STRAMSA: Systematic Techno-economic RAMS Analysis Approach for Hydrogen Refueling Stations

The Case Study: Total Energies Breda Hydrogen Refueling Station

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Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in Complex System Engineering and Management (COSEM) Faculty of Technology, Policy and Management

by

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Executive Summary

The shifting global climate patterns present an imminent threat to human existence. Addressing this critical issue necessitates decisive action in multiple sectors, including the mobility service, to mitigate climate change. As the world seeks cleaner alternatives, hydrogen has emerged as a promising solution. TotalEnergies, a prominent energy company, has invested substantially in hydrogen technology to facilitate the transition toward sustainability. Although commendable, it is essential to recognize that the current environment remains a high-risk prototype phase. The successful establishment of hydrogen infrastructure and mobility services demands meticulous planning, robust technological advancements, and comprehensive risk assessment.

Thus, there is a need to comprehend the potential areas of development within a high-risk prototype environment by harnessing the company's extensive 40 years of experience in Reliability, Availability, Maintainability, and Safety (RAMS) analysis. This need entails conducting a comprehensive and systematic RAMS analysis specifically tailored to the unique challenges and requirements of hydrogen refueling stations. However, a notable gap exists in the existing literature, as there is a lack of established guidelines or published research that specifically addresses the intricacies of RAMS analysis for the stations. This knowledge gap poses a significant burden in effectively assessing and mitigating risks, ensuring optimal performance, and fostering the safe and reliable operation of hydrogen refueling infrastructure. In order to address this critical knowledge gap, the main research question has been formulated as follows:

Research Question - Main

How can a systematic RAMS study-based approach be developed to improve the availability of hydrogen refueling stations by leveraging conventional RAMS methodological frameworks?

An extensive literature study was conducted to address the main research question. The aim of that part was to gather insights and identify best practices from existing research from other industries. As a result of the literature study, a Systematic Techno-Economic RAMS Analysis (STRAMSA) framework was developed. The STRAMSA framework introduces significant contributions to RAMS analysis for hydrogen refueling stations. It integrates system engineering, RAMS analysis, and techno-economic analysis to maximize the availability of system design. The framework establishes a strong link between RAMS analysis and techno-economic evaluation, facilitating informed decision-making by considering financial aspects. In techno economic analysis, it incorporates novel elements such as inflation, learning-by doing effect (in terms of market growth), and deflation rates for hydrogen. Moreover, the framework separates maintenance costs from operational costs to facilitate targeted improvements for the operation. This part also quantifies safety by assessing risks in monetary terms for accidents/fatality occurrence. Lastly, its iterative nature allows continuous improvement and adjustment throughout the design and operation process. Overall, the STRAMSA framework provides a comprehensive approach for analyzing the reliability, availability, maintainability, and safety aspects of systems.

To evaluate the applicability and effectiveness of the STRAMSA framework, the Total Energies Breda Hydrogen Refueling Station was selected as a case study. The steps outlined in the framework were applied to this specific station. Throughout the process, an iterative approach was adopted, allowing for adjustments to the framework as necessary.

After applying the STRAMSA framework to the Breda Hydrogen Refueling Station, the Net Present Value (NPV) was calculated as 1,815,202.69 €. The analysis also revealed the uncertainty of attaining a positive NPV, with a 11.18%. Further investigation into the sources of uncertainty identified market-related parameters as the dominant contributors to the variance. Specifically, parameters such as ”Market Growth Rate,” ”Hydrogen Price,” and ”Hydrogen Sale” significantly influenced the uncertainty surrounding the NPV. These findings underscore the importance of a coordinated policy approach that encourages investments in both the hydrogen market and hydrogen infrastructure. Such an approach is crucial for the rapid adoption of hydrogen technology and the development of a robust hydrogen economy. In addition to market parameters, from the operational perspective, the dispenser is identified as a decisive contributor to the uncertainty that requires closer examination.

As a further theoretical research, exploration the applicability of the STRAMSA framework for multi-case studies can be conducted. Initially, the framework can be applied to hydrogen refueling stations as a potential case study, but its feasibility can also be assessed for other industries. Furthermore, the impact of a design configuration change can be evaluated for the case at stake. One potential modification to consider is the addition of a supplementary High-Pressure (HP) compressor, as this particular component has been identified as the least reliable subsystem based on the RAMS analysis. Conducting such assessments can provide valuable insights into the effectiveness and adaptability of the STRAMSA framework in different scenarios and improve the design of hydrogen refueling stations.

Preface

This thesis marks the end of my 20-year journey as a student. Although it may seem like the end of an era, it is merely the beginning of a new chapter in my life. When I moved to the Netherlands two years ago, I was an individual driven by a desire to explore life and learn with boundless enthusiasm. This life-altering change brought forth numerous challenges and uncertainties, allowing me to gain valuable insights each day and shape my personality. In pursuit of my dreams, I am immensely grateful to my extended family, who have consistently supported my decisions from childhood to the present. Their unwavering presence, even across thousands of kilometers, gives me reassurance that they will stand by me, even when I make mistakes.

Additionally, I owe the realization of this dream to EnerjiSA. This company holds a special place in my heart, as their support and commitment to nurturing young talent without any expectations are beyond words. Their backing has been instrumental in making my dream come true. Moreover, I would like to extend my heartfelt appreciation to Ihsan Erbil Baycol and Emre Erdogan, who have supported me throughout my master's journey, offering assistance whenever I needed it.

Furthermore, my dream has been sustained by the support of TotalEnergies Gas & Mobility. Not only have they provided financial assistance, but they have also given me the opportunity to write my thesis within their company and complete an internship, which has helped me grow both personally and professionally. Even during the organizational changes within the company, my colleagues have always been there to lend a helping hand. Hence, I would like to express my gratitude to the company and all my colleagues, with special recognition to my company manager, Casha Haddad, and my supervisor, Hernand Gomes de la Vega.

I am also indebted to my university supervisors. When I was negotiating the agreement for my master's thesis graduation with TotalEnergies, Nazli Yonca Aydin accepted the role of my supervisor without hesitation, despite having a different area of expertise. She came to my aid during a critical juncture, and her guidance was invaluable. I would also like to thank Ming Yang, who constantly pushed me beyond my limits and supervised me on a topic in which I had no experience in the past. Furthermore, the discussions with Zofia Lukszo have consistently helped me gain a better understanding of concepts, from my very first energy class to the culmination of this project. These conversations have continually nurtured my personal growth and increased my motivation to strive for more. Lastly, I would like to thank Emile Chappin since he accepted to be my chair on short notice period.

In addition, as a sociable person, I cannot overlook the indispensable contributions of my friends to both my life and this thesis. In the midst of the COVID-19 pandemic, I arrived in the Netherlands alongside four close friends who have supported me unwaveringly in every situation. I am confident that they will always stand by me. I extend my heartfelt gratitude to them. Additionally, I would like to express my appreciation to all my friends who remained in Turkey. Despite our physical separation of two years, our friendship remains as strong as it was on the first day we met. Moreover, during my time in the Netherlands, I have encountered numerous individuals and made new friends. Thanks to them, I have had the opportunity to comprehend diverse cultures and broaden my perspective. Therefore, in addition to my long-standing friends, I want to thank all the friends I have made here and grown close to.

In conclusion, while I may be the author of this thesis, it would not have been possible to succeed without the contributions of my family, EnerjiSA, TotalEnergies Gas & Mobility, my company and university supervisors, and my friends. I firmly believe that every person I have ever met and every experience I have had has played a significant role in shaping my life. Therefore, I express my gratitude to life itself for enabling me to cross paths with these extraordinary individuals and be in the right place at the right time.

To conclude, I would like to borrow the words of Mustafa Kemal Ataturk, the founder of Turkey: ”I send you as a spark, and you must return as a flame.” This quote was spoken when a group of talented young students was sent abroad for further education after the First World War. Two year ago, I came to the

Netherlands as a spark, and I aspire to return to my country one day as a blazing flame, fueled by the knowledge and experiences gained during this transformative journey.

Ugurcan Isik
Delft, July 2023

Contents

Nomenclature

List of Abbreviations

BIS	Business Information System
CCS	Carbon Capture and Storage
CDC	Cumulative Frequency Chart
CDF	Cumulative Distribution Function
CHSS	Compressed Hydrogen Storage System
EU	European Union
FFBD	Functional Flow Block Diagram
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
HP	High Pressure
KPI	Key Performance Indicator
LEL	Lower Explosive Level
MC	Monte Carlo
ML	Machine Learning
MP	Medium Pressure
NPV	Net Present Value
PDF	Probability Density of Frequencies
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RCA	Root Cause Analysis
RCDC	Reverse Cumulative Frequency Chart
RED	Renewable Energy Directive
RFNBO	Renewable Fuels of Non-biologic Origin
RQ	Research Question
SD	Standart Deviation
SoC	State of Charge
STRAMSA	Systematic Techno-Economic RAMS Analysis
TEN-T	Trans-European Network
UML	Unified Modeling Language

List of Symbols

t	Time-step
€	Euro

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Part I

Research Background

1

Introduction

1.1. Sustainable Energy Transition

The alarming shifts in global climate patterns pose an imminent threat to human life on the planet. Climate change mitigation is crucial to tackling this pressing issue, which demands to make substantial changes to humanity's lifestyle to address this crisis effectively [1]. A highly effective approach to addressing this issue is to reduce carbon emissions in critical sectors such as energy, transportation, and heavy industries. To this end, 191 countries have signed the Paris Agreement, an international accord aimed at curbing the rise in global temperatures to below 2°C by substantially cutting down greenhouse gas emissions as soon as possible [2]. This landmark agreement sets a target of achieving net-zero emissions by 2050.

To achieve this goal, the world has been transitioning from fossil fuels to renewable energy sources such as solar, wind, hydropower and etc.Over the last decade, there has been a significant increase in renewable energy capacity, with a 50% growth in the global renewable energy mix [3]. However, relying solely on renewables is not sufficient to fully decarbonize some industries that require energy sources that cannot be electrified [4]. Furthermore, the unpredictability of renewable energy production due to weather conditions and seasonal changes makes it challenging to depend on it exclusively. This unpredictability can lead to overproduction or shortages, which can threaten the electricity grid's stability and decrease society's overall welfare [5].

Therefore, to fully harness the potential of renewable energy sources, it is imperative to develop sustainable energy storage methods [6]. These storage methods can help mitigate the unpredictability of renewable energy sources by providing energy when primary sources are unavailable and facilitating energy transportation. Combining renewable energy sources with sustainable energy storage can create a reliable and sustainable energy system that contributes to decarbonizing our planet.

1.1.1. Sustainable Energy Transition in Transportation Sector

Specifically, the transportation industry is one of the major contributors to CO_2 levels. It is repsonsible quarter co2 emission of Europe [7]. Thus, it is one of the sectors most affected by decarbonization efforts as well[8]. This sector requires alternative energy storage than oil, gas, etc. To address this issue, there are already studies and commercial solutions for the energy needs of the transportation industry, such as electric batteries and hydrogen as energy storage and carrier. These solutions are promising to combat climate change, local air pollution and ensure the security of energy supply.

However, there is a challenge in deciding which option to choose for the transportation sector as both solutions have their unique advantages. For example, electric vehicles rely on battery storage, which has a relatively low energy density compared to hydrogen. Having a less energy density makes the use of batteries for long-distance transportation problematic [9]. For this reason, hydrogen fuel is considered the most viable alternative, particularly for heavy-duty trucks that require greater energy capacity and hard to abate industries. To accelarate the development of hydrogen technology for those sectors, an target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030 was set by European Union [10].

On the other hand, the cost of hydrogen fuel per kilometer is currently higher than the electricity price, but this is expected to decrease by 2030 due to the learning-by-doing effect [11]. Accurate predictions of fuel costs remain challenging due to the exponential growth in demand. Despite this uncertainty, the mobility sector continues to grow and is expected to expand further [12]. Therefore, the adoption of hydrogen as a fuel technology in the transportation sector remains a promising area of focus.

1.2. Hydrogen

Hydrogen (H) is recognized as the lightest, highly flammable, and most abundant element in the universe [13]. In its natural state, hydrogen primarily exists as molecular H_2 gas. However, due to the high flammability of pure hydrogen gas, it generally forms compounds by combining with other elements, such as O_2 to produce H_2O, or carbon to form organic compounds.

Hydrogen possesses a diverse range of applications, including its utilization as a fuel for vehicles and a feedstock in various industrial processes [14]. When employed as a fuel, hydrogen can be chemically reacted within a fuel cell to generate electricity. A notable advantage of hydrogen as a fuel source is its emission of only water as a byproduct, rendering it a clean and sustainable alternative to conventional fossil fuels [15].

Figure 1.1: Hydrogen

1.2.1. Hydrogen Types

However, it is significant to acknowledge that despite not emitting greenhouse gases during combustion, the production of hydrogen through state of the art methods such as natural gas steam reforming, gasification, or coal gasification results in the emission of approximately one billion metric tons of CO_2 annually [16]. This emission issue represents a significant impediment to achieving the desired goal of zero emissions. The reaction for state of the art process is shown below [17].

The reforming reaction with methane as:

$$CH_4 + H_2O \longrightarrow CO + 3\,H_2 \tag{1.1}$$

The water-gas shift (WGS) reaction is:

$$CO + H_2O \longrightarrow CO_2 + H_2 \tag{1.2}$$

These types of hydrogen are classified as fossil-based hydrogen, with prices averaging around 1.5 €/kg within the European Union [18]. However, if the carbon dioxide CO_2 produced during its production is captured and stored, it falls under the category of low carbon hydrogen. In the EU's 2020 hydrogen strategy, low carbon hydrogen is recognized as a transitional fuel, facilitating the shift from fossil fuel-based hydrogen to clean hydrogen. The estimated cost of low carbon hydrogen is approximately 2.00 €/kg.

On the other hand, the invasion of Ukraine by Russia has led to a significant shift in focus towards hydrogen production through electrolysis even it is not still cost competitive with fossil based or low carbon hydrogen [10]. This process involves the splitting of water H_2O into hydrogen H_2 and oxygen O_2 using renewable energy sources [15]. By producing hydrogen from renewable sources such as wind and solar power, it can serve as a carbon-free and highly sustainable energy resource for the future.

Moreover, hydrogen offers additional advantages that position it as a promising alternative and sustainable fuel option for the future. For instance, its exceptional capacity as an energy carrier enables efficient energy transportation, while its ability to retain high energy density over prolonged periods makes it a key component in the future energy mix portfolio [9]. Consequently, hydrogen is anticipated to play an essential role in meeting the energy demands of sectors characterized by substantial CO_2 emissions, such as heavy industry, shipping, aviation, and transportation [19]. This expectation and strategic planning have caused the growth of the hydrogen market, with further expansion projected in the coming years [12].

1.3. European Union Hydrogen Strategy

Before diving into the details of the research, it is beneficial to provide an overview of the current legislative environment and the key stakeholders involved to gain a comprehensive understanding of the market. In this section, the European Union's hydrogen strategy is elucidated to provide insights into the fundamental aspects of the hydrogen business within the European Union.

The Renewable Energy Directive (Directive (EU) 2018/2001) of the European Union aims to promote the utilization of renewable energy sources by outlining the regulatory framework for the transition [7]. In line with this directive, the Union introduced a hydrogen strategy on 8th July 2020, which highlights the significance of hydrogen in achieving a sustainable energy transition. The strategy provides a roadmap for the development of hydrogen utilization within the Union and compares various hydrogen sources in terms of their emissions, current costs, and projected costs.

In 2020, the strategy positioned low carbon hydrogen as a transitional fuel from fossil fuel to clean hydrogen, with the Union anticipating that clean hydrogen would eventually become cost-competitive with the current state-of-the-art fossil fuel-based hydrogen. However, the Russian invasion of Ukraine in sparked an urgent need to expedite the transition from Russian fossil fuel to clean hydrogen. This invasion resulted in a severe energy crisis and jeopardized energy supply security. Consequently, the European Union swiftly adjusted its Sustainable Transformation Strategy in response to this threat. On 18th May 2022, the Union published a plan called REPowerEU, which aims to rapidly reduce dependency on Russian fossil fuels [10]. The plan focuses on enhancing energy efficiency, diversifying energy sources, and facilitating rapid advancements in hydrogen and solar technologies, thereby promoting a green transition. The renewed emphasis on hydrogen's role in achieving sustainable transition aligns with the previous hydrogen strategy. Additionally, the plan sets a target to achieve 10 million tonnes of domestically produced renewable hydrogen and 10 million tonnes of hydrogen imports by 2030.

As part of further legislative measures, on 13th February 2023, two delegated acts were added to the Renewable Energy Directive, specifically addressing the deployment of hydrogen for sustainable transition [18]. These acts emphasize the criteria for classifying hydrogen as renewable fuels of non-biological origin (RFNBO). Furthermore, in late March 2023, member states reached an agreement to establish a hydrogen network every 200 kilometers along the core Trans-European Network (TEN-T) [20]. All these strategic developments underline the European Union's commitment to advancing sustainable energy solutions and reducing reliance on fossil fuels while supporting the hydrogen development as a mean of sustainable energy as its assocaiated market.

1.3.1. Hydrogen Market Projection in the Netherlands

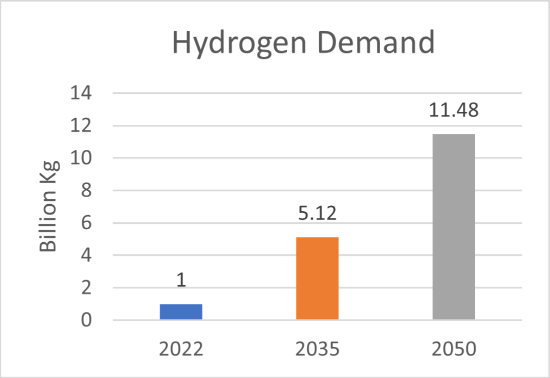


Figure 1.2: Hydrogen Market in Netherlands

The Netherlands as a member of European Union has agreed to hydrogen legislation and have been already working on the sustinable transition for already existed hydrogen market. Currently, the hydrogen market is already established, with a significant contribution from the chemical industry. According to research by Weeda & Segers, the fertilizer industry and refineries in the Netherlands have an annual demand for 0.968 billion kilograms of hydrogen [21]. However, this demand is projected to witness substantial growth in the coming years. By 2035, the demand for hydrogen is estimated to surge to 5.12 billion kilograms, primarily driven by the mobility sector and low-energy industrial processes. Furthermore, this demand is anticipated to further rise to a staggering 11.48 billion kilograms by 2050, with the increasing involvement of high-temperature industrial applications such as aviation and shipping.

These projections highlight the crucial role that hydrogen is expected to play in satisfying the energy requirements of various industries while simultaneously reducing carbon emissions. Figure 1.2 provides an expected projection of the hydrogen market. Among the industries poised to benefit significantly from hydrogen integration is the mobility sector in the Netherlands, which is targeting zero-emission vehicles by 2030. This aim indicates the growing importance of hydrogen in achieving sustainable transportation solutions soon.

1.3.2. Hydrogen for Transport Sector

The global climate agreement aims to achieve the target of selling only zero-emission vehicles by 2030, which has resulted in increased attention towards battery electric vehicles and hydrogen vehicles [14]. Although electric battery vehicles are expected to dominate the mobility market, hydrogen is the most significant alternative fuel for long-way heavy trucks due to the low capacitance of electric batteries [9]. Thus, the Netherlands is investing in hydrogen fuel technology for heavy transport, with plans to replace diesel trains with hydrogen buses. To achieve this goal, the Netherlands has set a target of constructing 50 hydrogen refueling stations by 2025 [22] . Based on the strategic objectives of the Dutch government, the demand for hydrogen in mobility sector is projected to reach saturation at around 50 TWh or 1.49 billion kg per year [21]. Since the government aims to transform all mobility sector to electric and hydrogen vehicles by 2030, the demand for hydrogen in 2050 is predicted to remain at similar levels. Therefore, significant investments in hydrogen infrastructure, particularly in the development of refueling stations for mobility sector, will be required to meet this growing demand.

In the Netherlands, the number of hydrogen refueling stations is on the rise, with 14 stations currently in operation and an additional 14 under construction [23]. These stations cater to the diverse needs of various vehicle types, including trucks, buses, and regular vehicles. The stations are designed differently depending on the vehicle type they serve, with heavy-duty trucks and buses being supplied with 350 bar hydrogen and light-duty vehicles and passengers being supplied with 700 bar hydrogen based on the ISO protocol [24].

On the other hand, hydrogen market development for the transport industry has not still reached the expected level of investment, which slows the acceleration of the sociotechnical regime transition as well [25]. Having limited market is a significant bottleneck for the technology development of today due to spending on more operation where the hydrogen cost is still high to compete with electric and fossil fuel. Therefore, policymakers should not only focus on expanding the number of hydrogen refueling stations but also prioritize market development to create an attractive investment environment for stakeholders such as energy companies.

From the operational perspective, although hydrogen fuel cell technology offers promising benefits, it relies heavily on the availability of reliable and secure refueling stations. Safety, availability and stability of the refueling stations are crucial for ensuring a steady energy supply. Unfortunately, any abnormal situations, such as a leak in the system, can be potentially explosive and pose a significant threat to the permanency of these stations. This situation may have a detrimental impact on the development of niche technology and the profitability of companies operating in this space [26]. Therefore, it is essential to prioritize safety and availability measures and implement robust protocols to prevent and address any potential safety hazards to ensure the longevity of this technology by niche technology developers.

1.4. Role of TotalEnergies

As one of the world’s largest energy companies, TotalEnergies has made a decision to take on responsibility for investing in hydrogen refueling stations and building a hydrogen refueling network in the Netherlands, particularly in a less developed hydrogen market and a high-risk environment, in order to promote sustainable mobility [27]. With a wealth of experience in energy retail business and having already established oil and gas stations, the company aims to leverage this expertise for the new technology.

In order to accomplish this objective, TotalEnergies has already established 4 operational hydrogen refueling stations and has 2 under construction projects in the pipeline. The company’s primary focus is to enhance the availability of its existing hydrogen refueling stations while simultaneously working on cost-reduction initiatives within a high-risk prototype environment. However, attaining this goal which involves improving availability and safety, necessitates a significant shift from old fashion maintenance management to more intricate managerial decision-making processes [28].

To address this challenge TotalEnergies plans to conduct comprehensive reliability, availability, maintainability, and safety (RAMS) analysis. Drawing on their extensive experience of over 40 years in conducting RAMS analyses for the oil and gas sector, the company aims to apply its expertise to this specialized technology [29]. By undertaking this analysis, TotalEnergies aims to enhance the overall availability of its existing system, leveraging its knowledge and insights to drive improvements.

1.4.1. Risk of Hydrogen

Hydrogen is a highly combustible gas that any leakage or ignition source can lead to fires or explosions. It has unique challenges including a wide flammable range, low ignition energy, and a propensity for self-ignition under high pressure. These characteristics increase the probability of ignition if a leak occurs in the system. Additionally, unlike other flammable gases, hydrogen is odorless, colorless, and tasteless, making it undetectable by human senses, which increases the risk of hydrogen. Therefore, for the technology developers mitigation of these risk are essential to foster the development of the technology. This study will focus on the mitigation measures of these risks while trying to preserve energy supply security.

1.5. Net Present Value (NPV) Analysis

To gain insights about possible improvement points, financial metrics like Net Present Value (NPV), which is supported by RAMS analysis can be utilized. It is a financial metric utilized to assess the profitability of an investment or project by taking into account the time value of money [30].

NPV holds significant value in financial analysis and investment decision-making due to its ability to consider the timing and magnitude of cash flows, as well as the cost of capital. It facilitates the comparison of different investment options, evaluation of project financial feasibility, and determination of potential profitability and value creation over time.

For niche technologies like hydrogen refueling stations, which often involve substantial initial investments, the NPV analysis plays a crucial role in assessing their financial viability. These stations are typically in the early stages of development and face uncertainties and risks. By conducting an NPV analysis, decision-makers can gauge the financial impact of these uncertainties and evaluate the project's feasibility. The analysis helps identify key parameters and variables that influence the project's profitability, allowing for sensitivity analysis to understand how changes in these factors affect the NPV. By focusing on improving potential bottlenecks in technology and market aspects, the NPV analysis contributes to the development of hydrogen refueling stations as a promising socio-technical regime for the future.

1.6. Structure of the Report

The next Chapter 2 of this thesis report will focus on formulating the research based on the current research problem. Research formulation will be followed by a comprehensive literature study to gain a better insights of the systematic RAMS analysis concept in Chapter 3. Subsequently, STRAMSA will be explained in the following section, Chapter 4, serves as a guideline for conducting a systematic techno-economic RAMS analysis on hydrogen refueling stations. Once the theoretical part is completed, the applicability of the concept and STRAMSA framework will be assessed through a case study in the subsequent, Chapter 5. Since the design of the framework is an iterative process, the key findings from the case study will be incorporated into the previous section, Chapter 4. Upon verifying the applicability of the framework in the case study, the research will be concluded. In chapters 6, 7, and 8, the study's conclusion will be summarized, the research process and its findings will be discussed, and relevant recommendations will be provided, respectively.

2

Research Formulation

2.1. Research Problem

Research Problem

Lack of guideline or published research available on how to conduct a systematic RAMS analysis specifically for hydrogen refueling stations

Promoting sustainability awareness within society is crucial to achieving the goal of zero carbon emissions by 2050. One promising solution is hydrogen, which boasts lower emissions than gas and oil and can even achieve zero emissions when produced through sustainable methods like water splitting using renewable electricity. To harness the full potential of hydrogen, it is imperative to rapidly develop hydrogen infrastructure, especially in the context of mobility sector [31]. While many energy companies are already interested in building hydrogen refueling systems, it's important to note that due to the unique thermochemical properties of hydrogen, further research and investment are necessary [32].

According to Meyer et al., the availability and presence of hydrogen refueling stations play a critical role in the sustainable energy transition within the mobility sector [31]. Any incidents, losses, or unavailability of these refueling systems can significantly hinder the development of hydrogen technology, especially given the current economic conditions. Moreover, the accumulation of such problems becomes increasingly obstructive to technological advancement.

The absence of a hydrogen supply due to system downtime can cause delays in transportation systems, particularly since hydrogen is predominantly used by long-haul vehicles [33]. These delays in the transportation industry have a cascading effect on service providers and other industries reliant on the transportation of goods. The breakdown in these sectors reduces the satisfaction levels of both service providers and end customers. All of these issues can ultimately lead to a decrease in the acceptance rate of this niche technology.

Further investigation and research are necessary to address these problems and foster the development of hydrogen refueling stations. One significant challenge identified in this development process is the lack of published research and understanding regarding the operational analysis of these stations, which hinders the improvement of overall system availability.

To tackle this challenge, Totalenergies has leveraged its extensive expertise of over 40 years in reliability, availability, maintainability, and safety (RAMS) analysis. RAMS analysis serves as a decision-making tool to enhance the availability of existing hydrogen refueling stations and to inform the design of future stations based on the insights gained from this analysis. By assessing the system's overall availability, a system engineering approach is also needed to be employed to adjust the prototype design of the stations.

The combination of system engineering and RAMS analysis enables a systematic examination of the relationships between system failures and component faults [34]. However, there is no guideline or published research available on how to conduct a systematic RAMS analysis specifically tailored for hydrogen refueling stations.

2.2. Research Objective

Research Objective

The primary objective of this research project is to develop a systematic RAMS study-based approach to identify ways for improving the availability and development of hydrogen refueling stations.

The principal aim of the research project is to establish a comprehensive aaproach based on Reliability, Availability, Maintainability, and Safety (RAMS) studies to effectively identify and explore potential avenues for enhancing the availability and advancement of hydrogen refueling stations. Lack of published research in this domain necessitates the development of a systematic framework that encompasses rigorous assessment and analysis of the various factors affecting the reliability, availability, maintainability and safety of hydrogen refueling infrastructure. In the end, the project provides evidence-based recommendations and strategies that can be employed by stakeholders and policymakers to improve the overall performance and accessibility of hydrogen refueling stations.

2.3. Research Scope

Research Scope

Systematic Techno-economic RAMS analysis for Hydrogen Refueling Stations - Case study: Total Energies Breda Hydrogen Refueling Station

The scope of this research project entails utilizing a TotalEnergies Breda hydrogen refueling station as a representative case study to establish a RAMS (Reliability, Availability, Maintainability, and Safety) study-based approach aimed at identifying strategies to enhance the availability and development of hydrogen refueling stations. The research specifically concentrates on further advancing the RAMS study-based methodology while also incorporating off-site predictions derived from the case study. By focusing on the development of the RAMS approach, the research aims to refine and expand upon existing methodologies, ensuring a comprehensive framework for assessing and improving the performance of hydrogen refueling stations. Moreover, by incorporating off-site predictions based on the case study, the research clarifies the interplay between various external factors and their influence on on-site activities and system design for the future.

2.4. Research Questions

Research Question - Main

How can a systematic RAMS study-based approach be developed to improve the availability of hydrogen refueling stations by leveraging conventional RAMS methodological frameworks?

The main research question focuses on developing a systematic RAMS (Reliability, Availability, Maintainability, and Safety) study-based approach to enhance the availability of hydrogen refueling stations by utilizing conventional RAMS methodological frameworks. The objective is to bridge the knowledge gap and adapt established RAMS practices from other industries to the specific context of hydrogen refueling stations. This research aims to explore and identify key components and techniques within conventional RAMS frameworks that can be effectively applied to improve the availability of hydrogen refueling infrastructure. By leveraging the insights gained from conventional RAMS methodologies, the research aims to develop a comprehensive approach that addresses the unique challenges and requirements of hydrogen refueling stations. Ultimately, the objective is to provide stakeholders in the hydrogen industry with evidence-based recommendations and strategies to enhance the availability and operational efficiency of hydrogen refueling stations, thereby promoting the wider adoption and accessibility of hydrogen fuel as a sustainable energy source for the mobility service. In order to attain the objective, the following sub research questions were formulated:

Research Question 1

What are the critical steps, approaches and KPIs for conventional systematic RAMS methodologies?

The research question at stake investigates the structure and characteristics of conventional RAMS (Reliability, Availability, Maintainability, and Safety) methodological frameworks. Exploring this question involves an in-depth analysis of the existing frameworks employed in various industries to assess and optimize the RAMS aspects of complex systems. Conventional RAMS frameworks typically encompass a systematic and structured approach that incorporates a combination of quantitative and qualitative methods. These frameworks commonly involve identifying and defining key system elements, analyzing failure modes and their probabilities, evaluating the impact of failures on system performance and availability, assessing maintenance strategies and requirements, and addressing safety considerations. The frameworks may also involve conducting risk assessments, incorporating reliability-centered maintenance practices, and implementing safety measures and protocols. By investigating the structure and components of conventional RAMS methodological frameworks, the research question aims to provide a comprehensive understanding of established practices in the field, which can further inform the development and improvement of the systematic RAMS-study approach in hydrogen refueling station to fill the knowledge gap about how to improve the overall availabilities of the system.

Furthermore, it is to explore and identify the RAMS analysis metrics and techniques from conventional RAMS methodology that can be effectively applied to the context of hydrogen stations. This investigation aims to bridge the gap between the established RAMS practices in other industries and the unique requirements of hydrogen refueling systems. By examining the existing conventional RAMS methodologies, the research endeavors to pinpoint specific metrics and techniques that can be adapted and utilized to assess the RAMS aspects of hydrogen stations. This exploration may involve analyzing key performance indicators, such as system uptime and failure rates, as well as employing techniques like fault tree analysis, failure mode and effects analysis, and reliability block diagrams to assess the potential failure modes and their impacts.

Research Question 2

How can historical failure data of a hydrogen refueling station be structured to be used in appropriate RAMS KPIs for the life cycle assessment of system components?

The previous sub-research question was dealing with the exploration of RAMS-study from different industries. In this question, the practical application of RAMS will be questioned. According to Zio et al., to conduct systematic RAMS analysis below steps are critical [34]:

- How to gather the data and enter it into the appropriate mathematical format, e.g., in the form of expert opinion.
- How to combine data from various sources to create a single representation of uncertainty.
- How to properly represent the uncertainty in the analysis output by propagating the uncertainty through the model.

Under this guidance, this sub-research question was formulated to construct a structured approach for utilizing historical failure data from a hydrogen refueling station to develop appropriate RAMS metrics for the life cycle analysis of the system and its components. By examining the historical failure data of the station, the research question targets to identify patterns, trends, and common failure modes that can inform the RAMS metrics used in assessing the availability performance of the system and reliability of various components throughout their life cycle. This objective involves step for designing a systematic framework to collect, organize, and analyze the failure data, including factors such as system uptime, failure rates, and maintenance records. By structuring this data in a meaningful and standardized manner, the research seeks to develop RAMS metrics that accurately reflect the behavior and availability of the system over time.

Research Question 3

What is the way to assess the system availability with uncertain KPIs?

The research question focuses on finding a way to assess the availability of a system with associated uncertain key performance indicators (KPIs). System availability refers to how well a system is operational and accessible when needed, while KPIs are measurable metrics used to evaluate system performance. The term ”uncertain KPIs” implies that the system’s performance indicators as system uptime and downtime, cannot be accurately predicted. The sub-research question aims to identify a methodology or approach that can effectively handle this uncertainty and provide a comprehensive assessment of system availability. This process may involve statistical techniques, probabilistic modeling, or simulation methods to quantify the impact of uncertain KPIs. Ultimately, it seeks to enhance the reliability of systems in real-world scenarios.

Research Question 4

How can the integration of techno-economic analysis into a systematic RAMS analysis facilitate the decision-making process?

The objective of this sub-research question is to explore and identify method for integrating the techno-economic analysis of a hydrogen refueling station into the systematic RAMS framework that can facilitate the decision-making process. It aims to develop a comprehensive understanding of how the techno-economic aspects of the station, such as capital costs, operational and maintenance expenses, revenue generation, potential revenue losses resulting from unplanned downtime or failures, as well as the potential costs associated with risk factors, such as injured/fatality incidents can be incorporated into the process [26, 35]. By incorporating these aspects into the systematic RAMS analysis, a comprehensive evaluation can be conducted to assess the environmental, social, and economic impacts of the station. This integration enables stakeholders to make informed decisions regarding the design, operation, and safety of the system.

Ultimately, the holistic approach enables to perform the sensitivity analyses to provide insights with respect to which input uncertainties dominate the output uncertainties, so as to guide resources towards an effective uncertainty reduction [34]. Moreover, achieving this objective and insights will contribute to optimizing the life cycle performance of the station by considering both the technical and economic factors to facilitate the transition towards a more sustainable and cost-effective hydrogen economy. All these processes are summarized with following Figure 2.2 Research Flow Diagram.

2.5. Targeted United Nation Sustainable Goals by the Research

Given the increasing societal pressure to foster sustainable societies and address the potentially catastrophic effects of climate change by reducing CO_2 emissions, the United Nations has established a set of goals called the United Nations Sustainable Development Goals (SDGs) [36]. SDG 13 specifically centers around climate action and aims to tackle the challenges posed by climate change. In line with these objectives, the present project aims to develop a systematic approach based on RAMS studies to identify and improve the availability and development of hydrogen refueling stations. These stations play a crucial role in the broader agenda of transitioning to clean and affordable energy, aligning with SDG 7. Additionally, as hydrogen refueling stations represent relatively new technology and form the foundation of the hydrogen infrastructure,

Figure 2.1: Targeted Sustainable Development Goals by the Project

enabling the supply of energy fuel to end consumers, they also align with the goals set forth in SDG 9, which emphasizes industry, innovation, and infrastructure.

Consequently, this research initiative inherently contributes to the reduction of CO_2 emissions. By transitioning from fossil fuels to hydrogen as the primary fuel source for mobility sector, a substantial decrease in CO_2 emissions can be achieved. This reduction is particularly significant when sustainable energy sources, such as electrolysis, are employed in hydrogen production, effectively reducing emission levels to almost zero. Therefore, the current plan, by embracing this sustainable fuel transition, has the potential to save approximately 0.514 million metric tons of CO_2 emissions annually, replacing fossil fuel usage with hydrogen [17, 37]. Such a substantial reduction in emissions directly contributes to the advancement of SDG 11, which is dedicated to the development of sustainable cities and communities.

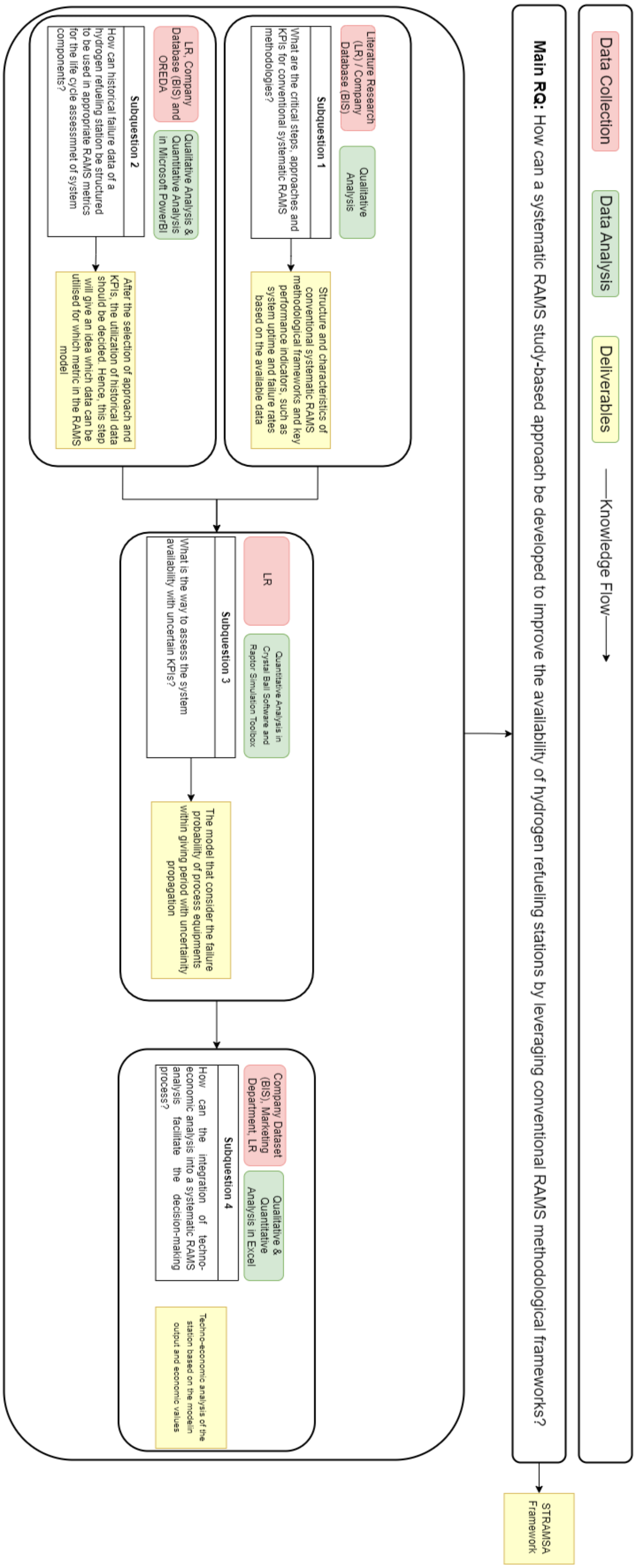


Figure 2.2: Research Flow Diagram

Part II

Theoretical Research

3

RAMS and System Engineering

3.1. System Risk Assessment Methodologies

In the past, the analysis of the old system operated under the assumption that the system's boundaries were fixed. There was a clear and defined objective to achieve, and actuarial data was accessible to support quantification models [34]. This approach heavily relied on reductionism and cause-and-effect relationships to comprehend how the elements of the system behaved. However, experts in risk, safety, and reliability are now recognizing the need for a new approach to analyze and manage the complex distributed systems and critical infrastructures that form the fundamental basis of modern industry and society.

As hydrogen refueling stations are regarded as a fundamental infrastructure for energy supply in current and future mobility services, it becomes essential to adopt comprehensive methods to effectively manage inherent complexity and uncertainty of this system [38]. Consequently, various methods and toolboxes for analyzing system operations have been thoroughly examined for this purpose.

Among the different methods for systems risk assessment modeling, such as Root Cause Analysis (RCA), Failure Mode and Effect Analysis (FMEA), and Quality Control Tool, RAMS (Reliability, Availability, Maintainability, and Safety) stands out as an engineering methodology that can be employed at various stages of the design process and system operation [39]. It is not only focuses on operational efficiency but also emphasizes safety considerations. By pinpointing areas within the system or process that require improvement, RAMS enables the initiation of targeted actions to enhance performance. Therefore, it proves to be a practical methodology suitable for operational purposes that can effectively manage the uncertainty and complexity of the system.

3.1.1. Detailed comparison of system risk assessment methods

Table 3.1: System risk assessment methods and their comparison

Method	Type of Method	Advantages
RAMS	Qualitative & Quantitative	Easy to apply for both operational and design stages
FTA	Qualitative	Easing the understanding of the root cause of a failure
FMEA	Qualitative	Enabling the mitigation measures for different failure modes
Condition Monitoring	Quantitative	Enabling proactive maintenance based on the real time data

Fault tree analysis (FTA)

Fault tree analysis (FTA) is utilized to assess the impact of both independent and dependent failures on the system, aiming to uncover the underlying causes of any issues within the system [40]. FTA provides a qualitative approach that enables users to understand potential problems within the system and helps identify their root causes. However, RAMS can encompass both qualitative and quantitative analyses for evaluating system performance and identifying potential faults within the system.

Failure mode and effect analysis (FMEA)

A failure mode and effect analysis (FMEA) is another qualitative method for identifying the critical components, failure modes, and root causes that significantly impact a system's reliability and availability [41, 42]. By conducting an FMEA, you can gain insights into suitable preventive measures that can help mitigate the likelihood or severity of failures. This approach can ultimately lead to improved system performance, greater customer satisfaction, and reduced costs associated with downtime or repairs. [43].

However, RAMS employs probabilistic analysis, which utilizes the outcomes of qualitative analysis as a foundation for quantitatively conducting comparative evaluations to facilitate informed decision-making [42]. By doing so, RAMS effectively mitigates engineering uncertainty.

Condition Monitoring

Condition monitoring is a systematic process of monitoring and assessing the performance and health of equipment or systems in real-time to detect any deviations or abnormalities from their normal operating conditions. It can be a reliable approach in order to understanding the reality of alarms [34]. However, the accuracy of alarms is a critical issue in this approach. For niche technologies, since the expected number of alarms is high in the beginning, these false alarms can decrease the quality of the condition monitoring process. Moreover, false alarms result in extra cost for the system because it requires further diagnosis and manpower.

RAMS

RAMS (Reliability, Availability, Maintainability, and Safety) represents a comprehensive both qualitative and quantitative methodology that encompasses a range of vital performance attributes of a system. It takes a strategic approach to integrating these attributes by utilizing various methods, tools, and engineering techniques. By identifying and quantifying equipment and system failures that hinder the achievement of objectives, RAMS aims to address operation and safety issues throughout the design process and system operation [28].

Furthermore, RAMS plays a crucial role in optimizing system performance by identifying necessary modifications. It ensures a holistic approach to system design and operation by addressing operational and safety aspects. This comprehensive methodology empowers engineers to make informed decisions, leading to improved system reliability, availability, maintainability, and safety. It enhances the decision-making process for management, boosts the system's profitability, and minimizes the environmental impacts associated with its operation in maintaining the license to operate, by providing real and up-to-date data concerning the actual state of the plant [28].

The RAMS analysis can be carried out during the operational stage by utilizing actual data gathered from the facilities. This utilization enables the identification of equipment that could potentially face reliability issues or maintenance difficulties. Thus, this analytical procedure involves examining patterns and incorporating valuable input from technicians and users. Ultimately, it helps extend the lifespan of the plant and ensures a reliable energy supply, promoting its security [44].

For the data collection process of RAMS analysis, there is already established standardization ”ISO14224: Petroleum, petrochemical, and natural gas industries - Collection and exchange of reliability and maintenance data for equipment”, which enables data sharing among the different industry parties [45]. It aims to ease the data-sharing process among sector stakeholders to foster the development of niche technology. Codification for failures and their details can ease the data collection and its structuring [46].

3.1.2. Drawbacks of RAMS

When comparing various approaches, methodologies, and their associated benefits and drawbacks, a rational and quantitative approach has emerged as the preferred option for the design, regulation, and management of safety in hazardous systems [34, 46]. Additionally, the extensive experience accumulated over more than 40 years in conducting RAMS analysis further justifies the selection of this methodology for operational performance and safety analysis. Furthermore, combining RAMS analysis with techno-economic assessment provides an important Key Performance Indicator (KPI) like Net Present Value (NPV) for businesses, facilitating decision-making processes for policymakers and companies alike [46].

Despite the benefits of RAMS analysis, it is important to consider its drawbacks. RAMS analysis can be complex, requiring specialized knowledge and resources. Data availability and quality can pose challenges, especially for the niche technologies like hydrogen refueling stations. Assumptions and uncertainties are inherent in the analysis, and its scope may be limited to a specific system level. Interpreting the results and making decisions based on the analysis can be challenging. Additionally, the dynamic nature of systems necessitates regular updates and validation.

3.2. Reliability, Availability, Maintainability and Safety (RAMS) Analysis

Within the RAMS methodology, reliability refers to the system's probability of functioning properly, while availability quantifies the frequency of its operational status. Maintainability assesses the ease of repairing and maintaining the system, whereas safety pertains to the level of user protection it ensures [47]. Before diving into further explanations of these metrics, it is essential to define the key terms within this method. This step plays a crucial role in enhancing our understanding of the concept. To accomplish this, ISO 19880 - Hydrogen Gaseous Standard and the book Glossary of Reliability and Maintenance Terms" are utilized as guidelines. This standard is widely regarded as the most comprehensive and up-to-date resource for hydrogen-related practices where the book defines the key terms very precisely [24, 48]:

3.2.1. Definition of Key Terms in RAMS Method

Failure: The loss of the ability of a system/subsystem/component to perform its required function.

Incidents: Any unforeseen occurrence resulting in injury or ill health of people, damage and loss of assets, plants, materials, and the environment, or a loss of business opportunities.

RAMS Data: Raw data, which is gathered during the life cycle of the system, specifically failure mode, failure causes, operation condition data [46].

RAMS Information: Reliability, availability, and maintainability distributions or functions of the system.

Probability: Expressing the likelihood of an anticipated event occurring to a particular property, system, business, or environment.

Risk: Risk is the inherent potential for experiencing harm, loss, or adverse consequences due to uncertain events or circumstances. It is a multiplication of two critical elements: the probability or likelihood of an undesirable event occurring and the potential impact or magnitude of the resulting consequences.

$$\mathcal{R} = \sum_{n} f_n * c_n \tag{3.1}$$

where, R is overall risk based on n selected scenarios, f_n is the frequency of scenarios,and c_n is the consequence of scenario n.

Risk assessment: Risk assessment is a process of evaluating and assigning a numerical or descriptive value to the level of risk associated with a particular situation and a known threat (also referred to as a hazard). It encompasses a comprehensive approach that includes identifying risks, analyzing them, evaluating their significance, and devising strategies to mitigate or reduce those risks. Various toolboxes, such as HyRAM and SAFETI-NL, are commonly employed in the field of risk assessment to aid in the assessment and management of risks [49].

3.2.2. Reliability

The concept of reliability engineering gained significant momentum during World War II, as the need for efficient utilization of materials became critical for both the German and American allies. This military-driven demand led to the establishment of the reliability engineering discipline [34]. Nevertheless, these early efforts were primarily focused on materials and understanding the measures that could improve equipment reliability.

This effort leads to a collection of failure data and root cause analysis of failures. During the Korean War, this discipline gained more popularity because of the high expenditure on spare materials. It required more developed techniques such as redundancy modeling, bayesian statistics, Markov chain, etc. Moreover, the reliability engineering's focus shifted from components to the system level during the war. However, the system level requires a significant level of computational power. Thus, until the last 20-25 years, the development of reliability engineering was less than expected. With the development of computational power significantly, the system level reliability has gained more attention.

Today, reliability engineering is a well-established multi-disciplinary scientific discipline that enables reliable-based system design and operations. It aims at providing an ensemble of formal methods to investigate the uncertain boundaries between system operation and failure [34, 50]. Reliability as a metric of reliability engineering can be defined as the probability of equipment, machinery, or systems performing their required function satisfactorily under given conditions for a specific period [41]. It is measured by mean time between failures (MTBF) which states the duration or probability of failure-free performance under stated conditions.

In more robust statistical methodologies, the MTBF can be defined with a function that is called the reliability function, also known as the survival function or the complementary cumulative distribution function (CCDF). It is a tool used in probability theory and survival analysis, which describe the probability that a system or a component will survive beyond a certain time or age. It helps in understanding the failure characteristics of a system, estimating the remaining useful life, determining maintenance schedules, and making decisions regarding system design, maintenance and replacement. It is typically denoted as R(t), where 't' represents time. It gives the probability that a system or component will function properly or survive beyond time 't'. Mathematically, it is defined as:

$$R(t) = P(T > t) \tag{3.2}$$

,where P(T > t) represents the probability that the lifetime of the system or component, denoted by 'T', is greater than 't'. In below Table 3.2, there are some examples of reliability functions for different distribution types commonly used in reliability analysis, and which were utilized within this research:

Table 3.2: Reliability Functions for Different Distribution Types

Distribution Type	Reliability Function	Parameters	Reference
Exponential	$e^{-\lambda * t}$	λ = failure rate	[51]
Weibull	$e^{(-\lambda * t)^k}$	λ = scale & k=shape	[52]
Lognormal	$1 - \phi(\frac{\ln(t)-\mu}{\sigma})$	ϕ = CDF & μ = Mean & σ = SD	[53]
Normal	$1 - \phi(\frac{t-\mu}{\sigma})$	μ = Mean & σ = SD	[53]
Beta	$\frac{B(\alpha,\beta)}{B(\alpha,\beta,t)}$	B(α,β,t) = Beta Func.	[54]

The Weibull distribution is characterized by the shape parameter 'k', which determines the failure characteristics, such as decreasing, constant, or increasing failure rates while the scale parameter 'λ' represents the time scale. In addition to the Weibull distribution, lognormal and normal distributions are other common distribution types which utilize the cumulative distribution function, denoted by Φ.

The lognormal distribution is commonly employed for modeling the lifetimes of components that undergo multiplicative factors. Similarly, the normal distribution is used to model component lifetimes but assumes an additive factor instead of a multiplicative one. Lastly, in the beta distribution B(α, β) represents the beta function, and B(α, β, t) corresponds to the incomplete beta function. The beta distribution is highly versatile and can effectively model a wide range of failure characteristics.

These are just a few examples of commonly used distributions in reliability analysis, and each distribution has its own set of parameters and assumptions. The specific distribution to use depends on the characteristics of the system or analyzed component and the available data.

3.2.3. Availability

From the RAMS perspective, there are two different terms for availability in the literature: *Operational availability* and *Inherent availability*. Operational availability is defined as "The probability that a system or equipment, when used under stated conditions in an actual operational environment, shall operate satisfactorily at a given point in time. It includes ready time, logistics time, and waiting or administrative downtime.

On the other hand, inherent availability is defined as 'The probability that a system or equipment when used under stated conditions without consideration for any scheduled or preventive action in an ideal support environment, (i.e. available tools, spares, personal, data, etc.) shall operate satisfactorily at a given point in time. It excludes ready time, preventive maintenance downtime, logistics time, and waiting or administrative time. In our analysis, inherent availability is utilized, which caused the exclusion of preventive maintenance from the scope of the research.

Based on that selection, availability takes into account both the reliability and the maintainability or repairability of the system. It represents the overall effectiveness of a system in meeting its operational requirements. It is typically expressed as a percentage or a fraction of the system's uptime to the total duration. The total duration includes operating hours and downtime due to maintenance, repairs, or unplanned events.

Mathematically, availability (A) can be calculated using the following formula:

$$\mathcal{A} = \frac{MTBF}{(MTBF + MTTR)} * 100 \tag{3.3}$$

,Where:

- MTBF (Mean Time Between Failures) is the average time between consecutive failures of the system.
- MTTR (Mean Time To Repair) is the average time required to repair or restore the system to an operational state after a failure.

By considering both the mean time between failures and the mean time to repair, the availability metric provides a comprehensive view of a system's ability to remain operational and ready for use.

3.2.4. Maintainability

In RAMS methodology, maintainability refers to the ability of a system or component to be restored to an operational state within a given timeframe and using specified procedures and resources after a failure or a scheduled maintenance action [48]. It focuses on the ease, speed, and effectiveness of maintenance activities to minimize downtime and ensure that the system can be quickly brought back to its intended operating condition.

It is measured by MTTR is the average time required to repair or restore the system to an operational state after a failure. RAMS analysis aims to reduce MTTR as much as possible by lowering the maintenance cost. To reduce MTTR, there are several aspects that can be utilized:

1. Well-documented and standardized maintenance procedures are crucial for efficient and safe repairs. Clear instructions, checklists, and guidelines help maintenance personnel quickly diagnose faults, locate failed components, and perform necessary repairs or replacements under safe conditions
2. Implementing proactive maintenance strategies, such as predictive and preventive maintenance, can enhance maintainability. Predictive maintenance techniques, such as condition monitoring and predictive analytics, aim to identify potential failures in advance, allowing for planned maintenance actions. Preventive maintenance involves scheduled inspections, lubrication, cleaning, and replacement of components to prevent failures before they occur.

3.2.5. Safety

In the RAMS aspect, safety refers to the actions or steps taken to prevent hazardous events that could potentially cause harm or injury [48]. Safety analysis involves identifying and mitigating potential hazards and risks associated with the system. It aims to prevent accidents, failures, or malfunctions that could lead to harmful consequences. Key steps to conduct safety analysis are listed below [55]:

1. **Hazard Identification:** The first step in ensuring safety is to identify potential hazards associated with the system. This process involves analyzing the system components, their interactions, and the potential failure modes that could lead to hazardous conditions.
2. **Risk Assessment:** Once hazards are identified, a risk assessment is performed to evaluate the likelihood and severity of potential accidents or failures. This assessment helps prioritize risks and determine appropriate mitigation strategies.

3. **Risk Mitigation:** Risk mitigation involves implementing measures to reduce or eliminate identified risks. The mitigation process can include design modifications, safety devices, protective measures, warning systems, redundancy, fail-safe mechanisms, and safety protocols.
4. **Safety Standards and Regulations:** Compliance with safety standards and regulations are critical in ensuring the safety of systems. Reliability engineers must stay updated on relevant safety codes, regulations, and industry best practices to design and operate systems that meet or exceed safety requirements.
5. **Safety Testing and Verification:** Rigorous testing and verification processes are conducted to ensure the system meets safety standards and operates safely under various conditions. This step may include reliability testing, failure mode and effects analysis (FMEA), fault tree analysis (FTA), and other safety assessment techniques.
6. **Safety Training and Procedures:** Adequate training and clear procedures are essential for the safe operation and maintenance of the system. Training programs should address safety protocols, emergency procedures, and proper handling of the system to minimize risks.

By considering safety as an integral part of RAMS analysis, systems can be designed and operated in a manner that minimizes hazards, prevents accidents, and protects the well-being of individuals and the environment.

3.2.6. Conventional RAMS Process

Given that RAMS (Reliability, Availability, Maintainability, and Safety) is a well-established method widely adopted in various industries, the process for conducting this assessment is already firmly established. Several established frameworks provide common steps for conducting RAMS analysis, which can serve as a structured guide for designing systematic RAMS analysis for hydrogen refueling stations. The following steps, identified through a comprehensive literature review, are deemed critical for the conventional RAMS framework [26, 41, 46, 47, 56, 57]:

1. Data collection
2. Data quality assessment and cleaning
3. Building observed system’s block diagram
4. RAMS metric calculations and its parameter estimations
5. Process simulation for system’s availability and risk assessment
6. Economic, environmental and safety consequence analysis
7. System modification

A crucial aspect of the analysis is a data collection, which enables information sharing within the company and the industry. To ensure effective data sharing, it is essential to establish a standardized approach for failure identification codes and equipment part numbers that can be adopted globally.

In response to this need, ”ISO 14224: Petroleum, petrochemical, and natural gas industries — Collection and exchange of reliability and maintenance data for equipment” was introduced [45]. This comprehensive standard aims to establish common technical terminologies and methodologies for stakeholders, facilitating seamless data sharing between them. By adhering to this standard, organizations can enhance collaboration and streamline the exchange of reliability and maintenance data.

The forthcoming chapters will examine the systematic RAMS framework, elucidating each step in detail. The subsequent chapter 4 will clarify the intricacies of each individual step, furnishing a comprehensive guide for the proficient execution of RAMS analysis.

3.3. System Engineering

System engineering is an interdisciplinary approach and a systematic process used to design, analyze, develop, and manage complex systems [58]. It encompasses various engineering disciplines and considers the entire life cycle of a system, from conception to decommissioning.

System engineering focuses on defining system requirements, understanding stakeholder needs, and integrating various subsystems and components to create a cohesive and functional system [58]. It involves a holistic more structured perspective, considering not only the technical aspects but also the operational, logistical, economic, and societal factors associated with the system.

This study incorporates the system engineering discipline to assess the existing design of hydrogen refueling stations, considering their high-risk prototype environment. The purpose is to assess the system's performance and identify areas where adjustments may cause improvement in the overall availability of hydrogen refueling stations. Through an iterative assessment process, the station's design can be modified with any identified improvement points to optimize its design.

The evaluation of the design is conducted using a comprehensive systematic techno-economic RAMS analysis approach that combines techno-economic analysis and systematic RAMS analysis. This integrated analysis provides insights into the economic feasibility and overall availability of the system while also highlighting potential areas for development. The subsequent section examines further detail on how system engineering can be seamlessly utilized for RAMS analysis, and their application in the context of hydrogen refueling stations.

3.4. System Engineering & RAMS

The utilization process of system engineering into the RAMS (Reliability, Availability, Maintainability, and Safety) analysis is an iterative process that allows for the reconfiguration of system architecture based on RAMS results. This approach enables the applicability of RAMS analysis even to the design stage if there is sufficient available data for the components.

Given that hydrogen refueling stations are prototypes, the research highlights the need for developing new designs that can be better understood from a system engineering perspective. This need emphasizes the importance of applying systematic and holistic approaches to analyze and optimize the performance of these niche systems. By adopting a system engineering perspective, researchers can consider the interdependencies and interactions among various components, subsystems, and stakeholders, ensuring that the design of the stations is comprehensive, efficient, and effective. Utilizing the system engineering can enable a better understanding of the system's behavior, address potential challenges, and guide the development of improved designs that meet the requirements and objectives of the new technology.

Several studies have explored the combination of RAMS analysis with system engineering [28, 42, 43]. These studies highlight the commonalities between the conventional RAMS process and the integration with system engineering. The combined approach typically involves the following steps:

1. System selection and definition
2. Identification of system functions and functional failures, along with the creation of relevant diagrams
3. Data collection
4. Data quality assessment and cleaning
5. Construction of observed system block diagrams
6. Calculation of RAMS metrics and estimation of their parameters
7. Process simulation for system's availability and risk assessment
8. Analysis of economic, environmental, and safety consequences
9. Identification of possible maintenance actions and design alternatives. - This process is iterative, and the output of this step serves as input for adjusting the system architecture in the system function identification phase.

Drawing on these insights, the next chapter will introduce a new framework that shows how to conduct systematic techno-economic RAMS analysis on hydrogen refueling stations. This framework will combine system engineering and RAMS methodology, including techno-economic analysis. Moreover, it has more detailed safety considerations . As a result, it provides a comprehensive analysis of the stations' overall availability, reliability, safety, and economic viability.

4

STRAMSA Framework

This project focuses on developing a comprehensive systematic techno economic RAMS analysis (STRAMSA) framework for hydrogen refueling stations, which enhance their availability, energy supply security, and operational safety. Given the absence of existing RAMS analysis guidelines specific to hydrogen refueling stations, this research will serve as a significant milestone for industrial stakeholders, enabling them to promote this specialized technology within the sustainable energy transition for mobility services. During the design process of the STRAMSA, conventional RAMS frameworks from various industries were leveraged. These established frameworks provided valuable insights and served as a basis for the design of the following STRAMSA framework.

4.1. Novalties of the STRAMSA Framework

The STRAMSA framework introduces several significant contributions to the field of RAMS analysis for hydrogen refueling stations. It is the first framework to seamlessly integrate three distinct approaches: system engineering, RAMS analysis, and techno-economic analysis. By incorporating system engineering principles into the RAMS methodology, the framework enables the design of optimized hydrogen refueling station architectures through iterative requirement elicitation process. This integration fosters a comprehensive understanding of system needs, leading to improved designs.

Moreover, the framework establishes a strong link between RAMS analysis and techno-economic evaluation. By leveraging the findings from the operational study in the techno-economic analysis, stakeholders gain insights into the financial aspects of the hydrogen refueling station, represented by a single key value (NPV). This streamlined integration of operational and economic considerations provides stakeholders with a holistic perspective, facilitating informed decision-making processes. Notably, the techno-economic analysis within the framework extends beyond traditional RAMS studies by incorporating income statement evaluation, investments, subsidies, and net present value calculations. This broader financial analysis enhances decision-making by assessing the economic feasibility and profitability of the hydrogen refueling station.

The techno-economic framework of the STRAMSA framework also introduces novel elements. It includes considerations for inflation, doing-by-learning effects (such as market growth), and deflation rates for niche technology products. These factors enhance the realism and comprehensiveness of the economic analysis, supporting strategic decision-making. Additionally, the framework distinguishes maintenance costs from operational costs, allowing for a more precise understanding of the challenges within the operational subsystem. This distinction improves the accuracy of corrective maintenance cost analysis and facilitates targeted improvements in maintenance strategies.

Another noteworthy aspect of the framework is the quantification of safety in RAMS analysis by assessing associated risks in monetary terms. This approach enables a comprehensive evaluation of safety and risk management, empowering stakeholders to make well-informed decisions regarding safety measures and investments.

Finally, the STRAMSA framework adopts an iterative approach, setting it apart from traditional RAMS studies that are typically conducted once during the design or operation stage. This iterative nature is particularly valuable for niche technologies that require ongoing adjustments and improvements.

4.2. System Architecture Analysis

STRAMSA consists of three distinct phases enabling conducting a systematic RAMS analysis and utilizing its insights for effective decision-making processes. In the first phase, the system architecture of the design is thoroughly examined, which located on the left side of the framework. By considering functional, nonfunctional, and design requirements, the output is a comprehensive system design. This design and system analysis serve as inputs for the RAMS analysis processes, located in the top right section of the framework.

Within the RAMS analysis, in addition to the design/system model, failure rates of each component are required to assess component reliability and overall system availability. The output of the RAMS analysis becomes an input variable for the techno-economic analysis section, found in the bottom right section of the framework. Alongside the RAMS analysis output, this analysis necessitates operational and maintenance cost data, sales data, subsidies, and expected growth rates. The results of this section provides the Net Present Value (NPV) of the station, enabling users of this framework to evaluate the economic value of the design. Furthermore, sensitivity analysis of the NPV analysis offers insights into areas of improvement for the design and system.

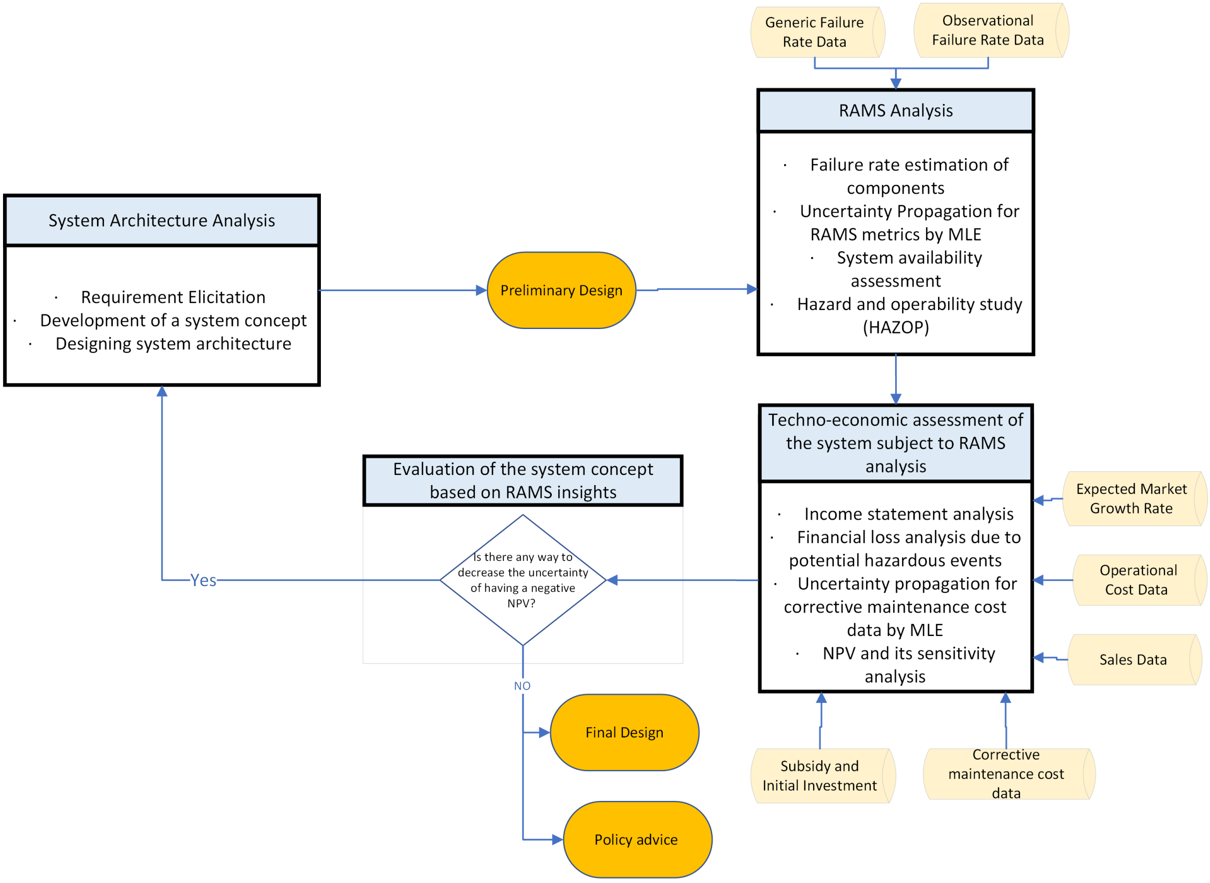


Figure 4.1: STRAMSA Framework

Based on these insights, a feedback mechanism is implemented to adjust the system design in the system architecture part. If further improvements are limited, the obtained design of the station in the current stage becomes the output of the overall design phase. Moreover, this framework provides guidance for policymakers by indicating areas of focus and incorporating political instruments such as taxes, subsidies, and market development as variables. This general overview of the 4.1 serves as an initial guideline for conducting RAMS analysis systematically and streamlining the decision-making process for this niche technology. Detailed explanations of each section of the framework will be provided in the subsequent sections.

4.2.1. Requirement Elicitation

From a systems engineering perspective, ”function” refers to the intended tasks and capabilities of a designed device or system [59]. The elicitation of functional requirements focuses on identifying what a component or design must accomplish, while non-functional requirements specify the desired behavior or structure of the system [60]. These functional, behavioral, structural, and experiential requirements are bounded by design constraints, which are limitations to ensure a safe and viable design implementation. Without these constraints, there would be no limits to realizing these requirements, potentially rendering the realization of the system/device impossible.

The requirement elicitation part of the system architecture analysis thoroughly examines the functional, behavioral, structural and experimental needs of a hydrogen refueling system. Initially, these requirements and design constraints are determined to express the desires and needs of stakeholders. However, this process is iterative throughout the various design stages, which means the requirements may change during the design process and even when the system is operational.

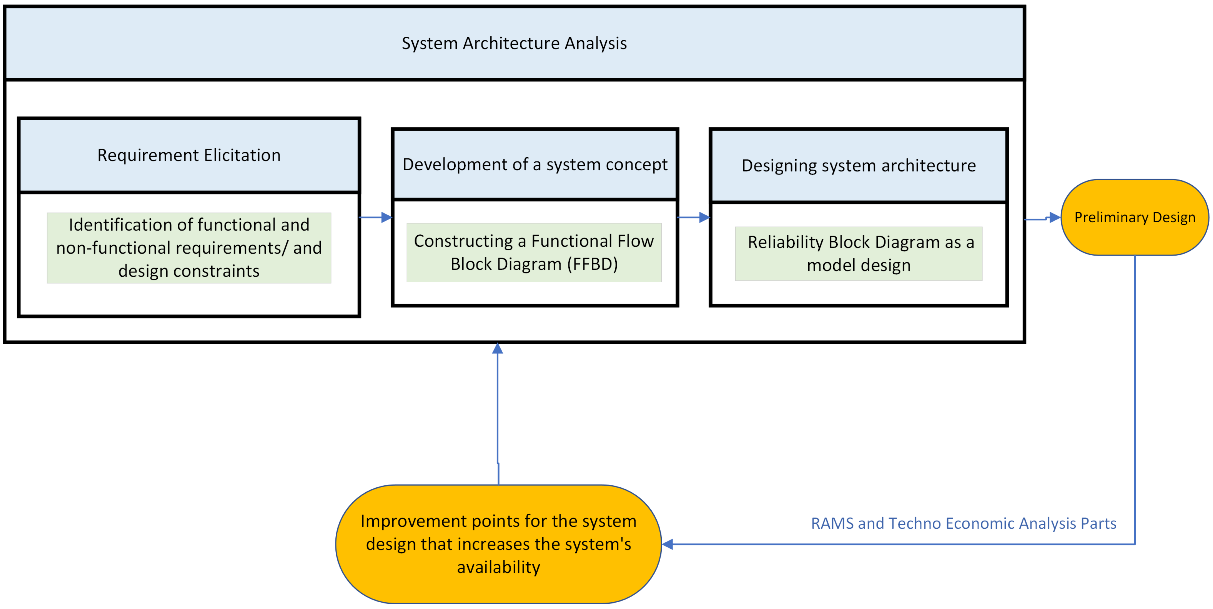


Figure 4.2: System Architecture Analysis

4.2.2. Development of System Concept

The emergence of component-based system development approaches has highlighted the significance of visualizing component interactions and their patterns [61]. Given the complexity of systems with diverse component interactions, architectural modeling is a beneficial tool understanding these patterns and interactions. While there are several methodologies for architectural modeling, two common approaches are the most popular methods for RAMS analysis in the literature: Unified Modeling Language (UML) and Functional Flow Block Diagram (FFBD) [62]. Each approach has its own advantages and limitations. For instance, UML is widely applicable throughout the system design and development phases, making it a popular choice. However, it may have constraints in accurately capturing system attributes and behavior, which could lead to overestimation in the reliability analysis of systems [63].

On the other hand, FFBD serves as a valuable system engineering toolbox, particularly suitable for operational and process research. It utilizes an iterative decomposition of functional requirements and examines the interaction among system requirements. Additionally, FFBD acts as a modeling notation that facilitates the construction of reliability block diagrams (RBDs), enabling the transformation of predefined system requirements into an RBD [64]. Considering its suitability for operational processes and ease of conversion into RBDs, FFBD emerges as a preferred system architecture-building tool for this research.

In this section of the STRAMSA framework, the system architecture is constructed using the FFBD methodology based on the elicited functional and non-functional requirements, as well as design constraints.

The process involves structuring the requirements in a top-down hierarchical manner. Subsequently, a block diagram is created to represent the requirements from top to bottom, explicitly illustrating the interactions between system requirements and components. This step-by-step construction through the FFBD process provides valuable insights into the desired system architecture.

4.2.3. Designing System Architecture

FFBD is a practical diagram that eases understanding of the overall system architecture and its components' interactions. However, it does not directly assess the reliability and overall performance of individual components within the system [65]. Therefore, using only FFBD can make the analysis of component reliabilities and system availability challenging. Further development is required to overcome this limitation by introducing a reliability aspect to the functional and non-functional requirements. The most common way to incorporate these aspects is by constructing a reliability block diagram (RBD).

The RBD depicts the flow of the system functions from left to right, illustrating the inputs and outputs of each component. Each block within the diagram includes a reliability aspect that contributes to the overall availability of the system. In practical terms, the RBD can be understood as a model that represents the reliability structure of the focused system.

Unlike FFBD, the RBD does not directly use ”AND” or ”OR” notations. Instead, it represents these logical operations through series and parallel connections [66]. For instance, in a series-connected configuration, if one system component fails, the entire system becomes unavailable. On the other hand, in a parallel-connected design configuration, the system can remain operational even if one system component fails.

Reliability data within this block diagram is typically calculated by estimating probabilities based on past observational data or generic databases. By accumulating reliability and maintainability data for each system component, its overall availability can be determined. The details regarding reliability calculations will be explained in the upcoming RAMS section. As a result, this block diagram allows users to combine a system architecture perspective with a reliability perspective, facilitating a more comprehensive RAMS analysis.

4.3. RAMS Analysis

4.3.1. Data Acquisition and Structuring

Generic failure rate data compilation from different databases

There are several available databases that provide data points for industry partners to conduct RAMS analysis, such as OREDA (Offshore Reliability Data). OREDA is particularly valuable for the offshore oil and gas industry, as it offers a comprehensive collection of reliability data for this sector. When the applicability of OREDA comes to hydrogen refueling stations, it is also highly suitable since hydrogen is a gas, and similar equipment used in natural gas systems can be applied to hydrogen systems. By leveraging this resource, specific reliability data for each component can be obtained, enabling the initiation of reliable RAMS analysis for the hydrogen refueling system.

Observational failure data acquisition for a specific case

Observational data is collected through real-life applications, and databases serve as repositories for such data gathered from various practices. However, due to the inherent limitation of databases generally storing a single value, it is advantageous to have a larger volume of observational data for more robust uncertainty propagation in system analysis. As stated by Osman et al., a minimum of three consecutive years' worth of data is necessary to conduct RAMS analysis [47]. Nevertheless, for niche technologies like hydrogen refueling stations, there are currently no available databases for conducting RAMS analysis. Consequently, the acquisition of observational data remains the sole means of initiating RAMS analysis for such systems where reliability engineers are responsible for determining the observational data acquisition process.

4.3.2. Failure Rate Estimation of Components

Time To Repair (TTR) and Time Between Failure (TBF) are crucial RAMS metrics widely employed in the industry to evaluate system maintainability and reliability analysis [48]. TTR refers to the duration between component failure and its restoration to operation, while TBF represents the time elapsed between

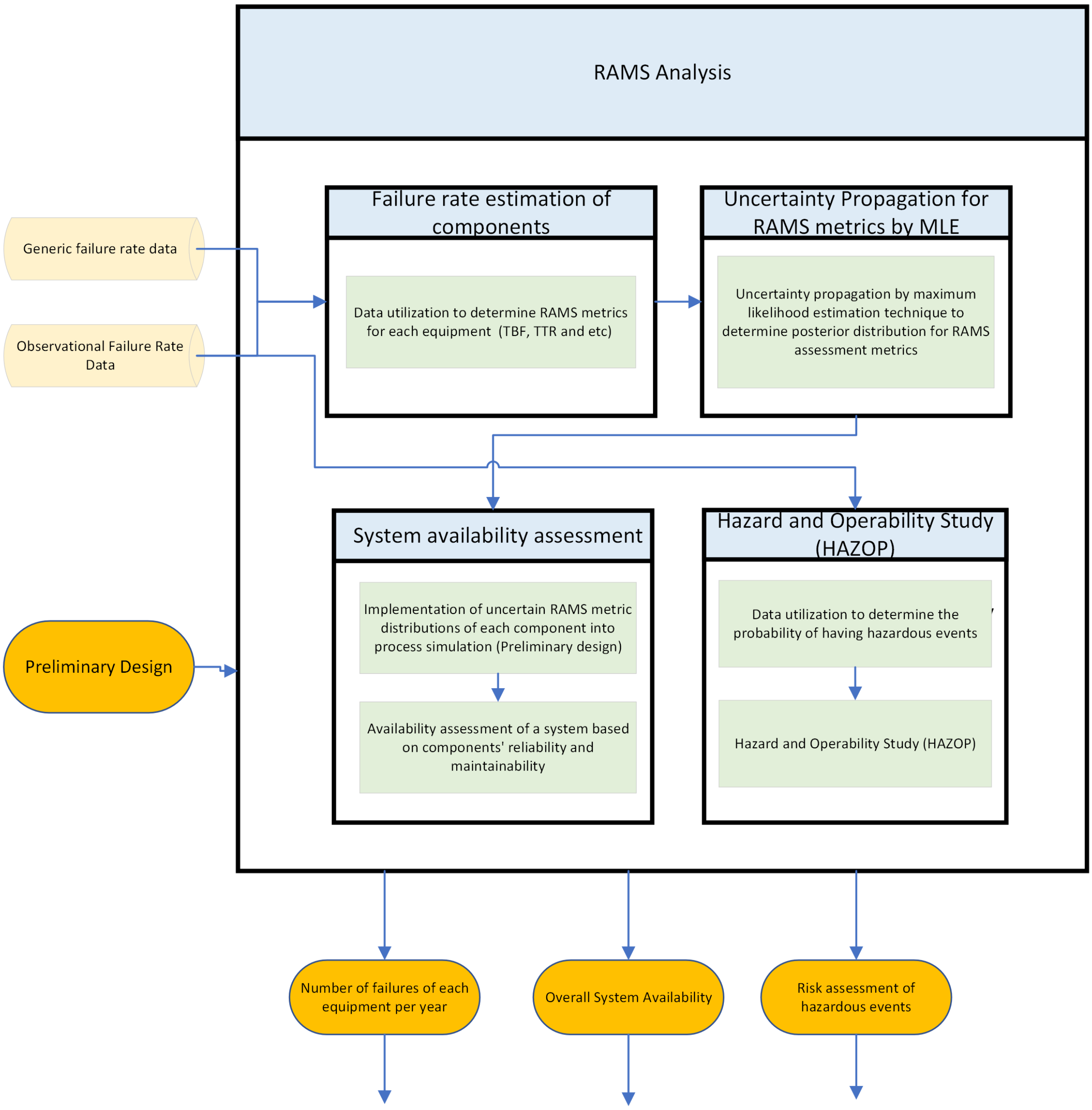


Figure 4.3: RAMS Analysis

subsequent failures after restoration. A schematic representation of these metrics can be observed in Figure 4.4.

Typically, databases offer mean values for these key metrics [24]. However, when utilizing observational data, it is necessary to structure and utilize the data to precisely determine the dates of failures and restoration times. In this particular phase of the framework, alongside the database data, observational data is organized and employed to establish the exact timing of failures and operational durations. The time intervals between failures and operations provide valuable insights into TTR and TBF, which will be further utilized in subsequent sections of the analysis.

4.3.3. Uncertainty Propagation for RAMS Metrics by MLE

In contrast to the approach taken by Al Douri et al., who utilized fixed failure rates and MTTR for each unit in the system, incorporating a probabilistic distribution based on historical failure rates can enhance the robustness of the analysis [26].

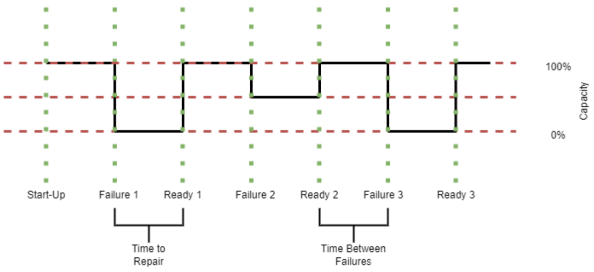


Figure 4.4: TTR and TBF Representation

The previous fixed failure rate approach had limitations in terms of adaptability to changing circumstances. To overcome this limitation, a new approach has been introduced—the utilization of Maximum Likelihood Estimation (MLE). MLE is a statistical method employed to estimate the parameters of a probability distribution that best aligns with the observed data [67]. It also refers as data characterization. The fundamental concept underlying MLE is to identify parameter values that maximize the likelihood of observing the given data. Once the MLE is obtained, the estimated parameter values can be utilized to draw inferences regarding the underlying distribution or generate predictions for future observations. The most commonly employed parameters in this method are:

Mod: In statistics, the mode refers to the value or values that appear most frequently in a dataset [68]. It is the data point that occurs with the highest frequency, making it the most common observation or category within the data. In mathematical explanation, it is where a derivative of a mathematical function (the fit function) with respect to variables is equal to zero. It is a measure of central tendency, along with the mean and median, and provides information about the most common or popular value(s) in the data.

Mean: In statistics, the mean is a measure of central tendency that represents the typical value of a dataset [69]. It is calculated by summing up all the values in the dataset and then dividing the sum by the total number of values.

Percentile: A percentile is a statistical measure that indicates the relative position of a particular value within a dataset [69]. It is used to understand how a specific observation compares to the rest of the data.

The adoption of a probabilistic approach has demonstrated its efficacy in evaluating system operational and safety analysis [34]. This approach surpasses the examination of worst-case accident scenarios by encompassing a comprehensive exploration of all potential scenarios and their corresponding outcomes. Moreover, quantifying the likelihood of such scenarios occurring plays a pivotal role in effectively managing uncertainty in a rational and numerical manner. Consequently, in this particular stage, the time to repair (TTR) and time between failures (TBF) sample data, computed during the previous phase, are subjected to characterization in order to facilitate the propagation of uncertainty. Various data characterization tools, such as Crystal Ball, can be employed to accomplish this task. The resulting output parameters from this statistical data utilization process serve as inputs for RAMS analysis toolboxes, which in turn assess the overall system's availability.

Monte Carlo Simulation

Monte Carlo simulation is a computational technique employed for modeling and analyzing intricate systems or processes characterized by uncertainty and randomness [70]. In this simulation, uncertain parameters within the system model are assigned random variables. These variables are sampled iteratively, generating a significant number of simulations. Each iteration represents a potential outcome of the system based on the assigned probability distributions of the variables.

By conducting numerous iterations, Monte Carlo simulation facilitates the estimation of probabilities and potential outcomes across various system scenarios. It offers a statistical approach to comprehend the range of possible results, assess risks, and make well-informed decisions.

As noted by Zio et al., Monte Carlo simulation is considered the most practical method for accurately capturing the true nature of multi-state stochastic behavior in a quantitative manner [71]. Therefore, this research adopts Monte Carlo simulation as its chosen methodology.

Drawback of Monte Carlo Simulation

However, it is important to note that Monte Carlo (MC) simulation has certain limitations when applied to dynamic systems. The dynamics of the system, including its evolution over time, are concealed within the life histories of the system [34]. Simply selecting random data for each simulation run fails to capture the aging effects of equipment, which can have a detrimental impact on the analysis. Therefore, it is crucial to incorporate the physical behavior of the system into MC simulations to ensure accurate and reliable results.

4.3.4. System Availability Analysis

Converting System Architecture into Simulation Model

The main objective of a Reliability Block Diagram (RBD) is to provide a comprehensive understanding of the system architecture and establish a robust structure for the corresponding system. However, there are instances where transforming the RBD into a simulation model using simulation toolboxes can be challenging, primarily due to the lack of sufficient data for certain components. Moreover, software tools often employ their own specific structured languages for constructing models. Therefore, incorporating the RBD into the model toolbox may require adjustments, which are addressed in this step of the framework if deemed necessary.

Implementation of uncertain failure rate distribution of each component into process simulation

The RAMS toolboxes are designed to incorporate statistical parameters for system simulation. In this step of the STRAMSA framework, the implementation of the maximum likelihood estimation parameters for the Time to Repair and Time Between Failures of each piece of equipment is applied. Each simulation block that represents system components utilizes these statistical parameters in order to predict the component's reliability and maintainability.

Overall System Availability Analysis

This section focuses on running the simulation. Once the RAMS simulation model is constructed within a simulation toolbox and uncertain parameters for component reliability (TBF) and maintainability (TTR) are defined, the system is ready for execution. To effectively propagate uncertainty, as addressed in previous sections, random value selection for the TTR and TBF of each component is necessary to enhance the robustness of the simulation output. This is where RAMS analysis toolboxes incorporate Monte Carlo Simulation, leveraging its ability to propagate uncertainty and introduce randomness into the simulation.

4.3.5. System Risk Assessment from HAZOP Study

In this part, the STRAMSA framework utilizes a System Risk Assessment from Hazard and Operability Study (HAZOP), which is a methodical and structured technique employed in process safety to thoroughly examine a system and pinpoint any deviations from its intended operation that may pose risks [40]. HAZOP study involves a diverse team of experts who meticulously analyze various system's aspects, including equipment, procedures, and human factors, intending to identify potential hazards and their underlying causes. The primary objective is identifying plausible scenarios where hazardous events can arise and assess their severity, likelihood, and potential impacts.

The results of a HAZOP study comprise a comprehensive compilation of identified hazards, their potential consequences, and recommendations for mitigating or managing the associated risks. These findings, coupled with the analysis consequences and probabilities determined in the previous step, are then utilized to calculate the risk of the hazardous event. The associated risk for the hazardous event can be exploit as the quantification of process safety and incorporated into the techno-economic analysis.

Data Utilization to determine the probability of having hazardous event

This section underscores the importance of data utilization in accurately assessing the probability of encountering hazardous situations. Through a comprehensive analysis of pertinent data, such as historical failure records, and incident reports, it becomes feasible to identify correlations that aid in estimating the likelihood of future hazardous events. Employing statistical techniques and advanced modeling approaches, organizations can effectively leverage this data to quantify risks, enabling them to make well-informed decisions, enhance their risk management strategies, and implement robust safety measures. By harnessing the power of probability calculations derived from hazardous event data, organizations can proactively mitigate risks, safeguard their operations, and promote safety.

4.4. Techno-economic analysis of the system subject to RAMS analysis

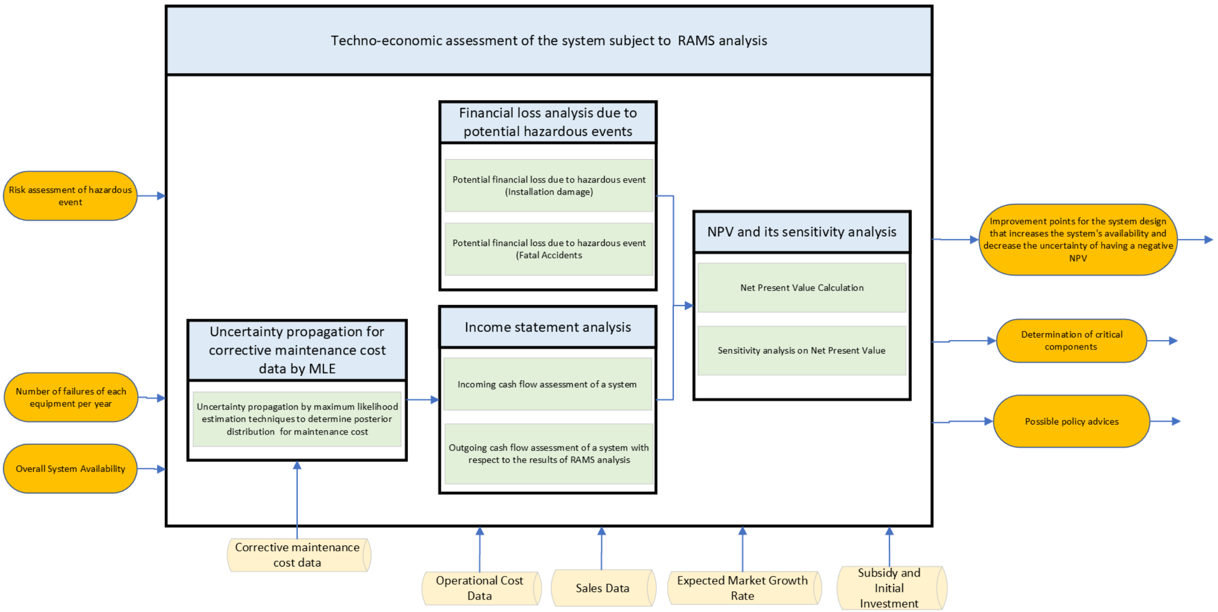


Figure 4.5: Techno-economic Analysis

The techno-economic analysis means the net present value calculation of the system with the various economic and operational data. It incorporates inputs derived from the RAMS analysis, specifically the ”Risk analysis of hazardous events,” ”Number of failures of each equipment per year,” and ”Overall System Availability.” These inputs form the foundation for conducting a comprehensive techno-economic analysis of the system. Furthermore, the analysis integrates five key data points. Among these five key data points, the ”Subsidy and Initial Investment” and ”Expected Market Growth Rate” data have particular emphasis, as they affect all economic analyses. Thus, these two data sources are directly incorporated into the analysis to calculate the NPV. The remaining data sources influence the subprocesses of the techno-economic analysis, which will be further elaborated upon in subsequent steps.

4.4.1. Income statement analysis

Income cash flow analysis is a financial evaluation method that focuses on assessing the cash inflow into a business or investment over a specific period [72]. It involves analyzing cash receipts from various sources, such as sales revenue, investments, loans, and other income streams. The purpose of income cash flow analysis is to evaluate the financial performance and sustainability of an entity to meet its financial obligations, like outgoing cash flow and payment of financial loans.

Incoming cash flow assessment of a system

The primary source of income for hydrogen refueling stations is their sales revenues, which are determined by the quantity of hydrogen sold and the corresponding price per unit. The multiplication of these two variables yields the total revenue, which represents the incoming cash flow for the station. While subsidies can be considered as a form of income, they are not explicitly included in this section as they do not pertain to a specific period.

Outgoing cash flow assessment of a system with respect to the results of RAMS analysis

The primary component of outgoing cash flow for hydrogen refueling stations is the cost of goods sold, which is determined by the quantity of hydrogen sold and the associated cost per unit. This cost of goods sold represents the expenditure incurred by the station. While initial investments can be considered as a form of income, they are not specifically included in this section as they do not pertain to a specific period. Furthermore, maintenance costs are part of the operational expenses and contribute to the outgoing cash flow. However, due to the focus of RAMS analysis on maintenance, the maintenance cost is separated from the operational cost to allow for a comprehensive evaluation of the maintenance aspects.

4.4.2. Corrective Maintenance Cost

Uncertainty propagation for corrective maintenance cost data by MLE

In this stage, similar to the uncertainty propagation for TTR and TBF, the maximum likelihood estimation method is applied to the corrective maintenance cost of each observational data. The maintenance cost sample data, obtained during the observational data acquisition phase, undergo characterization to enable the uncertainty propagation for the maintenance cost part of the analysis.

4.4.3. Financial loss analysis due to potential hazardous events

This section conducts an evaluation of the potential financial impact stemming from adverse events or incidents within the system. The primary objective of this analysis is to quantitatively assess the monetary consequences associated with hazardous events, such as accidents or fatalities. Specifically, it focuses on evaluating indirect costs, including operational downtime and potential fines resulting from such events. By undertaking this analysis, organizations can gain a clear understanding of the financial risks they face. The insights derived from this assessment hold significant value for effective risk management and informed decision-making. They enable organizations to allocate resources efficiently, implement preventive measures, and develop contingency plans to mitigate potential financial losses.

4.4.4. Net Present Value (NPV) and its sensitivity analysis

In this section, the net present value (NPV) of the station is calculated by combining all financial variables, including the initial investment and subsidy. The NPV is a financial metric that assesses the profitability of the project over time, taking into account the time value of money [30]. Future cash flows are discounted to reflect their present value, and the NPV is determined by subtracting the initial investment cost from the present value of expected cash inflows generated by the project while adding the subsidy to the current value of expected cash inflows.

Following the calculation of NPV, a sensitivity analysis is conducted to examine how changes in key variables or assumptions impact the project's profitability [73]. This analysis assesses the project's sensitivity to variations in factors such as costs, sales, market conditions, and system's design components.

By separating the maintenance cost from the operational cost, the framework aims to identify the contribution of maintenance objects (system components) to the NPV. This separation allows users to identify critical components within the system. Therefore, the outputs of this section are the "Determination of critical components" and "Improvement points for system design to enhance system availability."

Moreover, the sensitivity analysis provides insights into market conditions. It offers "Possible policy advice" to promote the development of the market, aiming to establish this niche technology as a socio-technical regime of the future.

4.5. Evaluation of the system concept based on sensitivity analysis

The evaluation of the outputs from the techno-economic analysis encompasses several key aspects, including "Improvement points for the system design that increases the system's availability," "Determination of critical components," and "Possible policy advice." The main objective of this part is reducing uncertainty and achieving a positive net present value (NPV).

When improvement opportunities are identified through sensitivity analysis, they are incorporated into the system architecture analysis, allowing for adjustments to the system design. This iterative process ensures that potential enhancements are thoroughly considered and integrated into the overall system architecture. Conversely, if no improvement points are identified, the design is finalized based on the existing findings.

Furthermore, if no market development suggestions arise from the analysis, the previously generated possible policy advices are published. These policy recommendations provide valuable insights to policymakers, facilitating market growth and fostering a favorable environment for the hydrogen refueling system.

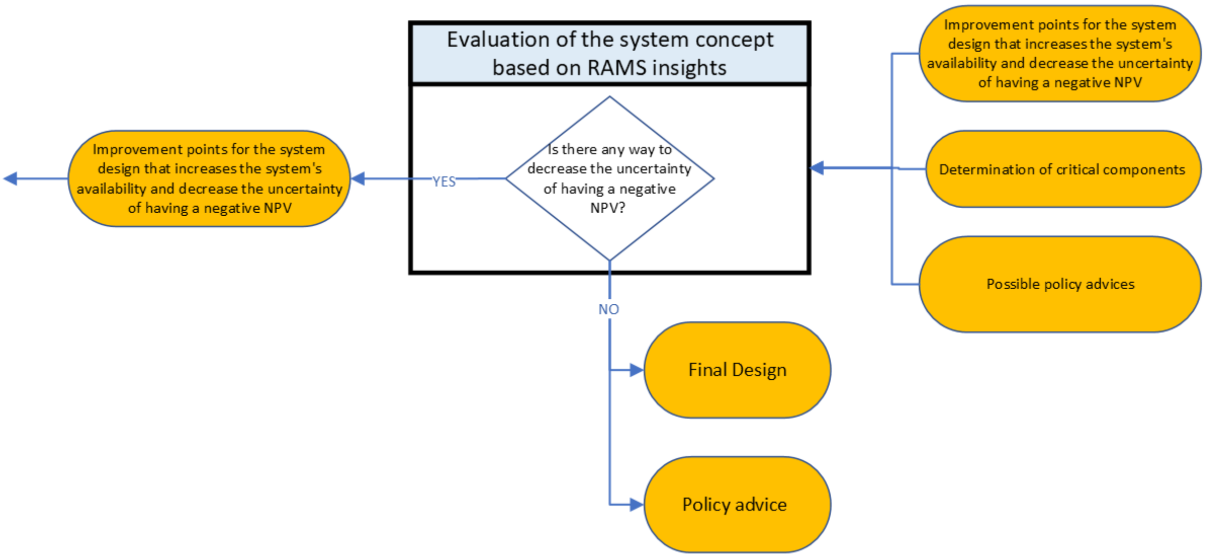


Figure 4.6: Evaluation of the system concept based on sensitivity analysis

Part III

Case Study: Total Energies Breda Hydrogen Refueling Station

5

Case Study: Total Energies Breda Hydrogen Refueling Station

5.1. System Architecture Analysis

The designed framework (STRAMSA) and analyses are applied to the case study of Total Energies Breda Hydrogen Refueling station. This station is one of the 14 hydrogen refueling stations in the Netherlands, which began operations in December 2021. It is designed to supply hydrogen gas to both heavy-duty vehicles (at 350 bar) and light vehicles (at 700 bar). Since the station is already in operation, the steps for system architecture analysis are conducted on the current design configuration. The first step involves analyzing and listing the first and second-level functional requirements as well as the non-functional requirements for the system, which are detailed below:

5.1.1. Requirement Elicitation

Table 5.1: First level Functional Requirement Elicitation

First Level Functional Requirements
Supply hydrogen to the station
Compress the gas from varying pressures between 15-200 bar up to 350 bar
Cool down the pressurized hydrogen
Store the chilled 350 bar hydrogen
Deliver 350 bar hydrogen to customer vehicles in a safe and reliable manner
Supply 350 bar hydrogen to high compression system
Compress the hydrogen from 350 bar to 700 bar
Cool down the 700 bar hydrogen
Store the chilled 700 bar hydrogen
Cool down the pressurized hydrogen before it is delivered to the vehicle
Deliver 700 bar hydrogen to customer vehicles in a safe and reliable manner
Enable the communication between the station and the vehicle
Enable the payment process for delivered hydrogen

Table 5.2: Second level Functional Requirement Elicitation

Second Level Functional Requirements
Keep the compression going while a vehicle is being refueled to prevent significant deep depressurization and better capacity utilization
Enable to start and stop the compression system frequently
Refuel the vehicle from the lowest pressure source possible
Relief of the pressure slowly when there is an ignition
Enable to dispense the hydrogen from either 350 bar or 700 bar system
Depressurize the nozzle line at the end of refueling to allow the customer to disconnect the nozzle

Table 5.3: Non-Functional Requirement Elicitation

Non-functional requirements
A starting pressure of supplied hydrogen to the station must be at least 200 bar
Easy to compensate the pressure differences
Maximum working pressure is 425 bar for 350 bar hydrogen compression system
Oil-free compressors
Regularly lubricated compressors
Maximum working pressure is 950 bar for 700 bar hydrogen compression system
Steady pressure supply for high-pressure compression system
Easy to commission and decommission of subunits
Being resistant to delamination (of composite layers)
Being resistant to metal embrittlement
Being resistant to high pressure with a thin wall thickness
Flexible hoses
Certified electrical components

Based on the provided functional requirements, a Functional Flow Block Diagram (FFBD) can be created to depict the explicit functions of each equipment and their interconnections with other components. This diagram serves as a valuable tool for developing the initial system architecture. However, since the station has already been designed, it would be easier to comprehend the operational principles through a component-based overview diagram. This diagram, which is a symbolic representation, illustrates the equipment and its functional relationships. The accompanying explanatory text provides a detailed explanation of the functions and requirements associated with each component block. This comprehensive component-based block diagram will serve as the foundation for constructing a reliability block diagram for the subsequent systematic RAMS analysis.

5.1.2. Development of System Concept

The hydrogen refueling process is a ”closed system’ because there is no interaction between open air and hydrogen in the system [24]. The provided diagram 5.1 showcases the comprehensive closed design system for the Total Energies Breda Hydrogen Refuelling station. This facility relies on tube trailers supplied by AirLiquide to transfer hydrogen, operating under 200 bar, to the site. The hydrogen then proceeds through a sequence of processes, including passing through ADTS and Air systems. Following this, the hydrogen undergoes separation into two pipelines, engineered to transfer the gas into a medium pressure (MP) compressor that can efficiently compress the hydrogen to 350 bar.

The station has been designed to incorporate two identical compression systems, boosting the facility’s availability. This redundancy in design serves as a critical aspect of the facility’s operation, ensuring continued operation even in the event of an abnormality or failure of one of the compressors.

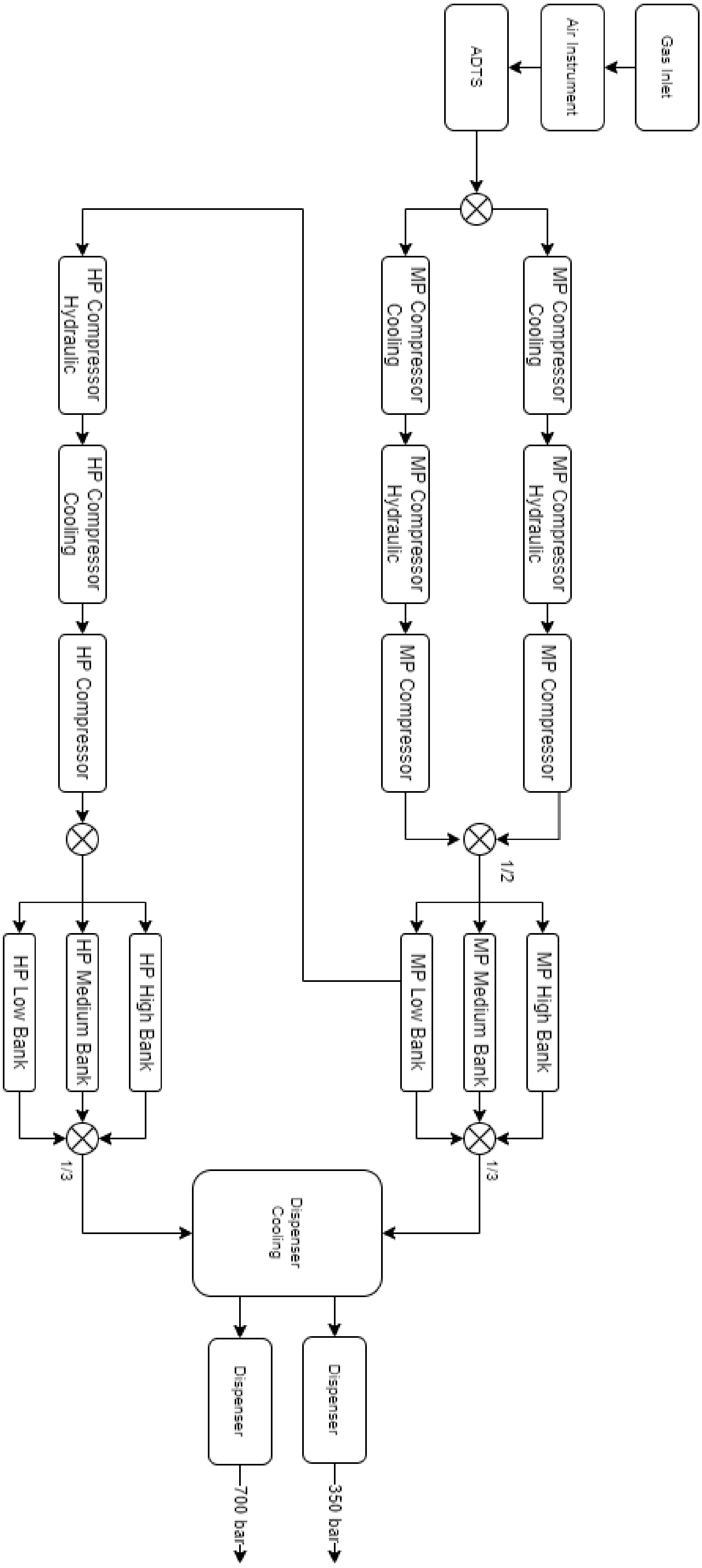


Figure 5.1: Overall Station's Design

Prior to entering the medium pressure (MP) compression stage, the hydrogen undergoes a critical step involving MP cooling and MP hydraulic systems to lower the gas's temperature. This precautionary measure is of paramount importance in ensuring the safe operation of the facility, as hydrogen compression typically leads to a rise in gas temperature. By cooling the hydrogen before the compression process, the facility can maintain a safe operating environment, minimizing the risk of accidents or incidents. After the cooling down process, the hydrogen is compressed from 200 bar to 350 bar via the MP compressor.

After the completion of the compression process, the hydrogen is conveyed to mid-pressure storage units. The storage units are composed of high-bank, mid-bank, and low-bank systems. Incorporating three distinct banking systems enhances the overall system availability, similar to having two identical mid-pressure compressors. In the event of an issue with one banking system, a working backup ensures that the station can continue to operate. Ultimately, these units play a crucial role in the facility's operations, as they facilitate the attainment of the requisite pressure and flow specifications for refueling purposes.

The medium pressure storage unit possesses the 60% of station's capacity to supply heavy-duty trucks or buses with hydrogen pressurized to 350 bars. In order to dispense the pressurized hydrogen to these vehicles, the gas within the mid-pressure storage units must first be transferred to the cooling system of the dispenser before delivery to the customer's vehicle. It is essential to cool down the hydrogen with a CO_2 coolant, as the hydrogen may heat up when transferred to the vehicle's tank, creating a potential ignition hazard. The pre-cooling process ensures that the vehicle's tank remains at a safe temperature, allowing for expedited refueling times without compromising safety measures [74].

Subsequently, the pre-cooled hydrogen is transported to the 350-bar dispenser system, which supplies the chilled and pressurized hydrogen to vehicles in a controlled manner. The dispenser operates in tandem with the current level and temperature of the vehicle's tank to regulate the quantity of delivered hydrogen. Communication between the vehicle and dispenser is must to measure the tank pressure and temperature. After the temperature and pressure within the tank are gauged, the dispenser computes the volumetric flow rate of hydrogen that will be dispensed to the tank, along with the corresponding cost. The dispenser then interacts with the payment system to issue the sales transaction.

In order to facilitate communication between the vehicle and the nozzle, the InfraRed (IR) communication protocol is employed. This protocol enables the transfer of critical data such as tank pressure, temperature, volume, and abort signals between the vehicle and the nozzle. However, it is noteworthy that due to limited infrared communication capabilities at 350 bars, only raw data can be exchanged between the trucks and nozzle.

Light-duty vehicles (LV) require a higher level of pressurized hydrogen for their internal system as opposed to the 350 bar hydrogen used for heavy-duty vehicles (HV). According to standards, the required pressure for LVs is 700 bar [75]. Some of the current hydrogen stations are designed to exclusively for heavy-duty vehicles. However, the Breda station is designed to cater to both HVs and LVs.

To prepare the gas supply for LVs in the station, a high-pressure compressor is installed to compress the gas up to 700 bar. The HP compression system is fed by the MP storage bank, specifically from the MP Low Bank. However, relying solely on this storage unit makes this system critical for the availability of high-pressure hydrogen.

The 350 bar hydrogen from the MP low bank is sequentially delivered to the HP Hydraulic system and cooling chiller to cool down the gas before compression. The cooling system is crucial for the safe operation of the system and to prevent potential ignition. After cooling, the hydrogen is compressed up to 700 bar and transferred to the HP pressure storage unit. This system has three banking systems (High bank, medium bank, low bank) as MP storage units, which store pressurized hydrogen to supply fuel for LVs.

When there is a demand from LVs, the 700-bar hydrogen is transferred from the HP banking system to the dispenser cooling system which is equaivalent to the 40% station's capacity. The cooling system is the same for 350-bar and 700-bar dispensing systems and aims to pre-cool the gas before dispensing it into the vehicle's tank. After cooling, the 700 bar of hydrogen is dispensed into the vehicle's tank.

There is a difference between the 700-bar and 350-bar dispensing systems. The 350 bar dispensing system can communicate either via infrared communication or hardware communication. On the other hand, infrared communication is the only way to transmit process information for the 700 bar dispenser. It shares volume, pressure, temperature, state of the fuel tank, and gas density safety signals (pause, stop, abort). The communication protocol for the 700-bar dispenser is more advanced than that of the 350-bar dispenser.

Lastly, since there is only one set of piping systems in the dispenser, it only allows refueling at either 350 bar or 700 bar at a time. It is not possible to dispense from more than one nozzle simultaneously. Additionally, it is the responsibility of the customers to connect the nozzle to their vehicle, which increases the vulnerability of the system due to users' limited knowledge. As a result, this design scheme serves as the foundation for further system and RAMS analyses of the TotalEnergies Breda Hydrogen Refueling station.

Before delving into the next section, it is important to mention the warranty condition, which means a manufacturer of the equipment guarantees the fix the problem without charging any fee for a specific time period, if the component fails. All equipment in the station, apart from the dispenser system, is supplied by a third-party manufacturer, which enables it to have a warranty for this equipment. However, since the dispenser system is an in-house design, there is no warrant for this equipment and any dispenser system-related maintenance action cost to the company.

5.1.3. Designing System Architecture

In order to convert a design scheme into a Reliability Block Diagram (RBD), it is essential to thoroughly analyze the system's complexity and characteristics. This process involves consulting reliability engineering guidelines and leveraging the expertise of design and reliability engineers within the company. With their input, the overall scheme of the station was successfully transformed into an RBD.The capacities for different pressurized systems were shown with its percentages in Figure 5.2.

Once the RBD is constructed using a RAMS modeling toolbox and reliability parameters are assigned to the components, a comprehensive reliability analysis can be conducted. This analysis enables the evaluation of the system's overall reliability, identification of critical components or pathways, assessment of the impact of component failures, and determination of system availability. In the RAMS analysis section, this analysis will be conducted.

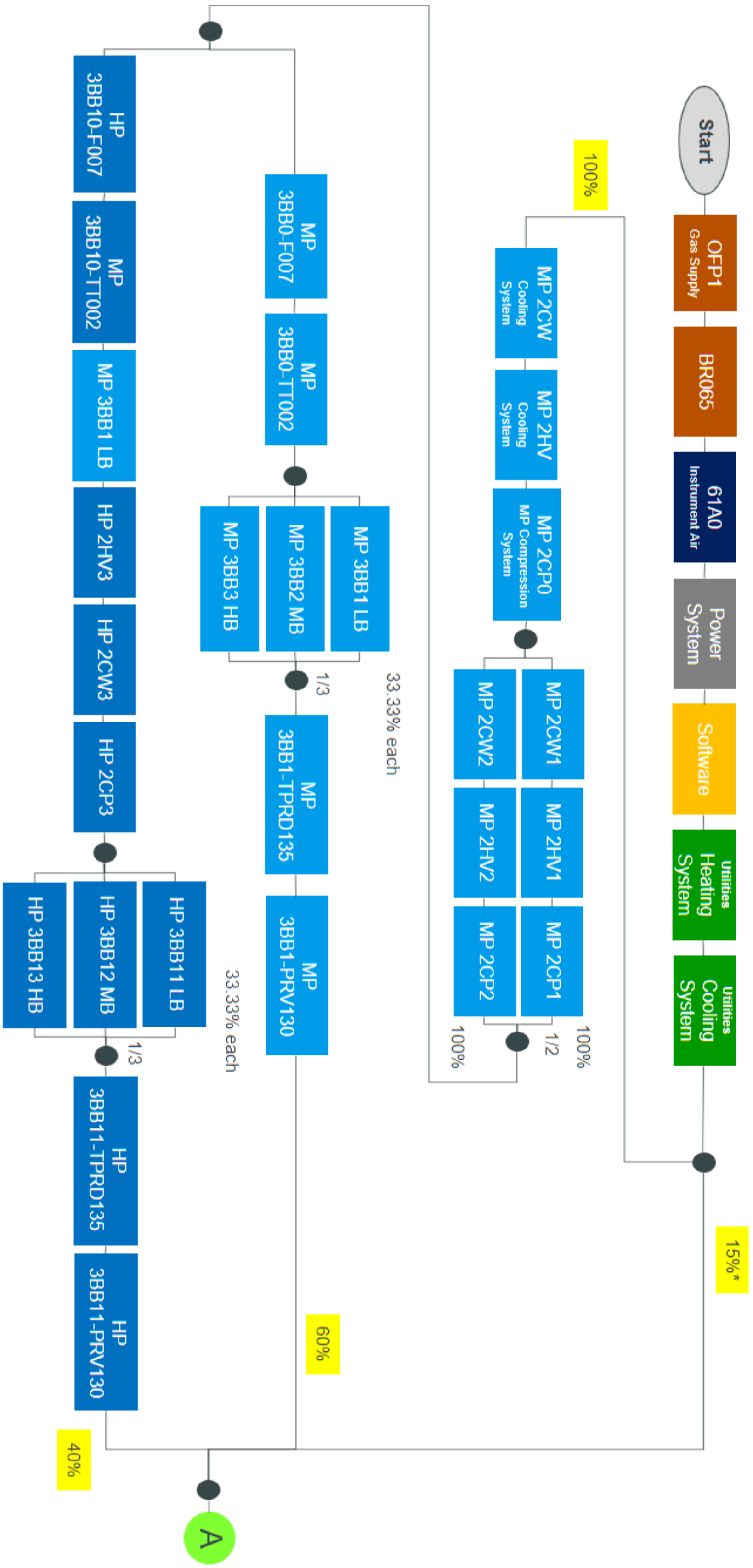


Figure 5.2: Reliability Block Diagram

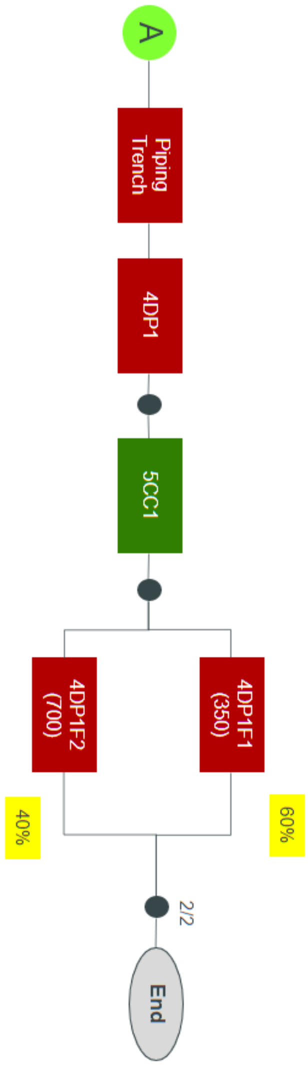


Figure 5.3: Reliability Block Diagram Continue

5.2. RAMS Analysis

5.2.1. Data Acquisition and Structuring

The data structuring process was implemented on the Microsoft Power BI query tool to maintain a comprehensive record of the applied changes in the database. This approach was chosen to facilitate efficient and effective data management to ensure its scalability for future expansion. By utilizing the capabilities of the Power BI query tool, the user can establish a standardized data formatting that can be readily applied to subsequent updates within the database. This utilization will enable other users to analyze the enlarged database by simply inputting the Excel sheet into a file that Power BI extracts data from Business Information System (BIS). Therefore, this approach provides a reliable and streamlined way of managing data in a complex database environment, allowing for greater accessibility and ease of use for end-users.

The Business Information System (BIS) serves as a comprehensive database for technical and business-related information. This system contains all the relevant data on Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), and hydrogen stations. All pertinent jobs or information related to these stations are registered within the BIS. However, due to the scope of the research, the focus was solely on the Breda Hydrogen refueling station for further analysis. Specifically, all work orders related to this station were listed for further review. There were 229 registered work orders within the system, each having 410 attributes initially. Yet, upon further examination of these attributes, it became apparent that detailed analysis was necessary to identify the critical attributes that could be tailored for Reliability, Availability, Maintainability, and Safety (RAMS) analysis. For that goal, a data reduction strategy was implemented whereby nine corrective maintenances were randomly sampled for review. This random selection allowed for a more effective review of the attributes associated with each work order. Ultimately, 22 attributes (rows) were identified as the main elements required for the RAMS analysis.

Upon identification of the 22 critical attributes required for the Reliability, Availability, Maintainability, and Safety (RAMS) analysis, the remaining 398 attributes were removed from the query to reduce the computational burden. While the presence of these columns did not pose any immediate issues given the one-year data set, their inclusion could have become problematic with the expected increase in the lifetime of the station. Thus, it was deemed necessary to remove these columns from the dataset to ensure the accuracy and efficiency of the RAMS analysis, both currently and in the future.

As a final step before the data utilization, the work orders (229) were filtered to include only those that have been technical ready for corrective maintenance. This filtering step was applied to the dataset as canceled work orders or ongoing work orders do not have a final date for the issue, making it impossible to calculate TTR and TBF metrics. As a result of this filtering process, 156 rows remained for further data utilization. The entire process is illustrated in Figure 5.4.

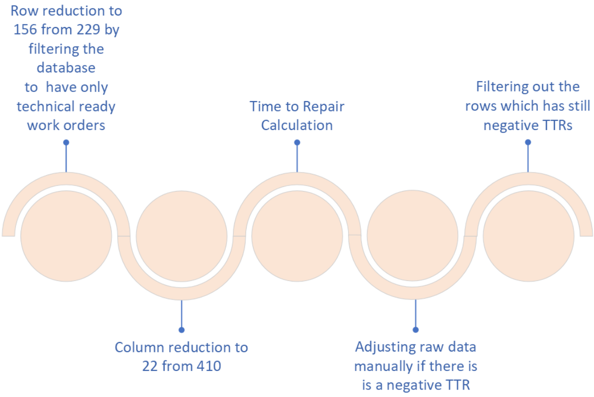


Figure 5.4: Data Acquisition and Utilization Process until Text Mining

5.2.2. Failure Rate Estimation of Components

Following the data reduction process, the analysis focused on the ”Date call” column as the starting point for analyzing downtime in the Breda H_2 refueling station. This column serves as the initial indicator of a problem or downtime event, making it a crucial element in the analysis. Subsequently, the ”actual solved” attributes were identified as the point at which the problem is resolved and the station returns to its operational state. While other attributes could have been considered to determine the problem-solving time, input from an expert and the responsible person for these work orders led to the determination of the ”actual solved” column as the endpoint of downtime.

After these selections, in order to calculate the Time to Repair (TTR) for each technical ready work orders, a new column ”TTR” was added to the PowerBI query that computes the time difference between the ”actual solved” and ”date call” columns.

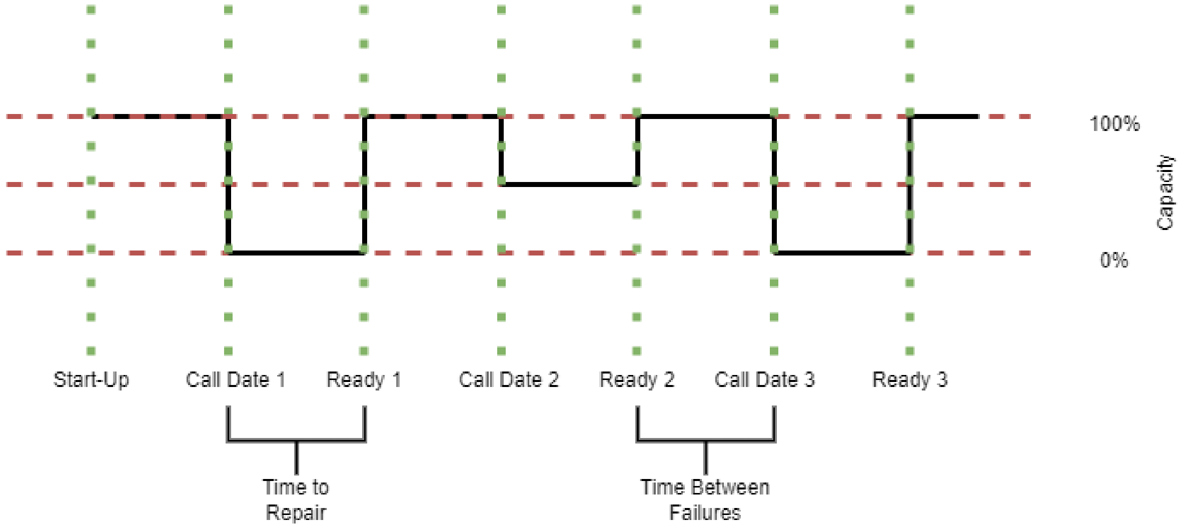


Figure 5.5: Representation of TTR and TBF

$$TTR_n = Ready_n - DateCall_n \tag{5.1}$$

In order to achieve this objective, the ”Duration.ToText” function embedded within PowerBI was utilized, enabling precise and efficient computation of the Time to Repair (TTR) values. Initially, the resulting data type for the TTR column was expressed as ”day.hours.minute.seconds,” which could confuse users. To enhance interpretability and facilitate subsequent RAMS analyses, the TTR data type was adjusted to represent a singular value in terms of hours. This modification ensures that the resulting data is easily comprehensible to all users.

During the calculation process, multiple instances of negative TTR values were identified, which is highly unlikely as it is not possible to resolve an issue before it has occurred. Further scrutiny was undertaken to identify any issues in the date call or ready time associated with these work orders. As a first step, the work orders with negative values were filtered for closer examination. The date call and ready time attributes of these work orders were manually checked via the BIS system, leading to the determination that 14 work orders required manual adjustments. Due to limited system access, the necessary modifications were made on the PowerBI platform instead of the company database. Once the adjustments were completed, the revised values were combined with the previously accurate work orders. The updated values can be reviewed at Appendix A.

To proceed with the TTR and TBF analysis, it was necessary to analyze the components that required corrective maintenance. However, out of the 156 work orders, 127 were registered as ”H_2 installation” in the object column, posing difficulties in classifying the work orders based on this column. Furthermore, there were three ”null data” in this column. To ease the classification of work orders, the work orders with already specified objects were filtered out, focusing on the remaining work orders that did not have a specified object. These remaining work orders required a more in-depth analysis, which involved the utilization of text-mining technique to identify the relevant components.

For the text mining process, the work order descriptions were used. The column ”Description full” was previously acquised into the PowerBI query. However, it was discovered that 60 out of the 153 work orders lacked a description in the ”Description full” column. Further investigation revealed the existence of three distinct description columns: one in Dutch and two in English, named ”Description,” ”Description full,” and ”Opm. Terugmelding.” To accurately classify work orders, these three attributes were merged into a new column called ”New Description.” In cases where this column contained no text and the object was not different from ”H_2 installation,” the work orders were excluded from the analysis, as it was challenging to determine where the corrective maintenance was required.

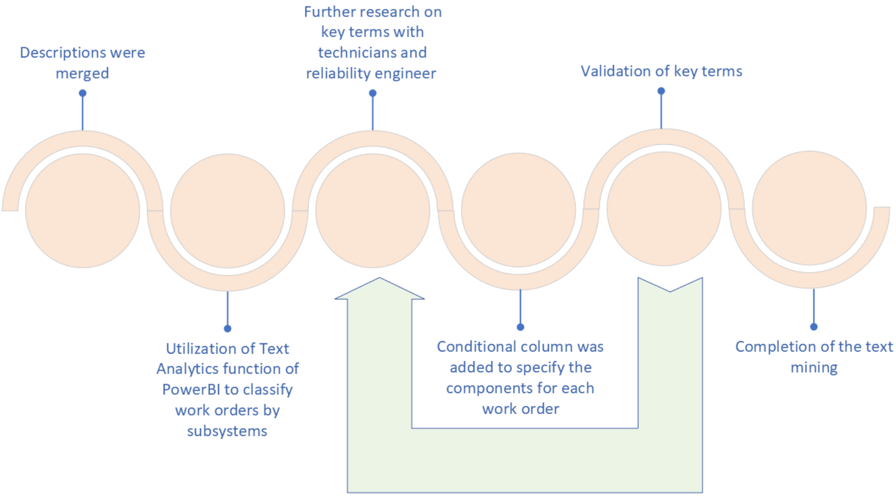


Figure 5.6: Text Mining Process for the Subsystem Classification

In order to classify the work orders based on their components, a conditional column ”Subsystem” was added utilizing specific keywords listed in Table 5.4. Microsoft Power BI follows a hierarchical structure for conditional clauses where the analysis proceeds from the first ”if” statement downward. This structure was implemented to improve the accuracy of the analysis. The hierarchy was constructed within the conditional query to precisely determine the associated component. It starts with the object number or budget code, followed by text mining from the description.

The text mining process illustrated in Figure 5.6, was followed to complete the analysis. This process was iterative and validated by technicians and reliability engineers at each step. For example, during one validation process, it was observed that SV005 is related to the gas inlet. However, specifically for work order 179, it was identified as related to the MP compressor. Therefore, a minor adjustment was made by checking if the new description included the term ”MP compressor” to correctly classify it, as other gas inlets have specific terms that distinguish them.

As a result of this iterative process, the key terms listed in Table 5.4 were organized in a hierarchical manner. The hierarchy begins with the first left row and proceeds downwards on the left side of the column, and then continues with the second column. The right bottom term represents the lowest level in the hierarchy.

After completing the component classification, the previous filtering step was removed to combine all work orders that had a specified object. As a subsequent step, all rows were sorted in ascending order based on the Ready column to prepare the data for TBF analysis. Filters were then added to the ”Subsystem” column, as TBF and TTR can be calculated for components. The time difference between different components does not provide any insight into the maintainability or reliability of the components. It can provide insight into the system availability if all subsystems were connected in series. However, since not all subsystems were connected in series for the Breda Hydrogen refueling station, the reliability (TBF) and maintainability (TTR) metrics must be analyzed at the component/subsystem level. The system availability will be determined by a simulation model based on the TBF and TTR of the components. For that purpose, filter processes were added to the query for components.

As a next step, an index column was added to the query when selecting a component to prepare

Table 5.4: Key Phrases for Subsystem Classification

Key Phrase	Subsystem	Key Phrase	Subsystem
ADTS	[New Description], ”PLC”	HP Cooling	[New Description], ”HEX”
ADTS	[New Description], ”ADTS”	HP Cooling	[New Description], ”hiller”
ADTS	[New Description], ”router”	Dispenser Cooling	[New Description], ”CO$_2$”
Air Compressor	[New Description], ”Air comp”	Dispenser Cooling	[New Description], ”CO$_2$”
Air Compressor	[New Description], ”air comp”	Dispenser Cooling	[New Description], ”cooling”
Air Compressor	[New Description], ”Luchtcompressor”	Dispenser Cooling	[”WO-number”], ”80550-189”
Gas Inlet	Objects = ”inlet”	Dispenser Cooling	[New Description], ”Cooling”
Gas Inlet	[New Description], ”iquide”	Dispenser Cooling	[New Description], ”koel”
Gas Inlet	[New Description], ”trailer”	MP Compressor	[New Description], ”IDRO”
Gas Inlet	[New Description], ”SV060”	MP Compressor	[New Description], ”MP”
Dispenser 350	[New Description], ”350”	Storage	[New Description], ”bank”
Dispenser 350	[New Description], ”PCV035”	HP Hydraulic System	[New Description], ”2HV3”
Dispenser 700	[New Description], ”700”	Hydraulic System	[New Description], ”olie”
Dispenser 700	[New Description], ”4DP1F2”	Hydraulic System	[New Description], ”Olie”
Dispenser	Budget code = ”SUB”	MP Cooling	[Objects], ”Loop”
Dispenser	Budget code = ”STG”	MP Cooling	[New Description], ”pomp”
Dispenser	[New Description], ”dispenser”	MP Cooling	[New Description], ”Pomp”
Dispenser	[New Description], ”owtie”	H_2-Installation	[New Description], ”ekkage”
Dispenser	[New Description], ”TSG”	H_2-Installation	[New Description], ”detec”
Dispenser	[New Description], ”tanken”	MP Compressor	[New Description], ”SV005”
Dispenser	[New Description], ”signal”	H_2-Installation	else
Dispenser	[New Description], ”slang”		
HP Compressor	Objects = ”Haskel”		
HP Compressor	[New Description], ”O-ring”		
HP Compressor	[New Description], ”askel”		
HP Compressor	[New Description], ”HB”		

the data for TBF calculation. The purpose of adding an index is to facilitate the calculation of the time difference between two subsequent rows. As shown in Figure 5.5, TBF is calculated by determining the time difference between when a problem occurred and the completion of the previous work order. Mathematically, this can be expressed as:

$$TBF_n = DateCall_{n+1} - Ready_n \tag{5.2}$$

In order to calculate the (n+1)th term by subtracting the nth term, PowerBI needs a way to identify the row number. Therefore, an index column was added to assign a unique row number to each work order. In the final step, TBF was calculated for each work order using the above mathematical formula, specifically for the selected component to understand its reliability. If any work order had a negative TBF value, the data was cross-checked within the BIS system and manually adjusted in PowerBI for accuracy. Once the data was verified, TBF and TTR values were transferred to a separate Excel sheet to propagate the uncertainty of these variables using Crystal Ball. All these data utilization process steps can be found in the PowerBI transformation page Appendix A.

After transferring the data to Excel for uncertainty propagation, the sample data was validated with the company’s reliability engineers and generic OREDA database to ensure its accuracy. During the validation process, work order 80550-168 was identified as having an extremely high TTR, which could potentially misrepresent the TBF estimation for the MP compressor in further analysis. Despite cross-checking the data with the BIS system, no additional information was available to modify the work order. The person who registered the work order had limited knowledge about it and recommended excluding it from further analysis. Since the cost associated with this work order was negligible, it was ultimately excluded from the MP compressor data. With this final step, the data utilization process was completed and ready for data characterization.

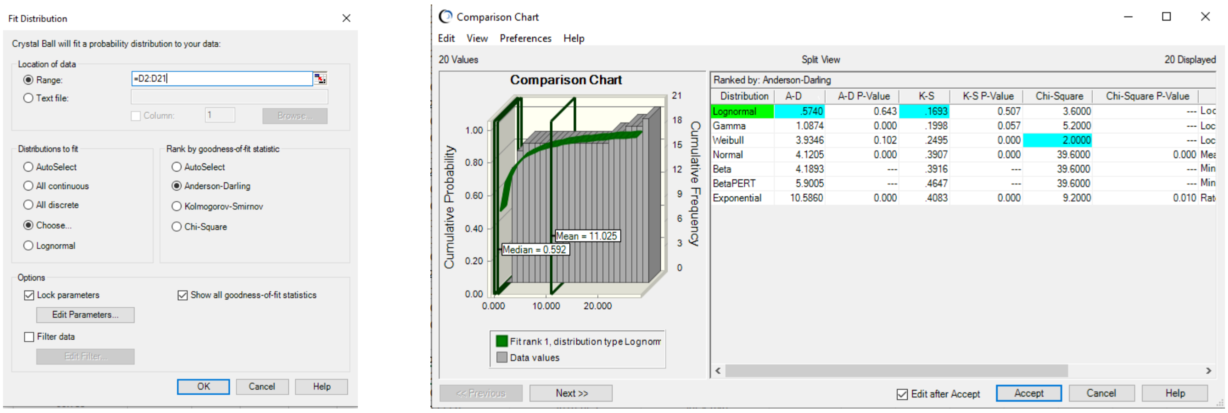
5.2.3. Uncertainty Propagation for RAMS Metrics by MLE

The process of uncertainty propagation (data characterization) involves fitting the data with the appropriate distribution type and generating its probabilistic distribution with a maximum likelihood estimation technique. This process was carried out using the Oracle Crystal Ball software, an extension for Microsoft Excel that enables users to generate probabilistic distributions for a given dataset and propagate the uncertainty of variables. The software's user interface can be seen in the Appendix B.

For the process, the first step is to select a cell and define an assumption, which essentially means specifying the distribution of the data. Upon clicking the "defining assumption" button, a menu of distribution types appears. While the Weibull distribution is commonly used for practical RAMS analysis, selecting a distribution type may introduce a bias toward the dataset. Therefore, evaluating different probabilistic distributions is necessary to avoid such bias attitude. The Crystal Ball software provides a "Goodness of Fit" test to enable users to assess different distribution types for the sample. In the distribution types menu, the user can either select a distribution if they know which probabilistic distribution type can be fitted to the sample data or use the goodness-of-fit option to evaluate different distribution types.

The determination of a suitable probabilistic distribution type is critical in understanding the data and forecasting the uncertainty, which requires either expertise or computer selection. To minimize the risk of human error, using the distribution generated by the software is always more reliable. However, to use the "goodness of fit" option, the software requires at least 15 data points as a sample size for fitting the data. If the component has sufficient data, the "goodness of fit" option was used to generate different distributions and evaluate their suitability. Figure **??**5.7.(a) illustrates how the "goodness of fit" was used for the Dispenser Cooling system.

The sample data range must have a minimum of 15 points to use "goodness of fit" option in Crystal Ball software. In the "Distributions to Fit" section, users can choose between continuous or discrete distributions based on the sample data type. Moreover, the software provides a ranking system for the goodness of fit statistics, which includes Anderson-Darling, Kolmogorov-Smirnov, and Chi-Square. Based on expert opinion, the Anderson-Darling statistic was chosen for further analysis. Following selecting these parameters, the software generates a comparison chart, as shown in Figure **??**5.7.(b) for the dispenser cooling system.



● Range: =D2:D21
○ Text file:
☐ Column: 1

Distributions to fit:
○ AutoSelect
○ All continuous
○ All discrete
● Choose...
○ Lognormal

Rank by goodness-of-fit statistic:
○ AutoSelect
● Anderson-Darling
○ Kolmogorov-Smirnov
○ Chi-Square

☑ Lock parameters
☑ Show all goodness-of-fit statistics
☐ Filter data

Ranked by: Anderson-Darling

Distribution	A-D	A-D P-Value	K-S	K-S P-Value	Chi-Square	Chi-Square P-Value	
Lognormal	.5740	0.643	.1693	0.507	3.6000	---	Loc
Gamma	1.0874	0.000	.1998	0.057	5.2000	---	Loc
Weibull	3.9346	0.102	.2495	0.000	2.0000	---	Loc
Normal	4.1205	0.000	.3907	0.000	39.6000	0.000	Mea
Beta	4.1893	---	.3916	---	39.6000	---	Min
BetaPERT	5.9005	---	.4647	---	39.6000	---	Min
Exponential	10.5860	0.000	.4083	0.000	9.2000	0.010	Rat

☑ Edit after Accept

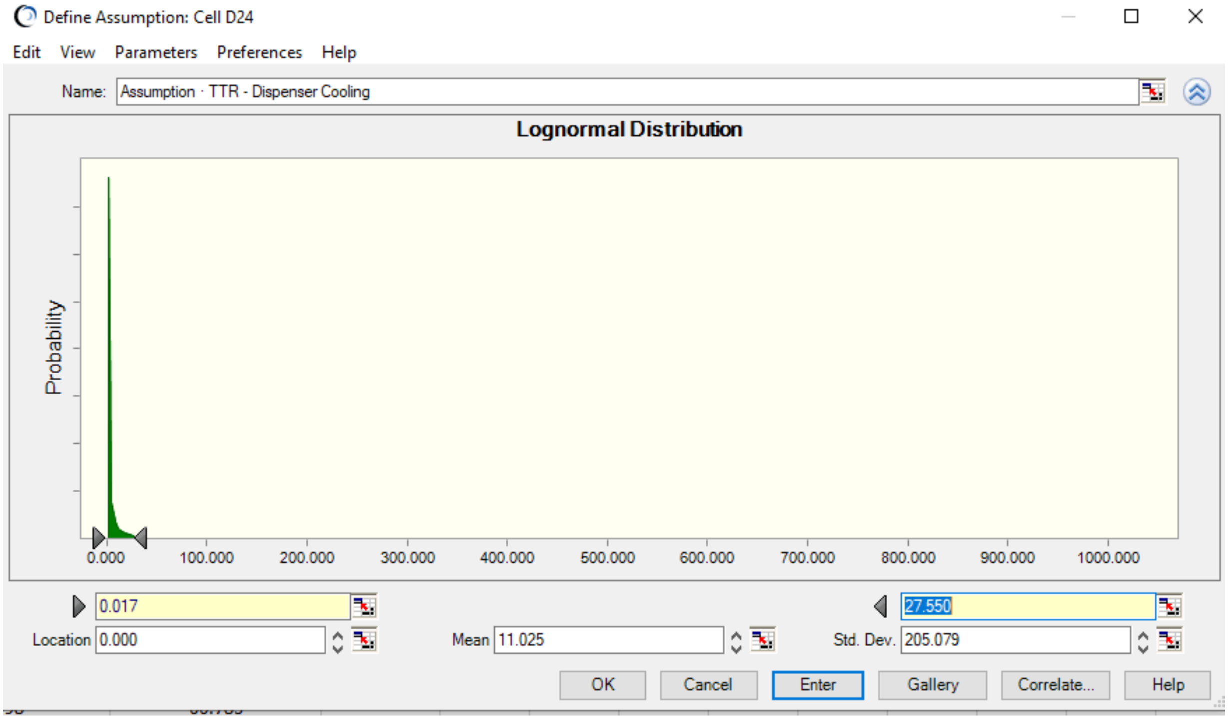
(a) Godness of Fit

(b) Comparison Chart

Figure 5.7: Defining the Assumption in Crystal Ball: Dispenser Cooling

Based on the sample data of the dispenser cooling system, various probabilistic distributions such as lognormal, gamma, Weibull, normal, beta, betapert, and exponential were generated by the software. The goodness of fit test was performed using the Anderson-Darling rank, and the lognormal distribution was found to have the lowest p-value, making it the best fit for this sample data. Therefore, the lognormal distribution was selected by the software for further analysis.

After selecting the best distribution type, the probabilistic distribution graph appears, as shown in Figure 5.8. However, this output distribution needs to be truncated with the historical maximum and minimum data points to avoid significant outliers that can decrease the reliability of the results. If the distribution is not truncated, it may generate negative values for time, which contradicts with real-world applications. Therefore, the outputs were truncated using the maximum and minimum values of the sample data, and the assumption definition was completed with this step.



Name: Assumption - TTR - Dispenser Cooling

0.017

27.550

Location 0.000

Mean 11.025

Std. Dev. 205.079

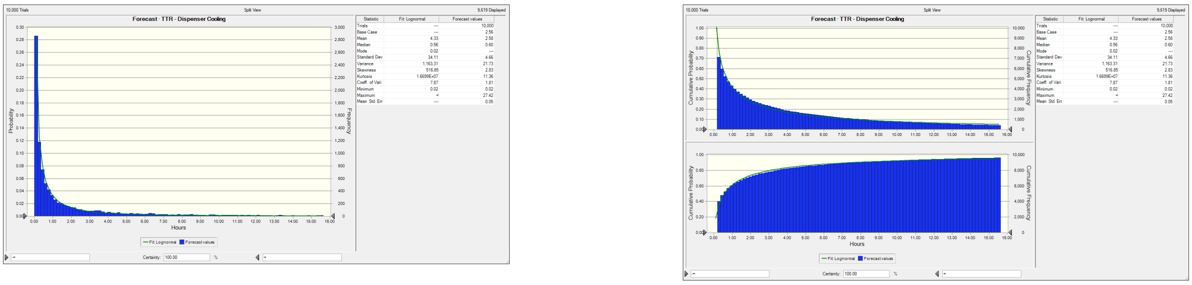
Figure 5.8: Truncation of the Assumption

In the subsequent step, the forecast was defined by selecting a cell to formulate the mathematical expression. Since the TTR and TBF analysis was conducted at the subsystem level, the forecast value should correspond to the previously determined distribution assumption for the components within that subsystem.

The Crystal Ball software utilizes the Monte Carlo Simulation method to forecast variable values. In this method, each randomly generated value based on the probabilistic distribution is independent of previously generated values. This allows for enhanced data analysis from a limited number of sample data, resulting in more robust forecasts regarding the data characteristics. In our case, a trial number of 10,000 was selected [76]. The reason of selecting 10,000 as a number of trials is to extend the number of trials as much as possible while decreasing the computational time. Upon completion of these processes, the software generated a frequency forecast chart, which is depicted in Figure **??** 5.9.(a) This forecast section enables users to propagate the uncertainty of KPIs.

The frequency chart displays the probability density of frequencies (PDF), with the X-axis representing hours and the Y-axis showing the probability density. The chart assigns a probability to each hour based on the frequency of occurrences. Although the frequency chart provides valuable insights, it can sometimes be challenging to interpret. The software generates two additional charts: the cumulative frequency chart (CDC) and the reverse cumulative frequency chart (RCFC) to overcome this potential challenge. These alternative charts can be observed in Figure **??**5.9.(b).

The forecast output plays a crucial role in this thesis by providing statistical information about the forecasted data and its fit. This statistical information is of utmost importance because the RAMS simulation toolbox used in this study exclusively accepts such statistical values. Consequently, this forecasted data becomes essential for the subsequent step of system modeling. Moreover, the simulation toolbox employs the Monte-Carlo simulation technique, which results in the double propagation of uncertainties. This double propagation of uncertainties contributes to improving the analysis results, as it considers the inherent uncertainties in both the forecasted data and the simulation process.



Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	2.56
Mean	4.33	2.58
Median	0.56	0.60
Mode	0.02	---
Standard Dev	34.11	4.66
Variance	1,163.31	21.73
Skewness	516.85	2.83
Kurtosis	1.6699E+07	11.36
Coeff. of Vari	7.87	1.81
Minimum	0.02	0.02
Maximum	∞	27.42
Mean Std. Err	---	0.05

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	2.56
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Coeff. of Vari	7.87	1.81
Minimum	0.02	0.02
Maximum	∞	27.42
Mean Std. Err	---	0.05

(a) TTR - Dispenser Cooling

(b) TTR - Dispenser Cooling Cumulative

Figure 5.9: Forecast Results

The aforementioned procedures were implemented for components that had a sample size of more than 15 data points. However, due to insufficient data points in most of the sample data for each component, the opportunity to utilize goodness-of-fit analysis was limited. As a result, the distributions for these components had to be determined manually. The decision-making process for selecting distribution types was conducted in consultation with the RAMS supervisor who has 30 years of experience in conducting RAMS analysis for various systems. Based on expert opinion, if the minimum, maximum, and most probable parameters were known, the probabilistic distribution was generated using either the BetaPERT or triangular distribution. However, since the modeling toolbox required two shape parameters to define the probability distribution for the beta distribution, the triangular distribution was selected for further analysis for data that exhibited a fit with the beta distribution after consultation with the expert. Furthermore, the lognormal distribution was employed for samples in which the 5th and 95th percentiles were known.

To illustrate the adjustments for the modeling process, the sample data for the H_2 installation can be considered. Initially, the data was characterized using a normal distribution. However, it ultimately exhibited a fit with the beta distribution, even though a normal distribution was initially assumed. Due to the limitation of the modeling toolbox in registering beta distribution, the assumption was adjusted to the triangular distribution, which closely approximates the beta distribution.

Thus, as a result of the goodness-of-fit analysis and the manual selection of distribution types, the required statistics for modeling were compiled in the following tables:

Table 5.5 presents the distribution types for the failure rate and the forecasted statistical data required for modeling. The third column of the table lists the input statistical variables for each distribution type. Similarly, distribution types for the repair rate of each component are listed in Table **??**6.

Table 5.5: Distribution Types and its Parameters for Component Failures

Components	Distribution Type for Failure Dist.	Parameters for Failure Distributions
Gas Inlet	Triangular	Min: 282.94; Mode: 1987.09; Max: 3761.74
Air Instrument	Gamma	Shape:5.69;Scale: 58.36;Loc:33.34;Mean:365.32;StDev:139.19
H_2 Installation	Triangular	Min: 412.06; Mode: 1909.61; Max: 3457.08
MP Cool	Triangular	Min: 21.15; Mode: 1429.06; Max: 2805.06
MP Hydraulic	Lognormal	Mean: 620.3; StDev: 154.44
MP Compressor	Lognormal	Mean: 841.45; StDev: 706.3
Disp 350	Lognormal	Mean: 455.82; StDev: 379.72
HP Comp	Lognormal	Mean: 807.74; StDev: 860.34
Disp 700	Lognormal	Mean: 1267.13; StDev: 1256.51
Disp. Cooling	Lognormal	Mean: 499.01; StDev: 2508.42
Dispenser	Lognormal	Mean: 245.19; StDev: 276.9

Table 5.6: Distribution Types and its Parameters for Component Repairs

Components	Distribution Type for Failure Dist.	Parameters for Repair Distributions
Gas Inlet	Triangular	Min: 0.06; Mode: 7.01; Max: 13.85
Air Instrument	Gamma	Shape:2.40;Scale:3.54;Location:0.42;Mean:8.91;StDev:5.43
H_2 Installation	Lognormal	Mean: 4.09; StDev: 19.96
MP Cool	Triangular	Min: 0.04; Mode: 4.32; Max: 8.69
MP Hydraulic	Lognormal	Mean: 10.41; StDev: 2.76
MP Compressor	Lognormal	Mean: 23.86; StDev: 13.56
Disp 350	Lognormal	Mean: 33.95; StDev: 430.01
HP Comp	Triangular	Min: 17.62; Mode: 58.77; Max: 99.52
Disp 700	Lognormal	Mean: 13.73; StDev: 59.22
Disp. Cooling	Lognormal	Mean: 4.33; StDev: 34.11
Dispenser	Lognormal	Mean: 4.9; StDev: 39.16

5.2.4. System Availability Analysis

Converting Reliability Block Diagram into a simulation model

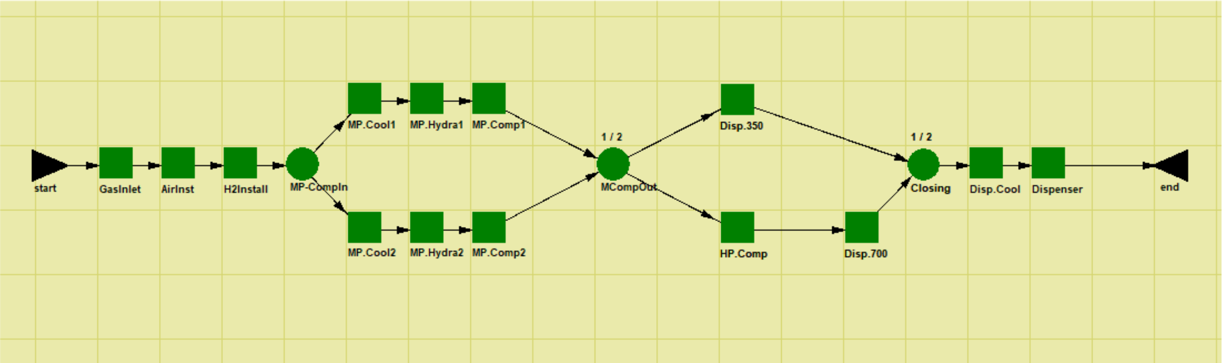


Figure 5.10: Model for RAPTOR

The reliability block diagram (RBD) serves as a crucial outcome of the system analysis for the hydrogen refueling station. It is a modeling tool to depict the station's components and component's interconnections. Initially, the industry-proven GRIF(GRaphical Interface for reliability Forecasting) modeling toolbox, which has been widely utilized for over three decades, was intended for use. However, due to compatibility issues with the company's current computer infrastructure, it was not feasible to acquire this toolbox. As an alternative, the RAPTOR modeling toolbox was chosen as a substitute for the project, as it provided a viable licensing option.

The RAPTOR toolbox offers several advantages and limitations. For instance, it allows users to input failure and repair data as statistical distribution types. Furthermore, it offers multiple options for a cost breakdown, such as man-hour costs and spare part costs, etc. However, a limitation of this toolbox is that it does not support distribution-based cost inputs. It only accepts fixed values for spare part costs and man-hour costs. However, in reality, these costs vary for each work order. Due to this limitation and the resultant decrease in cost uncertainty propagation, the costs were not incorporated into the modeling toolbox for further analysis.

Another limitation of RAPTOR is that it permits only one inlet and one outlet. However, there are two output pressures: 350 bar and 700 bar in the hydrogen refueling system. To address this issue in the RBD, a standby node was introduced to allow a single flow from the parallel flow configuration. However, during the conversion of the RBD into the RAPTOR model, it proved challenging to resolve this issue using a standby node.

The inability to address the issue using a standby node arises from the complexity of the gas flow within the model. Specifically, when transferring hydrogen at 350 bar to the dispenser cooling unit and subsequently to the dispenser itself, there is a possibility that the gas may also pass through the 700 bar dispenser nozzle. Consequently, adjustments were required to ensure the model accurately represents this scenario. The high-pressure (HP) compressor and the 700 bar nozzle were modeled in series to overcome this issue, as depicted in Figure 5.10.

Compared to the reliability block diagram (RBD), the model in the simulation software includes fewer components. The primary reason is the lack of data for some system components or the absence of observed failures thus far. As evident from the RBD, the gas inlet serves as the initial component of the system. Following this subsystem, only the air instrument subsystem was included in the model. The reason is there have been no registered work orders indicating failures, for the remaining series components up to the medium-pressure (MP) compressor. However, an additional block called the H_2 Installation subsystem was added before the medium-pressure compressor. This subsystem primarily addresses gas leakage and other failures that have not been precisely determined but are crucial for RAMS analysis.

The output of the H_2 Installation block branches into two parallel flows, feeding the inputs to the MP compressor. The MP compression system comprises the MP cooling, MP hydraulic, and MP compression subsystems. The input distribution data for both flows were registered as the same due to the lack of specifications on the BIS and the identical values for compressors of the same type in the database. The node 'MCompOut2' controls the flow from the two identical compressors. According to this node, if one of the MP compression systems is functioning properly, the flow from the other is not necessary. Hence, as long as one of these subsystems is operational, the system remains available. Only when both subsystems fail simultaneously does the system experience unavailability.

The next step in the model involves the gas being stored in the medium-pressure (MP) storage bank. However, due to insufficient data available for the storage units, they were excluded from the modeling process. After the 'MCompOut2' node, a solution was proposed to address the issue of having two outputs in the Raptor model. According to this approach, the gas is directed to either the dispenser 350 nozzle subsystem or the high-pressure compressor. A standby node is utilized after this pseudo-parallel flow to ensure that both systems cannot be used simultaneously. Instead, it allows for the use of either the 350-bar pressure system or the 700-bar pressure system. Since the dispenser cooling and dispenser are unified units for both systems, they are represented after this parallel flow.

In addition to this complexity, several components required a combination of higher-level subsystem data for modeling purposes. For instance, the high-pressure (HP) cooling subsystem had limited available failure data, with only one recorded work order, making reliability and maintainability analysis challenging. A similar situation was observed for the HP hydraulic subsystem, where only one work order was registered and promptly resolved. These subsystems were combined with the data from the HP compression system to include them in the analysis. This assumption was made based on the understanding that if both subsystems of the HP compression system fail, the entire HP system would also fail.

Furthermore, some system components were excluded from the modeling process. For instance, the high-pressure storage unit had no registered work orders, and the general database lacked specific data for this subsystem. Therefore, it was omitted from the modeling process for availability analysis. These assumptions and adjustments were thoroughly discussed and validated with both the company supervisor and the university supervisor. Consequently, the final model was derived, as depicted in Figure 5.10.

In the subsequent step, the simulation process was established to assess the system's availability over a period of 10 years. The initial setup involved running the simulation 50 times over a total of 8,760 hours (corresponding to one year). Subsequently, the simulation was repeated 50 times over extended durations: 17,520 hours (two years), 26,280 hours (three years), and so forth, up to 87,620 hours (ten years).

As a general guideline, in the presence of modeling uncertainties, it is advisable to conduct a sufficient number of simulation runs. However, due to computational limitations posed by an outdated company computer, only 50 simulation runs were feasible for each setup. This constrained computational power prolonged the simulation duration. For instance, completing the 10-year simulation with 50 runs took approximately 5 hours. Considering the various simulation durations for the ten setups, it was decided to utilize 50 runs per setup based on input from the company's reliability engineer.

Lastly, it is crucial to account for component aging in the modeling process. Regrettably, Raptor does not offer to incorporate aging factors for the system components, which restricts the insights obtained. As can be observed from the figures, the number of failures remains relatively consistent over the years. In normal circumstances, one would expect an increased number of failures as the components age.

As a culmination of these processes, the simulation output is presented in Figure 5.12a, illustrating the system's availability over one year. It provides insights into the minimum, maximum, and most probable availability of the station within this timeframe. Comparing these results with the current availability data of the station confirms their alignment. According to the company's report, the current availability is 92.0%, which closely matches the most probable availability predicted by the model. This concurrence further validates the reliability of our model for the station.

In addition to the availability result, the reliability of each component can be checked below in Figure 5.11. Yellow block represent the high pressure compressor which has the lowest reliability with 93.33%.Lastly, In Figure 5.12b, the number of failures for each component is depicted as an outcome of the simulation. These failure counts, along with the availability data, will serve as inputs for the techno-economic analysis of the station.

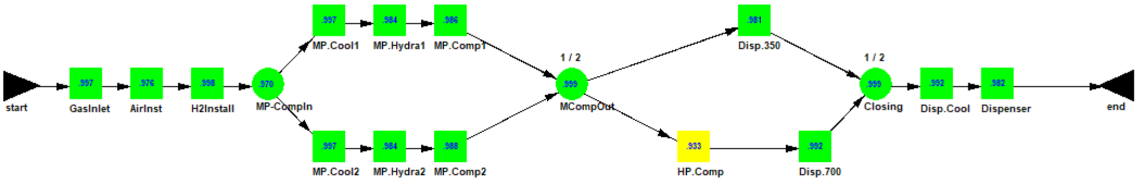
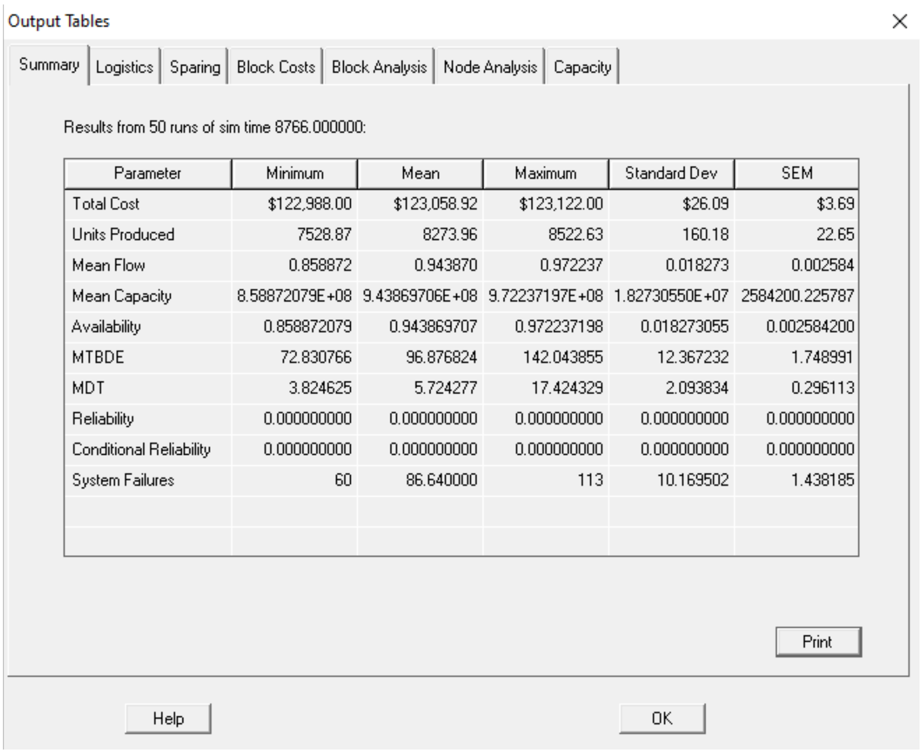


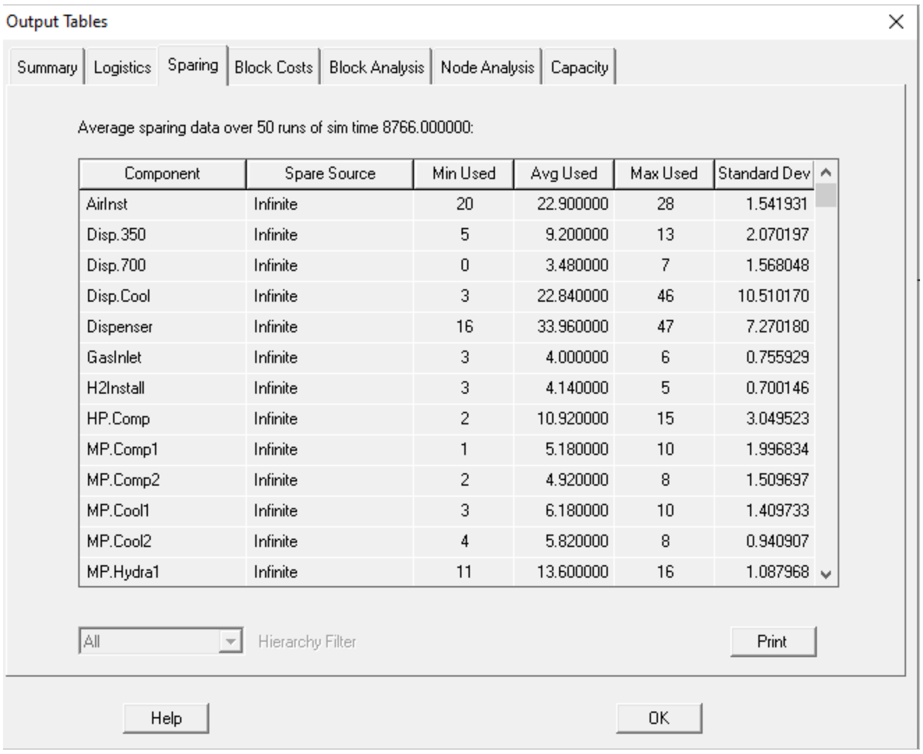
Figure 5.11: Component's Reliability



Results from 50 runs of sim time 8766.000000:

Parameter	Minimum	Mean	Maximum	Standard Dev	SEM
Total Cost	$122,988.00	$123,058.92	$123,122.00	$26.09	$3.69
Units Produced	7528.87	8273.96	8522.63	160.18	22.65
Mean Flow	0.858872	0.943870	0.972237	0.018273	0.002584
Mean Capacity	8.58872079E+08	9.43869706E+08	9.72237197E+08	1.82730550E+07	2584200.225787
Availability	0.858872079	0.943869707	0.972237198	0.018273055	0.002584200
MTBDE	72.830766	96.876824	142.043855	12.367232	1.748991
MDT	3.824625	5.724277	17.424329	2.093834	0.296113
Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
Conditional Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
System Failures	60	86.640000	113	10.169502	1.438185

(a) Simulation Output for the Availability



Average sparing data over 50 runs of sim time 8766.000000:

Component	Spare Source	Min Used	Avg Used	Max Used	Standard Dev
AirInst	Infinite	20	22.900000	28	1.541931
Disp.350	Infinite	5	9.200000	13	2.070197
Disp.700	Infinite	0	3.480000	7	1.568048
Disp.Cool	Infinite	3	22.840000	46	10.510170
Dispenser	Infinite	16	33.960000	47	7.270180
GasInlet	Infinite	3	4.000000	6	0.755929
H2Install	Infinite	3	4.140000	5	0.700146
HP.Comp	Infinite	2	10.920000	15	3.049523
MP.Comp1	Infinite	1	5.180000	10	1.996834
MP.Comp2	Infinite	2	4.920000	8	1.509697
MP.Cool1	Infinite	3	6.180000	10	1.409733
MP.Cool2	Infinite	4	5.820000	8	0.940907
MP.Hydra1	Infinite	11	13.600000	16	1.087968

(b) Simulation Output for the Number of Failures per Components

Figure 5.12: Simulation Outputs

5.2.5. System Risk Assessment from HAZOP Study

Safety for Hydrogen and its Risk

Hydrogen, as a chemical element, exists in a gaseous form that is colorless, odorless, and tasteless [77]. However, hydrogen is highly combustible and poses a significant risk to human safety if not handled with utmost care. It is worth noting that hydrogen presents numerous unique challenges compared to other flammable gases, such as methane and LPG, including its inability to be marked with odorants, high buoyancy, and susceptibility to self-ignition under high pressure [55]. It has a low ignition energy and wide flammable range, which cause a high probability of ignition if there is a leak in the system [78].

Moreover, hydrogen leaks cannot be detected through human senses such as smell or sound. This lack of detectability emphasizes the necessity for appropriate equipment and training when working with hydrogen. In terms of safety measures, it is crucial to ensure that the concentration of hydrogen in the air does not exceed 4 % - the maximum Lower Flammability Limit (LFL) - at windows, openings, air intakes, and locations where individuals may be present unless a lower concentration is mandated by risk assessment [24].

A risk assessment is required to assess potential safety concerns and obtain approval from authorities, considering the safety level criteria outlined in ISO 19880. This assessment should take into account factors such as potential leak rates and their frequency, formation of ignitable mixtures within enclosures with consideration of ventilation, the possibility of ignition, and the resulting over-pressure due to high flow rates from pressurized systems or ignition of flammable mixtures, including the impact of pressure peaking phenomenon.

ISO 19880 serves as a valuable guideline for examining potential hazards associated with hydrogen, particularly regarding jet flames and other specific hazards linked to hydrogen behavior. Jet flames may occur as a consequence of immediate ignition resulting from high-pressure hydrogen release. Conversely, if released hydrogen is not promptly ignited, flash fires or explosions (deflagration and detonation behavior) may ensue. Turbulence in hydrogen leakage can exacerbate the magnitude of overpressure generated.

While computational fluid dynamics toolboxes can be employed to model the potential effects of leakage for enhanced safety measures, such detailed simulations are beyond the scope of this research due to time limitations. As a result, the discussion of potential hazards primarily relies on empirical evidence from experts and phenomenological methods.

Mitigation measures

As an initial mitigation measure to ensure operational safety, setting the Maximum Operating Pressure (MOP) of the hydrogen station is essential, in accordance with the regulations stated in [24]. According to the standard, the MOP during regular fueling process should not exceed 125% of the desired hydrogen service level. For instance, if the desired operational pressure for light vehicles is 35 MPa, the maximum MOP for safe operation would be 43.75 MPa.

Additionally, the standart specifically focuses on the dispensing system with a another parameter known as the Maximum Allowable Working Pressure (MAWP). The MAWP sets the maximum permissible pressure at which the dispensing system can operate, and is typically set at 137.5% of the hydrogen service level. As an example, if the hydrogen service level is selected as 35 MPa, the MAWP would be 48.125 MPa. Beyond this value, the dispensing system must automatically shut down for safety.

In addition to setting the MOP and MAWP as initial mitigation measures, further actions should be taken to address hydrogen leakage in order to ensure safety since empirical findings strongly indicate a high likelihood of leak events[55]. Hence, when a leak occurs, it is crucial to promptly shut off the hydrogen supply to equipment within the enclosure from an isolation point located outside of the container. This decisive action effectively disconnects the hydrogen source, preventing the further release and potential hazards. Depressurizing the hydrogen equipment within the enclosure is also critical, ensuring that the hydrogen is directed to a safe location where it poses no risk. This step significantly mitigates the potential hazards associated with pressurized hydrogen.

Moreover, it is essential to de-energize electrical equipment that is not specifically designed for use in ignitable atmospheres to prevent potential ignition sources. By removing electrical energy from such equipment, the risk of fire or explosion due to electrical sparks is effectively minimized. Furthermore, increasing ventilation within the enclosure plays a crucial role in maintaining a safe environment. Proper ventilation helps disperse any leaked hydrogen, reducing the concentration of flammable gases and minimizing the risk of ignition and subsequent accidents.

It is worth noting that if the source of hydrogen cannot be isolated from the point of the leak, hydrogen fires should be allowed to burn until the hydrogen fuel is completely consumed, as stated in ISO 19880.

This approach prevents the accumulation of uncontrolled hydrogen, ensuring the safety of the surrounding environment. By implementing these mitigation measures, overall safety and security of hydrogen operations can be significantly enhanced while minimizing the risks associated with hydrogen-related hazards.

TotalEnergies Approach for Hydrogen Risk
In light of the high flammability of hydrogen, TotalEnergies adopts a conservative approach to ensure operational safety. It is assumed that the probability of hydrogen ignition is 1.00, meaning that any leak resulting in the shutdown of the station is treated as an ignition event. This practical approach emphasizes the need for stringent safety measures to prevent and mitigate potential risks associated with hydrogen leaks. By considering all leaks as potential ignition sources, TotalEnergies prioritizes the implementation of robust safety protocols and preventive measures to safeguard personnel, equipment, and the surrounding environment.

Data Utilization to determine the probability of having hazardous event
For the TotalEnergies Breda station, a detailed analysis of work orders was conducted to assess the potential ignition risks . An additional conditional column was introduced to examine the frequency of work orders associated with hydrogen leaks and the occurrences of shutdowns resulting from these leaks. Microsoft Power BI was employed as a data utilization tool for this analysis 5.2.2. Within the Power BI dashboard, keywords such as ”leakage” and ”detect” were identified as being predominantly related to hydrogen leakage incidents. Work orders containing these keywords in the ”New Description” column were classified as risky. This examination revealed that out of 154 work orders, 35 were identified as being associated with hydrogen leaks.

However, it is important to note that not all of these 35 work orders led to a station shutdown. Meetings were conducted with technicians and safety engineers to understand the station’s shutdown procedure in response to hydrogen leaks, . Through these discussions, it was determined that the following protocol is followed for hydrogen leakage incidents:

1. If the hydrogen sensor detects hydrogen levels exceeding 10% of the lower explosive limit (LEL) for five consecutive times, the system shuts down and releases pressure in a controlled manner.
2. If the hydrogen sensor detects hydrogen levels exceeding 20% of the LEL, the system immediately shuts down and releases pressure in a controlled manner.

In order to further analyze the hydrogen leaks and identify those that posed a potential ignition risk, the work orders associated with hydrogen leaks were filtered based on their urgency code. Work orders with unspecified urgency codes or urgency codes 1 (incidents) or 3 (no sales possible) were classified as potentially risky, as they could potentially result in ignition. As a result of this analysis, 9 work orders were identified as potentially causing ignition out of 154 work orders. In statistical terms, this corresponds to a probability of 5.85% for a leakage event to result in the ignition, as depicted in Figure 5.13.

Safety for Components
Given the time constraints, a detailed analysis of potential hazards for components was primarily focused on the dispenser and compressors due to their significant number of failures and maintenance costs. Additionally, the analysis was extended to include the storage tanks of vehicles, as they represent another equipment category with the potential to ignite.

Compressor’s potential hazards

When working with compressors, it is essential to acknowledge the inherent risks associated with the high-pressure gases involved, as they can pose significant hazards to human health and safety. It is important to note that these compressors utilize potentially toxic fluids, including glycol for cooling purposes and hydraulic oil for power supply. Thus, strict precautions must be taken to avoid any contact or ingestion of these substances in order to prevent potential harm to personnel.

Emphasizing the importance of electrical safety is paramount, considering that compressors typically operate on a high-voltage power supply of 400 volts. This voltage level presents a considerable risk of electrocution or short circuits if not handled with utmost care. It is crucial to recognize that such voltage surpasses the standard household level of 240 volts, amplifying the severity of any potential incidents.

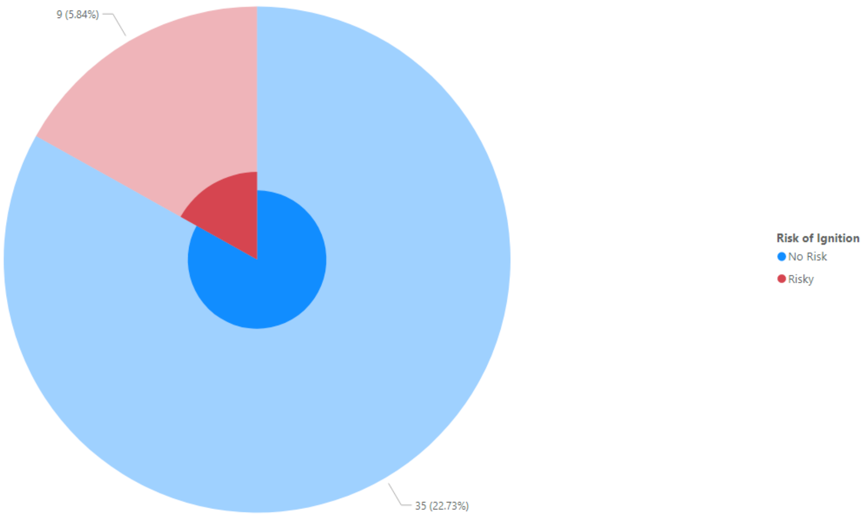


Figure 5.13: Probability of Ignition

To mitigate these risks, comprehensive training, cautionary practices, and the utilization of appropriate protective equipment are imperative.

Strict adherence to safety guidelines is vital throughout the handling and operation of compressors. This procedure involves ensuring correct installation, operation, and maintenance procedures to minimize the potential hazardous incidents. By consistently adhering to these protocols and regulations, a safe working environment can be maintained when dealing with compressors.

Dispenser's potential hazards

The hydrogen filling process into vehicles entails significant risks, necessitating a comprehensive understanding and mitigation of potential hazards to safeguard the well-being of all individuals involved. One critical hazard is the risk of over-pressurization of the customer vehicle tank, which can cause tank damage and lead to a hydrogen leak, ultimately resulting in an explosion. Additionally, the possibility of overheating the vehicle tank must be acknowledged, as it can also lead to tank damage, hydrogen leakage, and subsequent explosions.

The connection and disconnection of the nozzle during the filling process also introduce potential hazards. The connection process carries the risk of contamination on the vehicle receptacle and the accidental dropping of the nozzle, potentially damaging the inner seal. During the filling process itself, the possibility of a hydrogen leak exists, which poses a considerable risk of explosion.

Furthermore, the disconnection process has its own set of risks. The use of chilled hydrogen (-40 °C) for cooling purposes can result in freezing injuries when the metal of the nozzle comes into contact with human skin. Moisture present on the nozzle may also freeze, leading to potential leakage during the filling process. However, modern nozzles are equipped with an air purge feature to mitigate this particular hazard.

The utilization of chilled liquid CO_2 for cooling the hydrogen gas inside the dispenser introduces additional potential risks. Even a small leakage in the CO_2 lines or heat exchanger can cause CO_2 to accumulate within the dispenser, creating a severe hazard when the dispenser is opened for maintenance or inspection.

Lastly, the risk of a vehicle colliding with the dispenser must be considered, as it could cause to damage the cooling or hydrogen lines, leading to the major hazard of leaked CO_2 and/or hydrogen.

Given the diverse array of potential hazards associated with filling hydrogen in vehicles, it is crucial to implement stringent safety precautions and adhere to established protocols and regulations. Comprehensive training, heightened awareness, and the use of appropriate protective equipment are essential to mitigate these hazards effectively and ensure the safety of all individuals involved in the process.

Risk Assessment of Hazardous Event

In order to evaluate the risks associated with leakage and potential ignition events, a detailed analysis for the ignition consequences was conducted. The HAZOP study previously conducted for the entire hydrogen station served as a valuable resource for this assessment. TotalEnergies' HAZOP study findings were instrumental in establishing a station-specific risk matrix in Appendix D.2.

According to the risk matrix, the consequences of ignition were determined to range from a minimum of 100,000 € to a maximum of 1,000,000 € for any damage occurring within the installation. However, in the event of a fatality or any damage that permanently halts operations, the consequences escalate to a range of 1,000,000 € to 10,000,000 €. To account for these worst-case scenarios, the risk associated with these consequences were included as inputs for the net present value (NPV) analysis in the subsequent section.

5.3. Techno-economic assessment of the system subject to RAMS analysis

5.3.1. Data acquisition and structuring

In order to conduct the economic analysis of the system, a diverse range of data points was gathered, including cost data, sales data, initial investment, and subsidy amounts. The marketing and service department provided monthly sales figures for the station, along with associated prices, costs, and subsidy amounts. Operational costs were also obtained from this department. Initial investment data were acquired from the Business Information System (BIS), which also provided maintenance cost data for each work order.

The PowerBI query was customized to extract detailed maintenance cost data, with a specific focus on four attributes related to repair costs, encompassing technician costs, spare part costs, and total costs. However, some work orders did not have registered maintenance costs. This lack occurred in cases where issues were resolved without equipment replacement or when no technician was sent to the site. Additionally, some work orders displayed repetitive equipment and technician costs, despite having the same total cost in the respective column. Expert opinions on who is responsible for registering these work orders in the BIS were sought to determine the most suitable attributes for further analysis. Ultimately, the total cost attribute was identified as the key factor for conducting an in-depth cost analysis, serving as the total maintenance cost per work order.

Furthermore, relevant data to assess the potential costs associated with hazardous events or accidents leading to fatalities were obtained from the Health, Safety, Environment, and Quality (HSEQ) department, as was explained in the previous section. This information played a critical role in understanding the likelihood of severe events and calculating the associated costs, enabling a comprehensive evaluation of the system's overall risk. Additionally, market growth rates were extracted from existing literature to predict market development in future years. This insight was essential for considering future market trends and their impact on the economic analysis.

Table 5.7: Economic Data Types and its Resources

Data Name	Data Resources
Sales Data	Marketing and service department
Maintenance Cost	Business Information System
Cost of Goods Sold	Marketing and service department
Initial Investment	Business Information System
Subsidy	Marketing and service department
Market Growth Rate	Literature Study
Price of Goods Sold	Marketing and service department & Literature Study

5.3.2. Income statement analysis

Incoming cash flow assessment of a system

Incoming cash flow, also known as inbound cash flow, refers to the funds received by a company from external parties as a result of transactions conducted between the involved parties [79]. In the context of the station's current status, cash income primarily originates from government and partner company support, as well as sales issued to end customers.

Government support plays a significant role in fostering the development of this niche technology and facilitating the transition toward sustainable energy practices. Subsidies are one the key policy instruments to support niche technologies and ensure compatibility with existing fossil fuel infrastructure. The specific amount of subsidies varies depending on the project's nature. For instance, in the case of Total Energies' Breda Hydrogen station, the government issues 1,017,608 € as a subsidy.

The second component of the income cash flow is the turnover or sales revenue. In order to forecast the expected sales data for the first year, historical sales figures were analyzed using the Crystal Ball software. The same data characterization approach described in Section 5.2.3 for operational data was applied to the monthly sales data.

Since there were more than 15 data points in the database for sales, the ”goodness of fit” option in the Crystal Ball software was utilized. This option allowed for the determination of the best-fit sales distribution. Based on that analysis, the software fits the sales data to lognormal distribution with P95 621.71 kg/month.

When forecasting the annual sales for the current year, the previous year’s sales data was utilized. The sales data for the last year were obtained based on a station availability of 92%. However, instead of assuming the same availability for the upcoming year forecast, the availability data obtained from the simulation results were incorporated into the analysis. Specifically, the most probable availability data were utilized for further research, considering the known minimum, maximum, and most probable availability values.

The statistical results of the forecasted distribution fit can be found in the accompanying Table 5.8. These results provide valuable insights into the expected sales distribution for the first year.

Table 5.8: Statistical Results of First-Year Forecasted Sale Distribution

Statistical Parameter	Statistical Value
Distribution Type	Beta Distribution
Minimum	419.17
Maximum	648.57
Median	487.06
Mean	497.06

Given that this techno-economic analysis involves a 10-year projection to assess the net present value of the stations, it is essential to forecast the sales data for the upcoming ten years. The Crystal Ball software was utilized to generate these forecasts based on the characterized sales data assumptions. However, the hydrogen market is expected to experience strong growth due to significant investments in the hydrogen business. Therefore, it is necessary to incorporate the expected market growth rate into the sales forecasts for the upcoming years.

As the expected market growth rate is subject to uncertainty, the Crystal Ball software was employed to propagate this uncertainty. However, setting an assumption solely based on single expected market growth rate data may not provide sufficient information. To address this data limitation, various figures were collected from relevant literature sources, and these numbers are listed in the accompanying Table 5.9. This approach ensures a more comprehensive and robust assessment of the sales forecasts by considering a range of potential market growth scenarios.

Table 5.9: Literature based Expected Hydrogen Market Growth Rate

Author’s Name	Year	Expected Market Growth Rate
IEA [14]	2022	60%
MarketAndMarkets [80]	2023	63.4%
Precedence Research [81]	February 2022	60.1%
Wood Mackenzie [82]	2020	28%

Based on the table provided, the expected growth rate for the hydrogen market ranges from 28.0% to 63.4%. Since the number of data points is less than 15, it is not feasible to utilize the goodness-of-fit option for characterization. In order to enable the use of the Crystal Ball software for propagating uncertainty, the mean of all available data points was calculated and used as the most probable data point. Subsequently, the minimum, maximum, and most probable values were input into the Crystal Ball software to generate a fitted distribution. The statistical values pertaining to the fit distribution can be found in the Table 5.10 below.

Table 5.10: Statistical Results of Hydrogen Market Growth Rate Distribution

Statistical Parameter	Statistical Value
Distribution Type	BetaPert Distribution
Minimum	28.00
Maximum	63.4
Median	55.30
Mode	60.10
Mean	55.30

After establishing the assumption for the market growth rate using Crystal Ball, the annual sales data were forecasted using the straight-line method. This method assumes a consistent growth rate throughout the project's lifecycle and is commonly employed for forecasting asset growth or depreciation [83]. Due to its widespread usage and simplicity, it was deemed suitable for this analysis. The fixed growth rate determined by each run of Crystal Ball was applied to forecast sales for all ten years. To account for cumulative growth, the growth rate was multiplied by the previous year's sales figure. For instance, to forecast the sales data for the fifth year, the sales forecast for the fourth year was multiplied by the expected growth rate. This process was repeated for each year, utilizing the previous year's data and the market growth rate multiplication.

In order to complete the forecast of the business's expected turnover, it is necessary to project the future price of hydrogen. Given the uncertainty surrounding hydrogen prices, characterization and propagation of this uncertainty are required. The same approach with previous analyses for uncertainty propagation was employed in this case as well.

Moreover, it is expected that a significant reduction in hydrogen prices will occur throughout the projected duration, driven by cost efficiencies resulting from the learning effect and advancements in cost-effective green hydrogen technologies [84]. The reduction percentage has been determined to be 5.9%, based on a careful calculation of the deflation ratio for hydrogen costs which will be explained in Section 5.3.2. To incorporate this anticipated price reduction, the straight-line method, previously employed for the market growth rate, was utilized. This approach assumes a consistent reduction rate and applies it uniformly across all ten years of the forecast. By considering the cumulative effect of the reduction, each year's projected price was adjusted accordingly. Subsequently, these adjusted prices were multiplied by the corresponding volume of hydrogen sold to calculate the annual turnover of the station. In summary, Table 5.11 provided below presents the the most probably forecasted sales data for the next ten years, incorporating the projected turnover. It is crucial to note that these forecasts serve as estimations of the expected station turnover during the specified timeframe.

Table 5.11: Amount of sales forecast and its turnover

Year	Amount of Sale (kg/month)	Turnover (€/month)
1	531.61	97574.78
2	810.93	157624.87
3	1211.04	236170.33
4	1827.86	356527.12
5	2700.45	526733.58
6	4163.98	812202.64
7	6218.13	1212872.69
8	9425.39	1838461.19
9	14286.78	2786697.05
10	21609.38	4214999.91

Outgoing cash flow assessment of a system with respect to the results of RAMS analysis
Outgoing cash flow, as mentioned earlier, encompasses various components that represent the expenditures incurred by the company to sustain its operations [85]. The primary component of outgoing cash flow is the cost of hydrogen, which accounts for a significant portion of the expenses. It includes the procurement or production of hydrogen fuel. Operational costs also contribute to the outgoing cash flow. It encompasses a range of expenses associated with running the business, such as labor costs, utilities, maintenance expenses, and other necessary resources. However, maintenance costs was separated from operational costs in this project to identify critical equipment within the station. This scrutiny allows for a deeper analysis of the maintenance aspect and helps identify any potential cost-saving opportunities or risks associated with equipment failures. Understanding and accurately assessing the breakdown of outgoing cash flow are crucial for conducting a comprehensive financial evaluation of the station's operations. Therefore, in the next step, the breakdown of the outgoing cash flow cost is scrutinized.

Cost of Good Solds

Given the inherent uncertainty surrounding hydrogen costs in the future, it is crucial to characterize the data on hydrogen costs using the Crystal Ball software. This approach allows for the effective propagation and incorporation of uncertainties associated with the cost of hydrogen into the financial analysis. The resulting distribution statistics for hydrogen costs is shown in the Table 5.12 below.

Table 5.12: COGS of Hydrogen

Statistical Parameter	Statistical Value
Distribution Type	Triangular Distribution
Minimum	4.10
Maximum	6.10
Median	5.53
Mean	5.45

Moreover, significant cost reductions are expected in the coming years due to factors such as learning by doing and the development of cost-effective green hydrogen technologies. Based on these factors, an annual cost deflation rate of 5.9% has been calculated. This calculation takes into account the current hydrogen price for Total Energies, which is 6.1 € per kilogram, and the most probable projected cost of hydrogen in 2030, as determined through a literature review, which is 4.1 € per kilogram. Using a linear depreciation model and considering a 7-year projection period, a constant deflation rate is assumed, resulting in a year-on-year cost reduction based on the calculated deflation rate. This approach allows for the estimation of hydrogen costs for the Breda station over the specified years, assuming a constant deflation rate. These projections reflect the anticipated cost reductions for hydrogen during the specified period, taking into account the aforementioned assumptions and calculations.

Operational Cost

The overall operational cost, excluding maintenance cost, was derived from the financial tables provided by the company. However, it is important to consider potential risks and uncertainties that may impact the operational cost. In the context of unforeseen events, such as war, which can result in unexpected price spikes, a conservative approach was taken to assess the worst-case scenario. As a result, the operational cost increased by 20% compared to the previous year because of the Ukraine-Russian war.

An annual inflation rate for the operational cost was assumed as 20% to develop a robust financial model that incorporates worst-case scenarios. Building upon this assumption, the upcoming years' operational costs were forecasted by considering the past year's operational cost data as the baseline. This approach ensures that the financial model can withstand the potential impact of inflation and account for the uncertainties in operational costs. The forecasted operational costs, taking into consideration the assumed inflation rate, are summarized in the income statement Appendix E.1.

Tax

Income tax is a significant component of the outgoing cash flow. It is an essential consideration in the financial analysis of the business. It is calculated based on the company's profits and play a crucial role in determining the company's tax obligations. In the case of the Netherlands, the current tax system applies the rate of 21% to hydrogen, considering it as a product registered in general goods [86]. According to the accounting rules, the tax calculation is performed after deducting the operational costs, including the maintenance cost, from the sale income. This deduction results in the EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) figure, which serves as a key indicator of the company's profitability. If the EBITDA is positive, indicating a profit, the company is obligated to pay 21% of its income as tax. However, in the event that the EBITDA is negative, indicating a loss, the company is not liable to pay any income taxes.

5.3.3. Corrective Maintenance Cost

Current Maintenance Data and its Associated Cost

Since the beginning of the operation, 156 corrective maintenance work orders have been registered in the system. Figure 5.14 illustrates the distribution of failures per component, revealing that the dispenser system has experienced the highest number of failures. Dispenser system failures account for approximately 52% of all work orders. This finding provides valuable insight into the operational challenges associated with the dispenser system.

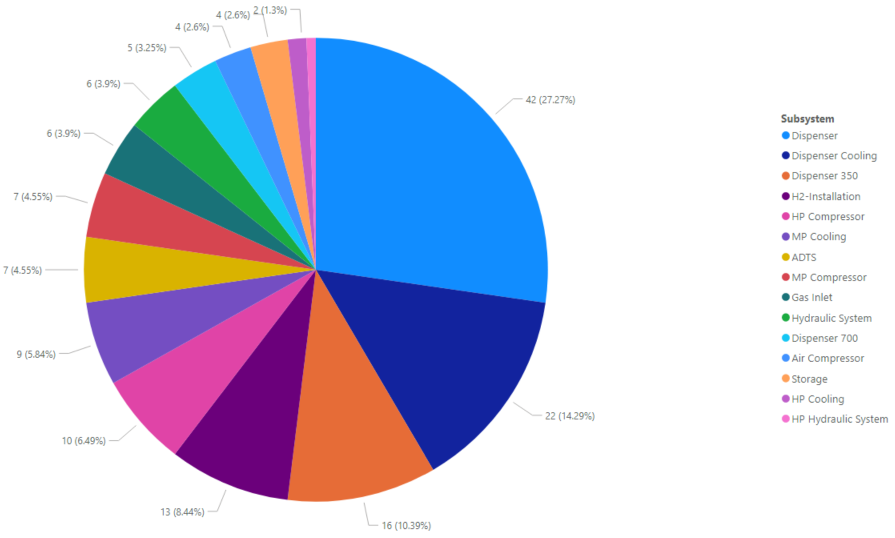


Figure 5.14: Work order classification by subsystems

In addition to analyzing the number of failures per component, a detailed examination of the associated maintenance costs was conducted. Up until now, TotalEnergies has incurred a total expenditure of 100,970 € for maintenance purposes, with the dispenser system requiring the highest expenditure among all components. This preliminary classification offers initial insights into the financial impact of failures on the station's maintenance expenses, Figure 5.15.

Considering the significant number of failures and corresponding expenditures, it is imperative to conduct a thorough investigation to the dispenser system. For that purpose, the results of the RAPTOR simulation were further analyzed to understand the reliability/availability of the dispenser system. The analysis revealed that the dispenser system exhibits a relatively higher availability of 98.1% than the HP compressor, which has the lowest availability data at 93.3%. This contradiction raises further questions and prompts the need for clarification.

In order to address these questions, meetings were set with technicians and reliability engineer to gain practical insights. Based on their expertise, two preliminary observations emerged:

1. The HP compressor, being a third-party supplied component, benefits from warranty coverage. However, the time required for repair or maintenance is longer due to the involvement of external

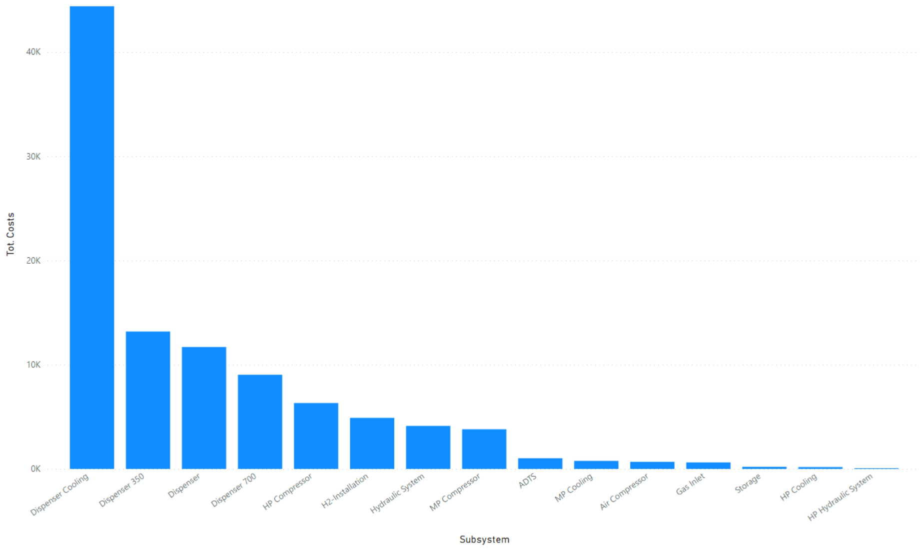


Figure 5.15: Cost Distribution for each Subsystem

suppliers, thereby reducing the overall availability of the component and the supply of 700-bar hydrogen.

2. Despite the abundant number of failures in the dispenser system, the repairs for these failures are relatively straightforward and require less time. Consequently, the availability of this system is not significantly affected. However, the increased expenditure associated with the dispenser system is attributed to its in-house design and production. Since the dispenser was not sourced from a third-party supplier, warranty coverage does not apply, and the company is responsible for bearing the costs of every work order. This prototype system's design leads to a higher frequency of failures and increased costs for the company. Consequently, the company may consider procuring dispensers from third-party suppliers, particularly when prioritizing the most competitive aspects of the business.

Uncertainty propagation for corrective maintenance cost data by MLE
The RAPTOR analysis provides valuable information on the number of failures per component per year, which can be found in the Appendix C. With this information, the maintenance cost can be calculated by multiplying the number of failures with the propagated uncertain maintenance cost, whose statistical distribution parameters can be checked from the below Table 5.13. However, not all work orders generated by failures incur a cost. In some cases, the problem may be resolved by changing the equipment or without dispatching technicians to the site.

Firstly, utilizing binomial distributions was considered to account for this variability by deciding the probability of incurring a maintenance cost per component based on historical data. However, due to limitations in the RAPTOR software, which provides cumulative failure counts per year rather than individual failures, it is not feasible to employ various binomial distributions in Excel alone. It could be solved by writing a code with for loop, but implementing such calculations would require extensive computational power or more advanced software tools like Matlab or Python.

Instead of computing this aspect with more advanced softwares, a simpler historical ratio approach was adopted. The number of work orders requiring a cost was divided by the total number of work orders. This calculation provides the proportion of work orders that necessitate an expenditure per component. It provides insight into the probability of incurring maintenance costs for each component, as summarized in the accompanying Table 5.14. Via implementing the probability of incurring maintenance costs into the forecast, upcoming maintenance costs were predicted. This forecasting process enables a more comprehensive analysis of the maintenance expenses associated with the station's operations.

5.3.4. Financial loss analysis due to potential hazardous events

Table 5.13: Distribution Types and its Parameters for Cost of Maintenance

Components	Distribution Type for Maintenance Cost	Parameters for Cost Distribution
Gas Inlet	Triangular	Min: 305.65; Mode: 312.15; Max: 319.10
Air Instrument	Weibull	Mode: 152.52; Mean: 215.5
H_2 Installation	Weibull	Mode: 659.58; Mean: 933.25
MP Cool	Triangular	Min: 246.69; Mode: 368.90; Max: 559.43
MP Hydraulic	Gamma	Mean: 350.72; StDev: 302.38
MP Compressor	Lognormal	Mean: 400.50; StDev: 419.93
Disp 350	Lognormal	Mean: 1229.48; StDev: 1728.76
HP Comp	Weibull	Mode: 433.02 ; Mean: 735.53
Disp 700	Gamma	Mean: 1865.20; StDev: 1208.75
Disp. Cooling	Weibull	Mean: 1217.34
Dispenser	Lognormal	Mean: 1226.57; StDev: 2399.31

Table 5.14: Probability of incurring maintenance cost per component

Components	Probability of incurring maintenance cost
Gas Inlet	0.33
Air Instrument	1.00
H_2 Installation	0.33
MP Cool	0.25
MP Hydraulic	0.83
MP Compressor	0.67
Disp 350	0.5
HP Comp	1.00
Disp 700	0.6
Disp. Cooling	0.32
Dispenser	0.53

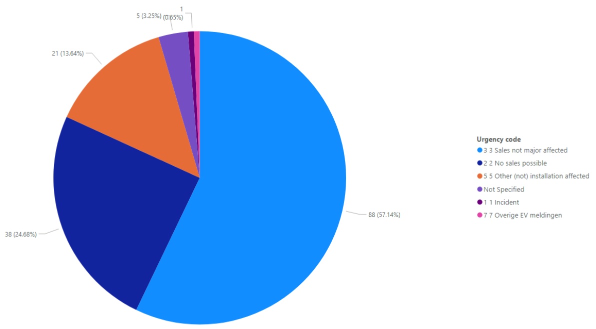


Figure 5.16: Urgency of Work Orders

In conducting a comprehensive financial assessment, it is advantageous to account for the potential risks arising from hydrogen non-availability and operational safety concerns, ensuring preparedness for worst-case scenarios. To address these risks from a financial standpoint, the potential financial implications resulting from hydrogen supply failures and unsafe operational incidents were considered as an outgoing cash flow. However, due to these being indirect costs, these aspects cannot be directly integrated into the income statement. To properly evaluate these risks, a distinct section was dedicated to analyzing the financial impacts associated with hydrogen non-availability and unsafe operations. This separate section allows for a comprehensive assessment that goes beyond the scope of the income statement analysis. Specifically, within the net present value (NPV) analysis, this analysis is treated as the outgoing cash flow, enabling an evaluation of the potential financial consequences related to the risks of non-availability and unsafe operation.

Risk of not supplying hydrogen
Furthermore, to comprehensively assess the potential risk of non-availability, the Crystal Ball software was employed to calculate the financial impact of hydrogen supply failures and the risk associated with unsafe operation, such as leakage and other hazards. These risks were considered as outgoing cash flow in the analysis.

In addition, considering that periodic maintenance checks of the station are conducted while it is operational. That is why, the operational duration of the station is assumed to be 365 days. Based on that assumpion. the nonavailability of the sation can be calcualated as

$$NonAvailaibility = 1 - Availability \tag{5.3}$$

By multiplying the non-availability by the price margin of one kilogram of hydrogen yields the risk of not supplying hydrogen.

$$Risk = NonAvailability * ExpectedAnnualSale * PriceMargin \tag{5.4}$$

$$WherePriceMargin = Priceofhydrogenperkg - Costofhydrogenperkg \tag{5.5}$$

Based on this calculation, the risk of non-availability was determined for each year, and the results can be found in the Figure E.

Risk of unsafe operation
For this part, the Crystal Ball software was once again utilized to address the inherent uncertainty of hazard consequences by leveraging its previous application in operational data characterization. A comprehensive risk assessment was conducted by incorporating the potential uncertain hazard consequence with its corresponding probability. This rigorous assessment enabled the integration of risk factors into the techno-economic evaluation, ensuring their proper inclusion in the determination of the station's net present value.

Based on these meticulous calculations, the forecasted risks can be summarized as follows: the projected damage in installation amounts to 983,500.87 €, while the estimated risk of fatality or permanent shutdown stands at 8,494,452.98 €. For more detailed information, corresponding section in the Appendix D can be checked.

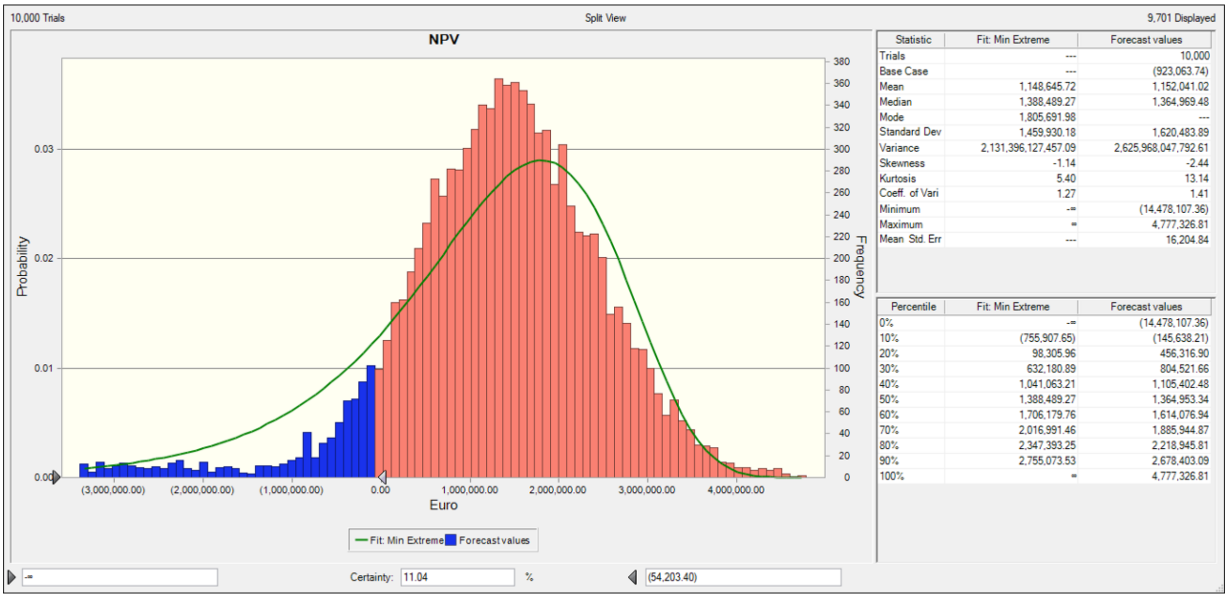
5.3.5. NPV Forecast

Upon completing all the necessary calculations, the net present value (NPV) of the station was calculated using a 10% discount rate over a 10-year period. In order to accurately assess the financial viability of the project, the initial investment was adjusted by deducting the subsidies provided by the company at the beginning of the project. Based on this comprehensive calculation, the most probable NPV of the station was forecasted. The detailed forecast results are presented in the Figure 5.17.

The graph illustrates the distribution of NPV possibilities using a Min extreme distribution, providing insights into the probability of occurrence for each value and its corresponding frequency. From the graph, it can be observed that the most probable NPV value for the station is 1,815,202.69 €. The associated uncertainity of not achieving a positive NPV over the 10-year timeframe is 11.18% . This forecast provides valuable information regarding the financial outlook and potential risks associated with the project's profitability.

5.3.6. NPV Sensitivity analysis

Upon completing the NPV forecast, the utilization of Crystal Ball software allows for the execution of a sensitivity analysis to examine the contibution of variables on the net present value (NPV). The outcomes of this sensitivity analysis are presented in the Figure 5.18 below. The software ranks the variables to



Statistic	Fit: Min Extreme	Forecast values
Trials	---	10,000
Base Case	---	(923,063.74)
Mean	1,148,645.72	1,152,041.02
Median	1,388,489.27	1,364,969.48
Mode	1,805,691.98	---
Standard Dev	1,459,930.18	1,620,483.89
Variance	2,131,396,127,457.09	2,625,968,047,792.61
Skewness	-1.14	-2.44
Kurtosis	5.40	13.14
Coeff. of Vari	1.27	1.41
Minimum	-∞	(14,478,107.36)
Maximum	∞	4,777,326.81
Mean Std. Err	---	16,204.84

Percentile	Fit: Min Extreme	Forecast values
0%	-∞	(14,478,107.36)
10%	(755,907.65)	(145,638.21)
20%	98,305.96	456,316.90
30%	632,180.89	804,521.66
40%	1,041,063.21	1,105,402.48
50%	1,388,489.27	1,364,953.34
60%	1,706,179.76	1,614,076.94
70%	2,016,991.46	1,885,944.87
80%	2,347,393.25	2,218,945.81
90%	2,755,073.53	2,678,403.09
100%	∞	4,777,326.81

-∞

Certainty: 11.04 %

(54,203.40)

Figure 5.17: NPV Analysis of the Station over 10 Years

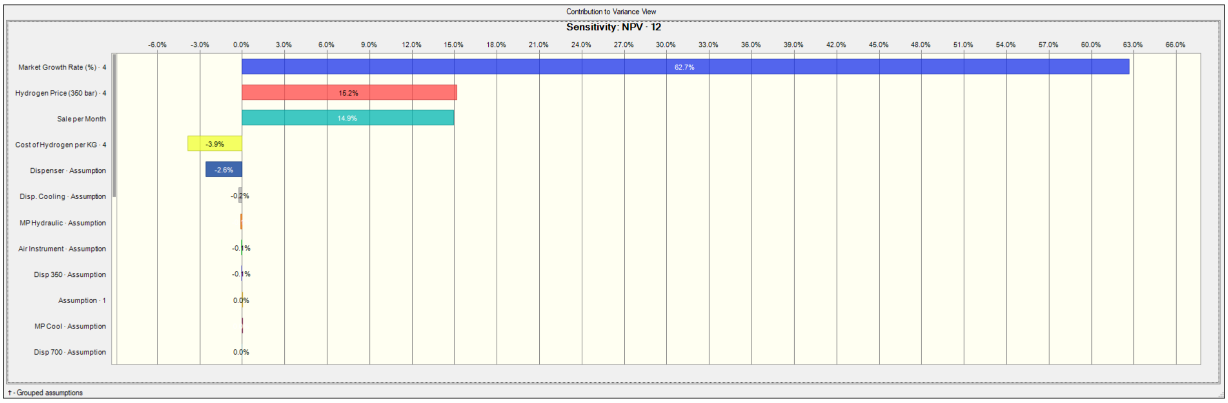


Figure 5.18: Sensitivity Analysis for NPV Analysis

illustrate their respective contributions to the station's NPV. The ranking provides insights into the factors that significantly influence the certainty or uncertainty of achieving a positive net present value over the 10-year period.

According to the ranking, it is evident that variables such as "Market Growth" and "Hydrogen Price" are the most influential contributors to the certainty of obtaining a positive NPV. These factors play a critical role in determining the financial viability of the station. On the other hand, variables like "Cost of Hydrogen" emerge as the primary source of uncertainty that impact the likelihood of achieving a positive NPV. These variables highlight hydrogen market that require attention and a further improvement in order to address the challenges faced by the niche technology's expansion.

According to Keles et al., their agent-based modeling suggests a direct causal loop relationship between the number of refueling stations and the demand for fuel cell vehicles (FCVs) [87]. As the number of refueling stations increases, the technology becomes more attractive, resulting in higher FCV demand. Conversely, when FCV demand rises, the number of FCVs in stock increases, leading to a greater need for refueling stations. Therefore, subsidizing either side of the equation can be considered a potential solution to foster development. For that purpose, it is important to highlight that a coordinated policy approach that encourages both side is deemed the most effective for the rapid adoption of technology and infrastructure [31].

From an operational perspective, it is essential for the company to prioritize its focus on Dispenser,

Dispenser Cooling, and Medium Pressure Compressor Hydraulic. These equipment components demand increased attention due to their significant impact on the overall operations of the station. By addressing the concerns related to these specific equipment elements, the company can enhance operational efficiency and mitigate potential risks, thus contributing to the long-term success of the technology's implementation.

Part IV

Closure

6
Conclusion

6.1. Research Questions

The research was initiated by TotalEnergies' investment in a hydrogen refueling station for mobility services, driven by the need to mitigate climate change. As this investment was made in a less-developed hydrogen market for mobility services, within a high-risk prototype environment, the company's objective is to maximize the overall availability and safety of these new systems, while minimizing costs and failures. The aim is to establish this niche technology as a sociotechnical regime of the future. To achieve this goal, TotalEnergies planned to conduct a comprehensive analysis of reliability, availability, maintainability, and safety (RAMS) to assess various aspects of the system. Drawing upon the company's expertise in RAMS analysis from the oil and gas industry, an important challenge was encountered due to the lack of established studies or guidelines within the company and academia specifically addressing RAMS analysis for hydrogen refueling stations. Considering the distinct thermochemical characteristics of hydrogen compared to LNG, CNG, and other energy fuels, it was imperative to scrutinize the process to conduct a systematic RAMS analysis for this niche technology. Consequently, for that purpose the main research question was formulated as follows:

Research Question Main

How can a RAMS study-based approach be developed to improve the availability of hydrogen refueling stations by leveraging conventional RAMS methodological frameworks?

To address this main research question, the subquestions were determined as:

Research Question 1

What are the critical steps, approaches and KPIs for conventional systematic RAMS methodologies?

In order to address this subquestion, a comprehensive literature review was conducted, primarily focusing on RAMS studies within the oil and gas industry. This choice was made due to the similarity in components used in this industry and hydrogen refueling stations. It is worth noting that there is a scarcity of studies that combine system engineering and RAMS analysis to perform a systematic RAMS analysis.

Drawing from insights derived from various industries regarding conventional RAMS frameworks and a limited number of studies that integrate systematic RAMS analysis, the following key steps have been identified for conducting a systematic RAMS analysis:

- System selection and definition
- Identification of systems functions and functional failures and its diagrams
- Data collection: Gather operational failure data.
- Data quality assessment and cleaning: Evaluate the quality of the collected data and remove any inconsistencies or inaccuracies.

- Construction of the observed system's block diagram: Develop a visual representation of the system's components and their interconnections.
- RAMS metric calculations and parameter estimations: Determine the relevant RAMS metrics and estimate their corresponding parameters.
- Process simulation for system availability and risk assessment: Utilize simulation techniques to assess the availability and risk of the system.
- Economic, environmental, and safety consequence analysis: Conduct an analysis of the economic, environmental, and safety implications resulting from failures. While some RAMS studies may not prioritize economic consequences, this step is included in the main RAMS process steps as it aligns with the project's ultimate goal.
- System modification: Identify necessary modifications or improvements to enhance the system's RAMS performance.

Based on an extensive qualitative literature review, the primary key performance indicators (KPIs) for assessing the reliability and maintainability of the system were identified as the Time Between Failures (TBF) and Time to Repair (TTR) metrics. These metrics are widely acknowledged in the literature as the predominant measures for operational analysis. While some variations in terminology were observed across the reviewed literature, the underlying conceptual framework consistently utilizes the concept of TTR and TBF. Leveraging these metrics enables us to examine the system's availability and evaluate components' reliability.

Before conducting an availability assessment of the station, it is imperative to appropriately structure and utilize the data in order to quantify these metrics. To address this requirement, the subsequent sub-research question was formulated:

Research Question 2

How can historical failure data of a hydrogen refueling station be structured to be used in appropriate RAMS metrics for the life cycle analysis of system components?

To address this question, a comprehensive case study on the TotalEnergies Breda Hydrogen Refueling station was conducted, supplemented by a thorough literature review. During a meeting with the company's reliability engineer, the maintenance database was acquired from the Business Information System (BIS) and leveraged within the Microsoft Power BI toolbox.

For the purpose of data analysis, the ”Date Call” information was identified as the failure starting time, while the moment when the failure was resolved, denoted as the ”Ready” data, served as the fixed time of failure. The time difference between these data points was determined as the Time to Repair (TTR) value, and as explained in 5.2.2, the Time Between Failures (TBF) values were also calculated. It is important to note that as these values are based on observational data, there are inherent uncertainties associated with predicting the next failure and its corresponding TTR. To propagate this uncertainty and assess the system availability, the next subresearch was determined as:

Research Question 3

What is the way to assess the system availability with uncertain KPIs?

In order to account for the inherent uncertainty associated with Time to Repair (TTR) and Time Between Failures (TBF), the Crystal Ball software was employed. This software utilized historical observational data and information from the ”OREDA” database to calculate the Maximum Likelihood Estimates (MLE) of TTR and TBF for each component. By propagating this uncertainty, the statistical distributions of the MLEs were integrated into the modeling toolbox, which incorporates a reliability block diagram model of the hydrogen refueling station. That process propagates the unknown failure modes of the niche technology and hidden future failures, which limits the modeling results.

During the simulation run, the toolbox assigns values to TBFs and TTRs of subsystems for each trial. Based on the availability and reliability of the subsystems, as well as the system architecture design, the simulation toolbox assesses the overall availability of the system. By running the simulation, the availability of the hydrogen refueling station is projected over a ten-year period. These availability projections serve as inputs for the subsequent sub-research question, which focuses on the techno-economic analysis of the station:

Research Question 4

How can the integration of techno-economic analysis into a systematic RAMS analysis facilitate the decision-making process?

In order to address this sub-research question, a thorough examination of existing RAMS frameworks was conducted. The aim was to understand the methodologies employed for integrating economic aspects into systematic RAMS analysis comprehensively. The analysis revealed that the inclusion of techno-economic analysis beyond maintenance cost estimation or environmental impact was limited within the conventional RAMS frameworks. However, further scrutiny of techno-economic studies conducted specifically for niche technologies revealed several noteworthy aspects pertaining to the techno-economic analysis of the system:

- Turnover of the company by sales
- Cost of goods sold
- Subsidy
- Initial investment
- Tax
- Operational cost

It is crucial to acknowledge that these economic values inherently possess uncertainties. The economic data was subjected to characterization using the Crystal Ball software to propagate this uncertainty. Additionally, these values directly correlate with the income statement of the system, which is cash flow-based. Nevertheless, upon scrutinizing previous studies, it became evident that there are additional economic aspects relevant to RAMS techno-economic analysis, specifically process safety and availability-related hindered costs, which are outlined below:

- Risk associated with the potential non-supply of hydrogen.
- Risk of installation damage resulting from ignition, explosion, or jet fire caused by hydrogen leakage.
- Risk of fatality resulting from ignition, explosion, or jet fire caused by hydrogen leakage.

In order to obtain the necessary cost data for these factors, collaboration with the company's marketing and sales (M&S) department and reliability engineer was established. The costs were either acquired directly from the company or calculated as hindered costs, determined through RAMS analysis.

To ensure the reliability and accuracy of the cost estimates, the M&S department and reliability engineer of the company provided their endorsement. Subsequently, all identified economic factors and their associated costs were integrated into a dedicated techno-economic analysis model developed in Microsoft Excel. This model incorporates relevant market data, including the anticipated market growth rate for the upcoming years, thus providing a comprehensive framework for techno-economic analysis. The techno-economic analysis culminated in the calculation of the net present value (NPV) of the system over a 10-year period, which represents a single value that combines operational and techno-economic data, streamlining the decision-making process. Furthermore, the NPV analysis in Excel, utilizing the Crystal Ball software, facilitated sensitivity analysis to determine the variables that contribute to the variance of NPV, whether in a positive or negative direction. This analysis aids decision-makers in identifying areas of focus for potential development opportunities.

As a reminder, the objective of these sub-research questions is to establish a systematic approach based on RAMS analysis to enhance the availability of hydrogen refueling stations. By addressing these sub-research questions, a comprehensive and systematic methodology is formulated for this purpose. When all the steps are consolidated, it results in a systematic techno-economic RAMS analysis. When visually represented, this analysis culminates in the STRAMSA framework, which serves as a systematic RAMS study-based approach designed to improve the availability of hydrogen refueling stations.

6.2. Closing Remarks

By incorporating all the cash flow-based aspects, including hindered potential risk costs, the net present value (NPV) of the TotalEnergies Breda Hydrogen Refueling station was projected as 1,815,202.69 € over a period of 10 years. However, this value is subject to uncertainty. To gain insights into the variables that contribute to this uncertainty, a sensitivity analysis of the NPV was conducted.

The results of the sensitivity analysis revealed that there is a 11.18% probability of not achieving a positive NPV. The ”Market Growth Rate” was identified as the major contributing parameter to decrease this uncertainty, whereas ”Cost of Hydrogen” was found to be the major contributor to the uncertainty. Additionally, from a technical perspective, Dipsenser and dispenser cooling systems are key subsystems that increase the uncertainty of not achieving a positive NPV.

The findings from the techno-economic assessment, supported by systematic RAMS analysis, demonstrate that the hydrogen refueling station, with the current RAMS results and subsidy scheme, represents a strategic business venture with high investment potential and a reduced risk of yielding a negative value. However, the market for hydrogen refueling stations is still underdeveloped, which may reduce the attractiveness for potential stakeholders, particularly energy suppliers for mobility services.

Thus, in addition to implementing subsidy schemes for these stakeholders, policymakers should prioritize market development through collaborative initiatives involving both the public and private sectors. Fostering the growth of the market and hydrogen refueling stations simultaneously will enhance the likelihood of achieving the goal of zero carbon emissions in mobility services at an earlier stage.

7

Discussion

7.1. Research Methodology

The qualitative component primarily relies on extensive literature research and expert opinions to provide a comprehensive understanding of the subject matter. Given the specialized nature of this niche technology, it is worth noting that design engineers and reliability engineers involved in the project have been actively acquiring knowledge and expertise in this relatively new domain. While the company boasts experts in CNG and LNG technologies, it is important to acknowledge that the thermochemical properties of hydrogen present unique system anomalies that differ from those encountered in existing technologies. Moreover, the scarcity of published research on hydrogen refueling stations further complicates the matter, as it necessitates a deeper understanding and exploration of the technology. These factors contribute to the challenge of acquiring sufficient knowledge about the technology, which can potentially create bottlenecks in the research process and impact the quality of the qualitative analysis.

In addition to the qualitative research component, the quantitative aspect of the study faces its own set of challenges. Notably, there is currently no established RAMS database specifically tailored for hydrogen refueling stations. This deficit in available data poses a significant limitation for conducting a comprehensive quantitative RAMS analysis. Furthermore, the company's database for the case study only includes a mere 1.5 years' worth of data. According to industry standards and best practices, a minimum of three consecutive years of data is required to conduct a robust and reliable RAMS analysis. Unfortunately, the limited data availability hampers the ability to perform a thorough quantitative analysis. To partially compensate for this data deficiency, similar components utilized in the natural gas industry have been employed for the qualitative analysis in conjunction with the available 1.5-year observational data from the company. Nevertheless, it is crucial to acknowledge that the limited data available can potentially compromise the quality and comprehensiveness of the quantitative analysis.

7.2. Data Acquisition

The existing generic database primarily contains data related to continuous processes. However, hydrogen refueling stations operate differently, as each subunit within the system needs to have the ability to start and stop independently. This unique characteristic of hydrogen refueling stations introduces a challenge when relying on the validity of data from the OREDA (Offshore Reliability Data) database for such subsystems. OREDA, while a valuable resource, may not fully capture the operational dynamics and requirements of these specific subsystems. As a result, caution must be exercised when applying the data from the generic database to the analysis of subsystems within hydrogen refueling stations. Additional research and data collection efforts specific to these subsystems are necessary to ensure the accuracy and validity of the analysis conducted in the context of hydrogen refueling stations.

Furthermore, the data obtained from the Business Information System (BIS) is initially reported by onsite maintenance technicians. Work orders are manually recorded by the maintenance department based on these reports, leading to potential errors in data registration and decreasing the reliability of the work orders. Despite these limitations, the available data from the work orders were utilized for this research. To ensure accuracy, the data was double-checked with technicians and reliability engineers. During the calculation of key performance indicators (KPIs) such as Time to Repair (TTR) and Time Between Failures (TBF), negative values were identified, which are not feasible. These problematic work orders were subjected to further analysis for validation. Although there is limited access to modify these work orders, the data associated with these specific cases were manually adjusted in PowerBI. Consequently, when the resulting parameters from the uncertainty propagation of the obtained data were registered into the simulation toolbox, the calculated availability data closely matched the real case data with a deviation of only 2%. This indicates the accuracy of the BIS data. However, there is room for improvement by implementing automatic registration of work orders based on sensor data. This approach has the potential to enhance the data quality and, consequently, improve the overall quality of analysis.

7.3. Statistical Data Utilization Approach

Relying solely on historical observational data for maximum likelihood estimation introduces a significant drawback in terms of capturing the dynamic nature of the estimation process. By exclusively considering past observations, this approach neglects the potential changes and variations that can occur over time. Estimations based solely on historical data fail to account for evolving conditions, new trends, or unforeseen events that can impact the underlying analyzed system. As a result, the estimation process becomes static and lacks the ability to adapt to changing circumstances. This drawback limits the effectiveness and reliability of the estimation, as it fails to incorporate up-to-date information that could significantly influence the outcomes. In order to overcome this limitation, other approaches can be utilized, which will be recommended in the next Chapter 8.

Moreover, it is important to note that in cases where the number of sample data points is less than 15, the Crystal Ball software is not generating goodness-of-fit measures. In such instances, expert opinions were sought to compensate for the limited data. However, it is evident that the utilization of the software would be maximized and more accurate forecasts could be obtained with a larger set of data. With an increased number of data points, the software can effectively identify the best fit for each sample, enhancing the accuracy and reliability of the forecasts. Therefore, efforts should be made to collect and incorporate a larger and more diverse dataset to fully leverage the capabilities of the Crystal Ball software and optimize the forecasting outcomes.

7.4. Simulation Toolbox Limitations

The current configuration of the Raptor software lacks the consideration of aging factors, which hinders the comprehensive assessment of component reliability over time, thereby diminishing trust in the analysis results. To ensure a more robust evaluation, it is imperative to incorporate aging factors, as they play a crucial role in determining the long-term performance and reliability of components.

Furthermore, a limitation of the Raptor software lies in its inability to handle dual outputs simultaneously, which contradicts the operational requirements of hydrogen refueling stations that often have 350-bar and 700-bar nozzles as outputs. This inconsistency restricts the software's applicability in accurately modeling the behavior of such stations.

Moreover, the software assumes fixed costs per failure when registering cost data within the software limits the ability to propagate uncertainty in cost analysis. This fixed assumption undermines the quality of cost analysis, as it does not account for the inherent variability in maintenance costs. Hence, the cost uncertainty was utilized with Crystal Ball software to address this limitation and implemented into techno-economic analysis Excel, which allows for a more accurate and realistic cost analysis of maintenance activities. However, more advanced simulation toolboxes can be utilized to address all these challenges effectively, which is recommended in the next Chapter 8.

7.5. STRAMSA Framework

The developed framework in this study was designed based on the utilization of conventional RAMS frameworks, primarily informed by existing literature and supported by expert opinions. However, it is important to note that there is a limited body of research that combines the systematic analysis of RAMS with system engineering principles, particularly in conjunction with techno-economic analysis and considerations of the product market. As a pioneering framework, STRAMSA represents a significant advancement by integrating system engineering, RAMS analysis, and techno-economic analysis into a cohesive approach. It is crucial to acknowledge that the application of the framework was limited to a single case study, necessitating further validation and refinement through multiple case studies. The next

Chapter 8 will outline strategies for its enhancement through the inclusion of additional case studies.

7.6. Hydrogen Market Data

On the other hand, the development of the hydrogen market for the transport industry has not yet attained the anticipated level of investment, thereby impeding the swift progression of the sociotechnical regime transition [25]. Thus, to address this concern and account for potential uncertainties in future forecasts, market growth rate data were sourced from relevant literatures. Although efforts were made to propagate the market growth rate data and incorporate associated uncertainties, there remains a substantial level of uncertainty regarding the projected high growth rate. Given the strong interdependency between the development of hydrogen refueling stations and the progress of the market, this uncertainty raises valid concerns regarding the reliability of the obtained Net Present Value (NPV). Consequently, it is imperative to approach the interpretation of NPV with caution and consider the potential impact of market uncertainties on the overall feasibility and long-term viability of hydrogen refueling station investments.

Furthermore, hydrogen cost and price were assumed to be constant on an annual basis, despite the fact that these values actually fluctuate on a monthly basis due to agreements with AirLiquide, hydrogen supplier. Hence, to enhance the accuracy of the forecast, it is necessary to incorporate the monthly variation in sales forecasts. By considering the monthly variation in sales, a more precise estimation of costs and prices can be achieved. This approach entails adjusting the sales forecast on a monthly basis to account for fluctuations in costs and prices throughout the year. It enables a more realistic representation of the income cash flow, as it reflects the actual dynamics of the market. This improvement allows for a more accurate calculation of the net present value and enhances the overall reliability of the techno-economic analysis.

7.7. Time Limitation

The allocated duration for this project is limited to 16 weeks. Within this relatively short timeframe, various critical tasks were accomplished, including an extensive literature study, framework design, implementation of the framework in a case application which requires two distinct models. Given the brevity of the time frame, each of these aspects had to be completed within a tight schedule. However, it is worth noting that the compressed timeline may have impacted the thoroughness and depth of the framework and models.

Given the circumstances, allowing for a more extended timeframe would likely have a positive impact on the overall quality of the framework and models. Additional time would afford the opportunity for a more comprehensive literature review, enabling a deeper understanding of existing research and best practices. It would also allow for a more meticulous design and refinement of the framework, considering various intricacies and potential complexities.

Furthermore, the applicability of the framework in the case scenario could be conducted with greater attention with a longer duration, facilitating a more robust and accurate analysis. Additionally, the development of the distinct models could be given the necessary time and attention to ensure a comprehensive representation of the system under study.

7.8. Cost of Hydrogen based on its Source

The consideration of the hydrogen source is of utmost importance in achieving the goal of a net-zero carbon target. While hydrogen production from fossil fuels is a viable and cheaper option, these approaches can still emit significant amounts of CO_2. To align with sustainability objectives, the source of hydrogen should be green. By harnessing clean energy sources, the hydrogen production can be accomplished without contributing to CO_2 emissions. This approach ensures a more sustainable and environmentally friendly way towards sustainable mobility transition.

Alternatively, when hydrogen is produced from fossil fuels or coal, carbon capture and storage (CCS) technologies can be employed to mitigate the associated emissions. CCS allows for the capture and storage of CO_2 generated during hydrogen production, effectively preventing its release into the atmosphere. By implementing CCS alongside hydrogen production processes, the carbon footprint can be significantly reduced, if not eliminated.

7.9. Discussion on Results

The positive net present value (NPV) obtained indicates a favorable likelihood of achieving a high return on investment for the hydrogen refueling station project. This positive value signifies that the strategic business venture holds promising prospects from a financial perspective. Furthermore, the level of uncertainty is comparatively low even for the high risky prototype technology. This aspect contributes to the overall attractiveness of the investment, as it implies a higher degree of predictability and stability. The endeavor not only offers the potential for favorable financial returns but also aligns with sustainable objectives and contributes to the reduction of carbon emissions. However, it is crucial to recognize that market growth and development play a pivotal role in the long-term success and viability of the hydrogen refueling station. Thus, concerted efforts are required from both the public and private sectors to foster market growth. It can maximize the project's potential success and contribution to the net-zero emission goal.

In particular, TotalEnergies, as a key stakeholder, should focus its attention on the dispenser system for their operation. Enhancing the efficiency, reliability, and accessibility of the dispenser system will be instrumental in minimizing the cost and increasing the safety of the design.

8

Recommendations

This chapter serves as a concise summary of the key recommendations that warrant consideration for the future advancement of this research project. These recommendations are geared towards maximizing the potential impact of the project and contributing to the existing body of knowledge. Adhering to these recommendations will enable researchers to establish a strong foundation for subsequent studies and endeavors, facilitating a comprehensive and robust continuation of the research. Notably, since the STRAMSA framework represents the first systematic techno-economic approach to conducting RAMS analysis, these recommendations become even more crucial. By following these guidelines, researchers can effectively address any identified limitations, enhance the rigor and validity of their findings, and uncover new insights that propel the research project toward achieving its ultimate objectives.

Validation of STRAMSA Framework

The validation of the STRAMSA framework can be enhanced through the application to multi-case studies. Therefore, it is recommended to apply the framework to other stations to evaluate its effectiveness and reliability across different contexts. To facilitate this process, data structuring was conducted using Microsoft Power BI. It enables users to apply the same steps to other stations. The program automatically structures the data when the extracted BIS data Excel file from different stations is uploaded the file. This approach ensures consistency and ease of use when expanding the application of the designed framework to multiple stations, fostering reliable and comparative assessments of RAMS parameters.

Furthermore, to ascertain the generalizability and applicability of the framework, it is recommended to conduct testing and validation with businesses operating in diverse industries beyond the hydrogen refueling sector. Researchers can evaluate its effectiveness and adaptability in addressing the unique challenges and requirements of various sectors by subjecting the framework to these industries. This broadening of the scope will contribute to a more comprehensive understanding of the framework's strengths, limitations, and potential modifications needed for its successful implementation in other industries. Moreover, researchers can uncover valuable insights into its transferability, enabling the identification of commonalities and distinctions in RAMS analysis practices across industries by exploring the framework's applicability across multiple domains. This knowledge can further enhance the framework's robustness and serve as a basis for developing industry-specific adaptations or extensions, ultimately fostering its wider adoption and utility in diverse business contexts.

Generic Data Acquisition

The current focus of RAMS databases predominantly revolves around continuous processes in industries like chemicals and oil & gas. However, refueling stations operate differently, as they are not continuously active. To address this disparity, the start-up of a specialized database for mobility service products, including refueling stations, is recommended. Such a database would provide comprehensive and generic data, allowing for more accurate analysis and utilization of information about these unique systems.

Statistical Data Utilization Approach

Bayesian updating technique, as a robust and well-established data analysis approach, provides a principled framework for incorporating prior knowledge and updating it with newly observed data, resulting in the generation of a posterior distribution [88]. This iterative process allows for the dynamic refinement of our understanding of the data, accounting for uncertainties and adjusting beliefs based on the available evidence. The Bayesian approach is particularly valuable in situations characterized by limited data availability, making it well-suited for the hydrogen refueling stations, where data is often scarce. Moreover, the posterior distribution provides a quantification of the uncertainty associated with the predictions, enabling decision-makers to make more informed choices and assess the potential risks. Overall the hydrogen refueling stations can benefit from a more comprehensive and informed assessment of system performance and safety by embracing Bayesian updating technique.

Scope of the Research and Data Management

Incorporating subunit-level data into RAMS analysis offers significant benefits for obtaining a more comprehensive understanding of system behavior and improving reliability and availability [46]. Hidden patterns, dependencies, and common-mode failures can be identified by analyzing data at a more granular level. This approach leads to more accurate risk assessments and targeted maintenance efforts.

In this study, RAMS analysis primarily focuses on subsystem level data, such as failure rates, repair times, and availability metrics. However, a more detailed picture of the system's behavior and potential failure modes can be uncovered by diving deeper into the subunit level. Ensuring data availability, quality, and effective data management is essential for this successful implementation. For that purpose, robust data management systems and data preprocessing techniques should be employed to handle the increased volume and complexity of the data like machine learning (ML).

The integration of machine learning (ML) techniques into RAMS analysis presents a significant opportunity to enhance the field, particularly in the context of hydrogen refueling stations. By leveraging the capabilities of ML algorithms, RAMS analysis can benefit from more accurate predictions, improved decision-making, and increased system reliability and availability. ML algorithms can analyze sensor data and operational parameters in real time, enabling the early detection of degradation or impending failures in the hydrogen refueling system.

Compared to traditional methods, which often rely on predetermined failure models and assumptions, ML algorithms can adapt and learn from data, allowing for the development of more accurate and adaptable models that account for the dynamic nature of the system. The application of ML in RAMS analysis also uncovers hidden patterns and relationships within the data, facilitating effective risk management strategies in this niche business domain. On the other hand, challenges related to data quality and algorithm transparency need to be addressed to ensure successful and responsible implementation in the RAMS domain. Upcoming research can focus on adjusting the designed framework for ML algorithms and exploring additional case studies to gain a deeper understanding of how ML algorithms can be effectively implemented in this specialized technology.

Simulation Toolbox Alternatives

In order to overcome the limitations posed by the Raptor simulation toolboxes, it is advisable to consider the utilization of GRIF (GRaphical Interface for reliability Forecasting) when it becomes compatible with the company's current computer infrastructure. This transition would allow for the redesign of the model, incorporating the most up-to-date operational and cost data. GRIF possesses the capability to handle both operational and cost data through the use of Maximum Likelihood Estimation (MLE) distributions. Notably, this toolbox also provides direct access to the OREDA database as a built-in feature, further enhancing the reliability and robustness of the model. By embracing GRIF and integrating it into the existing framework, the limitations associated with the Raptor simulation toolboxes can be effectively addressed, ultimately advancing the overall trustworthiness and accuracy of the model.

Techno-economic Market Analysis

In order to achieve the targeted availability of 98% for the station, it is crucial to maintain a consistent number of failures each year. Therefore, the modeling does not incorporate aging effects. However, it is important to recognize that components will eventually require replacement to meet the desired availability target, rather than relying solely on maintenance. This replacement approach incurs higher costs. Due to limited data on component lifecycles, the cost analysis focused only on the maintenance aspect. However, it can be improved by incorporating replacement costs considering the lifetime of the components.

Preventive Maintenance Scheme based on Model Prediction

Implementing a detailed preventive maintenance strategy has the potential to yield significant benefits in terms of reducing maintenance costs and enhancing the availability of niche technology. Potential issues and failures can be identified and addressed before they escalate into costly and time-consuming problems by conducting thorough and proactive maintenance activities. This approach involves regular inspections, scheduled maintenance tasks, and the replacement of aging or deteriorating components on time. Thus, the company can minimize the occurrence of unexpected breakdowns and unplanned downtime, resulting in improved system availability by adhering to a well-structured preventive maintenance plan.

Dispenser System

The analysis reveals that the Dispenser system experiences the highest number of failures. Although these failures are notable, the required repairs for the dispenser system are relatively straightforward and do not consume substantial time. Consequently, the overall system availability is not significantly affected. However, the increased expenses associated with the dispenser system primarily arise from its in-house design and production. Since the dispenser was not obtained from an external supplier, warranty coverage is not applicable, placing the burden of all maintenance costs on the company. Having a warranty in place would significantly mitigate the risk and reduce maintenance costs. The design of this prototype system contributes to a higher frequency of failures, resulting in amplified costs for the company. Considering the most competitive aspects of their business, it would be prudent for the company to explore the option of procuring dispensers from third-party suppliers.

In addition to the in-house prototype design, another primary root cause of the number of failures is attributed to the interaction between customers and the system. It has been observed that variations in customer knowledge and proficiency in operating the system contribute to these failures. In order to gain deeper insights and address this issue, it is recommended to conduct further analysis focusing on the interaction between customers and the system. Agent-based modeling can be employed as a research methodology to comprehensively understand customer behavior and reduce the occurrence of failures resulting from this interaction. By utilizing this approach, a more detailed understanding of customer interactions can be gained, enabling the development of targeted strategies to mitigate failures and improve system performance.

High Pressure Compressor

The HP compressor, which is sourced from a third-party supplier, is advantageous in terms of warranty coverage. Nonetheless, the involvement of external suppliers results in prolonged repair or maintenance durations, thereby diminishing the overall availability of the component and the supply of 700-bar hydrogen. Consequently, incorporating an additional HP compressor into the current design configuration can enhance the overall system availability. However, this modification entails additional costs, necessitating an assessment of its impact on the station's Net Present Value (NPV). Unfortunately, due to time constraints, this analysis was not conducted. For further RAMS analysis, it would be valuable to examine the effect of this configuration change on both the overall NPV and system availability.

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A

Data Utilization in Microsoft PowerBI

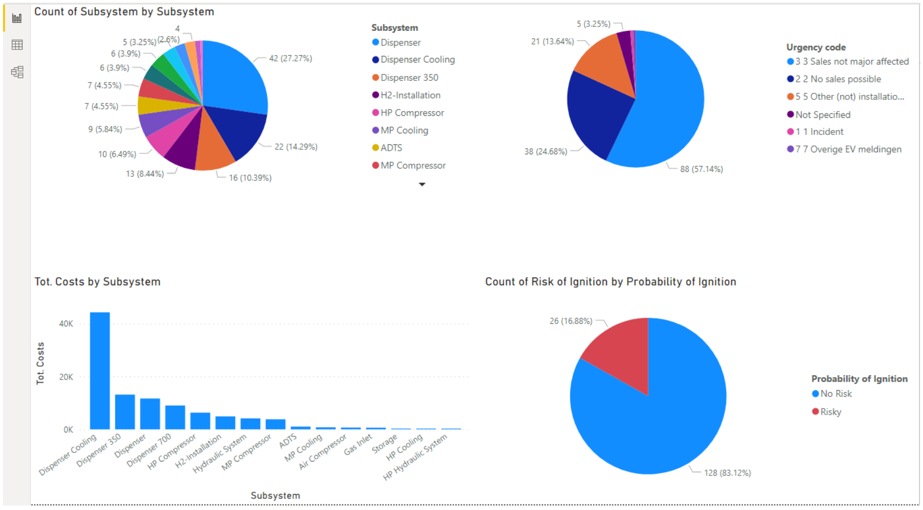
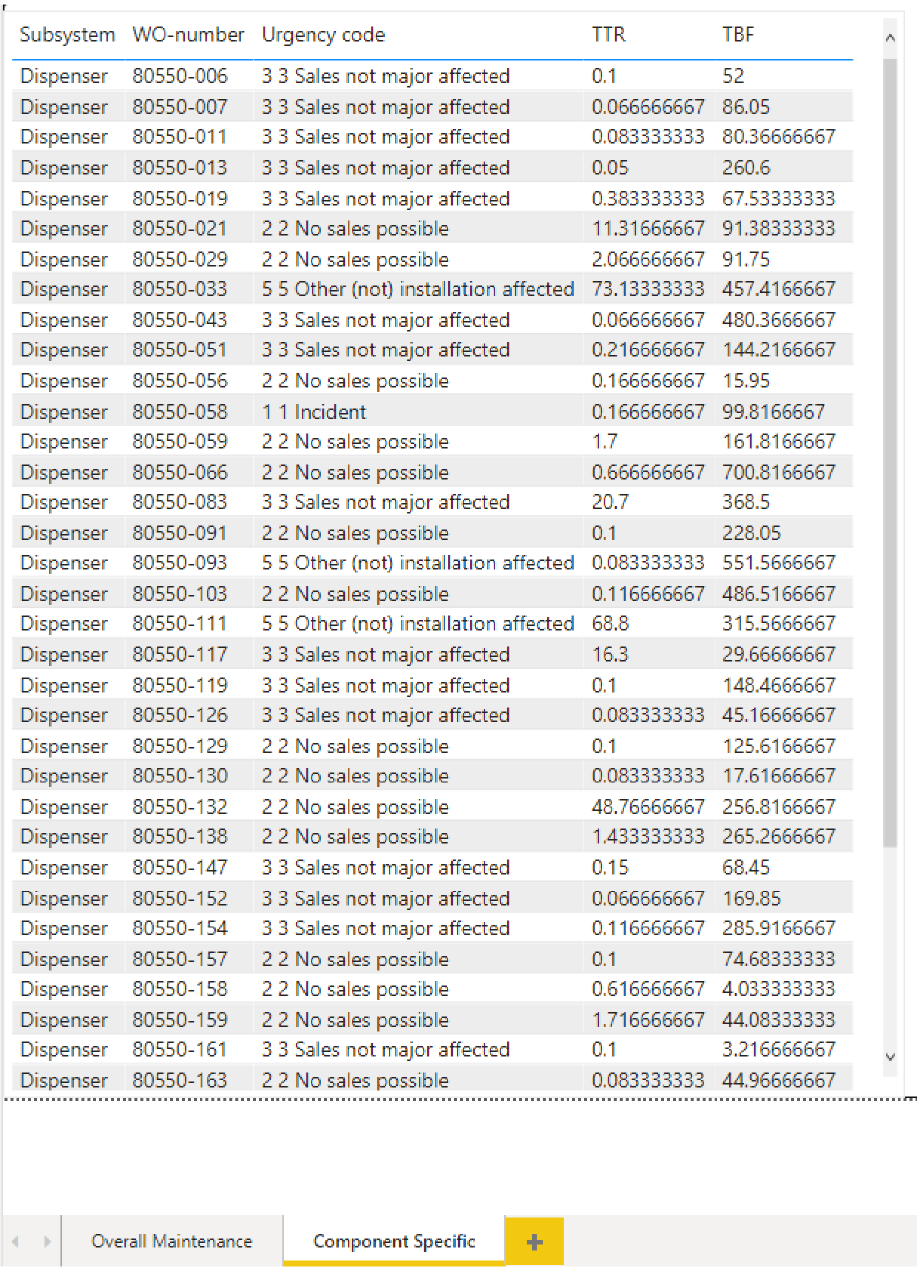


Figure A.1: Number of Failures for Components and System Overall Availability over Years - 1



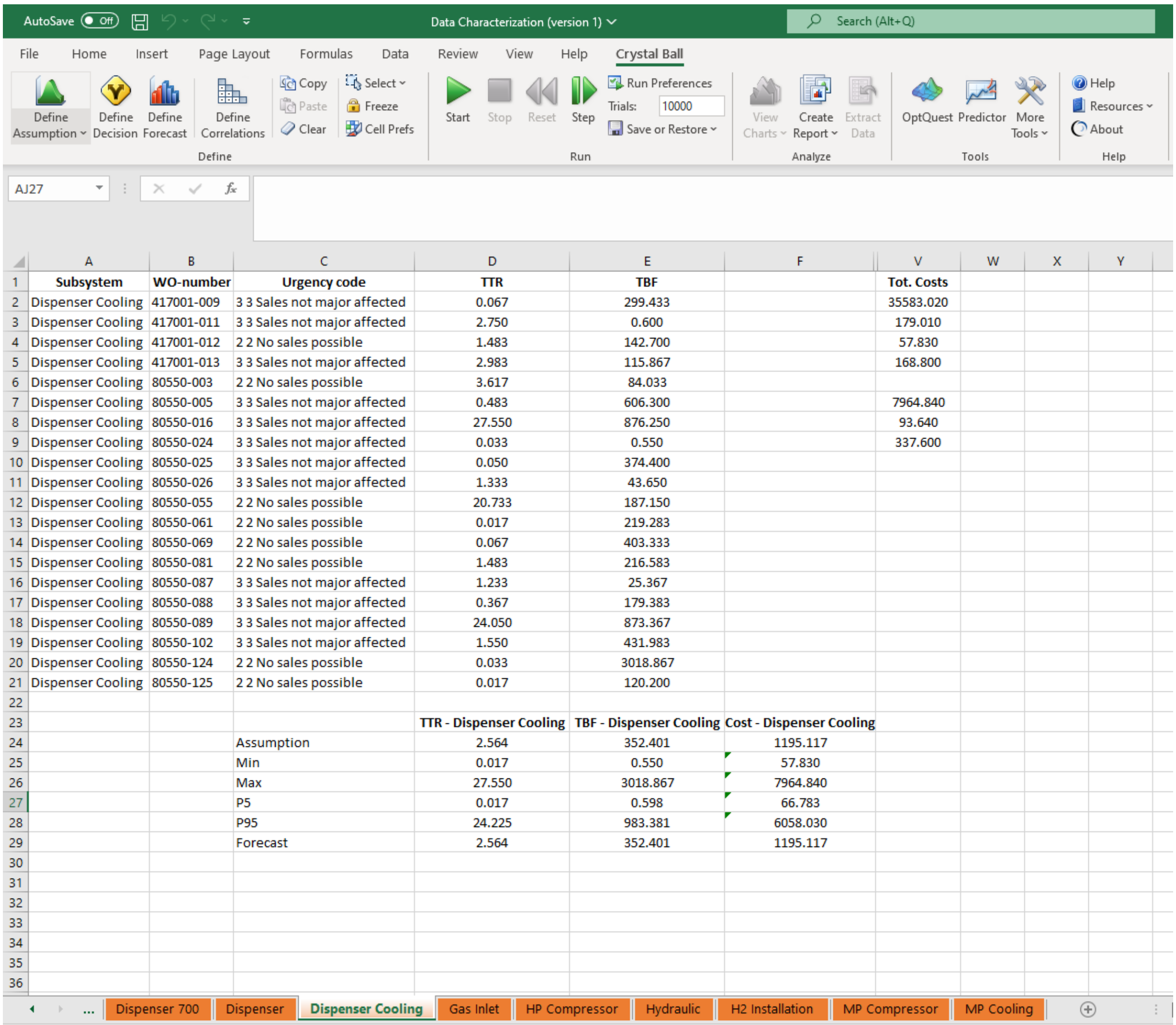
Subsystem	WO-number	Urgency code	TTR	TBF
Dispenser	80550-006	3 3 Sales not major affected	0.1	52
Dispenser	80550-007	3 3 Sales not major affected	0.066666667	86.05
Dispenser	80550-011	3 3 Sales not major affected	0.083333333	80.36666667
Dispenser	80550-013	3 3 Sales not major affected	0.05	260.6
Dispenser	80550-019	3 3 Sales not major affected	0.383333333	67.53333333
Dispenser	80550-021	2 2 No sales possible	11.31666667	91.38333333
Dispenser	80550-029	2 2 No sales possible	2.066666667	91.75
Dispenser	80550-033	5 5 Other (not) installation affected	73.13333333	457.4166667
Dispenser	80550-043	3 3 Sales not major affected	0.066666667	480.3666667
Dispenser	80550-051	3 3 Sales not major affected	0.216666667	144.2166667
Dispenser	80550-056	2 2 No sales possible	0.166666667	15.95
Dispenser	80550-058	1 1 Incident	0.166666667	99.8166667
Dispenser	80550-059	2 2 No sales possible	1.7	161.8166667
Dispenser	80550-066	2 2 No sales possible	0.666666667	700.8166667
Dispenser	80550-083	3 3 Sales not major affected	20.7	368.5
Dispenser	80550-091	2 2 No sales possible	0.1	228.05
Dispenser	80550-093	5 5 Other (not) installation affected	0.083333333	551.5666667
Dispenser	80550-103	2 2 No sales possible	0.116666667	486.5166667
Dispenser	80550-111	5 5 Other (not) installation affected	68.8	315.5666667
Dispenser	80550-117	3 3 Sales not major affected	16.3	29.66666667
Dispenser	80550-119	3 3 Sales not major affected	0.1	148.4666667
Dispenser	80550-126	3 3 Sales not major affected	0.083333333	45.16666667
Dispenser	80550-129	2 2 No sales possible	0.1	125.6166667
Dispenser	80550-130	2 2 No sales possible	0.083333333	17.61666667
Dispenser	80550-132	2 2 No sales possible	48.76666667	256.8166667
Dispenser	80550-138	2 2 No sales possible	1.433333333	265.2666667
Dispenser	80550-147	3 3 Sales not major affected	0.15	68.45
Dispenser	80550-152	3 3 Sales not major affected	0.066666667	169.85
Dispenser	80550-154	3 3 Sales not major affected	0.116666667	285.9166667
Dispenser	80550-157	2 2 No sales possible	0.1	74.68333333
Dispenser	80550-158	2 2 No sales possible	0.616666667	4.033333333
Dispenser	80550-159	2 2 No sales possible	1.716666667	44.08333333
Dispenser	80550-161	3 3 Sales not major affected	0.1	3.216666667
Dispenser	80550-163	2 2 No sales possible	0.083333333	44.96666667

Figure A.2: Number of Failures for Components and System Overall Availability over Years - 1

B

Uncertainty Propagation of RAMS KPIs of Each Component in Crystal Ball Software

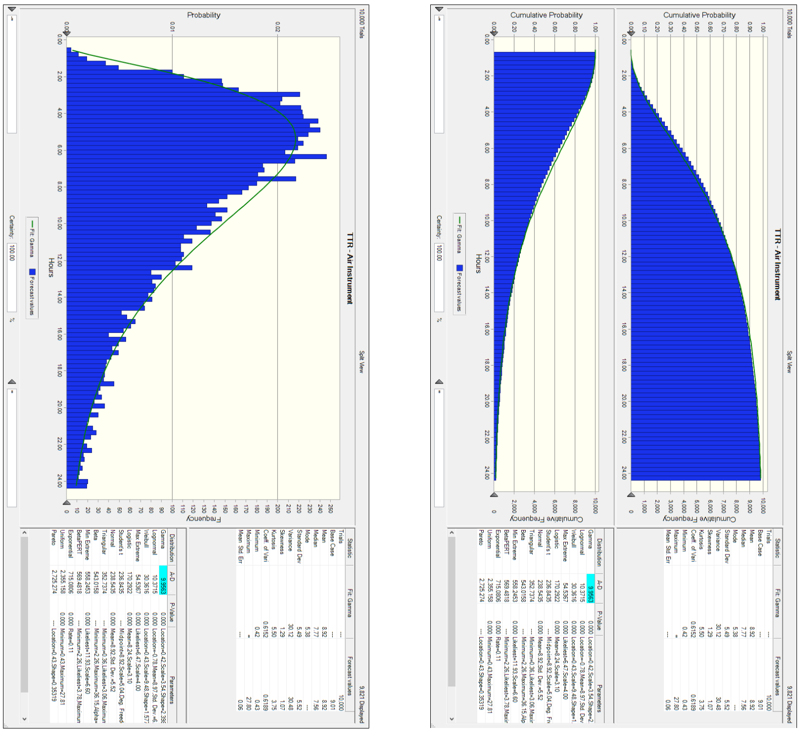
B.1. Crystal Ball



	A	B	C	D	E	F	V
1	**Subsystem**	**WO-number**	**Urgency code**	**TTR**	**TBF**		**Tot. Costs**
2	Dispenser Cooling	417001-009	3 3 Sales not major affected	0.067	299.433		35583.020
3	Dispenser Cooling	417001-011	3 3 Sales not major affected	2.750	0.600		179.010
4	Dispenser Cooling	417001-012	2 2 No sales possible	1.483	142.700		57.830
5	Dispenser Cooling	417001-013	3 3 Sales not major affected	2.983	115.867		168.800
6	Dispenser Cooling	80550-003	2 2 No sales possible	3.617	84.033		
7	Dispenser Cooling	80550-005	3 3 Sales not major affected	0.483	606.300		7964.840
8	Dispenser Cooling	80550-016	3 3 Sales not major affected	27.550	876.250		93.640
9	Dispenser Cooling	80550-024	3 3 Sales not major affected	0.033	0.550		337.600
10	Dispenser Cooling	80550-025	3 3 Sales not major affected	0.050	374.400		
11	Dispenser Cooling	80550-026	3 3 Sales not major affected	1.333	43.650		
12	Dispenser Cooling	80550-055	2 2 No sales possible	20.733	187.150		
13	Dispenser Cooling	80550-061	2 2 No sales possible	0.017	219.283		
14	Dispenser Cooling	80550-069	2 2 No sales possible	0.067	403.333		
15	Dispenser Cooling	80550-081	2 2 No sales possible	1.483	216.583		
16	Dispenser Cooling	80550-087	3 3 Sales not major affected	1.233	25.367		
17	Dispenser Cooling	80550-088	3 3 Sales not major affected	0.367	179.383		
18	Dispenser Cooling	80550-089	3 3 Sales not major affected	24.050	873.367		
19	Dispenser Cooling	80550-102	3 3 Sales not major affected	1.550	431.983		
20	Dispenser Cooling	80550-124	2 2 No sales possible	0.033	3018.867		
21	Dispenser Cooling	80550-125	2 2 No sales possible	0.017	120.200		
22							
23				**TTR - Dispenser Cooling**	**TBF - Dispenser Cooling**	**Cost - Dispenser Cooling**	
24			Assumption	2.564	352.401	1195.117	
25			Min	0.017	0.550	57.830	
26			Max	27.550	3018.867	7964.840	
27			P5	0.017	0.598	66.783	
28			P95	24.225	983.381	6058.030	
29			Forecast	2.564	352.401	1195.117	

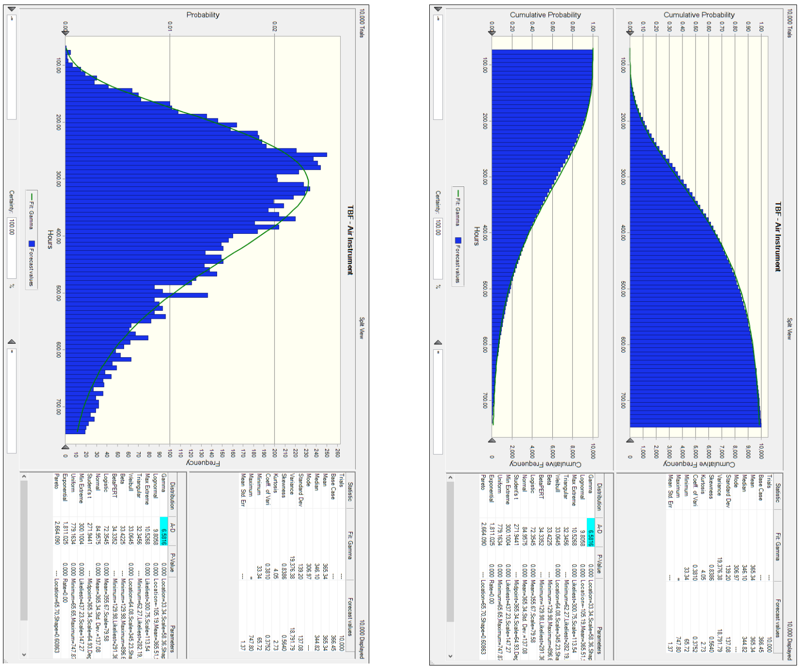
Figure B.1: User Interface of Crystal Ball

B.2. Air Instrument



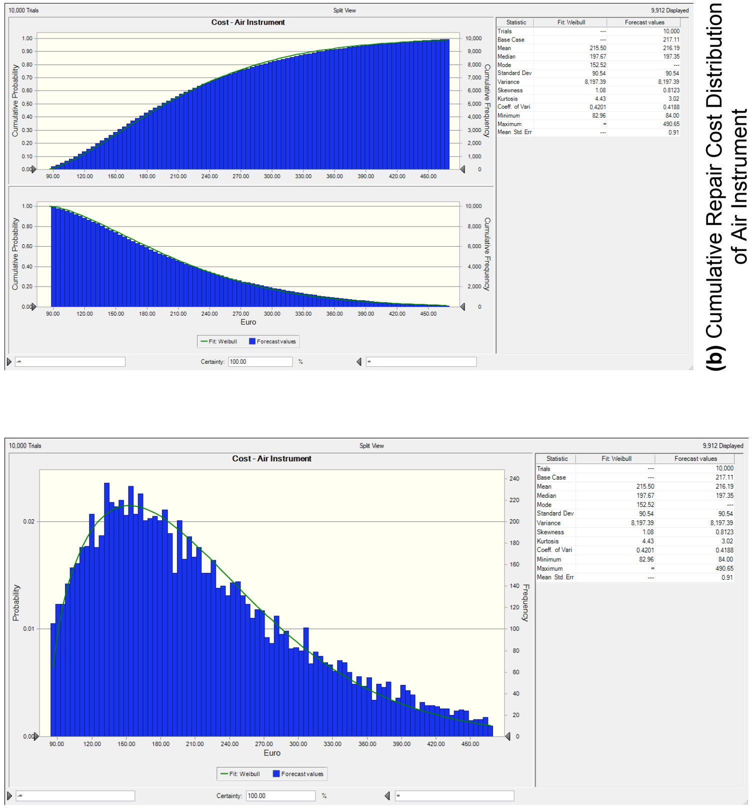
(a) TTR - Air Instrument **(b)** TTR - Air Instrument Cumulative

Figure B.2: Time To Repair (TTR) Distribution for Air Instrument



(a) TBF - Air Instrument **(b)** TBF - Air Instrument Cumulative

Figure B.3: Time Between Failures (TBF) Distribution for Air Instrument



Statistic	Fit: Weibull	Forecast values
Trials	---	10,000
Base Case	---	217.11
Mean	215.50	216.19
Median	197.67	197.35
Mode	152.52	---
Standard Dev	90.54	90.54
Variance	8,197.39	8,197.39
Skewness	1.08	0.8123
Kurtosis	4.43	3.02
Coeff. of Vari	0.4201	0.4188
Minimum	82.96	84.00
Maximum	∞	490.65
Mean Std. Err	---	0.91

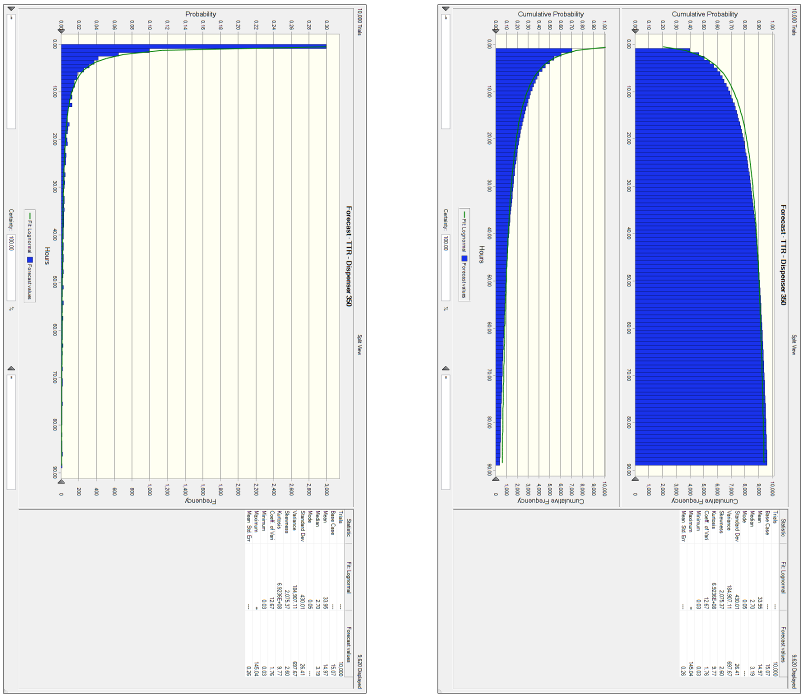
(a) Repair Cost Distribution of Air Instrument

Statistic	Fit: Weibull	Forecast values
Trials	---	10,000
Base Case	---	217.11
Mean	215.50	216.19
Median	197.67	197.35
Mode	152.52	---
Standard Dev	90.54	90.54
Variance	8,197.39	8,197.39
Skewness	1.08	0.8123
Kurtosis	4.43	3.02
Coeff. of Vari	0.4201	0.4188
Minimum	82.96	84.00
Maximum	∞	490.65
Mean Std. Err	---	0.91

(b) Cumulative Repair Cost Distribution of Air Instrument

Figure B.4: Repair Cost Distribution of Air Instrument

B.3. Dispenser 350 bar Nozzle



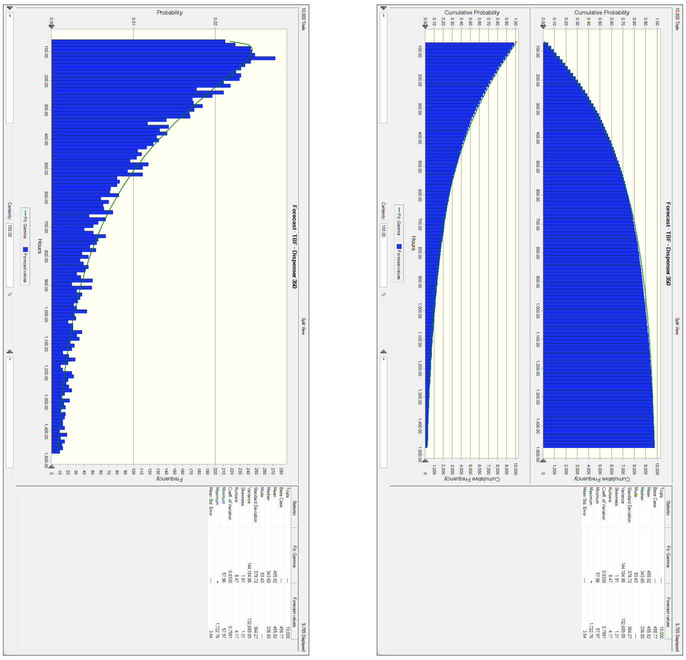
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	15.07
Mean	33.95	14.97
Median	2.70	3.19
Mode	0.05	---
Standard Dev	430.01	26.41
Variance	184,907.11	697.67
Skewness	2,075.37	2.60
Kurtosis	6.9236E+08	9.77
Coeff. of Vari	12.67	1.76
Minimum	0.03	0.03
Maximum	∞	145.04
Mean Std. Err	---	0.26

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	15.07
Mean	33.95	14.97
Median	2.70	3.19
Mode	0.05	---
Standard Dev	430.01	26.41
Variance	184,907.11	697.67
Skewness	2,075.37	2.60
Kurtosis	6.9236E+08	9.77
Coeff. of Vari	12.67	1.76
Minimum	0.03	0.03
Maximum	∞	145.04
Mean Std. Err	---	0.26

(a) TTR - Dispenser 350

(b) TTR - Dispenser 350 Cumulative

Figure B.5: Time To Repair (TTR) Distribution for Dispenser 350 Nozzle System



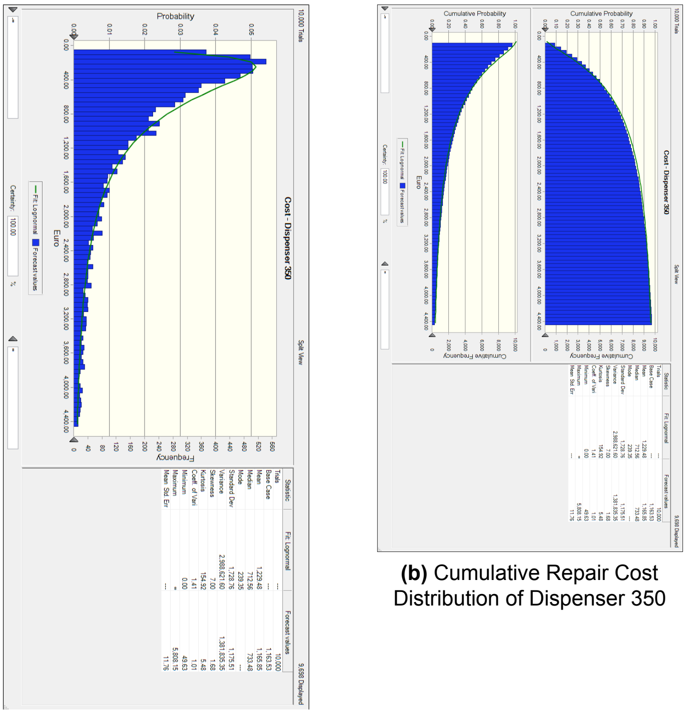
Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	458.77
Mean	455.82	455.82
Median	343.60	336.80
Mode	93.43	---
Standard Deviation	379.72	364.27
Variance	144,184.86	132,689.85
Skewness	1.91	1.31
Kurtosis	8.47	4.17
Coeff. of Variation	0.8330	0.7991
Minimum	57.96	57.97
Maximum	∞	1,722.76
Mean Std. Error	---	3.64

Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	458.77
Mean	455.82	455.82
Median	343.60	336.80
Mode	93.43	---
Standard Deviation	379.72	364.27
Variance	144,184.86	132,689.85
Skewness	1.91	1.31
Kurtosis	8.47	4.17
Coeff. of Variation	0.8330	0.7991
Minimum	57.96	57.97
Maximum	∞	1,722.76
Mean Std. Error	---	3.64

(a) TBF - Dispenser 350

(b) TBF - Dispenser 350 - Cumulative

Figure B.6: Time Between Failures (TBF) Distribution for Dispenser 350 Nozzle System



Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,163.53
Mean	1,229.48	1,165.85
Median	712.56	733.48
Mode	239.35	---
Standard Dev	1,728.76	1,175.51
Variance	2,988,621.60	1,381,835.35
Skewness	7.00	1.68
Kurtosis	154.92	5.48
Coeff. of Vari	1.41	1.01
Minimum	0.00	49.63
Maximum	∞	5,808.15
Mean Std. Err	---	11.76

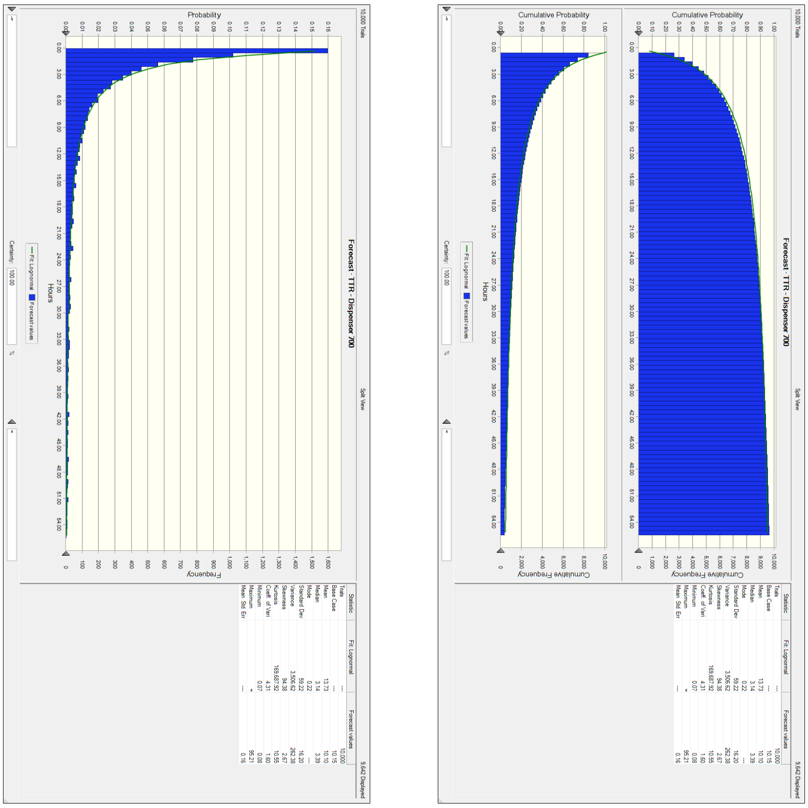
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,163.53
Mean	1,229.48	1,165.85
Median	712.56	733.48
Mode	239.35	---
Standard Dev	1,728.76	1,175.51
Variance	2,988,621.60	1,381,835.35
Skewness	7.00	1.68
Kurtosis	154.92	5.48
Coeff. of Vari	1.41	1.01
Minimum	0.00	49.63
Maximum	∞	5,808.15
Mean Std. Err	---	11.76

(a) Repair Cost Distribution of Dispenser 350

(b) Cumulative Repair Cost Distribution of Dispenser 350

Figure B.7: Repair Cost Distribution of 350 Nozzle System

B.4. Dispenser 700 bar Nozzle



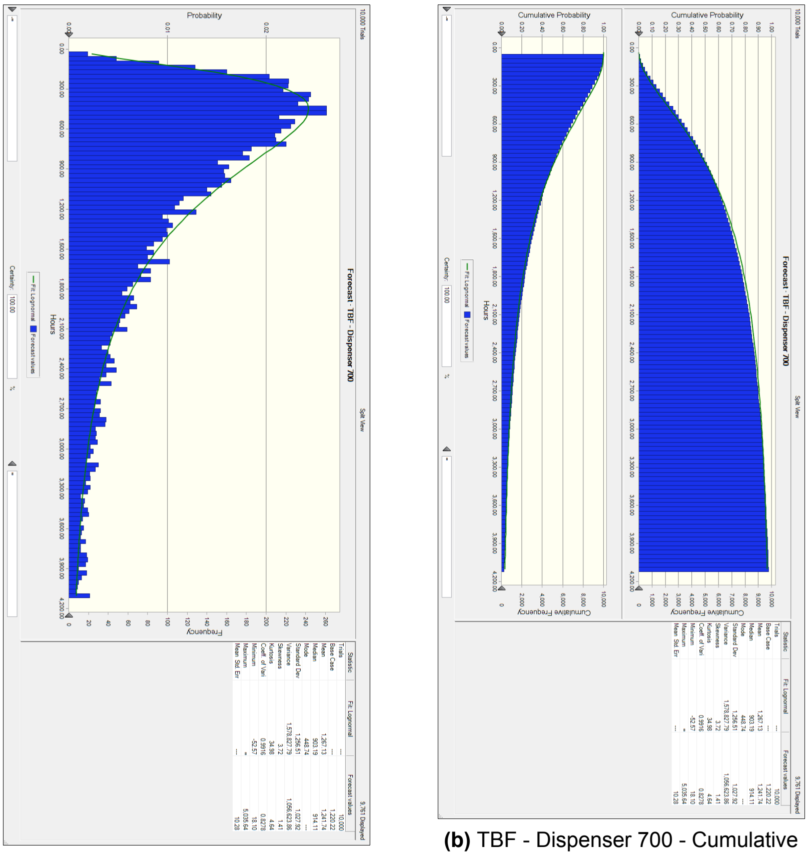
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	10.15
Mean	13.73	10.10
Median	3.14	3.39
Mode	0.22	---
Standard Dev	59.22	16.20
Variance	3,506.62	262.38
Skewness	94.38	2.67
Kurtosis	169,687.92	10.55
Coeff. of Vari	4.31	1.60
Minimum	0.07	0.08
Maximum	∞	95.21
Mean Std. Err	---	0.16

(a) TTR - Dispenser 700

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	10.15
Mean	13.73	10.10
Median	3.14	3.39
Mode	0.22	---
Standard Dev	59.22	16.20
Variance	3,506.62	262.38
Skewness	94.38	2.67
Kurtosis	169,687.92	10.55
Coeff. of Vari	4.31	1.60
Minimum	0.07	0.08
Maximum	∞	95.21
Mean Std. Err	---	0.16

(b) TTR - Dispenser 700 Cumulative

Figure B.8: Time To Repair (TTR) Distribution for Dispenser 700 Nozzle System



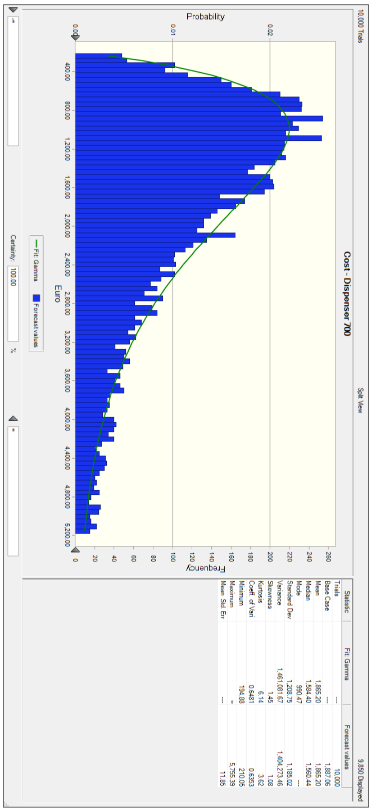
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,220.22
Mean	1,267.13	1,241.74
Median	903.19	914.11
Mode	448.74	---
Standard Dev	1,256.51	1,027.92
Variance	1,578,827.79	1,056,623.86
Skewness	3.72	1.41
Kurtosis	34.98	4.64
Coeff. of Vari	0.9916	0.8278
Minimum	-52.57	18.10
Maximum	∞	5,035.64
Mean Std. Err	---	10.28

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,220.22
Mean	1,267.13	1,241.74
Median	903.19	914.11
Mode	448.74	---
Standard Dev	1,256.51	1,027.92
Variance	1,578,827.79	1,056,623.86
Skewness	3.72	1.41
Kurtosis	34.98	4.64
Coeff. of Vari	0.9916	0.8278
Minimum	-52.57	18.10
Maximum	∞	5,035.64
Mean Std. Err	---	10.28

(a) TBF - Dispenser 700

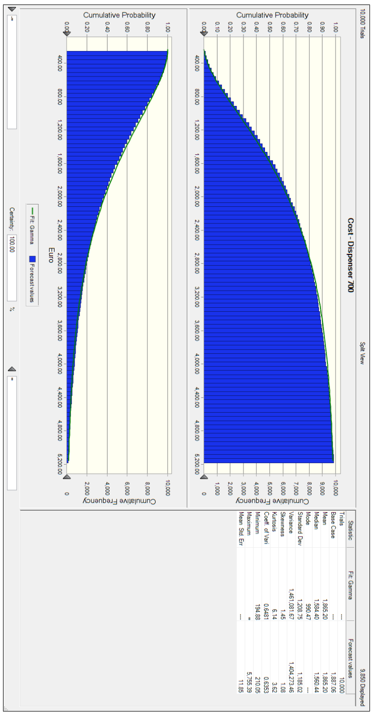
(b) TBF - Dispenser 700 - Cumulative

Figure B.9: Time Between Failures (TBF) Distribution for Dispenser 700 Nozzle System



Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	1,887.06
Mean	1,865.20	1,865.20
Median	1,584.40	1,560.44
Mode	990.47	---
Standard Dev	1,208.75	1,185.02
Variance	1,461,081.67	1,404,273.46
Skewness	1.45	1.08
Kurtosis	6.14	3.62
Coeff. of Vari	0.6481	0.6353
Minimum	194.88	210.05
Maximum	∞	5,755.39
Mean Std. Err	---	11.85

(a) Repair Cost Distribution of Dispenser 700

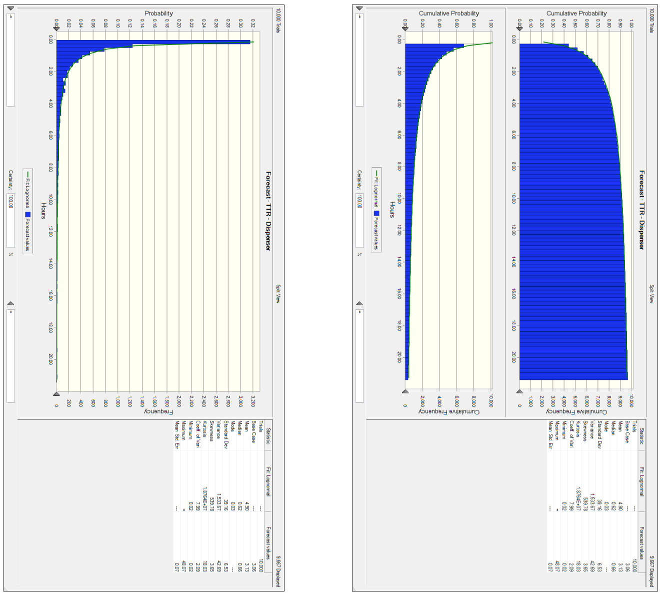


Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	1,887.06
Mean	1,865.20	1,865.20
Median	1,584.40	1,560.44
Mode	990.47	---
Standard Dev	1,208.75	1,185.02
Variance	1,461,081.67	1,404,273.46
Skewness	1.45	1.08
Kurtosis	6.14	3.62
Coeff. of Vari	0.6481	0.6353
Minimum	194.88	210.05
Maximum	∞	5,755.39
Mean Std. Err	---	11.85

(b) Cumulative Repair Cost Distribution of Dispenser 700

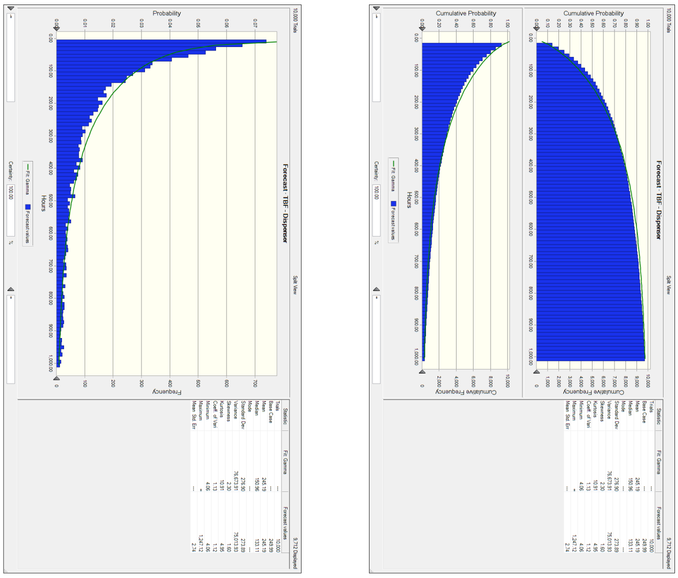
Figure B.10: Repair Cost Distribution of 700 Nozzle System

B.5. Dispenser



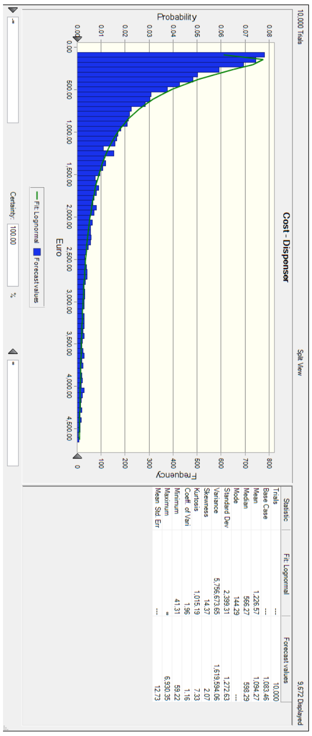
(a) TTR - Dispenser **(b)** TTR - Dispenser Cumulative

Figure B.11: Time To Repair (TTR) Distribution for Dispenser



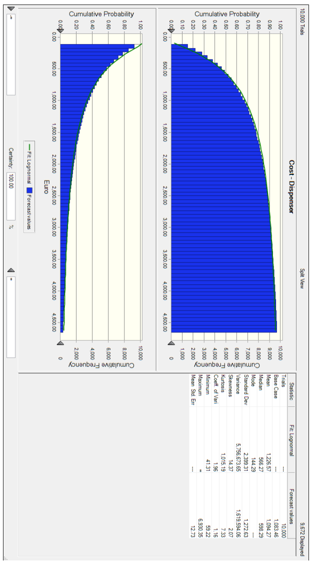
(a) TBF - Dispenser **(b)** TBF - Dispenser Cumulative

Figure B.12: Time Between Failures (TBF) Distribution for Dispenser



Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,083.46
Mean	1,226.57	1,094.27
Median	566.27	598.29
Mode	144.29	---
Standard Dev	2,399.31	1,272.63
Variance	5,756,673.65	1,619,594.06
Skewness	14.37	2.07
Kurtosis	1,015.19	7.33
Coeff. of Vari	1.96	1.16
Minimum	41.31	59.22
Maximum	∞	6,930.35
Mean Std. Err	---	12.73

(a) Repair Cost Distribution of Dispenser

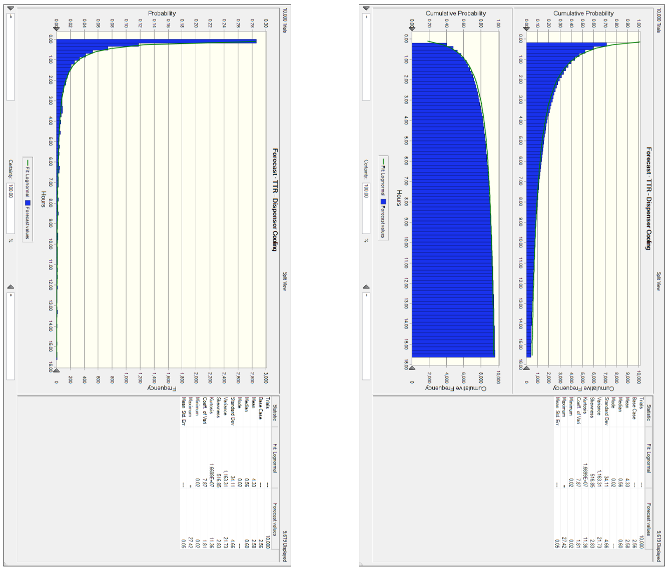


Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,083.46
Mean	1,226.57	1,094.27
Median	566.27	598.29
Mode	144.29	---
Standard Dev	2,399.31	1,272.63
Variance	5,756,673.65	1,619,594.06
Skewness	14.37	2.07
Kurtosis	1,015.19	7.33
Coeff. of Vari	1.96	1.16
Minimum	41.31	59.22
Maximum	∞	6,930.35
Mean Std. Err	---	12.73

(b) Cumulative Repair Cost Distribution of Dispenser

Figure B.13: Repair Cost Distribution of Dispenser

B.6. Dispenser Cooling



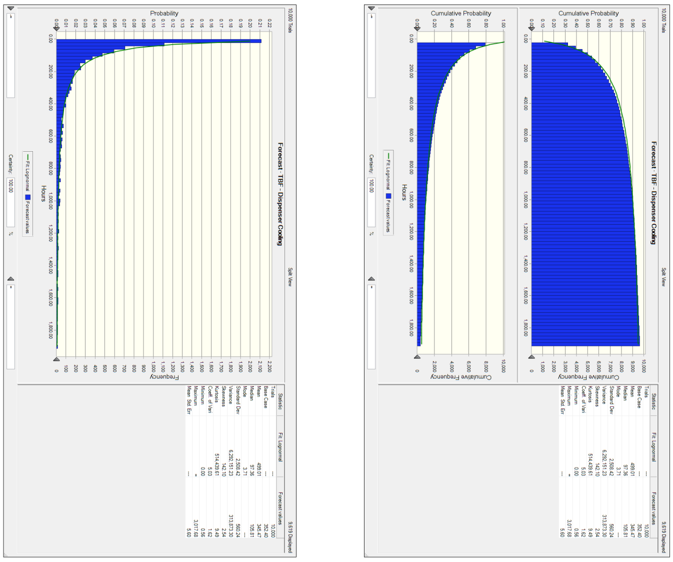
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	2.56
Mean	4.33	2.58
Median	0.56	0.60
Mode	0.02	---
Standard Dev	34.11	4.66
Variance	1,163.31	21.73
Skewness	516.85	2.83
Kurtosis	1.6699E+07	11.36
Coeff. of Vari	7.87	1.81
Minimum	0.02	0.02
Maximum	∞	27.42
Mean Std. Err	---	0.05

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	2.56
Mean	4.33	2.58
Median	0.56	0.60
Mode	0.02	---
Standard Dev	34.11	4.66
Variance	1,163.31	21.73
Skewness	516.85	2.83
Kurtosis	1.6699E+07	11.36
Coeff. of Vari	7.87	1.81
Minimum	0.02	0.02
Maximum	∞	27.42
Mean Std. Err	---	0.05

(a) TTR - Dispenser Cooling

(b) TTR - Dispenser Cooling Cumulative

Figure B.14: Time To Repair (TTR) Distribution for Dispenser Cooling



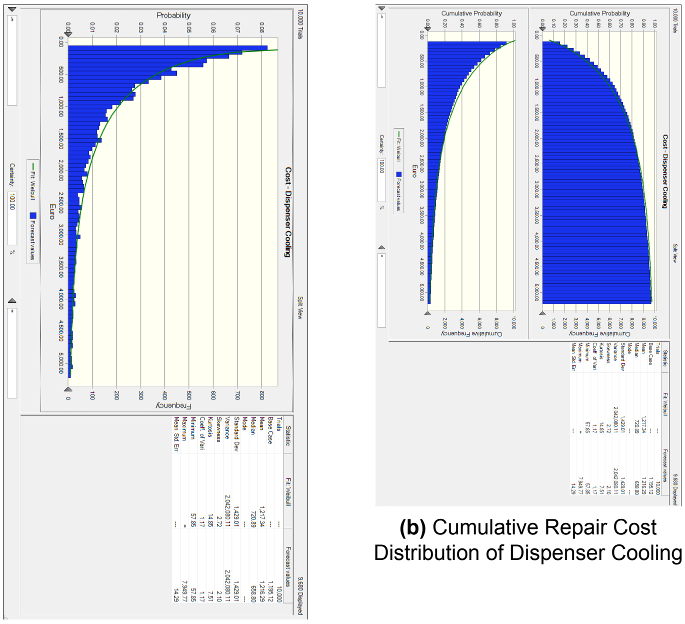
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	352.40
Mean	499.01	345.47
Median	97.36	105.81
Mode	3.71	---
Standard Dev	2,508.42	560.24
Variance	6,292,151.23	313,873.30
Skewness	142.10	2.54
Kurtosis	514,439.61	9.49
Coeff. of Vari	5.03	1.62
Minimum	0.00	0.56
Maximum	∞	3,017.68
Mean Std. Err	---	5.60

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	352.40
Mean	499.01	345.47
Median	97.36	105.81
Mode	3.71	---
Standard Dev	2,508.42	560.24
Variance	6,292,151.23	313,873.30
Skewness	142.10	2.54
Kurtosis	514,439.61	9.49
Coeff. of Vari	5.03	1.62
Minimum	0.00	0.56
Maximum	∞	3,017.68
Mean Std. Err	---	5.60

(a) TBF - Dispenser Cooling

(b) TBF - Dispenser Cooling Cumulative

Figure B.15: Time Between Failures (TBF) Distribution for Dispenser Cooling



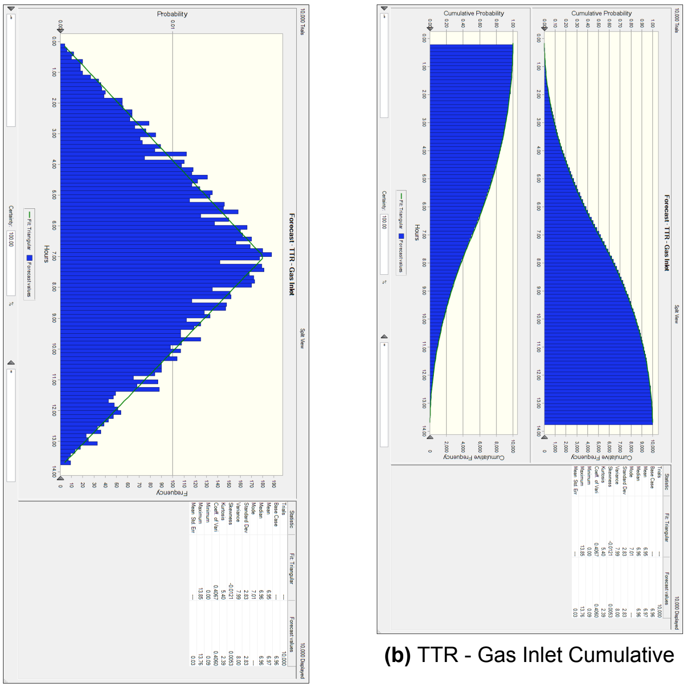
Statistic	Fit: Weibull	Forecast values
Trials	---	10,000
Base Case	---	1,195.12
Mean	1,217.34	1,216.29
Median	720.89	658.80
Mode	---	---
Standard Dev	1,429.01	1,429.01
Variance	2,042,080.11	2,042,080.11
Skewness	2.72	2.10
Kurtosis	14.85	7.51
Coeff. of Vari	1.17	1.17
Minimum	57.85	57.85
Maximum	∞	7,949.77
Mean Std. Err	---	14.29

(a) Repair Cost Distribution of Dispenser Cooling

(b) Cumulative Repair Cost Distribution of Dispenser Cooling

Figure B.16: Repair Cost Distribution of Dispenser Cooling

B.7. Gas Inlet

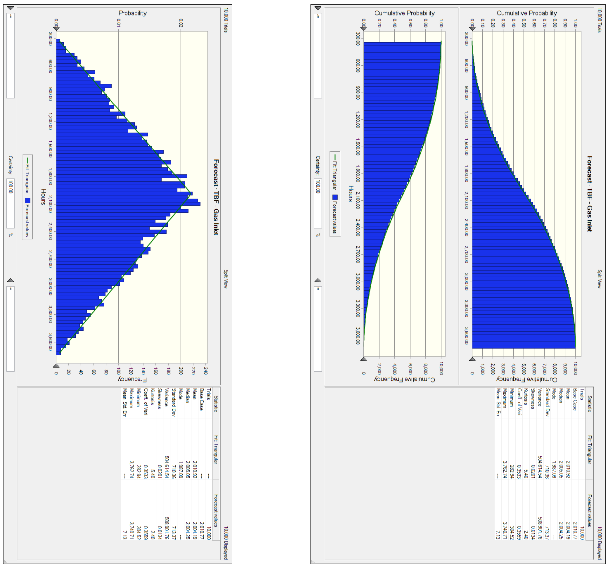


Statistic	Fit: Triangular	Forecast values
Trials	---	10,000
Base Case	---	6.96
Mean	6.95	6.97
Median	6.96	6.96
Mode	7.01	---
Standard Dev	2.83	2.83
Variance	7.99	8.00
Skewness	-0.0121	0.0053
Kurtosis	5.40	2.39
Coeff. of Vari	0.4067	0.4060
Minimum	0.00	0.09
Maximum	13.85	13.76
Mean Std. Err	---	0.03

(a) TTR - Gas Inlet

(b) TTR - Gas Inlet Cumulative

Figure B.17: Time To Repair (TTR) Distribution for Gas Inlet

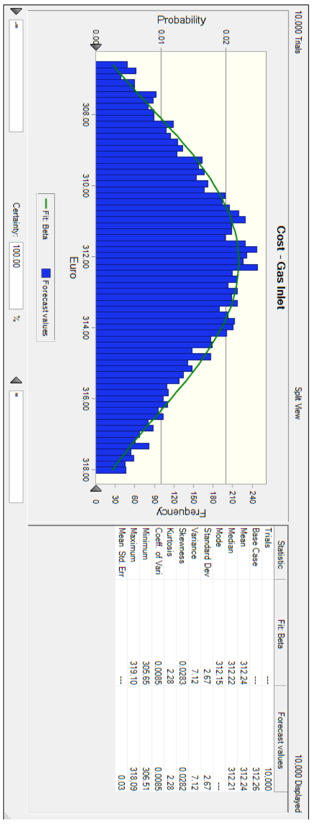


Statistic	Fit: Triangular	Forecast values
Trials	---	10,000
Base Case	---	2,010.77
Mean	2,010.92	2,004.19
Median	2,005.05	2,004.25
Mode	1,987.09	---
Standard Dev	710.36	713.37
Variance	504,614.54	508,901.76
Skewness	0.0201	0.0134
Kurtosis	5.40	2.40
Coeff. of Vari	0.3533	0.3559
Minimum	282.94	304.52
Maximum	3,762.74	3,740.71
Mean Std. Err	---	7.13

Statistic	Fit: Triangular	Forecast values
Trials	---	10,000
Base Case	---	2,010.77
Mean	2,010.92	2,004.19
Median	2,005.05	2,004.25
Mode	1,987.09	---
Standard Dev	710.36	713.37
Variance	504,614.54	508,901.76
Skewness	0.0201	0.0134
Kurtosis	5.40	2.40
Coeff. of Vari	0.3533	0.3559
Minimum	282.94	304.52
Maximum	3,762.74	3,740.71
Mean Std. Err	---	7.13

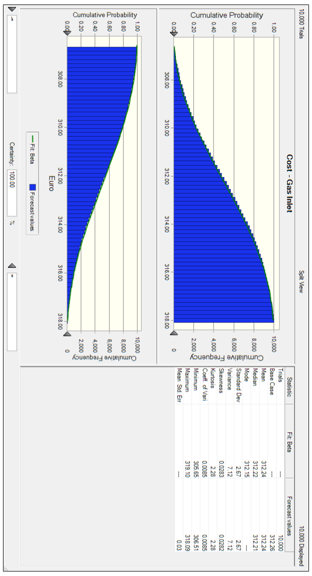
(a) TBF - Gas Inlet **(b)** TBF - Gas Inlet Cumulative

Figure B.18: Time Between Failures (TBF) Distribution for Gas Inlet



Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	312.26
Mean	312.24	312.24
Median	312.22	312.21
Mode	312.15	---
Standard Dev	2.67	2.67
Variance	7.12	7.12
Skewness	0.0283	0.0282
Kurtosis	2.28	2.28
Coeff. of Vari	0.0085	0.0085
Minimum	305.65	306.51
Maximum	319.10	318.09
Mean Std. Err	---	0.03

(a) Gas Inlet

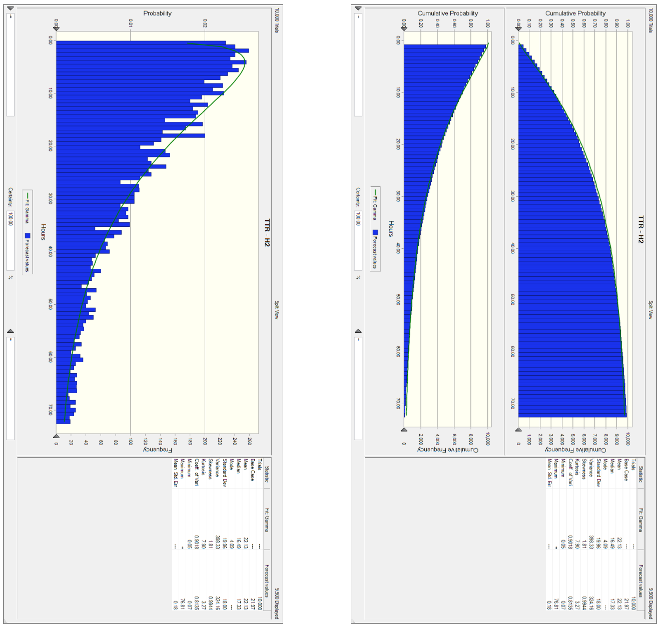


Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	312.26
Mean	312.24	312.24
Median	312.22	312.21
Mode	312.15	---
Standard Dev	2.67	2.67
Variance	7.12	7.12
Skewness	0.0283	0.0282
Kurtosis	2.28	2.28
Coeff. of Vari	0.0085	0.0085
Minimum	305.65	306.51
Maximum	319.10	318.09
Mean Std. Err	---	0.03

(b) Gas Inlet Cumulative

Figure B.19: Repair Cost Distribution of Gas Inlet

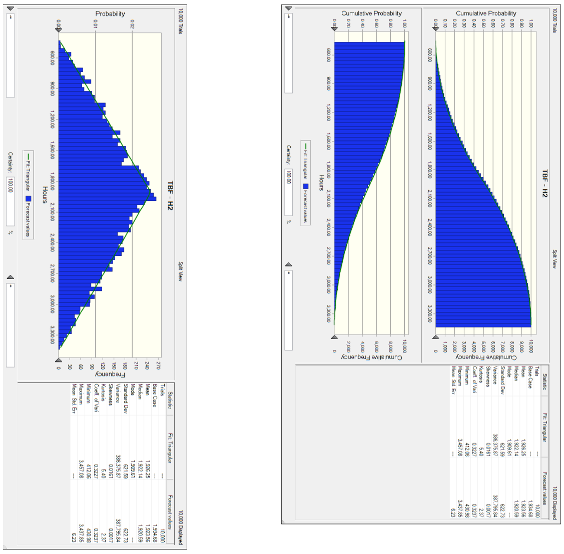
B.8. H2 Installation



(a) TTR - H2 Installation

(b) TTR - H2 Installation Cumulative

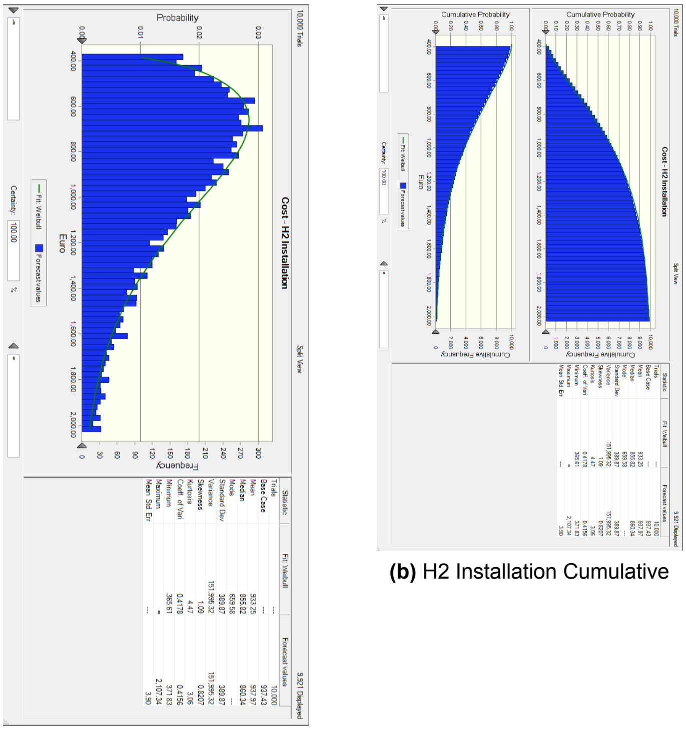
Figure B.20: Time To Repair (TTR) Distribution for H2 Installation



(a) TBF - H2 Installation

(b) TBF - H2 Installation Cumulative

Figure B.21: Time Between Failures (TBF) Distribution for H2 Installation



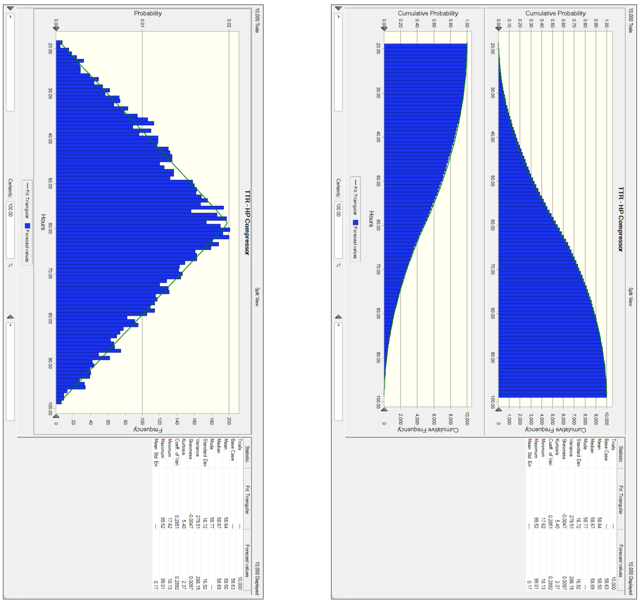
Statistic	Fit: Weibull	Forecast values
Trials	---	10,000
Base Case	---	937.43
Mean	933.25	937.97
Median	855.82	860.34
Mode	659.58	---
Standard Dev	389.87	389.87
Variance	151,995.32	151,995.32
Skewness	1.09	0.8207
Kurtosis	4.47	3.06
Coeff. of Vari	0.4178	0.4156
Minimum	365.61	371.83
Maximum	∞	2,107.34
Mean Std. Err	---	3.90

(a) H2 Installation

(b) H2 Installation Cumulative

Figure B.22: Repair Cost Distribution of H2 Installation

B.9. HP Compressor

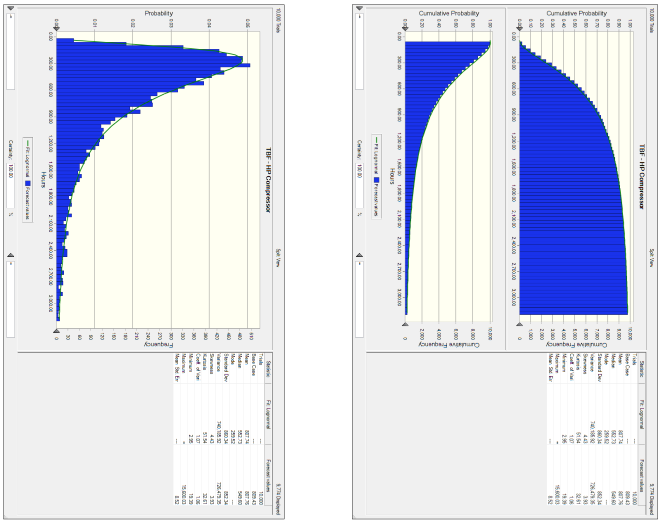


Statistic	Fit: Triangular	Forecast values
Trials	---	10,000
Base Case	---	58.63
Mean	58.64	58.50
Median	58.67	58.69
Mode	58.77	---
Standard Dev	16.72	16.92
Variance	279.51	286.15
Skewness	-0.0047	0.0097
Kurtosis	5.40	2.37
Coeff. of Vari	0.2851	0.2892
Minimum	17.62	18.13
Maximum	99.52	99.01
Mean Std. Err	---	0.17

(a) TTR - HP Compressor

(b) TTR - HP Compressor Cumulative

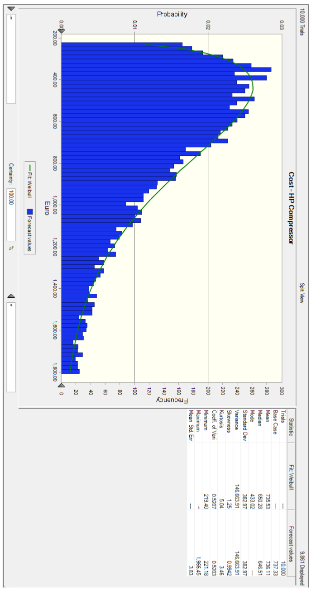
Figure B.23: Time To Repair (TTR) Distribution for HP Compressor



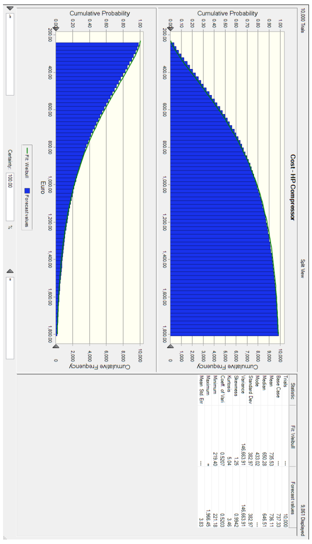
(a) TBF - HP Compressor

(b) TBF - HP Compressor Cumulative

Figure B.24: Time Between Failures (TBF) Distribution for HP Compressor



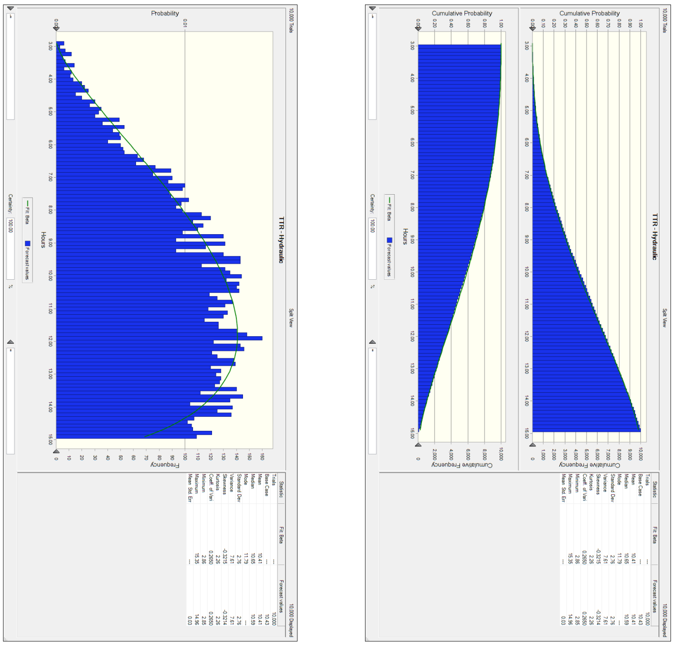
(a) HP Compressor



(b) HP Compressor Cumulative

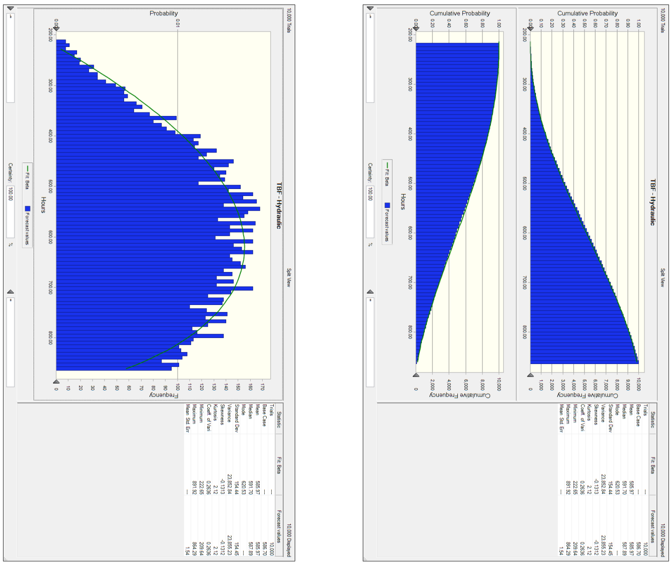
Figure B.25: Repair Cost Distribution of HP Compressor

B.10. Hydraulic System



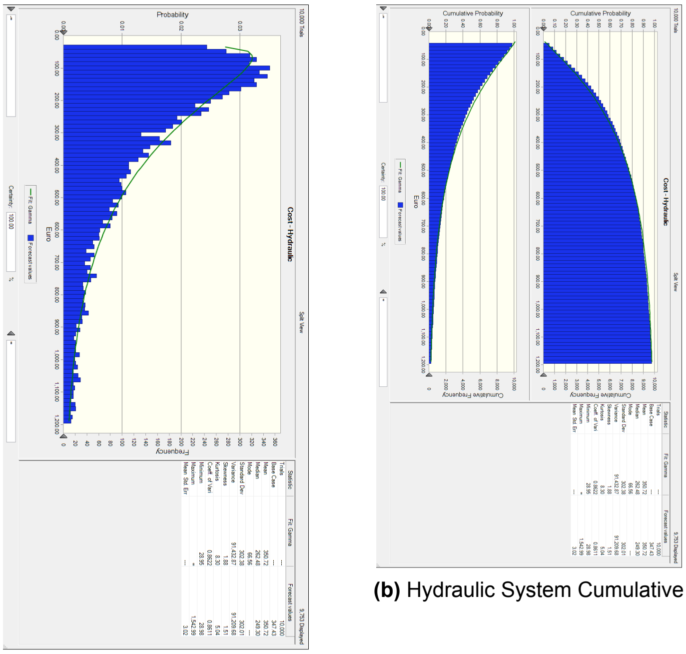
(a) TTR - Hydraulic System **(b)** TTR - Hydraulic System Cumulative

Figure B.26: Time To Repair (TTR) Distribution for Hydraulic System



(a) TBF - Hydraulic System **(b)** TBF - Hydraulic System Cumulative

Figure B.27: Time Between Failures (TBF) Distribution for Hydraulic System



Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	347.43
Mean	350.72	350.72
Median	262.48	249.30
Mode	66.56	---
Standard Dev	302.38	302.01
Variance	91,432.87	91,209.68
Skewness	1.88	1.51
Kurtosis	8.30	5.04
Coeff. of Vari	0.8622	0.8611
Minimum	28.95	28.98
Maximum	∞	1,542.99
Mean Std. Err	---	3.02

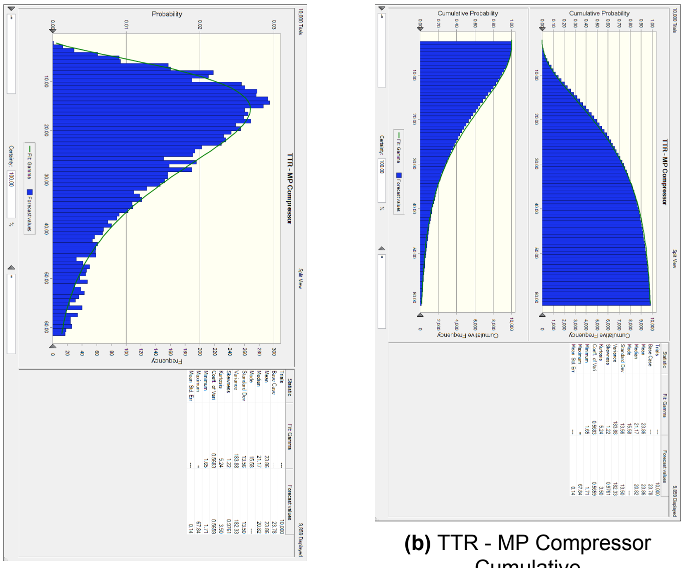
(a) Hydraulic System

Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	347.43
Mean	350.72	350.72
Median	262.48	249.30
Mode	66.56	---
Standard Dev	302.38	302.01
Variance	91,432.87	91,209.68
Skewness	1.88	1.51
Kurtosis	8.30	5.04
Coeff. of Vari	0.8622	0.8611
Minimum	28.95	28.98
Maximum	∞	1,542.99
Mean Std. Err	---	3.02

(b) Hydraulic System Cumulative

Figure B.28: Repair Cost Distribution of Hydraulic System

B.11. MP Compressor System



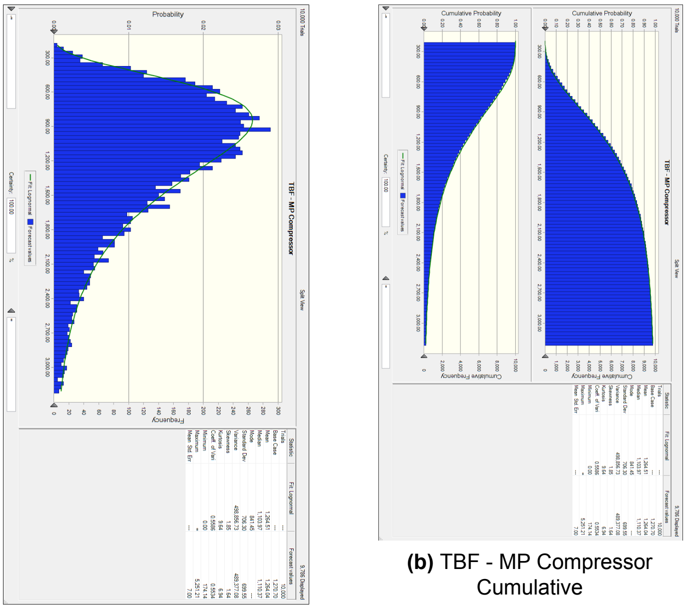
Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	23.78
Mean	23.86	23.86
Median	21.17	20.82
Mode	15.58	---
Standard Dev	13.56	13.50
Variance	183.88	182.33
Skewness	1.22	0.9761
Kurtosis	5.24	3.50
Coeff. of Vari	0.5683	0.5659
Minimum	1.65	1.71
Maximum	∞	67.84
Mean Std. Err	---	0.14

(a) TTR - MP Compressor

Statistic	Fit: Gamma	Forecast values
Trials	---	10,000
Base Case	---	23.78
Mean	23.86	23.86
Median	21.17	20.82
Mode	15.58	---
Standard Dev	13.56	13.50
Variance	183.88	182.33
Skewness	1.22	0.9761
Kurtosis	5.24	3.50
Coeff. of Vari	0.5683	0.5659
Minimum	1.65	1.71
Maximum	∞	67.84
Mean Std. Err	---	0.14

(b) TTR - MP Compressor Cumulative

Figure B.29: Time To Repair (TTR) Distribution for MP Compressor



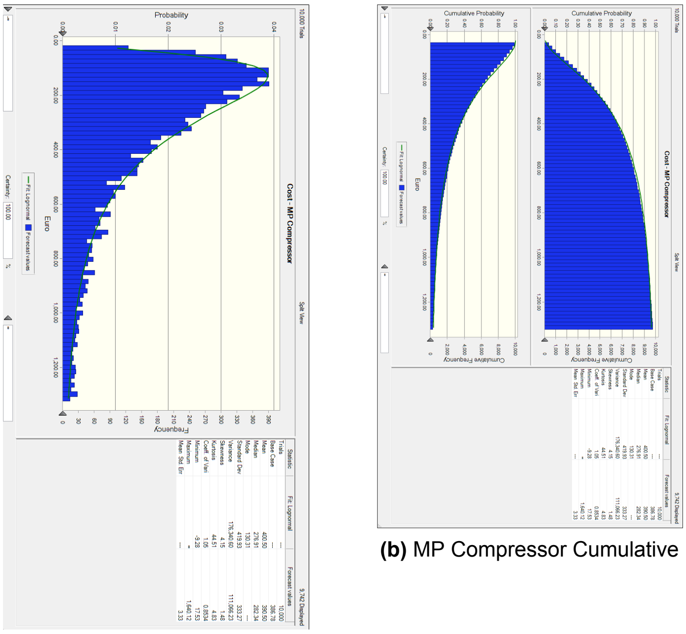
Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,270.70
Mean	1,264.51	1,264.04
Median	1,103.97	1,110.37
Mode	841.45	---
Standard Dev	706.30	699.55
Variance	498,856.73	489,377.08
Skewness	1.85	1.64
Kurtosis	9.64	6.94
Coeff. of Vari	0.5586	0.5534
Minimum	0.00	174.14
Maximum	∞	5,251.21
Mean Std. Err	---	7.00

(a) TBF - MP Compressor

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	1,270.70
Mean	1,264.51	1,264.04
Median	1,103.97	1,110.37
Mode	841.45	---
Standard Dev	706.30	699.55
Variance	498,856.73	489,377.08
Skewness	1.85	1.64
Kurtosis	9.64	6.94
Coeff. of Vari	0.5586	0.5534
Minimum	0.00	174.14
Maximum	∞	5,251.21
Mean Std. Err	---	7.00

(b) TBF - MP Compressor Cumulative

Figure B.30: Time Between Failures (TBF) Distribution for MP Compressor



Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	386.78
Mean	400.50	390.50
Median	276.91	282.34
Mode	130.31	---
Standard Dev	419.93	333.27
Variance	176,340.60	111,066.23
Skewness	4.15	1.48
Kurtosis	44.51	4.83
Coeff. of Vari	1.05	0.8534
Minimum	-9.28	17.53
Maximum	∞	1,640.12
Mean Std. Err	---	3.33

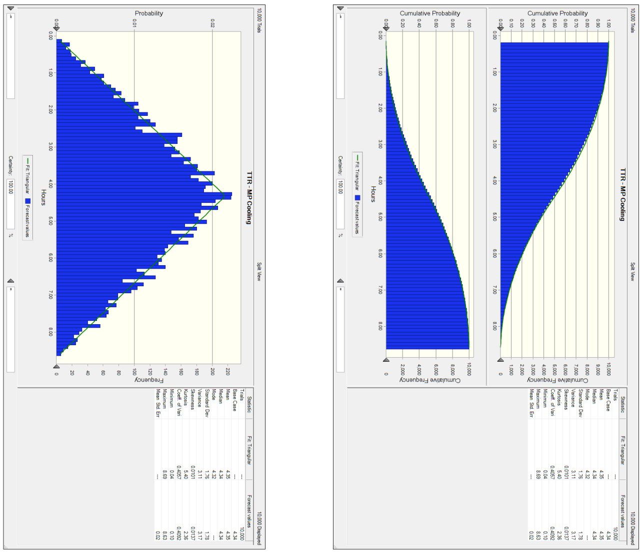
(a) MP Compressor

Statistic	Fit: Lognormal	Forecast values
Trials	---	10,000
Base Case	---	386.78
Mean	400.50	390.50
Median	276.91	282.34
Mode	130.31	---
Standard Dev	419.93	333.27
Variance	176,340.60	111,066.23
Skewness	4.15	1.48
Kurtosis	44.51	4.83
Coeff. of Vari	1.05	0.8534
Minimum	-9.28	17.53
Maximum	∞	1,640.12
Mean Std. Err	---	3.33

(b) MP Compressor Cumulative

Figure B.31: Repair Cost Distribution of MP Compressor

B.12. MP Cooling

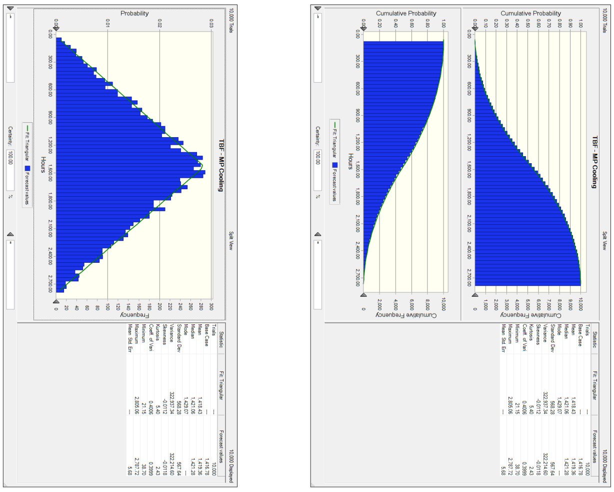


Statistic	Fit: Triangular	Forecast values
Trials	---	10.000
Base Case	---	4.34
Mean	4.35	4.35
Median	4.34	4.34
Mode	4.32	---
Standard Dev	1.76	1.78
Variance	3.11	3.17
Skewness	0.0101	0.0137
Kurtosis	5.40	2.36
Coeff. of Vari	0.4057	0.4092
Minimum	0.04	0.10
Maximum	8.69	8.63
Mean Std. Err	---	0.02

Statistic	Fit: Triangular	Forecast values
Trials	---	10.000
Base Case	---	4.34
Mean	4.35	4.35
Median	4.34	4.34
Mode	4.32	---
Standard Dev	1.76	1.78
Variance	3.11	3.17
Skewness	0.0101	0.0137
Kurtosis	5.40	2.36
Coeff. of Vari	0.4057	0.4092
Minimum	0.04	0.10
Maximum	8.69	8.63
Mean Std. Err	---	0.02

(a) TTR - MP Cooling **(b)** TTR - MP Cooling Cumulative

Figure B.32: Time To Repair (TTR) Distribution for MP Cooling

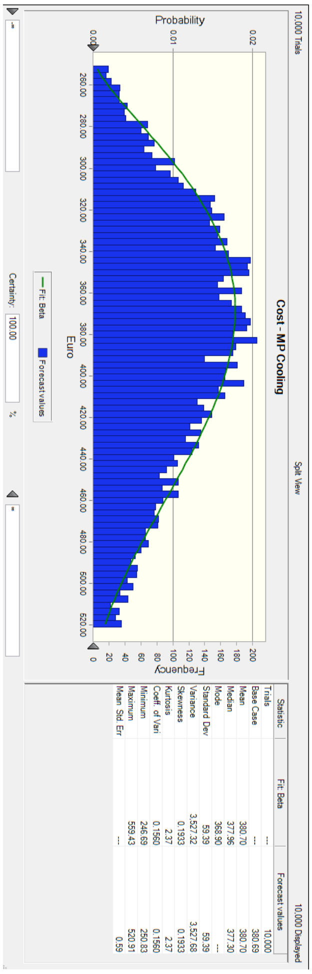


Statistic	Fit: Triangular	Forecast values
Trials	---	10.000
Base Case	---	1.416.78
Mean	1.418.43	1.419.36
Median	1.421.06	1.421.28
Mode	1.429.07	---
Standard Dev	568.28	567.64
Variance	322.937.34	322.214.60
Skewness	-0.0112	-0.0118
Kurtosis	5.40	2.43
Coeff. of Vari	0.4006	0.3999
Minimum	21.15	38.70
Maximum	2.805.06	2.787.72
Mean Std. Err	---	5.68

Statistic	Fit: Triangular	Forecast values
Trials	---	10.000
Base Case	---	1.416.78
Mean	1.418.43	1.419.36
Median	1.421.06	1.421.28
Mode	1.429.07	---
Standard Dev	568.28	567.64
Variance	322.937.34	322.214.60
Skewness	-0.0112	-0.0118
Kurtosis	5.40	2.43
Coeff. of Vari	0.4006	0.3999
Minimum	21.15	38.70
Maximum	2.805.06	2.787.72
Mean Std. Err	---	5.68

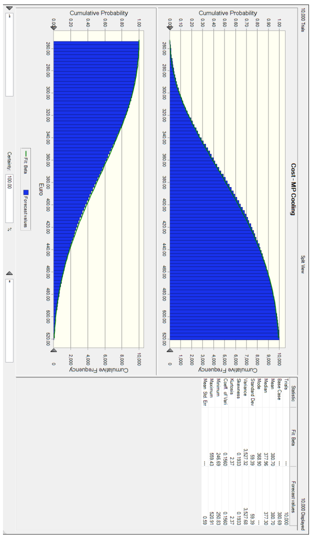
(a) TBF - MP Cooling **(b)** TBF - MP Cooling Cumulative

Figure B.33: Time Between Failures (TBF) Distribution for MP Cooling



Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	380.69
Mean	380.70	380.70
Median	377.96	377.30
Mode	368.90	---
Standard Dev	59.39	59.39
Variance	3,527.32	3,527.68
Skewness	0.1933	0.1933
Kurtosis	2.37	2.37
Coeff. of Vari	0.1560	0.1560
Minimum	246.69	250.83
Maximum	559.43	520.91
Mean Std. Err	---	0.59

(a) MP Cooling



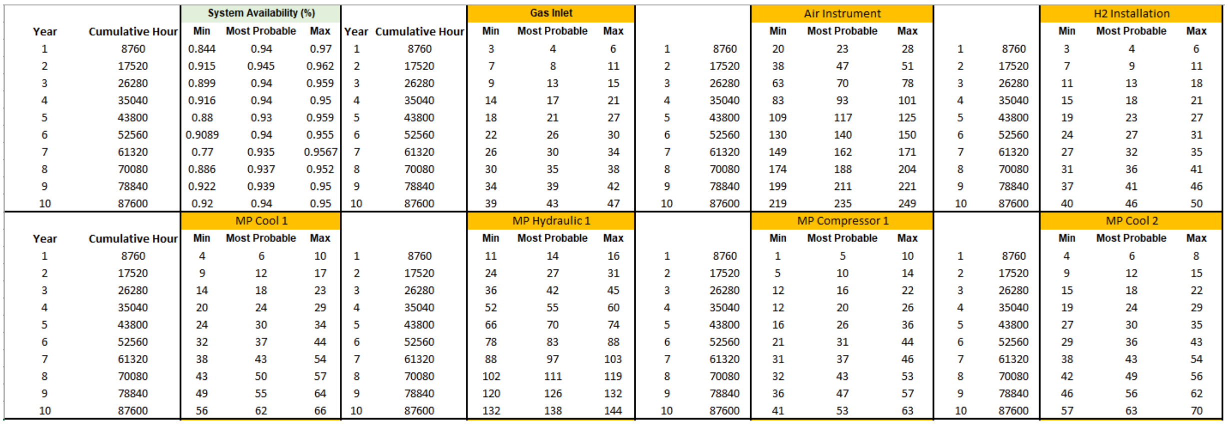
Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	380.69
Mean	380.70	380.70
Median	377.96	377.30
Mode	368.90	---
Standard Dev	59.39	59.39
Variance	3,527.32	3,527.68
Skewness	0.1933	0.1933
Kurtosis	2.37	2.37
Coeff. of Vari	0.1560	0.1560
Minimum	246.69	250.83
Maximum	559.43	520.91
Mean Std. Err	---	0.59

(b) MP Cooling Cumulative

Figure B.34: Repair Cost Distribution of MP Cooling

C

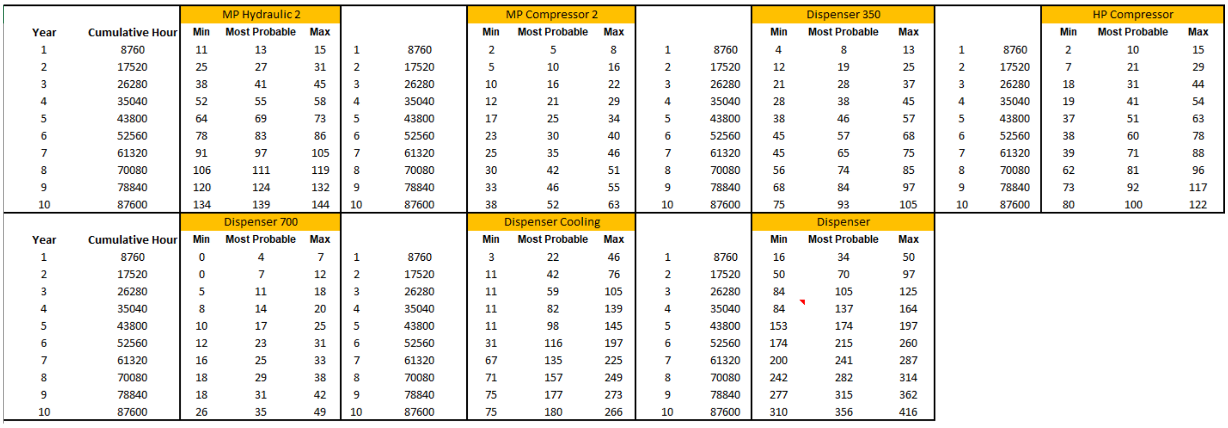
RAMS Simulation Output for 10 Years



		System Availability (%)					Gas Inlet					Air Instrument					H2 Installation		
Year	Cumulative Hour	Min	Most Probable	Max	Year	Cumulative Hour	Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max
1	8760	0.844	0.94	0.97	1	8760	3	4	6	1	8760	20	23	28	1	8760	3	4	6
2	17520	0.915	0.945	0.962	2	17520	7	8	11	2	17520	38	47	51	2	17520	7	9	11
3	26280	0.899	0.94	0.959	3	26280	9	13	15	3	26280	63	70	78	3	26280	11	13	18
4	35040	0.916	0.94	0.95	4	35040	14	17	21	4	35040	83	93	101	4	35040	15	18	21
5	43800	0.88	0.93	0.959	5	43800	18	21	27	5	43800	109	117	125	5	43800	19	23	27
6	52560	0.9089	0.94	0.955	6	52560	22	26	30	6	52560	130	140	150	6	52560	24	27	31
7	61320	0.77	0.935	0.9567	7	61320	26	30	34	7	61320	149	162	171	7	61320	27	32	35
8	70080	0.886	0.937	0.952	8	70080	30	35	38	8	70080	174	188	204	8	70080	31	36	41
9	78840	0.922	0.939	0.95	9	78840	34	39	42	9	78840	199	211	221	9	78840	37	41	46
10	87600	0.92	0.94	0.95	10	87600	39	43	47	10	87600	219	235	249	10	87600	40	46	50

		MP Cool 1					MP Hydraulic 1					MP Compressor 1					MP Cool 2		
Year	Cumulative Hour	Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max
1	8760	4	6	10	1	8760	11	14	16	1	8760	1	5	10	1	8760	4	6	8
2	17520	9	12	17	2	17520	24	27	31	2	17520	5	10	14	2	17520	9	12	15
3	26280	14	18	23	3	26280	36	42	45	3	26280	12	16	22	3	26280	15	18	22
4	35040	20	24	29	4	35040	52	55	60	4	35040	12	20	26	4	35040	19	24	29
5	43800	24	30	34	5	43800	66	70	74	5	43800	16	26	36	5	43800	27	30	35
6	52560	32	37	44	6	52560	78	83	88	6	52560	21	31	44	6	52560	29	36	43
7	61320	38	43	54	7	61320	88	97	103	7	61320	31	37	46	7	61320	38	43	54
8	70080	43	50	57	8	70080	102	111	119	8	70080	32	43	53	8	70080	42	49	56
9	78840	49	55	64	9	78840	120	126	132	9	78840	36	47	57	9	78840	46	56	62
10	87600	56	62	66	10	87600	132	138	144	10	87600	41	53	63	10	87600	57	63	70

Figure C.1: Number of Failures for Components and System Overall Availability over Years - 1



		MP Hydraulic 2					MP Compressor 2					Dispenser 350					HP Compressor		
Year	Cumulative Hour	Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max
1	8760	11	13	15	1	8760	2	5	8	1	8760	4	8	13	1	8760	2	10	15
2	17520	25	27	31	2	17520	5	10	16	2	17520	12	19	25	2	17520	7	21	29
3	26280	38	41	45	3	26280	10	16	22	3	26280	21	28	37	3	26280	18	31	44
4	35040	52	55	58	4	35040	12	21	29	4	35040	28	38	45	4	35040	19	41	54
5	43800	64	69	73	5	43800	17	25	34	5	43800	38	46	57	5	43800	37	51	63
6	52560	78	83	86	6	52560	23	30	40	6	52560	45	57	68	6	52560	38	60	78
7	61320	91	97	105	7	61320	25	35	46	7	61320	45	65	75	7	61320	39	71	88
8	70080	106	111	119	8	70080	30	42	51	8	70080	56	74	85	8	70080	62	81	96
9	78840	120	124	132	9	78840	33	46	55	9	78840	68	84	97	9	78840	73	92	117
10	87600	134	139	144	10	87600	38	52	63	10	87600	75	93	105	10	87600	80	100	122

		Dispenser 700					Dispenser Cooling					Dispenser		
Year	Cumulative Hour	Min	Most Probable	Max			Min	Most Probable	Max			Min	Most Probable	Max
1	8760	0	4	7	1	8760	3	22	46	1	8760	16	34	50
2	17520	0	7	12	2	17520	11	42	76	2	17520	50	70	97
3	26280	5	11	18	3	26280	11	59	105	3	26280	84	105	125
4	35040	8	14	20	4	35040	11	82	139	4	35040	84	137	164
5	43800	10	17	25	5	43800	11	98	145	5	43800	153	174	197
6	52560	12	23	31	6	52560	31	116	197	6	52560	174	215	260
7	61320	16	25	33	7	61320	67	135	225	7	61320	200	241	287
8	70080	18	29	38	8	70080	71	157	249	8	70080	242	282	314
9	78840	18	31	42	9	78840	75	177	273	9	78840	277	315	362
10	87600	26	35	49	10	87600	75	180	266	10	87600	310	356	416

Figure C.2: Number of Failures for Components over Years - 2

D

Risk Safety Assessment

SAFETY DATA SHEET

Hydrogen

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier : Hydrogen
Chemical name : hydrogen
Other means of identification : Dihydrogen; o-Hydrogen; p-Hydrogen; Molecular hydrogen; H2; UN 1049
Product type : Gas.
Product use : Synthetic/Analytical chemistry.
Synonym : Dihydrogen; o-Hydrogen; p-Hydrogen; Molecular hydrogen; H2; UN 1049
SDS # : 001026
Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : FLAMMABLE GASES - Category 1
GASES UNDER PRESSURE - Compressed gas

GHS label elements

Hazard pictograms :

Signal word : Danger
Hazard statements : Extremely flammable gas.
Contains gas under pressure; may explode if heated.
May displace oxygen and cause rapid suffocation.
Burns with invisible flame.
May form explosive mixtures with air.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Approach suspected leak area with caution.

Prevention : Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking.

Response : Leaking gas fire: Do not extinguish, unless leak can be stopped safely. In case of leakage, eliminate all ignition sources.

Storage : Protect from sunlight. Store in a well-ventilated place.
Disposal : Not applicable.
Hazards not otherwise classified : In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

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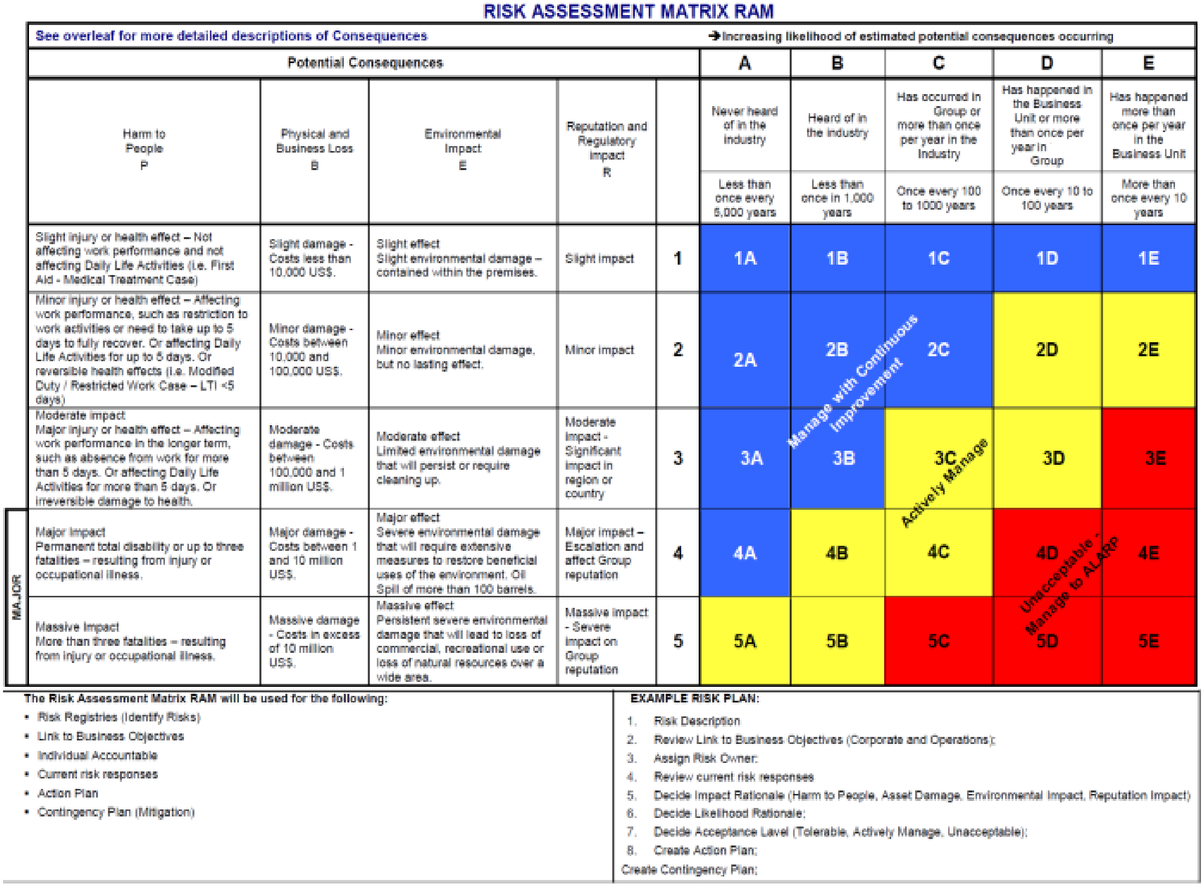
Figure D.1: Safety Sheet of Hydrogen



RISK ASSESSMENT MATRIX RAM

	See overleaf for more detailed descriptions of Consequences					➔Increasing likelihood of estimated potential consequences occurring				
	Potential Consequences					A	B	C	D	E
	Harm to People P	Physical and Business Loss B	Environmental Impact E	Reputation and Regulatory impact R		Never heard of in the industry Less than once every 5,000 years	Heard of in the industry Less than once in 1,000 years	Has occured in Group or more than once per year in the Industry Once every 100 to 1000 years	Has happened in the Business Unit or more than once per year in Group Once every 10 to 100 years	Has happened more than once per year in the Business Unit More than once every 10 years
	Slight injury or health effect – Not affecting work performance and not affecting Daily Life Activities (i.e. First Aid - Medical Treatment Case)	Slight damage - Costs less than 10,000 US$.	Slight effect Slight environmental damage – contained within the premises.	Slight impact	1	1A	1B	1C	1D	1E
	Minor injury or health effect – Affecting work performance, such as restriction to work activities or need to take up to 5 days to fully recover. Or affecting Daily Life Activities for up to 5 days. Or reversible health effects (i.e. Modified Duty / Restricted Work Case – LTI <5 days)	Minor damage - Costs between 10,000 and 100,000 US$.	Minor effect Minor environmental damage, but no lasting effect.	Minor impact	2	2A	2B	2C	2D	2E
	Moderate impact Major injury or health effect – Affecting work performance in the longer term, such as absence from work for more than 5 days. Or affecting Daily Life Activities for more than 5 days. Or irreversible damage to health.	Moderate damage - Costs between 100,000 and 1 million US$.	Moderate effect Limited environmental damage that will persist or require cleaning up.	Moderate impact - Significant impact in region or country	3	3A	3B	3C	3D	3E
MAJOR	Major impact Permanent total disability or up to three fatalities – resulting from injury or occupational illness.	Major damage - Costs between 1 and 10 million US$.	Major effect Severe environmental damage that will require extensive measures to restore beneficial uses of the environment. Oil Spill of more than 100 barrels.	Major impact – Escalation and affect Group reputation	4	4A	4B	4C	4D	4E
	Massive impact More than three fatalities – resulting from injury or occupational illness.	Massive damage - Costs in excess of 10 million US$.	Massive effect Persistent severe environmental damage that will lead to loss of commercial, recreational use or loss of natural resources over a wide area.	Massive impact - Severe impact on Group reputation	5	5A	5B	5C	5D	5E

The Risk Assessment Matrix RAM will be used for the following:

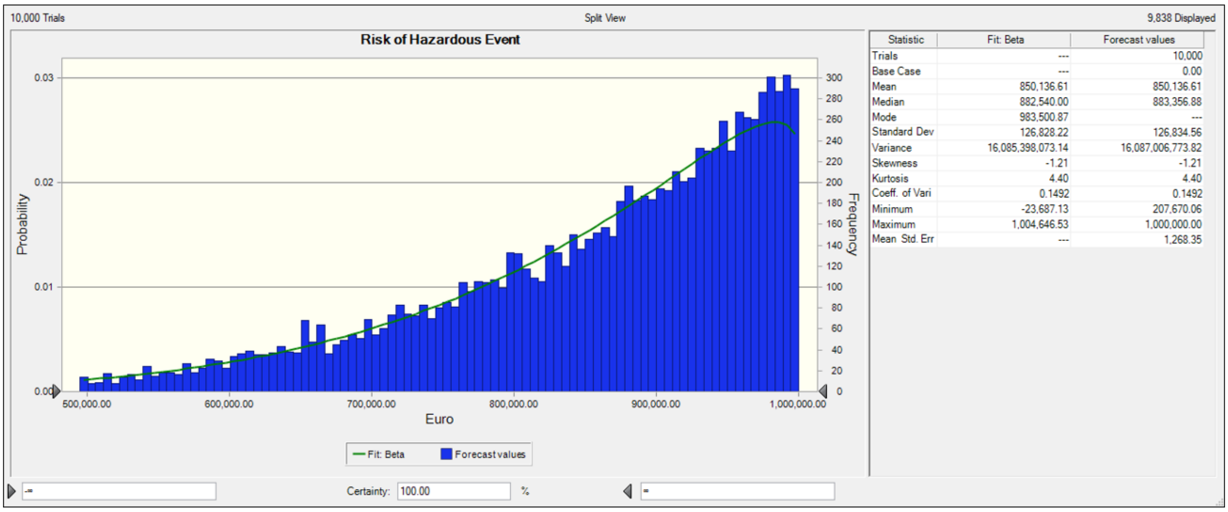
- Risk Registries (Identify Risks)
- Link to Business Objectives
- Individual Accountable
- Current risk responses
- Action Plan
- Contingency Plan (Mitigation)

EXAMPLE RISK PLAN:

1. Risk Description
2. Review Link to Business Objectives (Corporate and Operations);
3. Assign Risk Owner;
4. Review current risk responses
5. Decide Impact Rationale (Harm to People, Asset Damage, Environmental Impact, Reputation Impact)
6. Decide Likelihood Rationale;
7. Decide Acceptance Level (Tolerable, Actively Manage, Unacceptable);
8. Create Action Plan;

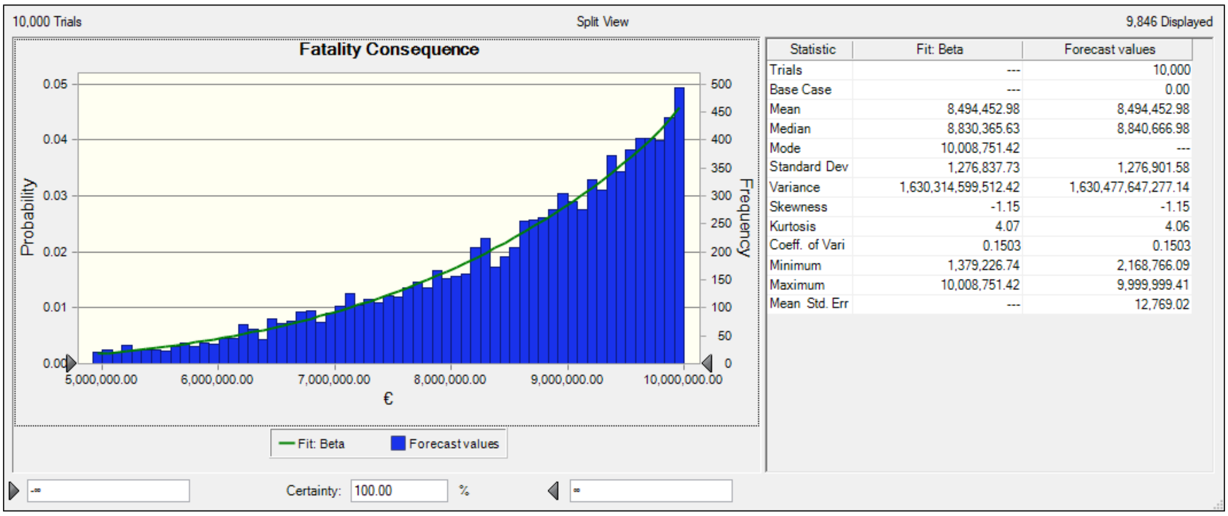
Create Contingency Plan;

Figure D.2: Risk Assessment Matrix



Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	0.00
Mean	850,136.61	850,136.61
Median	882,540.00	883,356.88
Mode	983,500.87	---
Standard Dev	126,828.22	126,834.56
Variance	16,085,398,073.14	16,087,006,773.82
Skewness	-1.21	-1.21
Kurtosis	4.40	4.40
Coeff. of Vari	0.1492	0.1492
Minimum	-23,687.13	207,670.06
Maximum	1,004,646.53	1,000,000.00
Mean Std. Err	---	1,268.35

Figure D.3: Risk of Hazardous Event - Accident

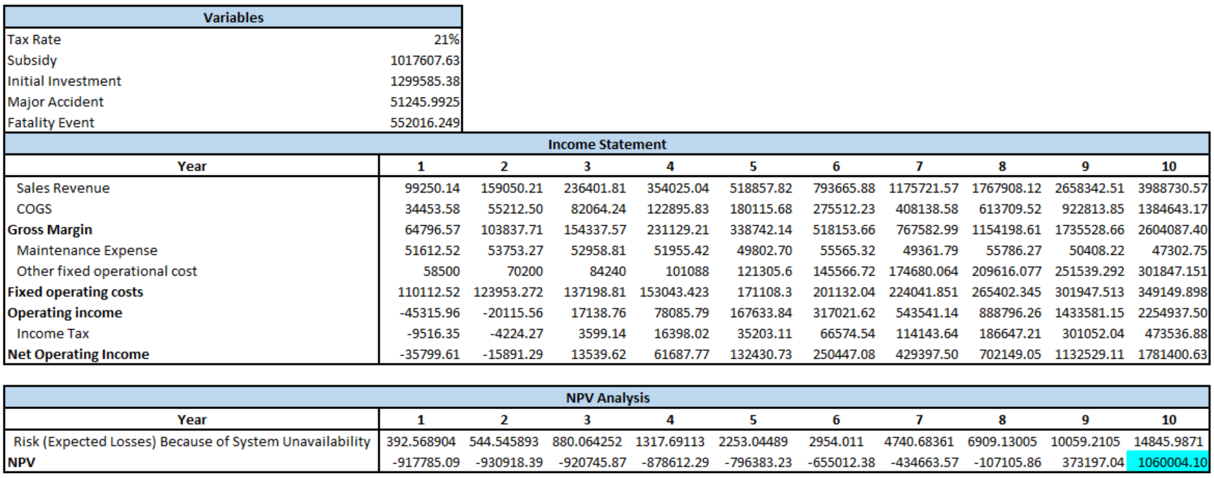


Statistic	Fit: Beta	Forecast values
Trials	---	10,000
Base Case	---	0.00
Mean	8,494,452.98	8,494,452.98
Median	8,830,365.63	8,840,666.98
Mode	10,008,751.42	---
Standard Dev	1,276,837.73	1,276,901.58
Variance	1,630,314,599,512.42	1,630,477,647,277.14
Skewness	-1.15	-1.15
Kurtosis	4.07	4.06
Coeff. of Vari	0.1503	0.1503
Minimum	1,379,226.74	2,168,766.09
Maximum	10,008,751.42	9,999,999.41
Mean Std. Err	---	12,769.02

Figure D.4: Risk of Hazardous Event - Fatality/Permanent Shut Down

E

Techno-economic Analysis Output for 10 Years



Variables	
Tax Rate	21%
Subsidy	1017607.63
Initial Investment	1299585.38
Major Accident	51245.9925
Fatality Event	552016.249

Income Statement

Year	1	2	3	4	5	6	7	8	9	10
Sales Revenue	99250.14	159050.21	236401.81	354025.04	518857.82	793665.88	1175721.57	1767908.12	2658342.51	3988730.57
COGS	34453.58	55212.50	82064.24	122895.83	180115.68	275512.23	408138.58	613709.52	922813.85	1384643.17
Gross Margin	64796.57	103837.71	154337.57	231129.21	338742.14	518153.66	767582.99	1154198.61	1735528.66	2604087.40
Maintenance Expense	51612.52	53753.27	52958.81	51955.42	49802.70	55565.32	49361.79	55786.27	50408.22	47302.75
Other fixed operational cost	58500	70200	84240	101088	121305.6	145566.72	174680.064	209616.077	251539.292	301847.151
Fixed operating costs	110112.52	123953.272	137198.81	153043.423	171108.3	201132.04	224041.851	265402.345	301947.513	349149.898
Operating income	-45315.96	-20115.56	17138.76	78085.79	167633.84	317021.62	543541.14	888796.26	1433581.15	2254937.50
Income Tax	-9516.35	-4224.27	3599.14	16398.02	35203.11	66574.54	114143.64	186647.21	301052.04	473536.88
Net Operating Income	-35799.61	-15891.29	13539.62	61687.77	132430.73	250447.08	429397.50	702149.05	1132529.11	1781400.63

NPV Analysis

Year	1	2	3	4	5	6	7	8	9	10
Risk (Expected Losses) Because of System Unavailability	392.568904	544.545893	880.064252	1317.69113	2253.04489	2954.011	4740.68361	6909.13005	10059.2105	14845.9871
NPV	-917785.09	-930918.39	-920745.87	-878612.29	-796383.23	-655012.38	-434663.57	-107105.86	373197.04	1060004.10

Figure E.1: Income Statement