considered indicative of work process problems.

  Inadequacies within the utility's corrective action program (CAP), such as failure to prioritize, implement, respond to industry notices, or perform root cause analyses as required by regulations, are regarded as work process variables within SPAR-H. Given the diverse range of potential concerns falling under the work process category, analysts are encouraged to provide comprehensive information in the designated worksheet space, listing the reasons for assigning a particular work process PSF level.

3.7 Determine the probability of failure

The Human Error Probability is the final value assigned to a task that represents the probability that the safety operator will fail. According to the SPAR-H handbook (D. Gertman et al. 2004), there are several cases to consider:

1. The number of negative PSFs is lower than 3.
   The HEP is then calculated with the following formula:

   $$HEP = NHEP * PSF_{composite}, \text{ where } PSF_{composite} = \prod PSFs$$

2. The number of negative PSFs is greater or equal to 3.
   The HEP is then calculated with the following formula:

   $$HEP = \frac{NHEP*PSF_{composite}}{NHEP*(PSF_{composite}-1)+1}$$

3. In case the task is a combination of a Diagnosis and an Action, the probability becomes:

   $$HEP = HEP_{Diagnosis} + HEP_{Action}$$

CHAPTER

FOUR

RESULTS

In this section will be presented the results of the HRA. Each failure from Table 3.4.1 has been assigned PSFs levels and a nominal HEP, following the guidance from Section 3.5 and Section 3.6. It has been done twice, the operator being considered onboard first and in a remote control room afterward. The final HEPs will be compared for each task to estimate if moving the operator to the control room is as safe as keeping them onboard.

4.1 Failure 1: The operator can't find the charging cable

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.1.1

This task is particular as it cannot be performed when the operator is in a control room. We then only have the possibility to estimate the HEP for an onboard operator. This probability is 0.005.

4.2 Failure 2: The operator can't connect the charging cable

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.2.1

This task is related to the previous one and is also non-doable when the operator is not onboard. The probability of failure when onboard is 0.005.

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available $>$ 5 x time required	Time available $>$ 5 x time required
Stress/ Stressors	Nominal	Nominal
Complexity	Nominal	Nominal
Experience/ Training	Nominal	Nominal
Procedures	Not available	Not available
Ergonomics/ HMI	Nominal	Nominal
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	5	5
HEP		
	0.005	X

Table 4.1.1: PSF detail for the task 'The operator can't find the cable'

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available $>$ 5 x time required	Time available $>$ 5 x time required
Stress/ Stressors	Nominal	Nominal
Complexity	Nominal	Nominal
Experience/ Training	Nominal	Nominal
Procedures	Not available	Not available
Ergonomics/ HMI	Nominal	Nominal
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	5	5
HEP		
	0.005	X

Table 4.2.1: PSF detail for the task 'The operator can't connect the cable'

4.3 Failure 3: The operator can't limit the number of passengers

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.3.1

We can see in the table that the HEP is highly increasing when the operator is in a control room. It has to do with the fact that they have no direct contact with the passengers, so the Ergonomics factor goes from nominal to poor. The Procedure and Experience are also modified, as the remote control room is still new and has not been fully developed. The probability increases from 0.1668 to 0.7061, which is more than 4 times the initial failure rate.

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Nominal time	Nominal time
Stress/ Stressors	High	High
Complexity	Moderately complex	Moderately complex
Experience/ Training	Nominal	Low
Procedures	Not available	Incomplete
Ergonomics/ HMI	Nominal	Poor
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	200	2400
HEP		
	0.1668	0.7061

Table 4.3.1: PSF detail for the task 'The operator can't limit the number of passengers'

4.4 Failure 4: The operator doesn't manage to talk with the passengers and make them leave

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.4.1

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Nominal time	Nominal time
Stress/ Stressors	High	High
Complexity	Moderately complex	Moderately complex
Experience/ Training	Nominal	Low
Procedures	Not available	Incomplete
Ergonomics/ HMI	Nominal	Poor
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	200	2400
HEP		
	0.1668	0.7061

Table 4.4.1: PSF detail for the task 'The operator doesn't manage to talk with the people and make them leave'

This task is directly related to the previous one, and therefore, shows the same evolution in terms of changes in the probability. It also increases from 0.1668 to 0.7061.

4.5 Failure 5: The operator doesn't detect an error message on the HMI display

This task is categorized as Diagnosis, therefore the NHEP is 0.01. The detail of the PSFs can be found is Table 4.5.1

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available = time required	Nominal time
Stress/ Stressors	High	Nominal
Complexity	Moderately complex	Moderately complex
Experience/ Training	Low	Low
Procedures	Nominal	Nominal
Ergonomics/ HMI	Nominal	Good
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	120	3
HEP		
	0.5479	0.0300

Table 4.5.1: PSF detail for the task 'The operator doesn't detect an error message on the dashboard'

For this task, the probability is lower for an operator in a control room. Not being on the ferry reduces the stress and gives more time to react. In addition, the design of the control room improves the ergonomics and then, reduces its impact on the overall probability. The error probability decreases from 0.5479 to 0.03, which is a huge reduction, considering the error detection is prior to other important tasks, such as manual takeover.

4.6 Failure 6: The operator decides to leave without enough battery

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.6.1

For this task also, being in a control room reduces the stress and improves the ergonomics. Consequently, the probability decreases from 0.002 to 0.0005.

4.7 Failure 7: Bad management of the ferry speed

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.7.1

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Nominal time	Nominal time
Stress/ Stressors	High	Nominal
Complexity	Nominal	Nominal
Experience/ Training	Nominal	Nominal
Procedures	Nominal	Nominal
Ergonomics/ HMI	Nominal	Good
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	2	0.5
HEP		
	0.002	0.0005

Table 4.6.1: PSF detail for the task 'The operator decides to leave without enough battery'

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available = time required	Time available = time required
Stress/ Stressors	Extreme	Extreme
Complexity	Moderately complex	Highly complex
Experience/ Training	Low	Low
Procedures	Nominal	Nominal
Ergonomics/ HMI	Nominal	Nominal
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	300	750
HEP		
	0.2309	0.4288

Table 4.7.1: PSF detail for the task 'Bad management of the speed'

When in a remote room, managing the speed becomes more complex as the perception and the estimation is reduced to only the cameras and the sensors. However, this situation occurs when the system fails, so the equipment may not be reliable. The probability of error then increases, from 0.2309 to 0.4288.

4.8 Failure 8: Bad management of the vision around the ferry

This task is categorized as Diagnosis, therefore the NHEP is 0.01. The detail of the PSFs can be found is Table 4.8.1

The management of the vision is also highly impacted by being in a control room,

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available = time required	Time available = time required
Stress/ Stressors	High	Extreme
Complexity	Moderately complex	Moderately complex
Experience/ Training	Nominal	Low
Procedures	Nominal	Nominal
Ergonomics/ HMI	Nominal	Good
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	40	150
HEP		
	0.2878	0.6024

Table 4.8.1: PSF detail for the task 'Bad management of the vision'

as the operator has to rely on the sensors to detect other vessels and boats. It is then more stressful to maintain a good vision the whole time of the operations. The probability increases from 0.2878 to 0.6024.

4.9 Failure 9: Bad management of the direction

This task is categorized as Action, therefore the NHEP is 0.001. The detail of the PSFs can be found is Table 4.9.1

	Operator onboard	**Operator in a control room**
PSF		
Available Time	Time available = time required	Time available = time required
Stress/ Stressors	High	High
Complexity	Moderately complex	Moderately complex
Experience/ Training	Nominal	Low
Procedures	Nominal	Nominal
Ergonomics/ HMI	Poor	Poor
Fitness for Duty	Nominal	Nominal
Work Processes	Nominal	Nominal
Total	400	1200
HEP		
	0.2859	0.5457

Table 4.9.1: PSF detail for the task 'Bad management of the direction'

The management of the direction is being impacted by the lack of training, to steer a boat is very different between onboard and in a remote control room, when you don't have access to the regular equipment. The probability of failure increases from 0.2859 to 0.5457.

4.10 Evolution of the HEP

The different HEPs are summarized in Table 4.10.1 and a graph showing the changes for each failure when the operator is considered in a remote control room is presented in Figure 4.10.1.

Failure	$HEP_{onboard}$	HEP_{remote}
The operator can't find the cable	0.0050	0.0050
The operator can't connect the cable	0.0050	0.0050
The operator can't limit the number of passengers	0.1668	0.7061
The operator doesn't manage to talk with the people and make them leave	0.1668	0.7061
The operator doesn't detect an error message on the dashboard	0.5479	0.0300
The operator decides to leave without enough battery	0.0020	0.0005
Bad management of the speed	0.2309	0.4288
Bad management of the vision	0.2878	0.6024
Bad management of the direction	0.2859	0.5457

Table 4.10.1: HEPs summarized for the two different situations

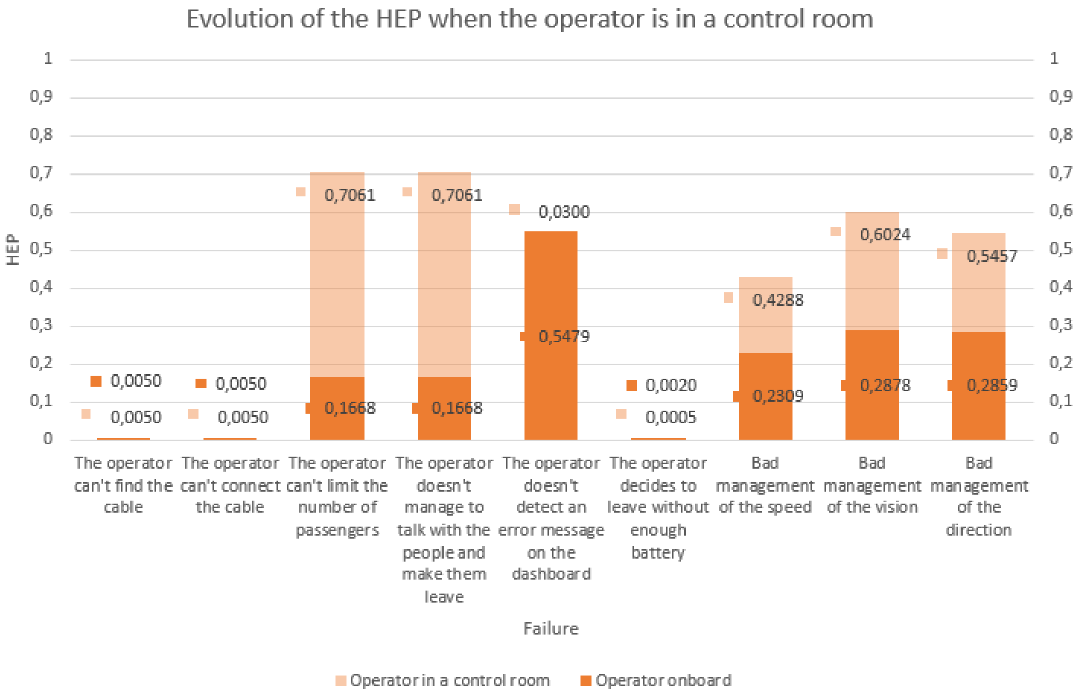

Figure 4.10.1: Evolution of the HEP when the operator is in a control room

From Table 4.10.1 and Figure 4.10.1, it can be assumed that the failures related to the manual charging and the one related to the low battery will not affect the decision to keep the operator onboard or not, their probability of failure being under 0.5%. The main concern is related to the passenger handling and the manual takeover, both tasks appear more likely to fail if the operator is in a remote control room. Keeping the number of passenger under the limit to allow the departure is more than four times more unsuccessful if the operator is not onboard, and take over manually the ferry to complete the travel is twice more unsuccessful. The only task that is easier to perform is to detect an error on the HMI display, going from 50% chance of error to 3%, which is a significant reduction.

CHAPTER

FIVE

DISCUSSION

5.1 Assumptions

In order to perform this HRA, assumptions were made. The tasks selected for the analysis are only concerning the safety operator, the equipment nor the system was considered possibly failing for what they have to do. If an equipment problem or a system failure is the cause of the task, it is considered, but not if it is involved in the completion of the task. Another big assumption was made for the data concerning the remote control room. It has not been developed yet, so the PSFs were attributed guessing what it would be like to operate from this kind of room. This assumption could make the data seem unreliable, but this is just an initial guessing and the only possibility to estimate the HEPs so far. Whenever a control room is tested, the PSFs can be adjusted in consequence to recalculate the HEPs.

Concerning the Event Tree representation, in Figure 3.3.1, the part representing the transitions of the autonomous system has been simplified for the clarity of the overall scheme. The complete representation of the different states of the system can be found in Figure B.1. The system can switch between two states according to the situation, or it can be overruled by the operator and forced to transition. The operator can also decide to take over and switch to Minimum Risk Maneuver (MRM). This simplification does not impact directly the HEPs but in case of future work using the chart and the data, it may affect the End Event probability. Considering that the transitions can de done automatically or forced by the operator, and the possibility to go back and forth between the states, the general model is way more complex to assess in terms of probability.

Furthermore, as explained in Section 1.3, this thesis focused only on the regular operations and the system failures. The emergency situations were not analysed as they were analysed in Tørressen 2021 and it has been decided with Zeabuz that it could be done in the future if this analyzes was conclusive. Another reason is that emergency is a very large term and embraces a lot of situations, which would have made the list of tasks too long and still not exhaustive.

5.2 Implications

As one can see in chapter 4, and specifically in Figure 4.10.1, there are five tasks that see their probability of failure largely increase and one that sees its probability decrease. The three tasks that have both probabilities under 0.5% can be allegedly considered successful. The most critical tasks concern the management of the people onboard and the manual takeover, when the improved task is about the error detection. So only considering the number of tasks improved and deteriorated, the solution would be to keep the safety operator onboard. However, the goal of Zeabuz is to be able to move them. These results give them the point to focus when designing the control room and the ferry, in order to make the probabilities decrease. The detail of the PSFs should also be reviewed to see what makes the difference and adapt the changes accordingly.

5.3 Uncertainties and limitations

The results presented should not be taken as guaranteed and exploited directly. In order to assess the PSFs, only one person worked on it and as reliable can be someone, a work like this should be done by several to compare opinions on the PSFs. It could have been done with more time to contact the right people. Another reason is also that an operator working from the control room has not been tested yet, as explained in Section 5.1, and therefore, make the data likely to change when it will happen.

The choice of the SPAR-H method is also a limitation, as it sets the way the probabilities are calculated. Each method has a different way to assess NHEP and PSF, as well as the formula used to calculate the final HEP. The SPAR-H method has its own boons and banes, the main ones being probably the number of choices to assign NHEPs and PSFs. There are only two categories for the task to analyze that give the NHEP, Action and Diagnosis, so it restrains the possibilities. On the other hand, the way the PSFs are divided give more freedom to the analysts to assess the situation and make it match to what actually happens.

5.4 Future work

In order to pursue this work, an analysis of how the control room can be design should be done. Based on the changes in probabilities it brings, some adjustments can be done directly to try to anticipate the possible mistakes. Regarding the passengers' management, some functionalities can be implemented to avoid non-desirable situations and for the manual takeover, more practice can be done to reduce the risk of error while operating.

Another continuation could be to estimate the overall probabilities of success for the end events presented in Figure 3.3.1. To do so, it is important to have all the system failures' probabilities first. This would require a much deeper analysis of the system and trial data, but it can lead to a good planning of the improvements that need to be done on the whole system.

Finally, testing other methods could be interesting to compare the results and have more options to consider when improving the system.

CHAPTER

SIX

CONCLUSIONS

In this thesis, an HRA has been conducted to determine whether a safety operator could perform their tasks from a control room instead of being onboard the autonomous ferry. The different tasks in which only the operator is involved have been identified and specified in order to allocate them a NHEP and some PSFs, based on the SPAR-H method. The final HEPs have then been calculated according to the same method.

The comparison of the results implies that the operator is more willing to do a mistake if they operate from a control room. The goal of Zeabuz being to still do so, it enlightens where they should focus while designing the room, to keep the failure rate low, which answer to the main objective of this thesis. A system to maintain the number of passenger below the limit has to be set, as the operator is not on site to deal with it. More training should be considered for guiding the ferry remotely, this operation is already difficult to perform in regular conditions, but it is even more when you have to rely on sensors instead of your own perception.

This work can be continued by analyzing more situations, especially emergencies, as they were excluded from the analysis. With more data about the system itself, it could also lead to a more global reliability analysis of the whole ferry.

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APPENDICES

APPENDIX

A

PSFS' LEVELS EXPLANATION

Table A.1: PSFs' levels explanation, adapted from the SPAR-H handbook

SPAR-H PSFs	**SPAR-H PSF Levels**	**SPAR-H Multipliers**	**Explanation of the levels**
Available Time	Inadequate Time	***P(failure) = 1.0***	If the operator cannot diagnose the problem in the amount of time available, no matter what s/he does, then failure is certain.
Available Time	Time available = time required	**10**	there is just enough time to execute the appropriate action.
Available Time	Nominal time	**1**	there is some extra time above what is minimally required to execute the appropriate action.
Available Time	Time available > 5 x time required	**0,1**	there is an extra amount of time to execute the appropriate action (i.e., the approximate ratio of 5:1).
Available Time	Time available > 50 x time required	**0,01**	There is an expansive amount of time to execute the appropriate action (i.e., the approximate ratio of 50:1).

Table A.1 continued from previous page

SPAR-H PSFs	SPAR-H PSF Levels	SPAR-H Multipliers	Explanation of the levels
Stress/ Stressors	Extreme	**5**	a level of disruptive stress in which the performance of most people will deteriorate drastically. This is likely to occur when the onset of the stressor is sudden and the stressing situation persists for long periods. This level is also associated with the feeling of threat to one's physical well-being or to one's self-esteem or professional status, and is considered to be qualitatively different from lesser degrees of high stress (e.g., catastrophic failures can result in extreme stress for operating personnel because of the potential for radioactive release).
Stress/ Stressors	High	**2**	a level of stress higher than the nominal level (e.g., multiple instruments and annunciators alarm unexpectedly and at the same time; loud, continuous noise impacts ability to focus attention on the task; the consequences of the task represent a threat to plant safety).
Stress/ Stressors	Nominal	**1**	the level of stress that is conducive to good performance.
Complexity	Highly complex	**5**	very difficult to perform. There is much ambiguity in what needs to be diagnosed or executed. Many variables are involved, with concurrent diagnoses or actions (i.e., unfamiliar maintenance task requiring high skill).

Table A.1 continued from previous page

SPAR-H PSFs	**SPAR-H PSF Levels**	**SPAR-H Multipliers**	**Explanation of the levels**
Complexity	Moderately complex	**2**	somewhat difficult to perform. There is some ambiguity in what needs to be diagnosed or executed. Several variables are involved, perhaps with some concurrent diagnoses or actions (i.e., evolution performed periodically with many steps).
Complexity	Nominal	**1**	not difficult to perform. There is little ambiguity. Single or few variables are involved
Experience/ Training	Low	**3**	less than 6 months experience and/or training. This level of experience/training does not provide the level of knowledge and deep understanding required to adequately perform the required tasks; does not provide adequate practice in those tasks; or does not expose individuals to various abnormal conditions.
Experience/ Training	Nominal	**1**	more than 6 months experience and/or training. This level of experience/training provides an adequate amount of formal schooling and instruction to ensure that individuals are proficient in day-to-day operations and have been exposed to abnormal conditions.

Table A.1 continued from previous page

SPAR-H PSFs	SPAR-H PSF Levels	SPAR-H Multipliers	Explanation of the levels
Experience/ Training	High	**0,5**	extensive experience; a demonstrated master. This level of experience/training provides operators with extensive knowledge and practice in a wide range of potential scenarios. Good training makes operators well prepared for possible situations.
Procedures	Not available	**50**	the procedure needed for a particular task or tasks in the event is not available.
Procedures	Incomplete	**20**	information is needed that is not contained in the procedure or procedure sections; sections or task instructions (or other needed information) are absent.
Procedures	Available, but poor	**5**	a procedure is available but it is difficult to use because of factors such as formatting problems, ambiguity, or such a lack in consistency that it impedes performance.
Procedures	Nominal	**1**	procedures are available and enhance performance.
Ergonomics/ HMI	Missing/Misleading	**50**	the required instrumentation fails to support diagnosis or postdiagnosis behavior, or the instrumentation is inaccurate (i.e., misleading). Required information is not available from any source (e.g., instrumentation is so unreliable that operators ignore the instrument, even if it is registering correctly at the time).

Table A.1 continued from previous page

SPAR-H PSFs	SPAR-H PSF Levels	SPAR-H Multipliers	Explanation of the levels
Ergonomics/ HMI	Poor	**10**	the design of the plant negatively impacts task performance (e.g., poor labeling, needed instrumentation cannot be seen from a work station where control inputs are made, or poor computer interfaces).
Ergonomics/ HMI	Nominal	**1**	the design of the plant supports correct performance, but does not enhance performance or make tasks easier to carry out than typically expected (e.g., operators are provided useful labels; the computer interface is adequate and learnable, although not easy to use).
Ergonomics/ HMI	Good	**0,5**	the design of the plant positively impacts task performance, providing needed information and the ability to carry out tasks in such a way that lessens the opportunities for error (e.g., easy to see, use, and understand computer interfaces; instrumentation is readable from workstation location, with measurements provided in the appropriate units of measure).
Fitness for Duty	Unfit	***P(failure) = 1.0***	the individual is unable to carry out the required tasks, due to illness or other physical or mental incapacitation (e.g., having an incapacitating stroke).

Table A.1 continued from previous page

SPAR-H PSFs	**SPAR-H PSF Levels**	**SPAR-H Multipliers**	**Explanation of the levels**
Fitness for Duty	Degraded Fitness	**5**	fitness—the individual is able to carry out the tasks, although performance is negatively affected. Mental and physical performance can be affected if an individual is ill, such as having a fever. Individuals can also exhibit degraded performance if they are inappropriately overconfident in their abilities to perform. Other examples of degraded fitness include experiencing fatigue from long duty hours; taking cold medicine that leaves the individual drowsy and nonalert; or being distracted by personal bad news (such as news of a terminal illness diagnosis of a loved one).
Fitness for Duty	Nominal	**1**	the individual is able to carry out tasks; no known performance degradation is observed
Work Processes	Poor	**2**	performance is negatively affected by the work processes at the plant (e.g., shift turnover does not include adequate communication about ongoing maintenance activities; poor command and control by supervisor(s); performance expectations are not made clear).

Table A.1 continued from previous page

SPAR-H PSFs	**SPAR-H PSF Levels**	**SPAR-H Multipliers**	**Explanation of the levels**
Work Processes	Nominal	**1**	performance is not significantly affected by work processes at the plant, or work processes do not appear to play an important role (e.g., crew performance is adequate; information is available, but not necessarily proactively communicated).
Work Processes	Good	**0,8**	Good—work processes employed at the plant enhance performance and lead to a more successful outcome than would be the case if work processes were not well implemented and supportive (e.g., good communication; well understood and supportive policies; cohesive crew).

APPENDIX

B

AUTONOMOUS SYSTEM TRANSITIONS

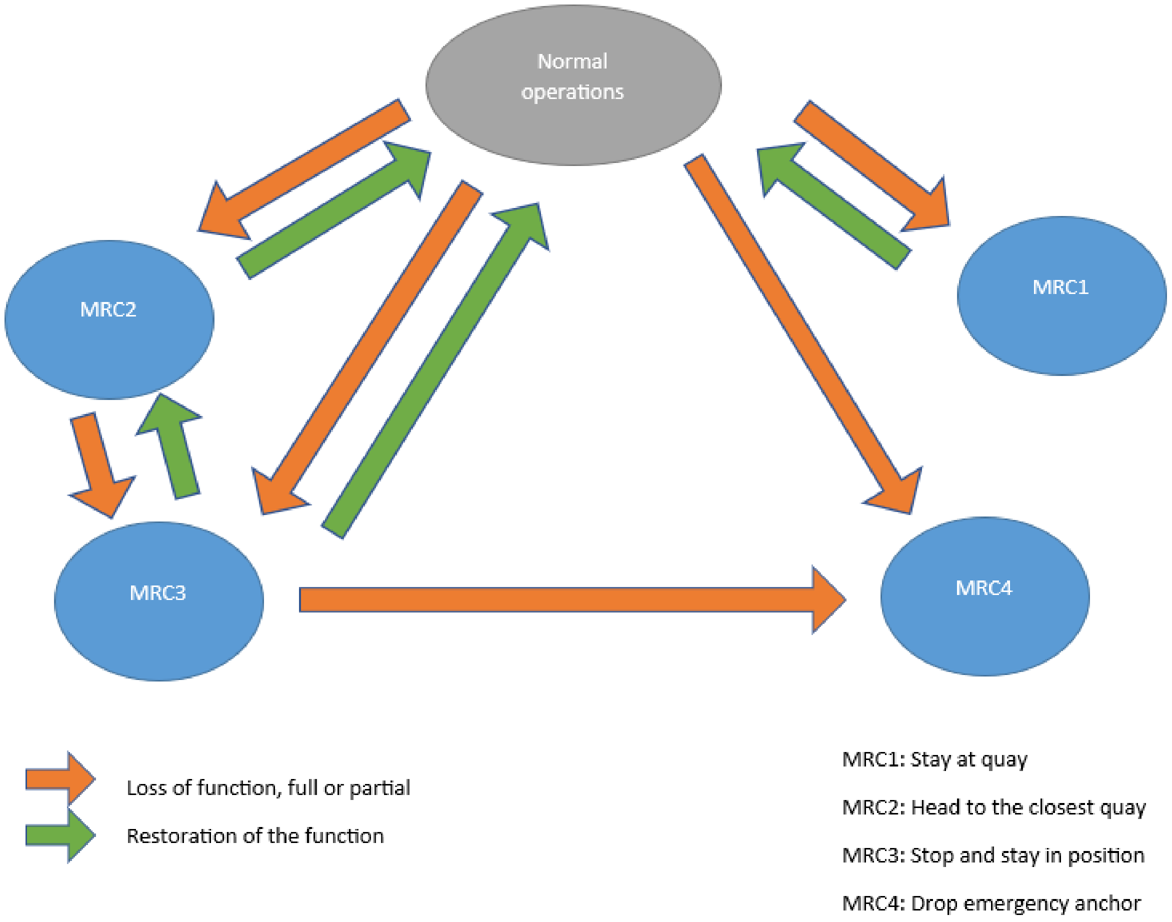
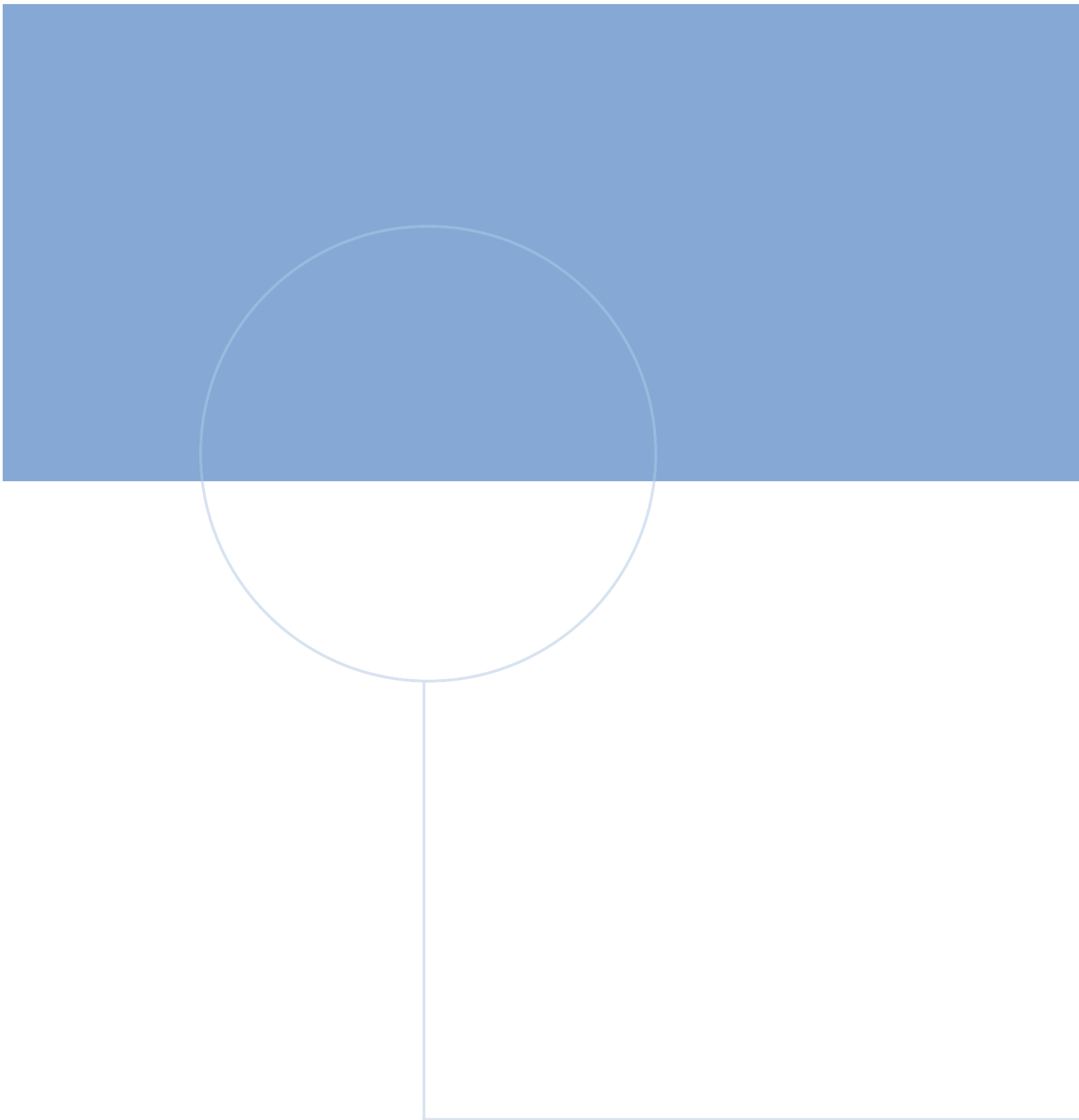


Figure B.1: Transitions of the autonomous system between the different states



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