Master’s Thesis

Intelligent Systems, 300 credits

An analysis of how a Digital Twin could be used throughout a process life cycle

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ABSTRACT

Within Industry 4.0, the concept of digital twins gains significant attention globally as organizations explore their potential in various industries worldwide. International research and development efforts focus on leveraging digital twins to monitor and optimize processes and products’ behavior and performance. When applied to automation systems, digital twins primarily support virtual commissioning, enabling the testing of virtual environments before actual processes become operational. However, a research gap exists concerning the utilization of digital twins in maintenance operations post-commissioning. This thesis aims to fill this gap and contribute to the knowledge of how the Real Digital Twin (RDT) can be used to maintain the automation process at Ringhals nuclear power plant. The research methodology involves interviewing maintenance workers to gain insight into their Way-of-Working (WoW) and identify key challenges and requirements. Based on these interviews, various maintenance cases are constructed and subjected to Failure Mode and Effects Analysis (FMEA), a proven method for identifying and evaluating potential failures. The cases are then compared between using and not using RDT to assess its impact on maintenance operations. Emulation is also employed to practically demonstrate the implementation of RDT. The findings highlight the significant benefits of RDT in maintenance operations at Ringhals. RDT enables swift and efficient testing of different operating strategies, leading to the identification of energy-efficient solutions and a reduction in downtime. The comparison of FMEA results demonstrates that RDT enhances the ability to proactively identify and address potential failures, reducing the likelihood of disruptions and ensuring safe and efficient operations. Overall, this thesis showcases the potential of RDT in maintenance operations beyond virtual commissioning, filling the research gap. Integrating RDT into the maintenance workers’ Way-of-Working revolutionizes maintenance practices, enhancing efficiency, minimizing downtime, and improving overall operational performance. These findings contribute to the evolving field of Industry 4.0 and digital twin technologies, offering valuable insights for organizations seeking to optimize their maintenance processes and leverage the full potential of digital twins.
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ABBREVIATIONS

AI  Artificial intelligence
ASIL  Automotive Safety Integrity Level
DFMEA  Design Failure Mode and Effects Analysis
DT  Digital Twin
FAT  Factory Acceptance Test
FMEA  Failure Mode and Effects Analysis
HiL  Hardware-in-the-Loop
HMI  Human-Machine-Interface
i4.0  Industry 4.0
IoT  Internet of Things
MiL  Model-in-the-Loop
PFMEA  Process Failure Mode and Effects Analysis
PLC  Programmable Logic Controller
RDT  Real Digital Twin
RPN  Risk Priority Number
SAT  Site Acceptance Test
SiL  Software-in-the-Loop
VC  Virtual Commissioning
WoW  Way of Working
INTRODUCTION

1.1 BACKGROUND

Automation processes have been used in industries for decades to improve efficiency, increase productivity, and reduce costs. The earliest forms of automation were simple mechanical systems that were used to automate repetitive tasks, such as assembly line production. Over time, automation has become increasingly sophisticated, incorporating computers, sensors, and other advanced technologies like specialized robots.

The use of automation processes in the industry can be traced back to the 1950s and 60s when the first programmable controllers were introduced [1]. These controllers, also known as Programmable Logic Controllers (PLC), allowed manufacturers to automate complex processes, such as those involved in producing automobiles and consumer goods. In the decades that followed, the use of automation in the industry continued to evolve and expand, driven by advances in computer technology and sensors. Today, automation processes are integrated into all manufacturing aspects, from the assembly line to the supply chain.

Automation offers several advantages, including enhanced productivity and cost reduction. By leveraging automated systems, tasks can be executed with greater speed and precision than human workers, resulting in increased output and reduced expenses. Additionally, automation plays a crucial role in mitigating human error, a prevalent factor contributing to defects and quality issues in manufacturing. Another benefit of automation is improved consistency and reliability [2]. Finally, automation can help improve workplace safety by performing dangerous tasks that would be too risky for human workers, reducing the risk of injury and improving overall safety.

Despite the many benefits of automation, implementing automation systems in the industry is often complex and challenging. There is a need for significant investments in technology and infrastructure and specialized expertise to design, implement, and maintain automated systems. Traditional commissioning and verification of the PLC code of an automated production system occur before the final set-up by manually debugging and executing online trials on the actual system and associated equipment. The documentation of the engineering areas is typically conducted independently, and engineers
from the different disciplines work sequentially to develop and verify the system. One example is that the control and instrumentation engineer programming the PLC cannot finish the code before the electromechanical engineer tasks and functions of the corresponding machinery in the plant are complete and deployable. The traditional commissioning approach, where PLC controllers are directly connected to real-world machinery or hardware, can lead to design and programming conflicts, lengthy commissioning and ramp-up times, and additional implementation and modification costs [3]. Virtual Commissioning (VC) methods such as Hardware and Software-in-the-Loop (described in Section 4.2.3) have increased in recent years to escape these traditional commissioning problems.

1.1.1 AFRY

AFRY is a global engineering and design consultancy company. It provides engineering, design, and project management services to various industries, including energy, industry, transportation, and infrastructure [4]. AFRY has been a consulting company for Ringhals Nuclear Power Plant for many years, with tasks in areas such as automation, electrical design, maintenance, and planning, among others. It is one of the largest nuclear power plants in the Nordic region, with two reactors currently operating. Large parts of the facility are controlled by automation systems that constantly require updates, modernization, and maintenance. This must be done safely since serious errors can devastate safety and critical infrastructure.

1.1.2 RDT

The Real Digital Twin (RDT) is a new product from AFRY that can automatically provide an exact copy of a production environment with everything it entails. It becomes a virtual testbed allowing the industry to build, test, and verify production equipment before it is physically available. Programmers can test their code against the virtual environment, enabling early detection of potential errors. This led to shorter commissioning and ramp-up times, saving the industry a lot of money. RDT will be further explain in Section 4.3.

1.2 PROBLEM AND RESEARCH QUESTIONS

Today, RDT is used from start-up to commissioning to find potential errors at an early stage. Once the automation process is in operation, maintenance is now required, which is often complex and challenging because the entire
1.3 Approach

Interviews are conducted to gain insight into the maintenance workers’ Way-of-Working (WoW) and assess various cases that reflect their work. These interviews provide valuable information about their current practices and challenges, forming the basis for further analysis.

A Failure Mode and Effects Analysis (FMEA) is a well-established method to identify, prevent, and evaluate potential process or product failures [5]. Three numerical parameters, Severity, Occurrence, and Detectability, are used in the FMEA methodology. With the use of RDT, it is possible to modify the detectability parameter and, to some extent, the occurrence parameter. FMEA is performed on each case to compare the detectability between using and not using RDT, providing valuable insights into the impact of RDT on failure prevention.

Furthermore, all constructed cases are emulated to demonstrate the practical application of RDT and showcase its potential. Emulation allows for replicating real-world scenarios within a virtual environment, providing a platform to simulate and analyze the performance and outcomes of different operating strategies. Through the emulation process, the capabilities and possibilities of RDT are effectively shown, highlighting its value in enhancing maintenance practices and optimizing operational efficiency.

Combining insights from the WoW interviews, FMEA analysis, and emulation demonstrations, this study aims to provide a comprehensive understanding of the benefits and potential applications of RDT in maintenance operations and throughout an automation process life cycle. The methodology will be described in more detail in Section 3.
1.4 **THESIS BOUNDARIES**

A digital twin is a broad concept used in many fields, and this thesis will be written from RDTs perspective. The work will not go into RDT’s technical specifications but instead into what it does and its function. FMEA consists of 3 parameters, and this thesis will mainly investigate how RDT can change the detectability parameter. The heaviest part of the work will primarily deal with the first three research questions, and the fourth, which deals with AI, will come secondarily and depending on time.

1.5 **OUTCOME**

The expected outcome is a thesis where the results show how the RDT could be used at Ringhals throughout a process life cycle and what this entails regarding, among other things, WoW, time consumption, and reducing risks.
This chapter critically evaluates and analyzes existing research studies, books, and other relevant sources related to the research topic.

2.1 INDUSTRY 4.0

The Fourth Industrial Revolution, also known as Industry 4.0 (i4.0), is a new stage that concentrates on cutting-edge technologies like AI and the Internet of Things (IoT) to enhance the efficiency of manufacturing processes [6]. Models such as Digital Twins lead to greater physical, digital, and biological integration, resulting in new capabilities and advancements in manufacturing processes and industries. Figure 1 below shows a brief description of all four industrial revolutions.

Figure 1: Brief description of every industrial revolution.

The i4.0 technologies are designed to increase efficiency, reduce costs, and improve product and service quality by enabling data integration and analysis from multiple sources, such as sensors and machine learning algorithms. i4.0 also aims to create more flexible and adaptable manufacturing systems that respond to real-time customer demands and market conditions. Some of the key features of i4.0 include the use of IoT technologies to connect and collect data from a wide range of devices and systems, using AI and machine learning to analyze and process data, combining physical and digital methods to create a manufacturing process that is more seamless and effective, using advanced robotics and automation to perform tasks more efficiently
and accurately, and the integration of cyber-physical systems, which allow the physical and digital worlds to interact in real-time [7].

2.2 DIGITAL TWIN

Digital twins (DT) have become increasingly popular lately for monitoring the behavior and performance of a process or product [8] [9]. Due to the significant differences between the applications, there is no common definition of a DT. Still, it can be defined as a replica of a physical system for industrial production [10]. Examples of Digital Twin applications are aircraft and automobile manufacturing [11], logistics and supply chain management [12], gas and wind turbine service optimization [13] and environmental monitoring [14].

The concept of the DT comes from NASA, where the challenge was to maintain, repair, and operate systems in space without having physical access to them. The solution was a simulator allowing engineers to better assist and guide the astronauts in space [15]. DT is now ubiquitous at NASA because it provides a virtual environment where equipment can be tested and built before being implemented in the real world.

The potential benefits of DT applications are, among other things, improved efficiency, better process/product quality, shorter commissioning, and reduced ramp-up times. DT can be applied early in a project, from initial factory planning and design to commissioning and maintenance [16]. The list of DT applications is constantly growing, and there is a very active area of research and innovation.

Despite the opportunities, research shows that DTs are far from realizing their potential since it’s a complex and long-drawn process [17][8]. In a digital twin that collects data in real time, all the objects in a system must be modeled, and an immense amount of data must be collected and merged. This is usually done with IoT sensors, and many are needed for the digital twin to work. Therefore, a DT could be used as a virtual environment testbed, which is cheaper and still effective without collecting real-time data such as the RDT.

2.2.1 Creating a DT

Creating a DT can be both difficult and time-consuming. Many parameters must be considered for the virtual representation to be as good as possible. The DT can be built in several ways but typically involves several steps [18]:

1. Literature review
2. Digital twin
3. Creating a DT
4. Benefits of DT applications
5. Challenges and opportunities for DT applications
6. Case studies of DT applications
7. Conclusion
• **Data collection:** The first step of creating a DT is to collect data from a physical system that will be replicated. Data could come from, e.g., pumps, sensors, machines, and valves.

• **Model the system:** Once all data is collected, the next step is creating a virtual system model that involves building digital representations of the system’s physical components, behavior, and interactions.

• **Integrate data:** To ensure that the virtual model accurately reflects the system, the collected data must be integrated.

• **Monitor and update:** Once the DT is created, it must be continuously monitored and updated with real-time data to ensure it accurately represents the physical system.

• **Analyze and optimize:** The digital twin can simulate different scenarios and analyze the system’s behavior under different conditions. This can be used to optimize the system’s performance, identify potential problems, and develop new solutions.

### 2.3 Virtual Commissioning

The design and implementation of a new automation solution is often a time-consuming and costly process. When the procedure is finalized and the equipment installed, there’s the last phase before handing over the production to the client - commissioning. This phase is where PLCs are integrated and tested, errors are found and fixed, and operators are trained with the new system. VC is one method that has become increasingly popular lately to overcome the challenges presented in Section 1.1. VC is a testing process that uses a virtual plant model and a virtual control system for simulation or emulation, which will be described in Section 4.2.1. The process allows the developer to map and reproduce a real-world automated system and its behavior in a virtual world for visualizing, commissioning, testing, and verifying the PLC code of the system [19]. Research shows that using VC has the potential to save up to 75% of the time required compared to traditional commissioning, and this automatically leads to cheaper commissioning [20].

In 2020, an article was written about creating a digital twin of a manufacturing process using a virtual reality interface for simulation and analysis [21]. The authors highlight the innovation of a virtual testbed, which allows for testing different scenarios before physical implementation. Furthermore, the article states that a testbed like this combines various elements such as design, virtual and real commissioning, and monitoring of multi-robot cells in a single application, resulting in a cost-effective and affordable solution for manufacturing industries of all types. It is mentioned that manufacturers
can use digital twins for maintenance, giving value throughout the production lifecycle, but no specific areas of use are presented.

EPRI (Electrical Power Research Institution) is a non-profit organization that conducts research and development related to the production, delivery, and use of electricity to help address challenges in the energy industry. In 2022, EPRI released a report investigating how DT technologies can help reduce costs while focusing specifically on applications pertinent to the next generation of advanced reactors at nuclear power plants [22]. More specifically, the report complements ongoing industry efforts to research DT applications and presents insights and guidelines to support stakeholders in understanding and adopting DT technology. The report concluded that costs must be significantly reduced to ensure future nuclear power plants’ successful construction and operation. Various industries have identified DT technology as an important opportunity to reduce such costs.

### 2.4 Simulation & Emulation

In 2014, a Hardware-in-the-loop simulation method was used to design, verify, and test the automation system on a gas carrier [23]. Since a gas carrier cargo handling system is installed on a seagoing vessel, troubleshooting, and maintenance are difficult to handle. The automation system was extensively tested and evaluated in the HIL simulation, and as a result, several logic faults and control algorithm-specific implementation errors were eliminated. The paper describes that the simulation testbed was originally used for virtual commissioning, but future work could be to use the simulation for activities such as maintenance and troubleshooting. The HIL method is based on real components interacting with simulated components, and this is an integrated component in the development process of electronic control units. RDT uses software-in-the-loop instead of hardware-in-the-loop because then you can simulate the behavior of the hardware without the physical hardware. This can save time and resources and protect the physical hardware from damage during testing.

Another article discusses Cyber-Physical Systems [24], which are widely used in automation processes. They connect physical processes and systems with digital technologies and control systems, creating a more integrated and efficient system. The author means that the challenge with CPS lies in the absence of comprehensive testing of its various components and aspects as a unified system. A solution to this problem could be the adoption of virtual testbeds, which offer the chance for integrated testing, validation, and verification in a realistic and controlled industrial environment. Leveraging
such testbeds makes it possible to experiment with emerging technologies before their actual deployment in the industry. Both articles above describe that a virtual testbed contributes to easier maintenance and troubleshooting but also for testing, validation, and verification.

In [25], the author highlights the importance of operator training in a virtual environment. People can gain knowledge in automation and IT systems using simulated software to work with digital models, manipulate and analyze data, or design interfaces. It also describes that a virtual environment could help modernize the learning process and bring it closer to the industrial world, reducing the risk of serious errors.

ASIL is a risk classification used in ISO 26262 [26], the standard for the functional safety of road vehicles. It assigns a level of safety risk to a specific function based on the severity of the potential harm that could result from a failure of that function, the likelihood of that failure occurring, and the controllability of the failure. This risk classification could be compared to FMEA, the method used in this thesis. Even though risk classification is not new, ASIL was first introduced in 2011, when the first edition of ISO 26262 was published. ASIL is typically divided into four classes, ASIL A, B, C, and D, where D has the highest safety requirements and A the lowest.

Like FMEA (described in detail in Chapter 3), ASIL uses a combination of 3 parameters to determine the risk, Severity, Exposure, and Controllability. Severity refers to the extent of the consequences resulting from a component failure, Exposure relates to the likelihood of the failure occurring, and Controllability evaluates the driver’s ability to manage the hazard scenario. The ASIL risk is then calculated by the following formula [27]:

\[
\text{Risk} = \text{Severity} \times \text{Exposure} \times \text{Controllability}
\]

The numerical value of the risk can then evaluate the risk of potential failures, similar to the Risk Priority Number (RPN) in an FMEA. Both methods aim to reduce the likelihood of potential failures and increase the safety and reliability of components and systems.

Article [28] describes how software or hardware-in-the-loop in Simulink can be used for ASIL classification, similar to this thesis using Simit for FMEA classification. Simit and Simulink are software tools for simulation and modeling in different fields. Simulink is mainly used in control engineering, especially for designing and testing dynamic electrical, mechanical, and hydraulic systems. On the other hand, Simit is a simulation software tool mainly used in process automation, specifically for simulating and testing
automation systems in industrial plants. It provides a realistic virtual environment that can be used for testing and validating automation processes.
In this chapter, the methods employed to address the research questions are presented in detail. The methodology involves interviewing maintenance personnel at Ringhals to gain insights into their daily work processes. Based on these interviews, different maintenance scenarios are developed. The Failure Mode and Effects Analysis (FMEA) is applied to each case to analyze changes in detectability. Subsequently, the Risk Priority Number (RPN) is calculated compared between using and not using the RDT. Additionally, all cases are emulated in the testbed provided by RDT to explore its capabilities and comprehensively understand its potential. Figure 2 shows a flowchart of the methodology used in this thesis.
3.1 Interviews

Interviews are suitable for collecting information about people’s experiences, thoughts, opinions, and feelings. They can be conducted in different formats, typically involving an in-person meeting between an interviewer and an interviewee [29].

The two main research methods are qualitative and quantitative interviews [30]: Quantitative interviews are structured, aiming to measure and quantify specific information, while qualitative interviews focus on understanding individuals’ thoughts and behaviors. Qualitative interviews can be semi-structured or unstructured, allowing for flexibility in the questioning approach.

This thesis uses a qualitative research interview method to gather rich and detailed information about the steps involved when implementing an automation system. Qualitative research is often associated with understanding human experiences and attitudes, but it can also be used to investigate how a process or system works [31]. The research is performed through semi-structured interviews, a hybrid of structured and unstructured interviews. It consists of asking predetermined questions and allowing follow-up questions and further exploration based on the participant’s responses [32].

The interviews aim to understand what the Way-of-Working (WoW) look like regarding the maintenance of processes at Ringhals. By asking questions about how their work looks today, this can then be summarized and taken for further analysis. The further analysis is the FMEA and emulation, where you can compare the maintenance work with or without the RDT.

Designing and preparing practical interview questions is crucial for obtaining relevant information on the research topic. The aim is to understand the maintenance of automation processes and analyze how RDT can improve efficiency. The initial set of questions for the pilot interview includes:

- What is your role, and how long have you worked at Ringhals with maintenance?
- What are your main tasks?
- What does your WoW methods look like?
- Can you give an example of typical maintenance work for an automation process?
- Do you have any examples of how your work could be simplified using the RDT?
There are risks involved when writing a report partly based on a few interviews such as selection bias, response bias, interviewer bias, and small sample size [33] [34]. For instance, the sample of participants may not accurately represent the population of interest. The participants may provide inaccurate or biased responses due to various factors, including how the questions are asked or the interviewer’s behavior. Moreover, small sample size may limit the ability to detect significant patterns or relationships in the data, compromising the reliability and validity of the findings.

To minimize these potential errors, it is crucial to take several measures, such as selecting participants carefully to ensure diversity and relevance, using open-ended questions that allow for spontaneous and detailed responses, avoiding biased or leading questions that may influence the participants’ answers [33].

Making a report based on three interviews is still possible, but it may not be as comprehensive as a report based on a larger sample size. However, three interviews can provide insights into the research topic and help identify common themes and issues [34]. Still, since only three people mainly work with maintenance in this department, it is considered sufficient to interview them to represent the whole department. As described above, the report aims to investigate how RDT can be used at Ringhals. Hence, it is only essential to their working methods, which likely work similarly at other workplaces.

The interview invitations were sent via mail to the potential participants, which included a short presentation of myself and the aim of the interview. The participants had to choose a time slot themselves because I could be more flexible. The interviews were selected to be done digitally for simplicity and flexibility for both the interviewer and interviewee. After summarizing the interviews, the interviewees got to look at it to clarify any matters, add afterthoughts, or correct misrepresentations. A flowchart of how the interviews should process is shown in Figure 3:
Based on the interviews, cases are developed that reflect real-life scenarios that maintenance works within their daily work. These aim to demonstrate how RDT can be used in their work, and by creating real-life scenarios, one can understand how RDT can be explicitly used at Ringhals. Detailed information about events and the approach taken to solve the problem is required from the interviews to make the cases as realistic as possible. Detailed descriptions provide the opportunity to compare how RDT can streamline maintenance procedures more clearly. A difference between the cases is necessary to get a bigger perspective on where RDT is applicable, which is vital.
3.3 Failure mode and effects analysis

FMEA is a method developed to identify, prevent and evaluate process or product failures. FMEA aims to identify and prioritize potential failures, assess their impact on the system, and identify actions to prevent their effects. The method was developed in the 1950s to examine potential issues that could arise due to failures of military systems. Today it is used in many areas, such as aviation [35], pharmaceutical [36], and automotive industries [37] [38].

A design FMEA (DFMEA) is often used when analyzing a product, and a process FMEA (PFMEA) is used for processes [39]. DFMEA focuses on potential failure modes associated with the functions of the product before they are released to production. In contrast, PFMEA focuses on the possible failure modes related to process effectiveness, safety, efficiency, and problems with equipment. This thesis use PFMEA since the maintenance of a process is analyzed. To perform the analysis, a team ranks the failure mode’s Severity, Probability, and Detectability. A failure mode is a potential way a particular operation may fail to meet the intended function and related requirements. A typical team for PFMEA often consists of 4-8 persons, including representatives from manufacturing engineering, testing, product engineering, and maintenance. The FMEA team in this thesis consists of five individuals from AFRY in Gothenburg, including the author. The team has extensive experience in FMEA, RDT, and automation processes, and they work with these areas on a daily basis.

Severity (S) is the ranking number associated with the most severe effect for a given failure mode based on the severity scale [39]. It is ranked with a number between 1-10 on how high the degree of severity is, where the worst is ten and the most minor 1, shown in Figure 4.
Occurrence (O) is the ranking number associated with the likelihood that the failure mode and its causes is present in the analyzed process [39]. This ranking ranges from 1 to 10, where ten is that it will happen, shown in Figure 5. The ranking has a relative meaning rather than an absolute value and is determined according to the occurrence scale’s criteria.
Detection (D) is the ranking number associated with how likely the failure mode will be detected [39]. It is ranked from 1-10, where ten is unlikely to be noticed, and 1 is the error guaranteed to be seen, shown in Figure 6. For instance, the detection parameter can be used to compare the effectiveness of different troubleshooting techniques.

<table>
<thead>
<tr>
<th>Detection</th>
<th>Likelihood of Detection</th>
<th>Ranking</th>
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<tbody>
<tr>
<td>Absolute Uncertainty</td>
<td>Cannot detect potential cause/mechanism and subsequent failure mode</td>
<td>10</td>
</tr>
<tr>
<td>Very Remote</td>
<td>Very remote chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>9</td>
</tr>
<tr>
<td>Remote</td>
<td>Remote chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>8</td>
</tr>
<tr>
<td>Very Low</td>
<td>Very low chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>7</td>
</tr>
<tr>
<td>Low</td>
<td>Low chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>6</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderate chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>5</td>
</tr>
<tr>
<td>Moderately High</td>
<td>Moderately High chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>4</td>
</tr>
<tr>
<td>High</td>
<td>High chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>3</td>
</tr>
<tr>
<td>Very High</td>
<td>Very High chance the potential cause/mechanism and subsequent failure mode will be detected</td>
<td>2</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>The potential cause/mechanism and subsequent failure mode will be detected</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 6: Table of Detection ranking

When the three parameters above are ranked, the RPN can be calculated. Traditionally, the RPN is a numerical value that indicates the potential risk of each failure mode to the process. It is calculated by multiplying the ranking values of the three parameters: Severity, Occurrence, and Detectability.

\[ \text{RPN} = S \times O \times D \] (2)

Once all failure modes have been analyzed and ranked based on the RPN value, the goal is to reduce each failure mode’s Severity, Occurrence, and/or Detectability ranking, ideally resulting in a decreased RPN value. The RPN values before and after implementing the corrective action, which in this thesis involves RDT, are compared. It should be noted that the severity and occurrence of the failure mode often remain the same, regardless of whether RDT is utilized. The main parameter affected by the implementation is detectability. Since the RPN is calculated based on three parameters, only detectability determines if there is a numerical value change, making it the primary investigation parameter.

By considering the impact of detectability on the RPN, this study aims to assess the effectiveness of using RDT as a corrective action measure. The focus
is on understanding how the integration of RDT influences the detectability parameter, leading to potential improvements.

3.3.1 FMEA Example

To show the purpose and usage of FMEA, an actual project using the RDT at a large pharmaceutical company in Europe is presented. The project aims to implement a new automation system in an existing facility and conduct an FMEA to compare the difference between using the RDT before commissioning or not using it.

One part of the project was to implement a new motor in the process, but the RDT detected at an early stage that the wrong type of motor in 800xA was programmed for the hardware to be used, presented in Figure 7. A potential effect for this failure mode is a time delay during Factory Acceptance Test or FAT (described in Section 4.1), a type of testing conducted to ensure that a new product or system meets the specified requirements and is functioning correctly. The FAT can include various tests such as functionality, performance, electrical safety, environmental, and durability tests. Once the equipment passes the FAT, it is ready for installation and operation at the customer’s site.

The severity for this failure mode is set to 5, meaning the system works without damage, but the engine does not start, causing problems. The probability is 10, indicating that the error is almost inevitable. The system shows an alarm, but the fault itself may be challenging to find.

The following two columns in Figure 7 are the detectability with and without the RDT. The first column is FAT’s detectability, set as 4, which is moderately high to be detected. RDT detectability is set to 1, meaning the error is guaranteed to be detected. This is because when RDT provides the virtual environment, permitted device types and hardware must be selected, and if the programming does not support these choices, an error will occur. In
this case, the programmed motor had the wrong device type for the chosen hardware, resulting in an error.

The RPN is 200 for FAT and 50 for RDT, indicating that RDT will detect the error faster than traditional FAT. As depicted in Figure 7, only the detectability changes while the other two parameters remain constant. This thesis will also perform an FMEA, with a specific focus on the detectability parameter since it is the parameter that varies depending on the usage of RDT.

3.4 Emulation

Emulation is the process of creating a virtual or simulated environment that behaves in the same way as a different, usually physical, system. Emulation is further explained in Section 4.2.1.

RDT provides an emulated test bed, and to understand how it can be used, all cases are emulated based on the interviews. Emulating the different cases demonstrates how RDT improves maintenance work in terms of time and energy efficiency, cost-effectiveness, and safety. Each case describes a scenario that maintenance workers may encounter in their everyday work, and the emulation shows how RDT serves as a tool in their standard approach. The virtual environment offers several advantages, including the ability to avoid constant testing in the physically operational plant.

Several types of emulations can be performed, depending on the specific case. This thesis focus on system-level emulations, which involve creating a high-level, comprehensive model of an entire system and running it on software to test and validate its behavior. The virtual environment used to emulate the cases is a copy of the waste facility at Ringhals, which is undergoing modernization by AFRY. The virtual environment is provided by RDT and used during modernization to test the new code and conduct virtual commissioning to detect potential errors.
This chapter provides an in-depth review and analysis of theoretical frameworks related to the research topic.

4.1 TRADITIONAL COMMISSIONING

Commissioning is usually the last step in the engineering process, where the automation system is designed, installed, tested, and operated according to the requirements and specifications. The tests are traditionally made with physical hardware during the Factory and Site Acceptance Test.

Factory Acceptance Test (FAT) is a testing process that verifies the functionality and compliance of a system or component before it is installed at a customer site. The FAT is typically conducted at the manufacturer’s facility and is attended by representatives from the customer to ensure that the product meets their specifications and requirements [40]. The testing process carefully examines the equipment’s functionality, performance, and documentation. FAT aims to identify and resolve any issues with the product before installation, thus reducing the likelihood of problems during commissioning and subsequent operation.

Site Acceptance Testing (SAT) is a process performed at a customer’s location to verify that a system or component has been installed and configured correctly and is functioning according to the customer’s requirements [40]. The SAT is usually performed after the FAT and involves testing the system in its actual operating environment. During the SAT, the system is checked for proper installation, wiring and connections, commissioning and configuration, and performance. The goal is to ensure that the system is ready for operational use and to identify any issues that may need to be addressed before the system goes live.

The main drawback of traditional commissioning is that the start-up time can take up to 25% of the total project duration, resulting in setbacks such as high unexpected expenses, damage, and a bad reputation [41]. Another drawback is delayed machinery downtime, which is crucial for the manufacturer’s competitiveness in the market. VC is a method that addresses these issues by allowing for virtual testing of the system before physical hardware
is available. This can lead to a reduction in setbacks and overall project duration.

4.2 VIRTUAL COMMISSIONING

Virtual commissioning is an essential concept for understanding how RDT is currently used. VC simulates or emulates a system’s functionality or process using computer-based models and simulations before the physical system or process is built or installed. In the automation world, VC aims to assist in solving problems that evolve when manufacturing systems are integrated with the PLC. This allows engineers and designers to identify and fix potential issues in the virtual environment before they occur in the real world, saving time and resources [42]. One example is performing a virtual FAT to ensure the system meets the design specifications before installation. Other benefits are the capability for parallel engineering development, testing, and debugging in the same virtual environment earlier in the design phase. VC can be used when commissioning a new or modernizing an existing system. A comparison of traditional vs. virtual commissioning is shown in Figure 8, where the result is that VC contributes to saved time for optimization or earlier delivery. It is under VC that RDT is used in today’s situation, and this thesis investigates how RDT can be used after delivery for, among other things, maintenance of the automation process.

![Figure 8: Comparison of traditional vs. virtual commissioning](image)

4.2.1 Simulation vs. Emulation

The level of accuracy required for a model to be valuable depends on the project it’s being used for and can change from model to model. The precision must be sufficient enough to produce meaningful results. For example, consider a bottling line that includes conveyor sections, filling machines, labelers, and packaging machines. To ensure the model’s accuracy, we need to
account for labeler breakdowns and its average cycle time, while the specifics of the labeler mechanism may not require too much attention. Suppose we incorporate the bottling line within a broader supply chain model, which includes warehouses, truck movements, and the production facility. In that case, we could model the entire line as a resource that produces products at an average rate [43].

Simulation and emulation are two approaches that both aim to mimic a real-world process or system. A simulator is "a device that enables the operator to reproduce or represent phenomena likely to occur in actual performance under test conditions [44]." At the same time, an emulator is "hardware or software that permits programs written for one computer to be run on another computer [45]."

Simulation models are used to replicate software and explore and improve alternatives to find the best solution based on established criteria [43]. They offer an impartial assessment of new ideas and prior experiences, providing a cost-effective and adaptable environment to demonstrate functionality and outcomes. Simulation results help define a system’s physical structure, operational limitations, and control system. Simulation models are often used for extensive experimentation to find reliable and optimal solutions in automation systems.

In contrast, emulation models can imitate hardware and software to substitute an actual device [43]. They are designed for more specific purposes, such as examining the control system’s performance under different system load conditions, serving as a test bench for various projects, and training system operators and maintenance personnel in a risk-free environment. An emulation model is more closely modeled after the system to be implemented, allowing it to perform a limited set of verification procedures to assess the control system’s performance or response.

In summary, a simulator is a quick and relatively straightforward method of creating a virtual environment for testing applications without replicating the hardware. In comparison, an emulator goes to the next level by replicating both software and hardware.

4.2.2 PLC

PLC stands for Programmable Logic Controller, an industrial control system used to control and automate machinery and processes in manufacturing plants, assembly lines, and other industrial settings. It is a digital computer
programmed to perform specific tasks, such as controlling motors, valves, and other equipment, based on inputs from sensors and other devices [46]. PLCs are designed to be rugged and reliable, and they are often used in harsh industrial environments where traditional computers cannot operate. They are a key component of modern automation systems and have revolutionized many industries operations.

4.2.3 System-level Emulation Methods

System-level emulation usually comprises three main stages [47] [48], shown in Figure 9:

- Model-in-the-Loop (MiL)
- Software-in-the-Loop (SiL)
- Hardware-in-the-loop (HiL)

The initial phase of virtual commissioning is MiL, which involves the creation of a block diagram model of the software logic for use by the PLC [48]. This model is then connected to a simulation model of the automation system, and these two models run simultaneously in real time. The block diagram model transmits commands to the automation system model, resulting in feedback into the logic model, completing the loop. If an error occurs, change the logic model and restart the simulation. The logic model can be tweaked until the wanted result occurs, and engineers can also change the model to explore new options and solutions. This method is a fast and easy digital verification method, which enables among other things, simulation and testing.

After the MiL stage, the next step is to verify that the code that will be implemented into the PLC is correct. The first step is to provide a compiled code from the logic model, and such code can be run on an emulator (Section 4.2.1) that mimics the electronic hardware in the PLC [48]. This is then connected to the automation system model, creating a closed loop called SiL. The aim at this stage is identical to the MiL simulation, which is to identify any errors in the compiled software. Although the logic model should now appear correct, translating it to software can reveal previously undetected issues. If the MiL simulation was successful, but the SiL failed, engineers can conclude that the failure was converting logic from the model to compiled software.

The final stage is HiL, which lets users verify that the compiled software runs correctly on the physical PLC [48]. The idea is to connect the physical
PLC to the automation system model, since the physical system might not be ready or unavailable. A failure at this point indicated an issue with the compiled software running on the physical PLC, which could be compared if failure occurred while running on the emulated PLC in the SiL stage.

To summarize, MiL is where the engineers can test and verify the control and behavior of the logic in the PLCs. SiL provides the compiled code, which is then run on a PLC emulator. HiL enables running the compiled code on the physical PLC to be used.
4.3 Real Digital Twin

RDT provides an emulated virtual testbed using SiL (Described in Section 4.2.3) that reduces costs, increases productivity, assures quality, and minimizes risks. The main benefits of using the RDT are that you can test the PLC code and find errors at an early stage. The outcome is reduced costs, better quality, and faster production time. Figure 10 shows how RDT is used today to emulate certain phases and thus be able to reduce costs and risks in other phases.

According to AFRY, the substantial impacts of using the RDT in automation projects are, up to 95% readiness before physical implementation, up to 80% reduction of commissioning and ramp-up time and up to 30% reduction of project development time.

Figure 10: RDT provides emulation of certain phases to reduce costs and risks in others.

A flowchart of how the RDT works in a process is shown in Figure 11. The typical process consists of PLC hardware, program code in the PLC, and HMI for the operators to control the objects in the facility. RDT provides an emulated virtual testbed that mimics all these four blocks where tests can be performed without disturbing the actual process.

The PLC code of the automation system can be written in any PLC program. Still, AFRY uses, for the most part, ABB 800xA, a control system produced by ABB Group, a leading global technology company. It is an integrated control system that provides an end-to-end solution for automation and control in various industrial applications [49]. All signals and components are programmed in ABB 800xA, but also the graphic design of the Human-Machine-Interface (HMI), where the operators control the automation process.
The virtual environment is provided in Siemens Simit, a simulation software platform for designing, configuring, testing, and maintaining automation and control systems [50]. The software supports various automation components and systems, including PLCs, drive systems, and HMIs. The users are given a realistic emulation environment that closely mimics real-world behavior by emulating signals, field devices like actuators and sensors, bus communications, and processes [51]. Testing and optimizing control systems becomes easier through this approach as it allows for the safe and efficient validation of relevant automation functions using the original automation programs prior to their on-site implementation.

Simit enables a straightforward integration between the simulation platform and the automation environment of ABB 800xA, used by the operators. This integration can be accomplished using hardware-in-the-loop (HiL) systems or by utilizing an integrated virtual controller without requiring any physical hardware, also known as software-in-the-loop (SiL) emulation. As mentioned, RDT employs a SiL emulation approach, utilizing a virtual controller. Figure 12 shows the HMI in ABB 800xA, including valves, tanks, and pumps. This is connected to the generated emulation, shown in Figure 13, which interacts with the actual plant giving correct feedback signals to the PLC program. The objects’ names have been removed due to security reasons.
Figure 12: The operators’ HMI in the abb8oxA where the process can be controlled and monitored. The objects’ names have been removed due to security reasons, in accordance with the wishes of Ringhals.

Figure 13: Virtual environment in Siemens Simit provided by RDT.
The simulations in Simit use the Flownet library, designed to facilitate the accurate simulation of thermodynamic processes in pipe networks. The primary focus of the Flownet library lies in simulating homogeneous media and single-material systems, particularly in scenarios like cold commissioning processes [52]. The library offers components that simulate the thermodynamic behavior of ideal gases, liquids, and vapor to accomplish this.

Within the Simit environment, a Flownet refers to a connected set of Flownet components specifically designed for simulating thermodynamic processes in pipe networks. These simulations are based on a particular solution method, parameterized and configured via the Flownet components. It is important to note that the modeling approach confines the Flownet to homogenous media. However, it applies to various substances, including liquids, ideal gases, and water in either liquid or steam.

Simulating piping networks involves mapping the connections of Simit components to Flownets, forming a graph comprising nodes and branches. The branches represent flow paths, while the nodes represent the intersections or joints of these flow paths [52]. The key variables considered at the nodes are pressure and specific enthalpy, while for the branches, the focus is on flow rates.

### 4.3.1.1 Limitations

One limitation of Simit is that it’s primarily designed for simulating PLC-based automation systems and may not be suitable for simulating more complex or heterogeneous systems that incorporate other control systems or components. Additionally, Simit may require some configuration and setup time, making it less suitable for small-scale or ad-hoc testing scenarios. Another limitation of Simit is that it might not fully replicate the behavior of a real-world automation system, particularly in cases where the simulation models do not capture all of the relevant system dynamics and interactions. This means that while SIMIT can provide valuable insights into system behavior and performance, it may not be able to identify all potential issues or problems that may arise in real-world operations.

### 4.3.1.2 Alternative Programs

Similar programs could have been used instead of SIMIT, e.g. Matlab, a well-known program widely used in engineering, science, and mathematical applications [28]. Matlab is a more general-purpose numerical programming software tool providing a wide range of tools and functions for data analysis, modeling, and simulation. The main difference between SIMIT and Matlab...
is their respective areas of specialization. Simit is designed explicitly for simulation automation systems, whereas Matlab is an available numerical computation and programming tool. Since Simit is expressly intended for automation systems and already has built-in functions, it is well-suited for this type of test bed. However, Matlab could have been added to the digital twin for more advanced analyses.

4.4 Bernoulli’s Equation

In Section 5.2.3 below, a simulation shows how pressure measurement can be used to automatically detect if a valve is open or closed. The theory behind this is Bernoulli’s equation, which describes the relationship between pressure, velocity, and elevation for a fluid’s frictionless and incompressible flow [53]. Bernoulli’s equation can be written as:

\[ P + 0.5 \cdot \rho \cdot v^2 + \rho \cdot g \cdot h = \text{constant} \]  

(3)

Where:
P is the pressure of the fluid
\( \rho \) is the density of the fluid
\( v \) is the velocity of the fluid
\( g \) is the acceleration due to gravity
\( h \) is the height of the fluid above a reference level

The equation can be understood as an expression of energy conservation along a fluid’s streamline; in this thesis, a streamline is a pipe in the process. The equation’s constant on the right side represents the total mechanical energy per unit mass [53].

Let’s consider a horizontal pipe with a valve in the middle and a pump on the inlet side pumping water to the outlet, see Figure 14. Assume that the pipe is frictionless and the liquid is incompressible. When the valve is open, the fluid flows smoothly through the pipe, and the pressure throughout the pipe is uniform. Let’s denote the pressure as \( P_2 \) and the velocity as \( v_1 \) when the valve is open.
When the valve is closed, the liquid flow is obstructed, causing the velocity of the fluid to decrease, see Figure 15. Let’s denote the pressure as $P_2$ and the velocity to $v_2$ when the valve is closed.

Bernoulli’s equation can be used to determine what happens on the upstream pressure side of the valve:

$$P_1 + 0.5 \rho v_1^2 + \rho g h = P_2 + 0.5 \rho v_2^2 + \rho g h \quad (4)$$

Since the pipe is horizontal and there is no change in elevation, the potential energy term cancels out on both sides ($\rho g h = 0$). The liquid density $\rho$ remains constant so that the equation can be simplified to:

$$P_2 - P_1 = 0.5 \rho v_1^2 - 0.5 \rho v_2^2 = (v_1^2 - v_2^2) \cdot 0.5 \rho \quad (5)$$

One can see that the pressure is related to the velocity change caused by the valve closure. If the velocity decreases, the pressure must increase to maintain energy balance.
RESULTS

5.1 INTERVIEWS

In this section, a summary of the three individuals interviewed is presented. To comply with Ringhals policy, the interviewees are not named to ensure safety. The interviewees have a combined experience of six, fourteen, and twenty-eight years working in the maintenance department of Ringhals, specifically in automation processes. They hold educational backgrounds in electrical engineering and mechatronics. Their job roles are qualified maintenance engineers.

The results of the interviews indicate that their primary task is to be responsible for the aftermarket of automation processes after commissioning. This can range from performing annual maintenance to dealing with sudden process failures.

The maintenance department is responsible for many different automation systems at Ringhals, which makes it difficult to be a specialist with each specific system. "It is impossible to know every single detail in the various systems, and therefore we use functional descriptions that describe how different parts of the process are controlled and how the software is programmed. "Once they know how the system operates, they can access and analyze the program code to identify the fault causing an error. "Sometimes we can explore the program code while the process is running, but usually, it has to be stopped because it is too risky to make changes while the process is running."

A typical scenario is that operators who control the process detect a bug or that something is wrong with the system. It could be that an automatic valve does not close or an engine does not start. This fault is then forwarded to the maintenance department, whose task is to investigate the source of the deviation because the operators do not have access to the program code.

Maintenance workers analyze different scenarios in the program code to see when a bug or fault arises. "One example is that the operators noticed that an automatic valve did not close during specific operating modes, so we had to go into the program code and see how the valve was related to other objects depending on which operating mode was used."

After the program
The code was analyzed, tests were done in the real plant. The conclusion was that the problem had nothing to do with the valve specifically, but it had a condition that said it couldn’t be closed if a specific pump was running.

This WoW leads to finding the cause of the fault, but it can take a very long time as the facility often needs to be in a particular operating mode. Objects might have different behaviors/conditions depending on the operating mode used, and sometimes a particular error only occurs in a specific operating mode. To investigate an alarm that occurs in a special operating mode, one must wait for it to be run, which can be very time-consuming.

A virtual testbed can be used for many things, such as troubleshooting and analyzing how the system operates and behaves in different situations and for training in a calm environment. For new operators, it is a tremendous opportunity to teach them how the plant works and is controlled, but also an excellent opportunity to stress test the operators and see how they react on different occasions. Serious errors at Ringhals can have devastating consequences; therefore, safety always comes first. Sometimes, unusual scenarios arise that only a few operators know how to handle, and if these scenarios can be created in a virtual environment, the relevant personnel can become more prepared through training.

"If parameter adjustments of an object are needed, we can comfortably sit in the virtual environment at our desk to analyze how the facility responds to the changes. What-if scenarios could be conducted, such as testing if a smaller pump that consumes less electricity can replace a bigger one, improving energy efficiency. Maintenance workers can train in the virtual environment instead of reading functional descriptions, and new operators can do operating instructions in the virtual environment before working with the physical system, leading to a shorter learning period. This is a prerequisite for running the plant in a good and safe way.

Regarding optimization and efficiency, testing against a virtual world before implementation in the physical facility would have made it easier and provided a sense of security. In today’s environment, improving and making the facility more efficient is difficult because testing must be done physically, which entails risks.

5.2 CASE 1 - MAINTENANCE

According to the interviews, maintenance gets error reports from the operators if an error occurs, so this case is created based on interviews and an actual error report that the maintenance workers have been given from the
operators. This error report concerns an operating instruction where the purpose is to move radioactive liquid through pipes from one tank to another. The two tanks can be seen in Figure 16, where the liquid will be transferred from T16 to T17.

![Flow Diagram](image)

**Figure 16:** Process overview with affected objects included in the operating instruction.

Although everything is done according to the instructions, the flow between the tanks is significantly lower than expected, which could be seen in the flow measurement B322, which is on tank T17, in Figure 17. The measured value is 21.5, but it should be around 100 kg/s so operators understand something is wrong. Figure 17 shows the view that the operators see, and one can see that V153, V160 & V161 are open, but the flow is still very low. One can also see the flow measurement over time, showing that the flow starts at zero and then continues up to 21.5 kg/s, where it stops for an unknown reason.
Figure 17: Liquid flow from T16 to T17 in ABB800xA when all valves are opened, showing a flow of 21.49 kg/s.

The problem was that when the operators gave a command for one of the valves to open, an immediate indication was shown that it was open. Still, in reality, no monitoring indicates that the valve is really open. Upon inspection of the valve, it was noticed that it only opened a little and not all the way due to being old and rarely used.

5.2.1 **FMEA**

This case involves troubleshooting an operating instruction failure where the intended transfer of liquid between two tanks is not functioning as expected. The root cause of the problem has been identified as a partially open valve resulting from infrequent usage. While the severity of this case in terms of individual safety is relatively low, it can have significant influences in other areas. If left undetected, it may necessitate a plant shutdown, leading to substantial costs and potential reductions in electricity production. Considering the broader impact beyond immediate safety risks, a numerical severity
value of 4 is assigned to this case. Although there is no direct danger to individuals, the potential for high costs and decreased production warrants attention. It is crucial to promptly address and rectify such failures to minimize disruptions, optimize resource utilization, and maintain efficient plant operations.

Valve binding, which occurs infrequently, is primarily attributed to extended periods of inactivity. Certain objects within the plant may be subject to infrequent usage, posing a potential risk for process errors. Accordingly, an occurrence value of 2 is assigned to this case. While instances of object binding due to infrequent usage can occur, it is important to note that they are typically not frequent throughout the year.

In the absence of RDT, the maintenance process would involve manual analysis of the program code to identify faulty or poorly constructed sections. This would require a step-by-step examination of the code. If the code is correct, the maintenance team would need to analyze facility blueprints to identify the objects involved in the affected route of the current operating instruction. Subsequently, physical testing of the objects would be required, which can risk system damage and necessitate specific plant operating conditions. The detectability without RDT is considered 5, as the fault would eventually be detected. However, the process of reviewing functional descriptions, program code, and waiting for the correct operating state is time-consuming.

By utilizing RDT, the plant can be immediately placed into the correct operating mode. As the emulation is based on the program code, the same scenario can be precisely tested as in the physical plant without incurring any risks. If the operating instruction functions correctly in the emulation, faults in the program code can be ruled out. Based on this, the detectability value is considered to be 2. While maintenance workers still need to assess the faulty valve within the plant, this process is estimated to require significantly less time compared to the current maintenance approach.

Therefore, the Risk Priority Number (RPN) without using RDT is calculated as:

\[
\text{RPN} = S \times O \times D = 4 \times 2 \times 5 = 40
\]  

(6)

The RPN using RDT is calculated as:

\[
\text{RPN} = S \times O \times D = 4 \times 2 \times 2 = 16
\]  

(7)
5.2.2 Emulation

The virtual environment provided by RDT is illustrated in Figure 18, where the relevant objects from the operating instruction are shown. The three valves are opened simultaneously to test the scenario in a virtual environment, all indicating an open state. As shown in the figure, the volume in T16 decreases while that in T17 increases. The emulated flow rate is displayed in Figure 19 and reads 98.78 kg/s. Given that the flow is near the expected value of 100 kg/s and the liquid flows from T16 to T17, the program code appears to function correctly.

Figure 18: Liquid flow from T16 to T17 indicated by arrows in Siemens Simit.
Further investigation of the three valves in Simit revealed that two could be operated from the control room and display their open/closed status. However, the third valve (V153) can also be controlled remotely, but it does not indicate any status if it is opened or closed. As shown in Figure 20, V153 has no associated status panel, only Open/Close commands, making it necessary to inspect the facility to determine its current state physically. This can be compared to Figure 21, where V160 & V161 has both Open/Close commands and status indications.

Physical examination of the valve showed that it opens 15% but then stops, and the reason is believed to be that it is used so infrequently that it has jammed.

5.2.3 Automatic Valve Failure Detection

By measuring the pressure difference between the upstream side and downstream side of a valve, it can be determined whether a valve is open or closed. This concept relies upon Bernoulli’s equation, expounded in Section 4.4, which states that the sum of pressure, kinetic energy, and potential energy per unit volume remains constant along a streamline within a flow field where no external work acts upon the fluid.
Conducting a simulation of a portion of Ringhals’ waste facility demonstrates the application of this principle. RDT creates an environment encompassing all components and their interactions, mirroring those in the actual plant. Typically, the emulation of a PLC occurs automatically through RDT’s provision of a virtual environment. However, an alternative emulation approach was adopted due to the high cost associated with purchasing such software licenses. In this case, a plugin in Simit, known as Simatic PLCSIM Advanced, was utilized. This software suite offers advanced simulation and configuration capabilities for technical functions, obviating the need for physical PLC connections [54]. It empowers the creation of virtual controls that accurately replicate actual controller behaviors, facilitating rigorous functional testing. This results in a more accurate simulation where hardware and software are simulated instead of only simulating software in Siemens Simit. While this software also requires a license, communication with Siemens yielded a one-month license solution.

Each object requires a corresponding template - an individualized simulation model for accurate emulation of real-world behavior. These templates capture crucial details about the intended operation of each object, including factors like valve opening speed and engine transition times from idle to full operation. While some pre-existing object templates exist in Simit, AFRY has crafted additional templates to closely align with reality, drawing from the Simit Flownet library. The object’s actual parameters are entered in the templates to achieve the utmost simulation accuracy. Due to safety considerations, the report cannot present these object parameters from Ringhals. These details encompass valve closing and opening times, valve dimensions, and responsiveness. Similarly, details such as maximum speed, current, power, temperature, flow rate, pressure, and efficiency are imputed for motors.

Upon obtaining PLCSIM Advanced, the connection of the emulated controller with Siemens Simit is established via incorporating a ‘Coupling.’ This ‘Coupling,’ a Simit plugin, interfaces with the SIMIT real-time behavior emulator software. Upon integration as a coupling, the controller interconnects with all objects, facilitating the simulation of the virtual environment.

Due to the sensitive nature of Ringhals’ information, the virtual environment undergoes modification by introducing a Test Stream. The Test Stream is meticulously designed to replicate the functions of the actual facility. However, specific components are strategically relocated and diverge from their real-world positions. This adjustment aligns with Ringhals’ decision to withhold precise facility layouts from public access. This process involves an initial simulation of the authentic plant setup to analyze the existing functionalities and the role of each process component. Subsequently, adjustments
are made to the objects, ensuring the modified process retains its intended functionality, consistent with the original setup. The process can be shown in Figure 22, and the Test Stream inside the red rectangle.

This report has conceptualized and implemented a solution for automatically detecting faulty valves. By going online in Simens Simit and utilizing Simatic PLCSIM Advanced, one can open valves, start pumps, and use transmitters to measure various parameters.

When the simulation starts, most objects turn orange, and when the pump is off and all valves are closed, the pressure on the transmitters can be read as 1 atm, which is expected; it is atmospheric pressure due to the absence of liquid flow. Figure 23 shows when the simulation is running, and the pressure values can be read in the boxes under the PT transmitters (Pressure Transmitter).
Upon opening all the valves and starting the pump, the pressure in the pipe equalizes, resulting in uniform pressure readings across the system. The objects are now blue indicating open/on. All pressure gauges show atmospheric pressure, see Figure 24.

If a valve malfunctions or fails to open, a pressure difference occurs before and after the affected valve. The pump continues to pump water up to the upstream side of the closed valve, leading to reduced flow and increased pressure. In this scenario, the pressure gauge shows a reading of 1.63 atm in Figure 25 on the upstream side while the downstream side remains at atmospheric pressure. By comparing the different pressure measurements, it becomes possible to determine the status of the valves, including identifying fully closed or partially opened valves that impact the flow.

Instead of manually reading and comparing the values of the pressure gauges, the objective is to enable the automatic detection of faulty valves by implementing an alarm system. This necessitates signal processing from all transmitters using so-called tags within the Simit framework. Tags are incorporated into a list, allowing the selection of input or output designation and specification of data types. This facilitates retrieval of each signal’s value from the tags via the emulated controller, which is crucial for generating alarms. An example of a tag is depicted in Figure 26, associated with PT_1 (Pressure Transmitter 1). Here, "PV" denotes the process value, representing...
the reading obtained by the transmitter within the process, and it is subsequently linked to the "IO-value" that can be transmitted.

![AFRY X RDT - PCDL Transmitter](image.png)

Figure 26: Tag in Siemens Simit for signal processing.

Initially, PT_1 (Pressure Transmitter 1) is compared with PT_2 (Pressure Transmitter 2), and if PT_1 exceeds PT_2, it indicates a fault in valve V202 located between these measurement points. Similarly, comparisons are made between different transmitter values to identify instances where one value surpasses another, indicating malfunctioning valves. A flowchart of this detection method is shown in Figure 27.

![Flowchart](image.png)

Figure 27: Flowchart of logic for detecting which valve(s) have an error.
If the compare blocks yield positive results, the boolean value is transmitted to a binary display in Simit, visually representing the outcome as a color. When the condition is true, indicating that one value exceeds the other, the circular ring turns red, indicating an anomaly in the valve between the two measurement points. Figure 28 illustrates the outcome of comparing the four pressure gauges, triggering alarms if discrepancies are detected. In this case, V202 was closed, and the alarm was activated as expected.

Figure 28: Implemented logic in Simit of how the pressures are compared indicating that V202 is closed.

Now we can ascertain any issue with V202, V251, V252, or V253. However, V250 remains situated immediately after the pump, where pressure measurement is absent on the upstream side; only the downstream side has this capability. During pump operation without any alarms triggered on the remaining valves, the liquid level in the inlet tank will gradually decrease. Conversely, if there is a malfunction with V250, the pump will operate, yet the level in the tank will not exhibit any reduction. This circumstance can be utilized to our advantage.
The tank incorporates a continuous level measurement system that effectively gauges the liquid level. By recording this value and comparing it with a subsequent reading obtained a few seconds later, it becomes possible to determine whether the tank level is diminishing or remaining constant. The issue is that when any valve malfunctions, the liquid level in the tank will consistently remain unchanged. To be sure none of the other valves have stopped the flow, their alarms are checked first. If none of the other valves have triggered the alarm, they can be disregarded, thereby establishing that V250 is the source of the error.

Figure 29 presents a flowchart of the implemented logic, wherein LT_1 (Liquid Transmitter 1) is connected to a delay mechanism that defers the transmission of its value by two seconds. Subsequently, this value is compared with the current reading of the tank. If they are identical, the inference can be made that the liquid level in the tank has not diminished. Furthermore, it is investigated whether any of the other valve alarms are active to rule out that these did not cause the error.

Figure 29: Flowchart containing the logic with delay to determine if V250 has an error.
In Simit, a boolean signal is propagated and becomes one of the inputs to an AND block. The second input to the aforementioned AND block first examines the activation status of any remaining alarms, and this is done with an OR block. If any alarms are active, it indicates that the fault lies not with V250. Consequently, the result of the AND block does not yield a true value. Conversely, if the remaining valves are free from faults, the AND block evaluates to true, triggering the V250 Error indication to turn red. The result of the implemented logic in Simit is presented in Figure 30.

Figure 30: Implemented logic in Siemens Simit with delay so an error of V250 can be detected.
5.3 CASE 2 - ENERGY EFFICIENCY

Based on the interviews, maintenance workers would like to be able to sit in a virtual environment to change parameters on an object to see how it affects the facility, as well as to analyze whether replacing objects can make the facility more energy-efficient. This case is therefore created to provide an example of how RDT can be used to analyze how two pumps, shown in Figure 31, should be operated to consume as little power as possible.

![Figure 31: Two pumps where P11 is the one used and P12 only for redundancy.](image)

In facilities that are sensitive to errors, redundancy is used for safety reasons, which means that there are duplicates of components and objects that can replace each other in case of operational problems. Ringhals is no exception and has redundancy in all sensitive facility parts. The waste facility has a section where a liquid is pumped from a tank into the facility. Here, one pump is always used, but there is another for redundancy in case the first one breaks down. This case investigate whether the pumps should be run together to achieve the expected flow and consume less energy instead of one being completely idle. Doing an FMEA in this particular case is difficult because you need to know what failure modes can occur. Still, since it is an important part of what RDT can be used for, a comparison of how mainte-
nance could have used the virtual test bed to investigate a potential energy efficiency improvement is presented.

5.3.1 Solution

This case study examines whether running two pumps together at half speed is more energy-efficient than one at full speed. Below are two scenarios, one without RDT and the other with RDT.

Without RDT, the first step is to investigate whether running the pumps together is advantageous. In addition, a risk analysis is needed to identify potential risks, and in this case, equipment failure is assumed to be the most significant risk. It may be the pumps being tested that will fail or the accompanying equipment affected during testing. The next step is physical testing, which is conducted in the plant to measure both pumps’ power consumption in various scenarios. This assumes that it is possible to measure its consumption; otherwise, extra sensors or measuring instruments are needed. In summary, this scenario requires a lot of time for investigation and risk assessment since physical equipment actively used in the process must be tested. The risk assessment is primarily carried out to investigate what risks there are for risks linked to personal safety, but also risks related to the facility and equipment.

With RDT, the pumps’ actual characteristics and parameters can be input into the virtual environment and emulated. This enables quick and easy testing to determine how the pumps should operate and which combination results in the lowest energy consumption while still producing the expected flow of the liquid. In addition to emulation, risk assessment and calculations are necessary, but a lot of information can be achieved by conducting virtual tests to observe how the equipment and the rest of the plant react. People often say that “if it ain’t broke don’t fix it”, but even plants with older equipment must be made more efficient as better and more modern equipment is available. The plant’s response can be observed by conducting tests in the virtual environment, and equipment that may fail can be identified.

5.4 Case 3 - Operator Training

This case is based on an actual operating instruction that is run very rarely, and only certain operators are allowed to perform it due to severe risks. It involves an operating instruction where a radioactive liquid is to be run from a tank through a filter and then filled into a container. There are some risks involved in this process, which means that extra care must be taken. Firstly, many pipes are connected to the specific path, and these must be closed
with valves to prevent the liquid from leaking out anywhere in the facility. Secondly, one needs to keep track of the pump that pumps the liquid so that it does not run dry as it will be destroyed. The final risk is the container may overflow, causing the liquid to leak. It is, therefore, a critical operating instruction that can lead to serious consequences if done incorrectly.

5.4.1 FMEA

Performing critical tasks in a facility carries serious consequences if not executed correctly. One of the most hazardous scenarios involves overfilling a container, resulting in the spillage of radioactive liquid. Such incidents can be directly life-threatening to people and can also damage the plant itself, therefore the severity of this scenario is considered to be 7. This is the only case in this thesis where RDT also affects occurrence since this type of incident can occur with and without RDT, but implementing RDT reduces the likelihood of such events. Putting a value on how much the numerical occurrence has decreased is very difficult, and therefore the value is set to 2 both with and without RDT.

In the current context, scenarios of this nature demand the involvement of experienced personnel who possess the necessary competence and prior experience with similar tasks. Relying on specific individuals for operating instructions is not suitable for large-scale facilities, where all operators must be capable of responding to any situation. Although documentation on handling specific cases is typically available, it may be unclear or outdated, potentially leading to inaccuracies.

The human factor introduces challenges in establishing detectability in this scenario. For instance, a new operator may misinterpret an operating instruction, resulting in the overflow of the radioactive liquid container. Detecting such incidents relies on previous occurrences. Therefore, the detectability of this scenario is considered to be high, with a value of 7, as accidents cannot be detected before they happen.

RDT offers operators the opportunity to train without the fear of real-world consequences. The virtual environment allows individuals to make mistakes and learn from them, fostering a sense of security in their work. While particular scenarios may initially require the expertise of only a few operators, training in the virtual environment significantly contributes to a safer working environment and minimizes potential risks. The shorter learning phase in the physical facility for new operators, facilitated by prior training in the
virtual environment, enhances overall operational safety.

In the case of a new operator misinterpreting an operating instruction and causing an overflow of the radioactive liquid container, RDT can immediately detect such errors in the emulated world, unlike in reality. The key distinction lies in the absence of consequences when mistakes are made in the virtual world. Based on this, the detectability of this case is considered to be 1. If the accident occurs, RDT guarantees its detection.

Therefore, the Risk Priority Number (RPN) without using RDT is calculated as:

$$\text{RPN} = S \times O \times D = 7 \times 2 \times 7 = 98$$ (8)

The RPN using RDT is calculated as:

$$\text{RPN} = S \times O \times D = 7 \times 2 \times 1 = 14$$ (9)

5.4.2 Emulation

To create this operating instruction, the operators’ HMI is connected to the test bed provided by RDT. Now, the operators can see the same thing as before, but the difference is that nothing happens if they make a mistake. Figure 32 shows the operator’s overview image where this case should be displayed. Objects that are not part of this operating instruction have been removed due to security reasons in accordance with the wishes of Ringhals.

![Figure 32: Process overview for operators containing components and objects in one part of the waste facility at Ringhals.](image-url)
Figure 33 shows the liquid’s path, starting in tank T11, passing through several valves to filter C12, and then continuing to tank T15.

Figure 33: Liquid route from T11 to T15 in Case 3 indicated by arrows.

According to the operating instructions in Appendix A, V177, V116, V138, V143, and V146 should be opened, and V117, V125, V137, and V118 closed. Then, V109 can be opened to 60%, and pump P11 can be started. In Figure 34, the objects are shown after following the instructions, and it is clear that the level in T11 decreases, and the level in T15 increases. The pressure can be read at 3.5 bar by looking at K202 on the filter C12, which is within the instruction’s 3-4 bar limit. The liquid flow can be controlled by looking at B321 on T11, which reads 27.76 kg/s, sufficient as the instructions state a minimum of 25 kg/s.
Figure 34: Operating instructions performed in the emulation showing that the level in T11 decreases and the level in T15 increases.

Figure 35 shows how the flow has changed over time, and as expected, it is 0 at the beginning, then moves towards a reduction of 27.76 kg/s.

Figure 35: Flow measurement in tank T11 indicating -27.76 kg/s.
Figure 36 shows a scenario that would have had severe consequences if done in the physical plant. Firstly, T11 has been completely emptied of liquid, and pump P11 is running dry, which would likely have caused it to break down. But even more severe is that T15 has been overfilled, and radioactive water leaks.

Figure 36: T15 is overfilled, and P11 is running dry, causing severe consequences.
DISCUSSION

The interviews conducted with three maintenance workers from the Ringhals maintenance department provide valuable insights into their roles, responsibilities, and challenges in maintaining automation processes. This first part in the discussion will focus on key findings from the interviews and their implications for maintenance practices at Ringhals.

One significant finding is that the maintenance department at Ringhals is responsible for managing multiple automation systems, making it challenging to specialize in each specific system. As a result, maintenance workers rely on functional descriptions that outline how different parts of the process are controlled and how the software is programmed. Maintenance workers analyze the program code to identify the root cause when addressing process deviations or operator error reports. However, the analysis sometimes requires the process to be stopped, making changes while the system runs can be risky. This highlights the need to balance maintenance activities and operational continuity carefully. A thorough understanding of the program code and the ability to analyze it effectively is crucial for efficient troubleshooting and resolution of issues.

The interviews also reveal that investigating faults can be time-consuming, particularly when specific operating modes are involved. Objects within the system may exhibit different behaviors or conditions depending on the operating mode, and certain errors may only occur in particular modes. Consequently, maintenance workers have to wait for the system to operate in the desired mode to investigate alarms or faults associated with it. This delay can prolong the troubleshooting process and potentially impact plant productivity.

The introduction of a virtual testbed is seen as a valuable tool for troubleshooting, system analysis, and training purposes. It provides a controlled environment to simulate various scenarios, understand system behavior, and train operators. The virtual testbed offers benefits such as improved operator training, the ability to stress-test operators’ reactions, and the opportunity to prepare for unusual or rare scenarios. Additionally, it enables maintenance workers to analyze facility responses to parameter adjustments or test "what-if" scenarios before implementing changes in the physical plant. This virtual environment enhances efficiency, reduces risks associated with physical test-
ing, and shortens the learning period for new operators. From an optimization and efficiency standpoint, the interviews highlight the limitations of relying solely on physical testing in the current environment. Testing in the physical facility carries inherent risks, making it challenging to implement changes and improvements. The ability to test against a virtual world before implementing changes in the physical plant would provide a greater sense of security and facilitate the exploration of optimization opportunities.

Overall, the interviews underscore the importance of leveraging virtual test-beds and advanced technologies in maintenance. Virtual environments enhance troubleshooting efficiency, system analysis, operator training, and operational safety. By reducing the reliance on physical testing and allowing for faster identification and resolution of faults, Ringhals can optimize maintenance practices, improve efficiency, and minimize disruptions to plant operations. The insights gained from the interviews emphasize the value of integrating virtual testbeds into maintenance workflows. The use of virtual environments should be explored further at Ringhals, considering its efficiency, safety, and training benefits. By embracing technological advancements and leveraging virtual testbeds, Ringhals can enhance its maintenance practices, optimize resource utilization, and ensure the smooth operation of automation processes.

Moving over to Case 1 - Maintenance Case, where the RPN was calculated as 40. The relatively high RPN indicates that if the maintenance process follows the traditional approach, it may take considerable time and effort to detect and rectify the valve problem. The manual analysis of the program code, examination of facility blueprints, and physical testing of objects are time-consuming steps. This approach can lead to potential delays in identifying and addressing the issue, resulting in increased costs and reductions in electricity production.

In contrast, when RDT is utilized, the RPN decreases significantly to 16. By leveraging RDT, the maintenance process becomes more efficient and streamlined. The plant can immediately be placed into the correct operating mode, and the emulation based on the program code allows precise testing without incurring any risks. This enables faster identification of faults in the program code, ruling out unnecessary manual analysis steps. Although maintenance workers still need to assess the faulty valve physically in this case, this process is estimated to require significantly less time than the traditional approach.

The comparison of RPNs demonstrates the advantages of RDT in this maintenance case. The utilization of RDT reduces the detectability value from 5
to 2, indicating that faults can be identified and addressed more promptly. This leads to lower overall risk, mitigating the potential impact of the operating instruction failure. By minimizing the time required for troubleshooting and rectification, RDT enables faster resolution of issues, reducing costs and maintaining efficient plant operations.

A solution has been developed to automate the detection of faulty valves within piping systems. This solution combines the principles of Bernoulli’s equation with practical implementation, presenting a comprehensive and automated approach to monitoring valve states. To demonstrate the practical efficacy of the developed solution, a virtual simulated environment is established through a two-step process. RDT initially provides the environment in Siemens Simit by replicating the objects present in the plant. Subsequently, each object gets linked to a dedicated template, meticulously crafted using the Simit Flownet Library components, with the input of its specific physical parameters.

To complete the setup, an emulated virtual controller is linked to the simulation through a Simit Plugin known as a ‘coupling.’ This connection results in a simulated virtual environment that mirrors the plant closely. This environment proves invaluable as it enables the automated detection of valve errors and facilitates comprehensive testing. Notably, this simulation faithfully replicates real-world operational dynamics while strictly adhering to stringent confidentiality guidelines. The automatic detection of faulty valves underscores the significance of this approach in industrial applications, particularly in scenarios where manual monitoring is impractical due to safety, complexity, or efficiency concerns.

Case 1 emphasizes the importance of modern technologies like RDT in maintenance processes. It highlights how RDT can enhance easier detectability, optimize resource utilization, and minimize disruptions. The significant reduction in RPN by implementing RDT underscores the effectiveness of this approach and the benefits it provides in improving maintenance efficiency.

**Case 2 - Energy efficiency** demonstrates the potential of RDT in analyzing energy efficiency in automation systems, specifically focusing on the operation of two pumps. The methodology employed in this thesis involves constructing cases based on interviews conducted with maintenance workers at Ringhals, which are subsequently subjected to analysis using Failure Mode and Effects Analysis (FMEA) and emulation. Initially, it is anticipated that an FMEA can be conducted for all cases, including Case 2, which focuses on energy efficiency. However, as the cases are developed and examined more closely, it becomes evident that conducting a traditional FMEA for Case 2
does not result in valuable Risk Priority Numbers (RPNs) for comparison.

The challenge lies in knowing what kind of failure mode could occur and being able to assign a value to the three parameters included in an FMEA. This makes it difficult to compare the RPNs using RDT and non-RDT approaches. Nevertheless, the thesis explains how RDT can be utilized in Case 2 to demonstrate its potential benefits.

The intended approach also involves emulation in the virtual testbed, where the characteristics and parameters of the two pumps are inputted. The objective is to determine if operating both pumps simultaneously rather than one at a time is more energy-efficient. However, the actual emulation cannot be performed due to the requirement for an additional license in Siemens Simit to simulate non-linear pumps. Nevertheless, the potential benefits of RDT can still be recognized.

The virtual environment provided by RDT offers distinct advantages, enabling quick and easy testing by emulating the pump characteristics and parameters. Engineers can assess energy consumption for different pump configurations and observe their impact on the facility. This facilitates the identification of the most energy-efficient operating conditions while maintaining the desired flow rate of the liquid. However, it is important to acknowledge that RDT is not a one-size-fits-all solution, and its effectiveness may vary depending on the specific system and context. Factors such as the accuracy of the simulation model and the availability of accurate data input play crucial roles in achieving reliable results.

In the context of pumps, there is a concept called the Best Efficiency Point, typically ranging from 70-90% of the maximum speed, where the pump operates optimally. At Ringhals, many motors and pumps have been in use since the plant’s inception, and an additional safety margin was incorporated to ensure sufficient performance. However, advancements in modeling, calculations, and simulations now allow re-evaluating these pumps using RDT. By conducting thorough analyses, it is possible to assess whether these pumps are oversized, drawing more energy than necessary and incurring unnecessary costs.

In conclusion, Case 2 highlights the potential of RDT in analyzing energy efficiency in automation systems, specifically focusing on pump operation. While technical constraints prevent the actual emulation in this case, the discussion emphasizes the advantages of the virtual environment provided by RDT. It also underscores the importance of considering factors such as the accuracy of simulation models and the potential for equipment optimization
to achieve energy efficiency improvements. By leveraging RDT effectively, maintenance teams can identify energy savings opportunities and optimize their automation systems’ performance.

In **Case 3 - Operator Training**, the RPN was calculated for the critical operating instruction involving the transfer of radioactive liquid both with and without the implementation of RDT. The comparison of the two RPN values clearly demonstrates the substantial risk reduction achieved through the implementation of RDT. With an RPN of 98 without RDT and an RPN of 14 with RDT, there is a significant improvement in operational safety when RDT is utilized. The considerable difference between these two values highlights the effectiveness of RDT in mitigating risks associated with critical operating instruction involving the transfer of radioactive liquid.

By integrating RDT into operator training, individuals can simulate and practice in a virtual environment without the fear of real-world consequences. This virtual training approach significantly enhances operational safety by allowing operators to learn from mistakes and develop a deeper understanding of the correct procedures. As a result, the occurrence of incidents is reduced, leading to a safer working environment and a decrease in potential risks. Additionally, the shorter learning phase in the physical facility for new operators, made possible by prior training in the virtual environment, further strengthens overall safety.

Analyzing the RPN values further emphasizes the positive impact of RDT. It not only reduces the likelihood and severity of incidents but also enhances the detectability of errors. This comprehensive risk mitigation strategy significantly lowers the overall risk associated with the critical operating instruction, especially when handling radioactive liquid. The RPN values serve as evidence of RDT’s effectiveness in improving operational safety and underscore the importance of integrating RDT into operator training programs and critical task execution.

The emulation process demonstrated the effectiveness of using RDT in creating and executing the operating instruction. By connecting the operator’s HMI to the RDT test bed, operators were able to view and interact with the same environment as before, but with the advantage of no real-world consequences for their actions. The visualization of the liquid’s path and the monitoring of various parameters enabled operators to follow the operating instructions accurately and identify any deviations from the desired outcomes. The emulation scenario depicted in Figure 36 illustrates the potentially severe consequences that would have occurred if the same actions had been performed in the physical plant. The complete emptying of tank
T11 and the running dry of pump P11 would likely have resulted in pump failure. Additionally, the overfilling of tank T15 and the subsequent contamination of the surrounding area would have led to safety hazards and environmental damage.

The automatic detection of valves demonstrates what RDT is capable of and how it can transform current workflows. If there is a fault in the process, RDT can provide a testbed where the affected object can be easily identified. If RDT were directly connected to the physical facility and able to acquire real-time data, alarms could be generated instantly, indicating any issues within the facility without the need for a shutdown. This contributes to easier detection, saving money, and enhancing the safety of the process.

6.0.1 Results Related to International Research and Development

The concept of digital twins has gained significant attention globally, and organizations worldwide are exploring its potential in various industries. International research and development efforts have focused on leveraging digital twins to monitor and optimize processes and products’ behavior and performance [16]. The research of digital twins, when it comes to automation processes, it mainly focuses on virtual commissioning and how a virtual environment could be used before the process is up and running. This thesis contributes to knowledge of how a digital twin can be used after commissioning to maintain the automation process.

RDT and its application in maintenance work at Ringhals can be compared to the use of a Hardware-in-the-loop (HIL) method described in the text from 2014 [23], in Section 2.4, where the aim was to use a testbed at a gas carrier since a seagoing vessel can be challenging to troubleshoot and maintain. Both studies explore simulation-based approaches for verifying and testing automation systems in complex environments. The work in this thesis uses emulation and the Software-in-the-loop method, where the advantage is that hardware can be tested before it is available and reduce the risk of hardware being damaged during testing. On the other hand, there are advantages to using HIL instead, as you can see that the components used in the process work as intended. Both studies show that a virtual testbed previously used for virtual commissioning can later be used to troubleshoot and maintain the automation process.

This thesis also highlights the significance of operator training in a virtual environment, which aligns with the findings of the references research in [25]. Both studies emphasize the importance of allowing operators to acquire knowledge and skills in automation and IT systems through immersive vir-
tual training experiences. By using a virtual environment for operator training, individuals can engage with realistic simulations or emulations and gain hands-on experience in a controlled and safe environment. This approach enables operators to familiarize themselves with complex processes, practice operating instructions, and develop a deep understanding of a system’s behavior without the potential risks associated with real-world operations.

6.0.2 Economic, Environmental and Safety Aspects

Economic considerations are important to consider when implementing digital twins and virtual testbeds. These technologies can be expensive to develop and maintain, hindering adoption for some companies. Additionally, the potential benefits of these technologies, such as increased efficiency and productivity, may only sometimes justify the costs associated with their implementation. Most studies have shown that the long-term benefits can outweigh the costs, particularly in manufacturing and energy industries where downtime can be costly [55]. All three cases in this thesis have some form of impact from an economic perspective; case 1 reduces the time for maintenance work since errors can easier be detected, which can prevent a potential stop. Case 2 makes the process more energy efficient, which also reduces costs. Case 3 gives new operators a training environment so they don’t need as long training in the physical plant, reducing errors that can cause various stops in the facility.

Environmental aspects are also essential to consider. Implementing virtual testbeds in the industry can lead to reduced energy usage and improved resource utilization and process optimization. These technologies can also simulate and test sustainable solutions before they are implemented in the real world, such as in case 2 when analyzing two pumps. Nuclear power plants generally have a lower carbon footprint than fossil fuel-based plants since they don’t emit greenhouse gases during electricity generation. However, nuclear power plants’ production, operation, and decommissioning require significant energy and resources, including fossil fuels, to transport and manufacture equipment [56]. By making nuclear power plants more energy efficient, more clean electricity can be sold on the market instead of buying fossil fuel-based energy.

Regarding safety, RDT can improve safety by allowing for more accurate and efficient testing of systems and equipment. Operator training in case 3 is an excellent example of how a facility can become safer by allowing operators to train on dangerous scenarios that may occur. This can lead to fewer accidents and a reduced risk of injuries and fatalities. Additionally, these technologies can be used to simulate and test emergency response proce-
dures, improving preparedness and response time in the event of an actual emergency [25]. But, these technologies are also associated with potential safety concerns, particularly in high-risk industries such as nuclear power plants. However, there are potential safety issues related to these technologies, especially in high-risk industries such as nuclear power plants, such as cyber security risks. Therefore, ensuring these technologies are developed and implemented with a strong focus on safety is essential.

Using digital twins can have significant economic, environmental, and safety implications. As these tools continue to develop and be implemented in various industries, it is important to consider these ethical and societal aspects and address potential concerns. Research in this area can help identify potential benefits and limitations of these technologies and develop methods for integrating them into industrial operations to maximize their benefits while minimizing potential risks.
CONCLUSION

In conclusion, this thesis has explored the application of RDT in the context of maintenance operations at Ringhals. Through interviews with maintenance workers and the analysis of their WoW, various cases and scenarios were constructed to assess the potential benefits of RDT. The methodology encompassed FMEA to identify and prioritize potential failures and emulation to demonstrate the practical implementation of RDT.

The findings of this thesis highlight the significant potential of RDT in enhancing maintenance processes and improving operational efficiency. By leveraging RDT, maintenance workers can sit calmly in a virtual environment, change parameters, and observe the effects on the facility, leading to informed decision-making and improved maintenance practices. RDT enables quick and easy testing of different operating strategies, facilitating the identification of energy-efficient solutions and reducing downtime.

The emulation process demonstrated the effectiveness of using RDT in creating and executing operating instructions. By connecting the operator’s HMI to the RDT test bed, operators could interact with a virtual environment and replicate real-world scenarios without any actual consequences. Visualizing the liquid’s path, monitoring parameters, and accurately following operating instructions facilitated the detection of deviations, preventing potential failures and improving system reliability. Automatic valve detection shows how an emulated virtual environment can detect faults in an automation process - immediately seeing if a valve is malfunctioning. This means you don’t have to make a significant maintenance stop in the plant, which is expensive and time-consuming.

Furthermore, the comparison of FMEA results between cases with and without RDT revealed the positive impact of RDT on failure detectability. Improving the detectability parameter through RDT empowers maintenance teams to proactively identify and address potential failures, reducing the likelihood of costly disruptions and ensuring safe and efficient operations.

The adoption of RDT is expected to impact maintenance workers’ WoW significantly. It introduces new ways of working, leveraging the virtual environment for testing, analysis, and decision-making. Maintenance workers will need to acquire new skills and knowledge to effectively utilize RDT tools.
and interpret the insights the digital twin provides. Additionally, their roles may evolve to encompass virtual testing and system optimization. Integrating RDT into their WoW can enhance their efficiency, improve their situational awareness, and empower them to make informed decisions based on the virtual emulation results.

However, the implementation of RDT has its challenges. One of the main challenges identified is the need for accurate data representation in the virtual environment. Obtaining reliable and up-to-date data for the digital twin is crucial for ensuring the accuracy and validity of the emulation and analysis. Additionally, integrating RDT into existing systems and processes requires careful planning and coordination. It involves adapting the maintenance workers’ WoW to incorporate RDT tools and techniques, which may require training.

While this thesis has demonstrated the effectiveness and potential of RDT, it is important to acknowledge that there are limitations and areas for further exploration. The inability to conduct a traditional FMEA in Case 2 due to its focus on energy efficiency highlights the need for more extensive emulation for credible analysis in specific scenarios. Future work should involve entering actual characteristics and parameters into the emulation to assess the optimal operating conditions that minimize energy consumption while maintaining the desired flow.

In summary, this thesis contributes to the growing knowledge of Industry 4.0 and digital twin technologies, showcasing the significant benefits of RDT in maintenance operations. Integrating RDT in the maintenance workers WoW at Ringhals can revolutionize maintenance practices, reducing downtime, improving energy efficiency, and enhancing overall operational performance. As industries continue to embrace digital transformation, RDT stands out as a valuable tool for optimizing maintenance processes and achieving higher levels of productivity and reliability.

7.0.1 Future Work

Industry 4.0 and digital twins are rapidly evolving research areas with significant potential for enhancing industrial operations. This report presents technical examples demonstrating how RDT can be leveraged at Ringhals to maintain automation processes. The cases tested in this thesis are based on real-world scenarios and highlight the potential of RDT for reducing downtime and improving maintenance efficiency. As a recommendation for future work, it is suggested to further explore Case 2 by inputting the actual characteristics and parameters of the pumps into the emulation environment. This would
allow for a more comprehensive investigation of how the pumps should be operated to achieve optimal energy efficiency while maintaining the desired flow rate of the liquid. By conducting such an analysis, valuable insights can be gained to guide maintenance teams in making informed decisions about energy-saving measures and equipment optimization.

Future research related to RDT will likely focus on how accurately the virtual test bed needs to mirror reality for various applications. For instance, if RDT is to be used for troubleshooting to simplify maintenance work, it may not need to be as precise as if it is used for proactive fault detection with the assistance of AI. The integration of AI and DTs has the potential to bring significant benefits to various industries. One possible area for future research is the development of more advanced AI models that can predict equipment failures with greater accuracy and precision [8]. This could involve using machine learning techniques to identify patterns and correlations in sensor data and other operational data, and then using these insights to make more accurate predictions about when equipment failures are likely to occur, leading to increased efficiency and productivity. With AI integrated into digital twins, it becomes possible to automate specific tasks and processes, saving time and reducing the risk of errors. [17]

Another benefit is the potential for increased safety. Using digital twins and AI to monitor and control processes make it possible to reduce the risk of accidents and injuries. AI can identify potential hazards, alert workers, or automatically shut down equipment [7]. This is an incredible advantage, not least for nuclear power plants that work with radioactive substances. A severe accident could lead to releasing radioactive substances that could affect the environment.

However, there are also several potential drawbacks to consider. One of the most significant is the cost and complexity of implementing and maintaining these systems. Creating accurate digital twins and training AI models can be time-consuming and expensive, and ongoing maintenance and updates will also be required [55]. Additionally, there may be concerns around data privacy and security, as these systems rely on large amounts of sensitive data. Ringhals is classified in Sweden as a protected object, a socially important business that has enhanced protection based on Swedish law to protect against sabotage, terrorist crimes, and espionage. A digital twin that controls the entire facility, therefore, becomes a potential target that can be exploited by foreign powers and threaten Sweden’s security.

Another potential drawback is the risk of over-reliance on technology. While digital twins and AI can be incredibly powerful tools, they should be seen
as something other than a replacement for human expertise and decision-making. It is essential to ensure that workers are adequately trained and empowered to make informed decisions, even with the support of these advanced systems.

Overall, the integration of AI with digital twins for automation processes has significant potential for improving efficiency, productivity, and safety in a variety of industries. However, careful consideration must be given to the potential drawbacks, including cost, complexity, and the risk of over-reliance on technology. Further research is needed to fully understand the benefits and limitations of these technologies and to develop better methods for integrating them into industrial operations.


[34] Richard A Krueger and Mary Anne Casey. Focus groups: A practical guide for applied research. 2015.


[54] Siemens AG. *SIMATIC S7-PLCSIM Advanced V4.0*, 5 2021.


### 7.2 Manöverdel

*M = Manual, A = automatisk, R = Read & Register*

<table>
<thead>
<tr>
<th>Operation</th>
<th>Maneuver</th>
<th>Component/Object</th>
<th>Åtgärd / Klartext</th>
<th>Utfört Beskr</th>
<th>Åtgärdat av, Sign</th>
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<tr>
<td>5.</td>
<td>M</td>
<td>V146 alt V147</td>
<td>Öppna.</td>
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<td>7.</td>
<td>M</td>
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<tr>
<td>8.</td>
<td>M</td>
<td>V137</td>
<td>Stäng.</td>
<td></td>
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</tr>
<tr>
<td>10.</td>
<td>M</td>
<td>V177</td>
<td>Öppna.</td>
<td></td>
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</tr>
<tr>
<td>15.</td>
<td>M</td>
<td>V109</td>
<td>Öppna till 60%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>M</td>
<td>K415 alt K416</td>
<td>Dä K415 alt K416</td>
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</tr>
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<td></td>
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<td></td>
<td>Visar 130 m³</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ska filtreringen</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>genom C12 avbrytas och antecknas.</td>
<td></td>
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</tr>
<tr>
<td>24.</td>
<td>M</td>
<td>Resterande ventiler</td>
<td>Stäng.</td>
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Figure 37: Operating instructions used in Case 1 - Maintenance.