



Failure Modes and Effects Analysis of Hydrogen in Gas Turbines

Versão final após defesa

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Dissertação para obtenção do Grau de Mestre em
Engenharia Aeronáutica
(mestrado integrado)

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Julho de 2025

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Acknowledgments

Firstly, I would like to express my sincere gratitude to my advisor, Dr. Francisco Brojo, for his continuous guidance, insightful feedback, and for generously sharing his knowledge. I am especially thankful that he agreed to be part of this final journey and supported me throughout the process of writing my dissertation.

I am also grateful to the faculty of the Department of Aerospace Sciences at the University of Beira Interior for their continuous support and encouragement. I extend my appreciation to all the professors who accompanied me throughout my bachelor's and master's degrees, always willing to help and teach to the best of their abilities.

Special thanks to all my friends for their support and motivation during the most difficult and stressful moments of the course, especially during long study sessions.

Finally, and most importantly, I am deeply grateful to my parents and brother for believing in me and supporting me throughout my life and every decision I have made.

Resumo

Em 2020, as turbinas a gás foram responsáveis por produzir 22% da procura global de eletricidade. Com a crescente necessidade de descarbonização para um futuro mais sustentável, o hidrogénio surge como uma alternativa promissora aos combustíveis convencionais nas turbinas a gás. Dessa forma, esforços significativos têm sido direcionados para a adaptação de turbinas existentes ou o desenvolvimento de novos modelos capazes de operar com hidrogénio. No entanto, esta transição introduz riscos e desafios de segurança, tornando essencial a avaliação e mitigação de potenciais perigos associados ao armazenamento e combustão do hidrogénio.

A Análise de Modos de Falha e Efeitos (Failure Modes and Effects Analysis) é uma ferramenta consolidada de avaliação de riscos, utilizada para identificar e analisar potenciais falhas em sistemas com base na sua probabilidade, deteção e severidade. O processo de FMEA normalmente segue sete etapas principais, desde a análise do sistema até à mitigação e comunicação dos riscos. Este trabalho aplica a metodologia FMEA ao uso de hidrogénio em turbinas a gás, garantindo uma operação mais segura e eficiente.

O estudo identifica riscos críticos relacionados com o armazenamento e combustão do hidrogénio, como fugas, mau funcionamento de componentes devido à baixa temperatura, extinção de chama (flame-out) e temperaturas excessivas na turbina e no compressor. Além disso, são propostas estratégias para mitigar estes riscos. Pesquisas futuras deverão concentrar-se na validação dessas estratégias em turbinas operacionais e na otimização do modelo FMEA para acompanhar os avanços tecnológicos do hidrogénio. Este estudo contribui para a integração segura do hidrogénio em sistemas de turbinas a gás, promovendo um futuro energético mais sustentável e fiável.

Palavras-chave

Hidrogénio; Hidógeno Líquido; Turbinas de Gás; Armazenamento de Hidrogénio Líquido; FMEA; Análise de Modos de Falha e Efeitos

Abstract

In 2020, gas turbines generated 22% of global electricity demand. As the world focuses on decarbonization for a sustainable future, hydrogen has emerged as a leading alternative to conventional fuels in gas turbines. Consequently, significant efforts are underway to adapt existing turbines or develop new ones capable of burning hydrogen, presenting new risks and safety concerns. Therefore, it is essential to evaluate and mitigate potential hazards associated with hydrogen combustion in turbines.

Failure Modes and Effects Analysis (FMEA) is a proven risk assessment tool that identifies and evaluates potential failure modes based on their occurrence, detection, and severity. The FMEA process typically involves seven key steps, ranging from system analysis to failure analysis, risk mitigation, and communication. This dissertation applies FMEA to the use of hydrogen in gas turbines, aiming to ensure safe and efficient utilization of hydrogen as an energy source.

The study identifies key risks related to hydrogen storage and combustion, including hydrogen leakage, malfunctions due to low temperatures, flame-out, and excessive temperatures in the turbine and compressor. It then proposes strategies to mitigate these risks. Future research will focus on validating these mitigation measures in operational turbines and refining the FMEA framework to accommodate advancements in hydrogen technology. This work aims to support the safe integration of hydrogen into gas turbine systems, contributing to a more sustainable and reliable energy future.

Keywords

Hydrogen; Liquid Hydrogen; Gas Turbines; Liquid Hydrogen Storage; FMEA; Failure Modes and Effects Analysis

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List of Abbreviations

FMEA	Failure Modes and Effects Analysis
UNFCCC	United Nations Framework Convention on Climate Change
IATA	International Air Transport Association
RPN	Risk Priority Number
STP	Standard Temperature and Pressure
NO _x	Nitrogen Oxides
BWB	Blended Wing Body
GTPPS	Gas Turbine Power Plant System
LH ₂	Liquid Hydrogen
FRPN	Fuzzy Risk Priority Number
MF	Membership Function
GH ₂	Gaseous Hydrogen
NDT	Non-Destructive Testing
HSI	Hot Section Inspection
TBO	Time Between Overhaul
MRT	Mandatory Replacement Time
DFMEA	Design FMEA
PFMEA	Process FMEA
FFMEA	Functional FMEA
SFMEA	System FMEA
AIAG	Automotive Industry Action Group
SAE	Society of Automotive Engineers
PFD	Process Flow Diagram
PCP	Process Control Plan
TBC	Thermal Barrier Coatings
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
ORC	Organic Rankine Cycle
CAES	Compressed Air Energy Storage

Chapter 1

Introduction

Sustainability is a rapidly growing field, and research into more sustainable fuels and energy sources is advancing at a fast pace. Greenhouse gas emissions, which cause global degradation and make the existence of life as we know it today impossible, are distributed across different sectors, with the energy sector being the largest contributor [1]. This is primarily because most of the world's energy is still derived from fossil fuel combustion, such as coal in coal-fired power plants and natural gas in gas turbines. These fuels are also widely used in industries like shipping and aviation, which contribute significantly to greenhouse gas emissions. However, over the last 10 to 15 years, this trend has begun to shift, with renewable energy sources growing at a faster rate than fossil fuel-based energy sources [2][3].

The future of reducing greenhouse gas emissions looks promising, with major organizations setting ambitious targets. The United Nations Framework Convention on Climate Change (UNFCCC) established the Paris Agreement, which aims for a greenhouse gas reduction of no less than 55% by 2030 [4]. Meanwhile, the International Air Transport Association (IATA) has gone even further, setting a goal of net-zero carbon emissions by 2050 [5]. These ambitious goals aim to create a more sustainable world, and hydrogen — particularly green hydrogen — emerges as a promising solution to replace non-renewable fuels and significantly reduce greenhouse gas emissions.

Hydrogen combustion, whether in gas turbines or other applications, does not release carbon dioxide, producing only water vapor as a byproduct. This alone gives hydrogen a major advantage over fuels like natural gas and coal. However, hydrogen can be produced through a more sustainable method: water electrolysis, leading to what is known as green hydrogen [6][7].

Given this, further research on hydrogen as a primary energy source and its practical implementation for a more sustainable world is crucial. Additionally, analyzing the failure modes and effects associated with hydrogen use is essential. In particular, conducting a FMEA of hydrogen combustion in gas turbines is of great importance before large-scale implementation, as it helps identify and mitigate risks related to hydrogen combustion. The objective of this dissertation is to perform a FMEA of hydrogen combustion in gas turbines, with a specific focus in gas turbines. These analyses will help identify potential risks and failures associated with hydrogen combustion in gas turbines by evaluating severity, occurrence, and detection of failure modes. Additionally, this study will propose

strategies for improving the quality, safety, and reliability of hydrogen as a primary fuel for gas turbines, ultimately contributing to a cleaner and more sustainable world.

As will be explored in more depth, FMEA is divided into four main categories, each with its own significance and application: Design FMEA, Process FMEA, Service FMEA and Systems FMEA.

Each type follows a structured seven-step process. However, this dissertation will focus on the most relevant and commonly analyzed FMEA types in the context of hydrogen combustion in gas turbines.

The present dissertation is organized into five chapters: Introduction, Literature Review, Methodology, Results and Analysis, and Conclusion.

The Introduction chapter provides a brief overview of the dissertation, including its main objective, the approach taken to conduct the study, and the motivation behind this research and its theme.

The Literature Review offers an explanation of the three main concepts addressed in this dissertation: Failure Modes and Effects Analysis (FMEA), Gas Turbines, and Hydrogen. This chapter explores their definitions, characteristics, and applications while highlighting their interconnections and relevance to the study.

The Methodology chapter describes the approach and rationale behind the two methodologies used to conduct the FMEA of hydrogen in gas turbines. This section also explains how the results were obtained, which are subsequently presented, analyzed, and discussed in Chapter Four: Results and Analysis.

In Results and Analysis, the findings of the study are examined in detail. Additionally, this chapter includes suggestions and recommendations for future research that the author considers relevant and important.

Finally, the Conclusion summarizes the main outcomes of this study, providing a concise overview of the results and their potential applications.

Chapter 2

Literature Review

2.1 FMEA

In 1940s-50s, in order to improve reliability and safety of the U.S. military assets, U.S. military create a method called Failure Mode and Effects Analysis. Since that, it has been growing across other industries [8]. Currently, competition between companies has been a driving force behind the evolution of products over the years. It is through competition that innovation thrives, leading to the creation of new products and research every day. To remain competitive, effective risk management has become essential.

Risk analysis plays a critical role in this process, aiming to answer two fundamental questions:

1. What can go wrong?
2. If something does go wrong, what is the probability of it happening, and what are the consequences?

Some more questions can be added such as:

- How can failure be prevented?
- What insights can be applied to current and future scenarios?

Historically, risk management focuses on identifying problems after they occur. However, modern approaches emphasize prevention, which justifies the emergence of tools like Failure Mode and Effect Analysis (FMEA).

FMEA is a structured and systematic method for evaluating systems, designs, processes, or services. It identifies, defines, and eliminates potential failures, analyzes their causes, and effects, and enables organizations to implement measures to prevent failures before the product or service reaches the customer. This approach helps eliminate waste, reduce unreliability and prevention of problems, thereby ensuring better quality, durability, and reliability.

FMEA is applied in the following scenarios:

- When new systems, designs, products, processes, or services are being developed;
- When existing systems, designs, products, processes, or services are about to undergo changes, regardless of the reason;
- When new applications are identified for the existing conditions of systems, designs, products, processes, or services;
- When improvements are planned for existing systems, designs, products, processes, or services;

- When quality and safety standards are imposed whether by regulatory bodies or through customer requirements to ensure compliance and demonstrate product reliability;
- When scaling production is planned to ensure the manufacturing process can reliably produce high volumes without defects;

To define the priority of failures are used three components:

- Occurrence (O) represents the frequency of failure;
- Severity (S) which is the effects of failure;
- Detection (D) that corresponds to the ability to detect failure.

Each component is assigned a numerical value based on qualitative or quantitative guidelines. The risk assessment is determined by the Risk Priority Number (RPN).

$$RPN = S \times O \times D \quad (2.1)$$

When all items considered have been analyzed and each one has his correspondent RPN, improvement actions are planned and executed to reduce the RPN to acceptable levels. Is important to note that, RPN by itself does not have inherent meaning or value, however it is used to rank and prioritize, in a decrescent order, potential failures, however the strategies of prioritization depend on the context, due to priority can focus on severity or occurrence. Beyond that, all FMEA must include too a recommended action to aim reduce RPN, which the most common one's are:

- No action at this time;
- Add built-in detection devices;
- Provide alternatives to the system;
- Adding a redundant subsystem [9][10].

The FMEA is complete only when the system, design, product or service is finalized or discontinued, and it can be reviewed, evaluated or improved as long as product lifecycle. Although FMEA may not anticipate every possible failure, it significantly contributes to reducing the severity and likelihood of risks. Its main benefits include:

- Improved reliability, safety, and quality of both product and process;
- Early risk identification and mitigation to prevent potential failures;
- Documentation of insights for current and future application;
- Reduced costs and issues throughout the product lifecycle;
- Enhanced customer satisfaction [9][10].

2.1.1 Approaches and Standards in the Application of FMEA

Given the critical importance of the FMEA approach in ensuring safety, reliability, high quality, and cost-effectiveness, the proper performance of its conduction is crucial. Therefore, the effectiveness and efficiency of FMEA execution can be significantly enhanced through the use of modern tools and technologies, such as:

- FMEA Software – These tools offer structured templates for documenting failure modes, causes, and effects. They can be tailored to the specific needs of a project or organization, enabling automation and effective management of large-scale data analysis;
- CAD and Simulation Tools – Used to model and analyze complex systems or products, these tools assist in identifying potential failure modes and allow the testing of different scenarios and mitigation strategies through simulations;
- Statistical Analysis Tools – These tools help analyze data from various sources, such as production lines, quality systems, and customer feedback. They assist in detecting patterns and anomalies, as well as evaluating the effectiveness of failure prevention measures;
- IoT and Sensor Technology – Enable the collection of real-time performance data from systems or products, improving the accuracy of identifying failure modes and their associated risks;
- Collaborative Tools – Platforms that facilitate real-time communication and information sharing among teams, enhancing collaboration and reducing the need for extended meetings [8].

However, several common mistakes can compromise the effectiveness of the FMEA process, such as:

- Delaying FMEA reduces its effectiveness;
- Lack of accountability, and necessary actions can be missed or delayed;
- Treating FMEA as a one-time task;
- Poor documentation can lead to repeated issues and loss of valuable insights;
- Poor root cause identification, leading to ineffective solutions and recurring defects.

The complexity of the final product, as a whole, implies that during its construction some steps are attained and consequently the 5 main FMEA types are:

1. Design FMEA (DFMEA);
2. Process FMEA (PFMEA);
3. Functional FMEA (FFMEA); System FMEA (SFMEA);
4. Software FMEA [9][10].

In addition, several standards provide essential guidance for the correct application of the FMEA methodology. These standards are widely recognized and ensure consistency, reliability, and quality throughout the FMEA process. The most notable ones include:

- AIAG-VDA FMEA Handbook – a unified framework developed by the Automotive Industry Action Group (AIAG) and the German Association of the Automotive Industry (VDA), widely used by automotive manufacturers and suppliers worldwide;
- ISO 9001:2015 quality management systems – specifies requirements for quality management systems, including risk-based thinking and the use of tools like FMEA to identify and address risks to product and process quality;
- IEC 60812:2018 – provides comprehensive guidance on performing FMEA for various systems, including electrical and electronic systems;
- MIL-STD-1629A – a standard issued by the U.S. Department of Defense outlining the FMEA process specifically for military and defense applications;
- SAE ARP5580 – a guideline developed by the Society of Automotive Engineers (SAE) for implementing FMEA in aerospace systems [8].

While other types of FMEAs do exist, the ones discussed below are the most commonly applied and widely referenced in practice. Therefore, a deeper understanding is essential, and an explanation of each is provided in the following sections:

1. Design FMEA – applied during the product design stage to identify, verify, and mitigate potential failures before manufacturing and deployment. It involves a systematic breakdown of the system, analyzing each component to assess risks and improve reliability;
2. Process FMEA – applied to processes (as opposed to products, as with DFMEAs) to analyze and ensure process control objectives. Unlike DFMEAs, PFMEAs use a worksheet that outlines each step of the process rather than product components. PFMEAs are often used in conjunction with Process Flow Diagrams (PFDs) and Process Control Plans (PCPs) to provide a complete view of process risks and controls [11].
3. Functional FMEA – Also known as System FMEA, this method differs from related tools such as DFMEA and PFMEA, which focus on identifying corrective actions. The primary purpose of Functional FMEA is to proactively avoid failures by identifying and analyzing potential functional failure modes, their effects, and causes. Additionally, it supports the discovery of new system functionalities or design ideas that can be integrated into the product. This proactive approach helps create more robust and failure-resistant solutions for the end user [12].

4. Software FMEA – A subtype of Design FMEA, this method analyzes software elements, focusing on potential software deficiencies. While it can be integrated within a System FMEA, a separate analysis is often recommended for complex software systems. Its primary focus is on software functions, aiming to improve design robustness, reliability, and safety during the product’s useful life [13].

2.1.2 FMEA Steps

FMEA process results by the collaboration of members from diversified functions and is commonly defined in seven steps that are distinguished here (see fig. 2.1):

1. Planning and preparation, where the team members clarify the objective and scope, sets boundaries and lays the groundwork for FMEA process;
 2. Structure analysis, which clarifies the system structure, and the boundaries configured are analyzed to define which will be part of FMEA. Block diagram, boundary diagram or other visualization tools are used too;
 3. Function analysis, analyze each system element for their corresponding requirements and functions, following the process, product and criteria for evaluating the performance of function are explored;
 4. Failure analysis, establishes a failure chain through, failure mode, failure effect and failure cause. Loss of function, degradation function, exceeding function are some of the potential failure modes;
 5. Risk analysis, is where the team analyzes causes and prioritizes them based on Severity, Occurrence, and Detection (see tables 3.1, 3.2, 3.6, 3.7, 3.8). The RPN is calculated, and a ranking of potential failures and action priorities is established. Instead of the old and usual kind of FMEA where just the RPN value counts, the new FMEA Method, also called as Action Priority, use the combination between severity, occurrence, and detection, followed by this order of importance, where a action priority is ranked in Priority High, Medium, and Low.
 - Priority High – Action is required to enhance prevention and/or detection controls, or to provide strong justification for maintaining current controls.
 - Priority Medium – Action should be taken to improve controls or justify existing measures.
 - Priority Low – Action could be considered to enhance controls, though it is not mandatory.
- Note that risks with severity score of 7 or above are predominately Priority High.
6. Optimization, is like an iterative process until an acceptable risk, that develop a procedure to mitigate risks and evaluate the effectiveness of preventive and detective

actions to optimize. Subsequent to actions implementation is made a review and risks is rescored;

7. Results documentation, is made a report that contain a summary of field, identification of high-risk failures, the procedure taken and is efficacy to mitigate risks and proposes for current and future processes [10][14].

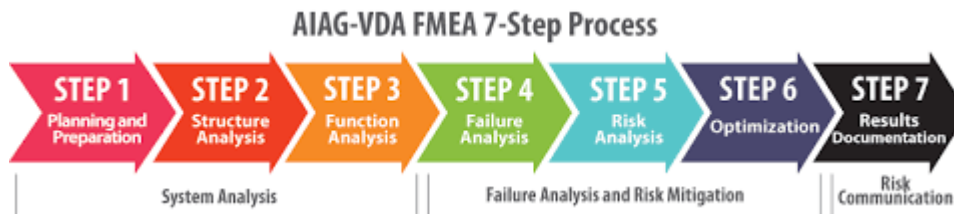


Figure 2.1 – 7 Steps of FMEA Process [10]

In summary, through the proper application of FMEA steps, adherence to relevant standards, and the use of modern tools, it is possible to conduct an effective and efficient FMEA. This enables the production – whether on a small or large scale – of competitive products that meet customer needs, enhance company profitability, and strengthen the brand image by delivering high-quality, cost-effective solutions.

2.2 Gas Turbine

The modern gas turbine has evolved through extensive research, development, and numerous patents. The theoretical principles behind gas turbines were established long before advancements in fluid dynamics and materials made them viable for practical use. Over time, many designs were proposed, but only a few were constructed, and those that were built initially produced minimal power output. The first successful gas turbine was designed by the French engineer Stolze, and testing began in 1900. Since then, continuous improvements have been made to meet growing energy demands [15].

Globally, energy generation has more than doubled from 1990 to 2018, and projections indicate a 50% increase over the next two decades. Gas turbines play a significant role in energy production and aviation, where they power most large commercial and military aircraft.

2.2.1 Fundamentals of Gas Turbines

To understand how gas turbines function, it is essential to define what they are. A gas turbine is a continuous-flow combustion engine, named for its use of hot, pressurized gases in the combustion process. All gas turbines share three primary components, typically arranged in the following sequence: a compressor, a combustion chamber, and a turbine. The compressor and turbine are connected by a shaft, and both can have axial or radial

configurations. Additionally, some gas turbine engines include a turbofan to enhance performance [15].

The centrifugal configuration of the compressor is known for its robustness, lower cost, and a compression ratio typically limited to 7:1. It is commonly found in smaller, modern gas turbines or in earlier models. In contrast, the axial configuration is more efficient and is used in the majority of contemporary gas turbines. An axial compressor consists of multiple stages, each containing a set of rotating blades and stationary blades, which work together to compress the gas flow. Some compressors combine both axial and centrifugal configurations. While the design and operation of axial turbines are simpler, as the flow expands within a favorable pressure gradient, they require fewer stages compared to centrifugal compressors. Consequently, axial turbines are more commonly used. The primary challenge in the production of these turbines lies in selecting materials that can withstand the high temperatures to which they are subjected. Similar to compressors and turbines, combustion chambers also have three common geometric configurations: cans, annular, and can-annular. The can configuration consists of individual cylindrical chambers arranged circumferentially, while the annular configuration features a single cylindrical structure with both an inner and outer shroud. The can-annular configuration is a combination of the can and annular designs [16].

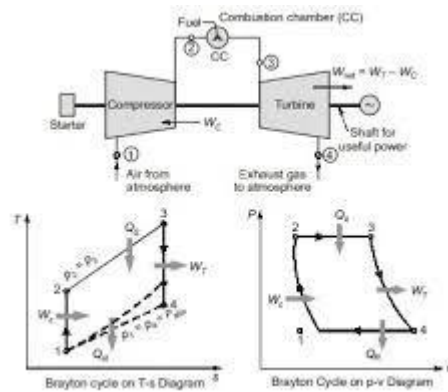


Figure 2.2 – Simple open gas turbine cycle based on the Brayton cycle [17]

The most basic and conventional gas turbines operate with air as the working fluid and follow the Brayton thermodynamic cycle – Figure 2.2. While the Brayton cycle is theoretically a closed system, in practical applications, it serves as a useful approximation for understanding gas turbine operations. The cycle begins with air compression, followed by the injection of fuel – such as natural gas, jet fuel, or hydrogen – which acts as the chemical energy source. The fuel is then ignited, generating high-temperature, high-pressure gases that expand through the turbine, producing mechanical energy to drive the compressor. Any excess energy is released through the exhaust gases, which can be used to

power an additional turbine connected to an electrical generator, pump, or propeller in aircraft applications.

There are several types of gas turbines, including regenerative gas turbines, steam-injected gas turbines, and intercooler-equipped gas turbines. While these advanced configurations offer improved efficiency compared to simpler designs, their implementation can be challenging in certain applications, such as aviation [18].

Compared to other types of power engines, gas turbines offer several advantages, including:

- High power-to-weight and power-to-size ratios;
- Long operational life and relatively low maintenance costs, thanks to the reduced number of moving parts;
- Ability to reach peak output within minutes;
- Capability to run on a wide variety of fuels;
- Use of atmospheric air as the working fluid, eliminating the need for a coolant;
- Very low levels of combustion-related pollution [16].

2.2.2 The Future of Gas Turbines

Even though modern gas turbines achieve a maximum efficiency of approximately 63%, they remain widely used due to their reliability and versatility. The overall efficiency of a gas turbine depends on factors such as the compression ratio, turbine inlet temperature, ambient conditions, fuel properties, and cooling technologies [20].

Significant research investments focus on improving efficiency, productivity and sustainability through:

- Advanced materials and coatings – Gas turbines operate at extremely high temperatures, often exceeding 1500°C, which traditional materials cannot withstand without degrading. This leads to reduced efficiency and increased maintenance requirements. To address this, advanced materials such as nickel-based superalloys and thermal barrier coatings (TBCs) are employed. These materials enhance the durability and thermal resistance of turbine components, thereby improving performance and reducing maintenance costs;
- Aerodynamics and blade designs – The high thermal loads experienced by turbine blades necessitate effective cooling solutions. Advanced cooling techniques, such as film cooling and internal cooling channels, are used to protect blade integrity. Additionally, the optimization of blade geometry through computational fluid dynamics (CFD) and additive manufacturing enables improved gas flow, reduced energy losses, and enhanced overall turbine efficiency;
- Additive manufacturing – Additive manufacturing enables the production of complex and highly precise components that are difficult or impossible to fabricate

using traditional methods. This technology allows for the rapid design, testing, and refinement of parts, significantly accelerating development cycles. Furthermore, it reduces the need for maintaining large inventories of spare parts, as components can be produced on demand;

- Digital twins and predictive maintenance – A digital twin is a virtual simulation of a physical gas turbine, capable of analyzing performance in real-time under various operational conditions. It enables early detection of potential failures and performance issues. When combined with predictive maintenance strategies—powered by real-time sensor data and AI algorithms—this approach helps to extend component lifespan, reduce downtime, and maintain turbines operating at peak performance;
- Combustion technology – Innovations in combustion systems aim to improve efficiency while reducing environmental impact. Low-NO_x combustors use advanced mixing techniques and lean-burn strategies to minimize nitrogen oxide emissions. Additionally, the use of alternative fuels such as hydrogen, which produces only water vapor during combustion, is gaining momentum due to its potential to eliminate CO₂ emissions;
- Exhaust gas recovery – The recovery and utilization of waste heat from turbine exhaust gases can significantly enhance system efficiency. Combined Heat and Power (CHP) systems use this heat to produce steam that drives a steam turbine, generating additional electricity. Similarly, the Organic Rankine Cycle (ORC) uses low-grade heat and organic fluids with lower boiling points than water to generate mechanical energy, particularly effective in small to medium-scale turbines;
- Compressed Air Energy Storage (CAES) – CAES systems compress air using excess electricity and store it in underground caverns or tanks. During peak demand, the compressed air is released, typically heated using a small amount of natural gas, and fed into a gas turbine. This process reduces the fuel required to reach operational temperatures and increases overall energy efficiency;
- Integration of renewable energy – Hybrid systems that combine gas turbines with renewable sources like solar and wind energy enhance operational flexibility and efficiency. These systems can balance the intermittency of renewables. Furthermore, energy storage solutions allow excess energy generated during low-demand periods to be stored and released when demand rises, optimizing overall system productivity and reliability [19][21].

As energy demand continues to rise, gas turbines will remain a critical component of power generation. However, technological advancements are essential to address emerging

challenges, including climate change, energy security, and decarbonization. The key trends shaping the future of gas turbines include:

- World demographic
- Energy security and reliance
- Decarbonization
- Customer profiles

In terms of decarbonization, the ability to use hydrogen as a fuel presents a promising solution. A 100% hydrogen combustion process produces no carbon emissions, making it an attractive option for reducing the environmental impact of gas turbines.[15]. Several initiatives are currently exploring hydrogen combustion in gas turbines, with ongoing research focusing on how to effectively integrate hydrogen into power generation and aviation systems.

2.3 Hydrogen as Fuel

The increasing global demand for energy and the unsustainable reliance on hydrocarbon fuels have highlighted the need for alternative energy sources. Hydrogen has emerged as a key player in this transition, offering a potential solution for decarbonizing energy production [22]. The combustion of hydrogen produces only water vapor (theoretically), making it a promising option for significantly reducing carbon dioxide emissions, particularly in achieving decarbonization goals, if the hydrogen used is 100% green [7][23]. However, to achieve optimal hydrogen combustion, certain modifications to existing engines are necessary to prevent operational issues. Some changes include:

- Ignition system – Modifications are necessary to prevent uncontrolled ignition. This includes adjusting the electrical resistance of the ignition cable or ensuring the system is properly grounded. Hydrogen mixtures require a higher secondary ignition voltage compared to hydrocarbon fuels—likely due to the lower ion concentration in hydrogen flames – so a high-voltage output ignition system is recommended. Alternatively, reducing the spark plug gap can lower the required ignition voltage;
- Injection system: Precise, timed injection is essential for efficient hydrogen combustion. One option is port injection, with timing set to allow an initial air cooling phase and ensure all hydrogen is inducted before the intake valve closes. However, some studies suggest timing may not strongly influence backfire or surface ignition. Another option is direct injection during the compression stroke, which requires high-flow injectors (4–6 g/s at 100 bar). In port fuel injection systems, multiple injectors can help meet flow demands. Timed injection also reduces unburned fuel in the intake manifold, lowering backfire risk.

- Valve seats and injectors: Due to hydrogen’s very low lubricating properties, appropriate valve seat materials must be carefully selected to prevent excessive wear. The design of injectors must also account for hydrogen’s lack of lubrication. While this issue is common to other dry gaseous fuels like natural gas, it is often more critical in hydrogen systems, as hydrogen compressors typically use tighter tolerances to minimize leakage and do not introduce oil mist, unlike natural gas compressors.
- Materials: Hydrogen can degrade the mechanical properties of metals like steel and iron, primarily through embrittlement, which reduces ductility and fracture strength. This makes material selection critical for hydrogen systems. Some materials like aluminum, brass, and copper alloys show better compatibility, while high-strength steels, titanium, and nickel alloys are more susceptible to hydrogen embrittlement [22].

Currently, 96% of hydrogen production relies on fossil fuels like natural gas, coal, and oil. While this remains the most practical and cost-effective method today, it is not sustainable in the long term. The remaining 4% is produced through water electrolysis using renewable energy, a process known as green hydrogen. Although this method is carbon-neutral, it is currently more expensive due to the high energy cost of electrolysis. Biohydrogen, produced via biological and microbial methods, represents a promising future alternative, though it requires more research to become commercially viable [24].

2.3.1 Features of Hydrogen

Table 2.1 – Present the properties of several fuels [25]

Properties	Hydrogen	Methane	Gasoline	Diesel
Density [kg/m ³] (1 bar; 273K)	0.089	0.72	730-780	830
Molar mass [kg/kmol]	2.016	16.043	110	170
Flammability limits in air [vol%]	4-76	5.3-15	1-76	0.6-5.5
Low heating value [MJ/kg] (1 bar; 273K)	119.9	45.8	43.9	42.5

Table 2.1 – Present the properties of several fuels (cont.) [25]

Low calorific value [MJ/m ³] (1 bar; 273K)	10.7	33	33000	35000
Laminar flame speed in air [m/s] (1 bar; 273K; stoichiometric)	1.85	0.38	0.37-0.43	0.37-0.43
Stoichiometric coefficient	34.4	17.2	14.7	14.5
Adiabatic flame temperature [K]	2480	2214	2580	2300
Autoignition temperature [K]	853	813	623	523
Minimum ignition energy in air [mJ]	0.02	0.29	0.24	0.24

Hydrogen has several unique properties that give it significant advantages as a potential substitute for fossil fuels. At standard temperature and pressure (STP), hydrogen is colorless, odorless, and tasteless. Due to its very low density, hydrogen burns and spreads easily; however, when liquefied (at temperatures below -253°C), its volume decreases by a factor of 700. Hydrogen has the highest specific energy of any fuel and superior flame stability, which makes it a strong candidate for both industrial and transportation applications, including in space exploration. Hydrogen ignition requires extremely low energy, has the potential to ignite over a broad range of concentrations, and exhibits a significantly higher flame velocity. Additionally, under identical stoichiometric conditions, hydrogen also produces a higher flame temperature [24].

2.3.2 Barriers to Hydrogen Deployment

Despite its promise, hydrogen faces several challenges. As a relatively new fuel, the technologies involved in hydrogen production, storage, and combustion are still in development. This results in high costs, preventing hydrogen from competing with traditional fuels. For instance, hydrogen should have cost about €0.28/kg in 2023 to be competitive with gasoline, but green hydrogen is currently (2024) priced between €2.10 and €6.81/kg (Cambio exchange rate as of April 2, 2025).

As noted above, flame stability is a challenge in hydrogen combustion. However, it can be addressed through modifications to gas turbines.

Another challenge arises from hydrogen combustion, which can lead to the formation of nitrogen oxides (NO_x) at high temperatures. To mitigate this, various fuel combinations and rich burn strategies are being explored for use in hydrogen internal combustion engines [22][24].

The low density of hydrogen presents another hurdle, especially in aviation. Liquid hydrogen has a lower energy density by volume compared to jet fuel (JP-8), requiring larger storage volumes even in its liquid form. Research into aircraft design, such as the use of Blended Wing Body (BWB) configurations, is ongoing to address this issue.

Although hydrogen presents several challenges, from production to combustion, it has the potential to emerge as a leading choice for a sustainable and clean energy source. Key areas for future research include enhancing the efficiency and sustainability of hydrogen production, particularly through the development of more cost-effective electrolysis methods utilizing renewable energy sources. Research is also needed in hydrogen storage and infrastructure to improve its transportation, distribution, and storage systems. Consequently, the establishment of safety standards, technologies, and regulations is essential. Additionally, further study is required to fully understand hydrogen combustion mechanisms and optimize combustion processes before hydrogen can be widely adopted as a primary clean fuel source.

In conclusion, hydrogen offers significant potential for innovation and discovery across various fields, including technologies, techniques, and materials. By addressing these gaps, hydrogen can be produced at a large scale and play a pivotal role in transforming the future of global energy systems and combustion engines [24].

Chapter 3

Methodology

3.1 Methodology

The FMEA study plays a crucial role in the implementation of new technologies, ensuring their safe and secure use for consumers [9]. While hydrogen combustion in gas turbines is a widely discussed topic in the pursuit of zero greenhouse gas emissions, it remains a developing technology that requires thorough risk assessment and mitigation [15][22]. Hydrogen combustion introduces unique challenges that necessitate modifications in gas turbine design compared to conventional turbines that typically burn natural gas or other fossil fuels. These modifications are required due to hydrogen's distinct properties, such as its flammability limits, laminar flame speed, adiabatic flame temperature, and turbulent flame speed. Additionally, adaptations must be made in the design and construction of storage tanks to safely handle hydrogen.

Gas turbine modifications can take two approaches:

- Designing and constructing a new hydrogen-compatible gas turbine from the ground up;
- Converting existing gas turbines to accommodate hydrogen combustion [22][23].

Due to the limited data available for a comprehensive analysis of hydrogen use in gas turbines, this dissertation focuses on two primary topics:

1. FMEA of Hydrogen Storage
2. FMEA of Gas Turbines (Gas Turbine Power Plant System – GTTPPS)

To systematically assess the risks associated with hydrogen storage and its combustion in gas turbines, this study conducts an FMEA analysis, following a structured approach. The methodology is outlined in the accompanying flowchart (see fig. 3.1), detailing each step of the analysis, starting with the FMEA of hydrogen storage followed by FMEA of Gas Turbines.

3.1.1 FMEA of Hydrogen Storage

Due to its low volume, liquid hydrogen (LH₂) appears to be the most suitable state for storage in general. In order of that, the present FMEA will focus on this state, although before his combustion in gas turbines a transformation from liquid to gaseous state is mandatory.

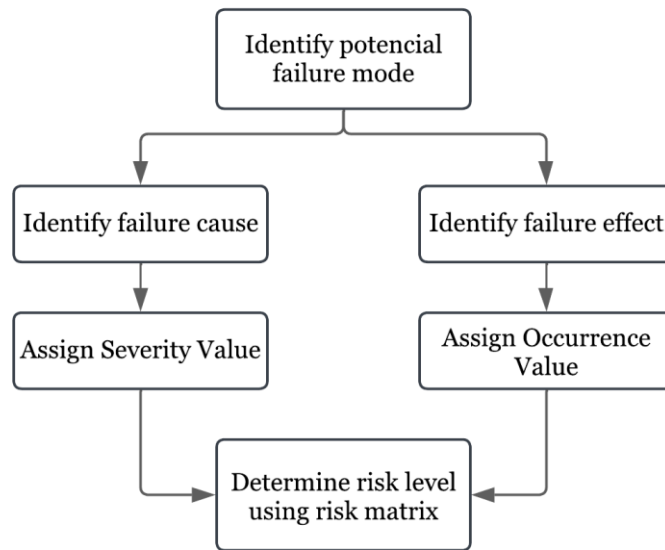


Figure 3.1 – Flowchart of FMEA of LH2 storage

For the FMEA of Hydrogen Storage, only the Severity and Occurrence classifications will be used. The data in this analysis comes from reports and articles based on the HyRAM model from Hydrogen Tools (h2tools), which classifies Severity and Occurrence levels according to the rankings presented in Tables 3.1 and 3.2, respectively, as referenced in articles [26][27][28].

Table 3.1 – Severity Scale [26][27][28]

Severity Level	Criteria
Minor	Failures that do not significantly degrade system performance or functionality
Moderate	Failures that reduce the system's performance level but do not cause complete loss of function
Critical	Failures that render the system inoperable or lead to complete functional failure

Table 3.2 – Occurrence Scale [26][27][28]

Occurrence Level	Criteria	Probability
Low	Failures are frequent or nearly inevitable, occurring repeatedly	More than 1 in 20
Medium	Failures occur occasionally, but not frequently	Between 1 in 80 and 1 in 2000
High	Failures are rare, with a low likelihood of occurrence	< 1 in 15000

A simplified risk matrix is used to rank the most relevant failure modes and risk scenarios that may arise from the identified components of the LH2 storage system. The matrix consists of three levels—high (H), moderate (M), and low (L)—based on the occurrence and severity levels, as shown in Table 3.3.

Table 3.3 – Risk Level Matrix [26]

Risk Level			
Severity Level	Occurrence Level		
	Low	Medium	High
Minor	L	L	M
Moderate	L	M	H
Critical	M	H	H

The identification of potential failure modes is categorized into three levels: Main Systems, Subsystems, and Components, as shown in Figure 3.25. Since each component is part of a larger system, a failure at the component level can impact all broader systems in which it is integrated.

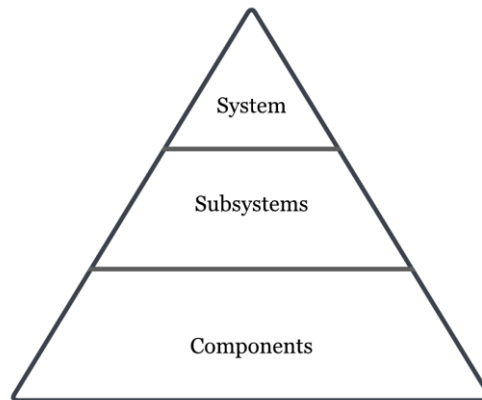


Figure 3.2 – Pyramid of the system hierarchy

The hydrogen storage system is the first major system analyzed and is composed of three subsystems, as shown in Figure 3.3. The primary component, the liquid hydrogen storage tank, has an estimated storage capacity of 800 kg of LH₂. Key safety and monitoring features incorporated into the storage subsystem include maintenance valve (not shown), pressure relief valve, pressure and temperature sensors, and an infrared thermal flame detector and alarm system.

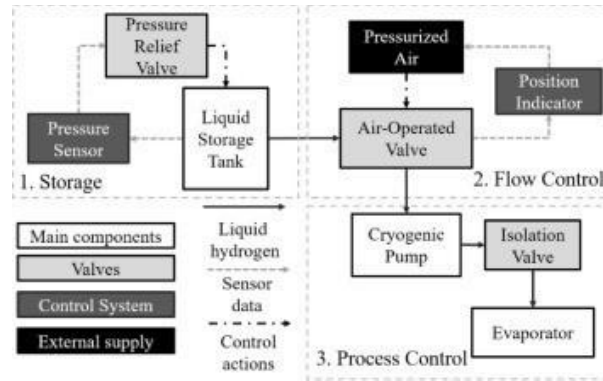


Figure 3.3 – Hydrogen Storage System Overview [26]

The system boundaries start from the storage tank and extend through the distribution network up to the evaporator. However, they do not cover the fuel delivery process, emergency fire cabinet operation, or the provision of external resources such as process air or electricity. The liquid storage tank is connected to a cryogenic pump, via double-walled piping, which ultimately supplies fuel to an ambient air evaporator. An air-operated valve, located between the tank and the pump, regulates the process. All components are essential and enable liquefied hydrogen storage functionality which can be used for various applications, such as gas turbines, due to the transformation of liquid hydrogen into its gaseous phase by the evaporator as shown in Table 3.4.

Table 3.4 – LH₂ storage components and their functions [26][30]

Subsystem	Component	Functional Description
Storage	Liquid storage tank	Storage of liquid hydrogen
	Pressure Sensor	Indicates the internal pressure of the storage tank, includes transmitter
	Pressure Release Valve	Manages controlled venting of gaseous hydrogen to maintain safe pressure levels
Flow Control	Air operated valve	Controls the flow of hydrogen through the system; designed as a spring-return closed-flow valve
	Position Indicator	Controls and indicates open/closed position of FV
	Air	Process air supply
Process Control	Cryogenic Pump	Transport of liquid hydrogen
	Isolation Hand Valve	Isolates flow to system downstream
	Ambient air evaporator	Converts liquid into gaseous hydrogen
	Piping	Liquid and gaseous hydrogen transport

With the fundamental data for the FMEA of LH₂ storage established, the following section presents the FMEA of a gas turbine. Given that hydrogen-powered gas turbines are a relatively recent technology, available data is scarce. However, analyzing a conventional gas turbine provides valuable insights and a broader perspective on the overall system.

3.1.2 FMEA of Gas Turbines

The high power per weight ratio made the gas turbines the most viable option for hydrogen combustion, and consequently can extract, in a more efficient form, the energy provides by hydrogen. Due to the recent and increased demand for hydrogen uses, the enable data is limited so, once again, this analysis will not be 100 accurate because it was done for natural gas (see table 3.5).

For FMEA of Gas Turbines using the Fuzzy Risk Priority Number (FRPN), seems to be the most beneficial form of analysis because the fuzzy approach can handle precise and imprecise information, allows a combination between occurrence, severity and detectability in a more pragmatic form. Finally, each system can vary the risk assessment function. The FMEA of the gas turbine, based on the FRPN approach, follows the flowchart of fig. 3.4:

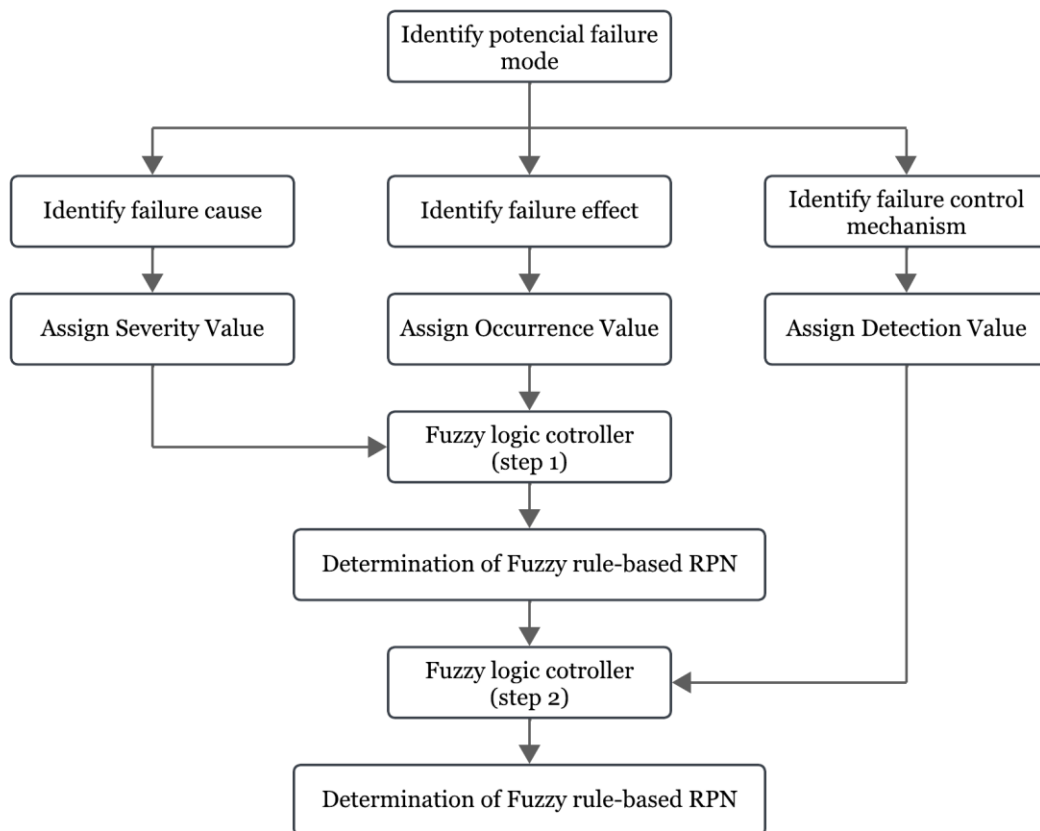


Figure 3.4 – FRPR Process Flowchart

In order to attain an accurate value while maintaining good efficiency, Fuzzy RPN will use an approach with 100 membership functions (MFs). A MF is a curve that maps each point in the input space, also known as the universe of discourse, to a membership value between 0 and 1. The output-axis represents this membership value, and the curve is labeled as μ . The key requirement for any membership function is that it must range between 0 and 1.

Fuzzy sets extend classical sets by assigning membership values to each element. A fuzzy set A in universe of discourse X is defined as ordered pairs: $A = \{x, \mu_A(x) \mid x \in X\}$, where $\mu_A(x)$ is the membership function. Linear membership functions, such as the triangular (trimf) and trapezoidal (trapmf) forms, are commonly used due to their simplicity and efficiency. The triangular MF forms a triangle with three points, while the trapezoidal MF has a flat top, resembling a truncated triangle.

Fuzzy logic uses fuzzy sets and operators to create if-then rule statements. An if-then rule takes the form: "if x is A then y is B ," where A and B are fuzzy sets in respective UODs X and Y . The antecedent (if-part) evaluates the input, while the consequent (then-part) provides an output value between 0 and 1. The output fuzzy set is later defuzzified to yield a final numerical output.

The FRPN uses these if-then rules and is determined through two stages of fuzzy logic control. The steps are:

1. Values of Severity (S) and Occurrence (O) are combined and processed using fuzzy rules to generate a fuzzy number;
2. The output from Step 1 and the Detection (D) value are processed similarly, maintaining the same rules to ensure consistency in the generated fuzzy surface.

Table 3.5 – Fuzzy rules based on 100 membership functions [31]

		The Input 2 Value									
		10	9	8	7	6	5	4	3	2	1
The Input 1 Value	10	10.00	9.569	9.093	8.616	8.140	7.664	7.187	6.711	6.325	5.758
	9	9.440	8.964	8.488	8.011	7.535	7.059	6.582	6.106	5.630	5.153
	8	8.835	8.359	7.883	7.406	6.930	6.454	5.997	5.501	5.025	4.548
	7	8.230	7.754	7.278	6.801	6.325	5.849	5.372	4.896	4.420	3.943
	6	7.625	7.149	6.673	6.196	5.720	5.244	4.767	4.291	3.815	3.338
	5	7.021	6.544	6.068	5.592	5.115	4.639	4.163	3.686	3.210	2.734
	4	6.416	5.939	5.463	4.987	4.510	4.034	3.558	3.081	2.605	2.129
	3	5.811	5.334	4.858	4.382	3.905	3.429	2.953	2.476	2.000	1.524
	2	5.206	4.729	4.253	3.777	3.300	2.824	2.348	1.871	1.395	0.919
	1	4.601	4.124	3.648	3.172	2.695	2.219	1.743	1.266	0.790	0.314

Summarily, the Severity, Occurrence values is attributed to a membership function (triangular or trapezoid), that output a membership value between 0 and 1. Their values are combined using the fuzzy logic, "If-Then", which is combined with a Detection mapped value. This final combined value is defuzzified to the Fuzzy RPN. A table with the combination modes of risk factors is shown in Appendix A, while all criteria used for the definition of RPN are presented in Tables 3.6, 3.7, and 3.8.

Table 3.6 – Criteria for severity rating of a failure in FMEA [31]

Rating	Effect	Severity of effect
10	Dangerous without warning	A very high severity ranking is assigned when a likely failure mode disrupts system operation without any prior warning
9	Dangerous with warning	A very high severity ranking is assigned when a potential failure mode disrupts system operation but provides a warning beforehand
8	Very high	The system becomes inoperable due to a destructive failure, without compromising safety
7	High	System inoperable with equipment damage
6	Moderate	System inoperable with minor damage
5	Low	System inoperable without damage

Table 3.6 – Criteria for severity rating of a failure in FMEA (cont.)

4	Very Low	The system remains operational but with significant performance degradation
3	Minor	The system remains operational but with some loss of performance
2	Very minor	The system remains operational with minimal disruption
1	None	No effect

Table 3.7 – Criteria for occurrence rating of a failure in FMEA [31]

Rating	Probability of Occurrence	Failure Probability
10	Almost Certain	>0.5
9	Very high	0.16666666
8	High	0.125
7	Moderately high	0.05
6	Moderate	0.0125
5	Low	0.0025
4	Very Low	0.0005
3	Remote	0.000066
2	Very remote	0.0000066
1	Nearly impossible	0.00000066

Table 3.8 – Criteria for detection rating of a failure in FMEA [31]

Rating	Detection	Likelihood of detection by control mechanism
10	Absolute uncertainty	The control mechanism is unable to detect the potential cause of the failure mode
9	Very remote	There is an extremely low likelihood that the control mechanism will detect the potential cause of the failure mode

Table 3.8 – Criteria for detection rating of a failure in FMEA (cont.) [31]

8	Remote	There is a low likelihood that the control mechanism will detect the potential cause of the failure mode.
7	Very Low	The control mechanism has a very small likelihood of detecting the potential cause of the failure mode
6	Low	The control mechanism has a small likelihood of detecting the potential cause of the failure mode
5	Moderate	There is a moderate likelihood that the control mechanism will detect the potential cause of the failure mode
4	Moderate high	There is a moderately high likelihood that the control mechanism will detect the potential cause of the failure mode
3	High	There is a high likelihood that the control mechanism will detect the potential cause of the failure mode
2	Very high	There is a very high likelihood that the control mechanism will detect the potential cause of the failure mode
1	Almost certain	The control mechanism will almost certainly detect the potential cause of the failure mode

The Fuzzy RPN is added to the FMEA worksheet, as shown in Table 3.9, and sorted to identify the most critical components. These components will then be evaluated to determine the appropriate maintenance policy. Additionally, strategies can be implemented to reduce RPN values.

Table 3.9 – FMEA worksheet [31]

Subsystem	Component	Failure mode analysis		Existing conditions					Ranking
		Failure mode	Failure cause	S	O	D	RPN	Fuzzy RPN	

Each gas turbine component to be analyzed is shown in Figure 3.5, providing a structured overview of the critical elements considered in the FMEA process.

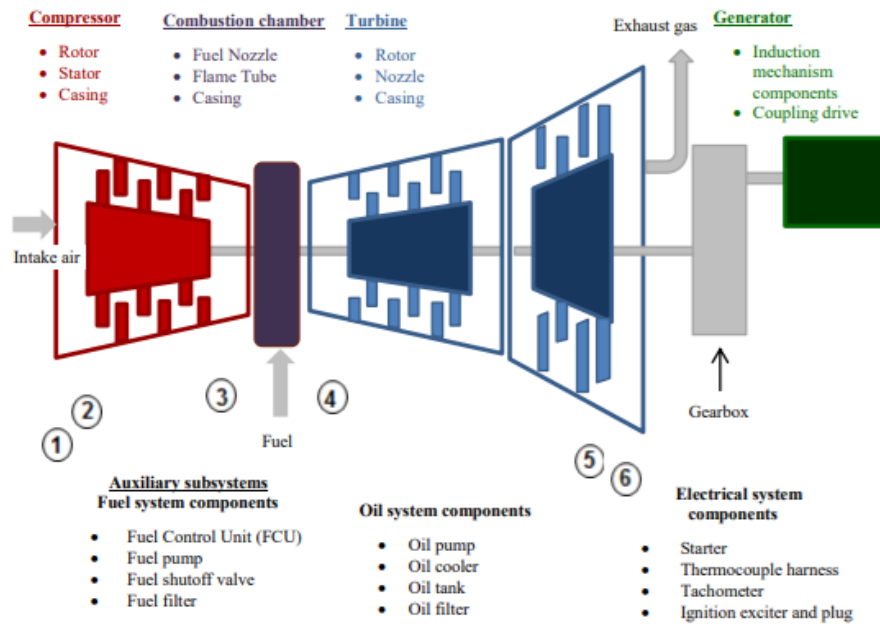


Figure 3.5 – GTPPS subsystems and detailed components [31]

The gas turbine system, as a whole, is susceptible to various failures. To facilitate the analysis, the gas turbine is divided into four main sections: compressor, combustion chamber, turbine, and auxiliary systems, which include oil, electrical, and fuel systems. A list of each failure mode, including its cause, effect, and disposition, is provided in the next section for a clearer and more straightforward understanding of each component [31].

3.2 The Likely System Failure Modes

3.2.1 Failure modes of Hydrogen Storage

Starting with the failure modes of LH₂ storage, data regarding problems related to LH₂ releases and their effects on infrastructure, instrumentation, and human safety remains limited. Despite this, some examples of issues include frostbite, ice formation on vents and valves, hypothermia, moisture accumulation within storage due to inadequate purging, damage to boil-off valves and release valves, and oxygen enrichment.

Although the evaporation and ignition of LH₂ is not completely quantified yet, existing data suggest that the most hazardous physical consequences for GH₂ include jet fire, flash fire, and explosion, and are caused by releases. Furthermore, uncontrolled accumulation in confined spaces that allow delayed ignition events is seen as the main hazard, at the same time that asphyxiation can occur too [26][29].

In LH₂ components a failure can cause an unintended release of it, however due to the different failure scenarios and its varying severity classifications that can occur, a distinction between GH₂ and LH₂ should be made. The identified failure modes and their severity, probability class and risk level are shown in Table 3.10.

Table 3.10 – Identified Failure Modes in Liquid Hydrogen Systems [26][30]

Component Code	Component Name	Failure Modes and Cause
Tank	Liquid storage tank	Tank rupture from crash or impact
		Fittings fail due to material or installation error
PSV	Pressure Release Valve	Malfunction due to extreme cold temperatures
FV	Air operated valve	Operation failure (premature operation)
		Operation failure (at prescribed time)
		Failure to close due to mechanical issues
CNL	Cryogenic Pump	Leakage from pump caused by seal malfunction or installation mistake
		Pump activates early due to controller malfunction
EV	Ambient air evaporator	Leakage from connections and pipe fittings
		Rupture from crash or impact
Piping Lines	Piping	Leak resulting from mechanical or material failure

3.2.2 Failure modes of gas turbines

The available data for the FMEA of gas turbines is more extensive, allowing for a deeper and more detailed explanation of each failure mode, cause, and effect, which is provided in this section.

1.Failure Mode: No ignition at Start

Failure cause

During the engine start process, primary ignition is required to initiate combustion. A common failure during startup is the absence of primary ignition, often caused by erosion of the ignition plugs. Over time, wear on the igniter tip reduces its efficiency, preventing it from producing the necessary spark to ignite the air-fuel mixture in the combustion chamber.

Failure effect

During the engine start, the electric starter and fuel supply prepare the system for ignition, but if the ignition plugs fail, the engine speed will not increase or be sustained.

Failure disposition

Ignition plugs are typically placed in inspection ports on the combustion chamber and are inspected during borescope inspections.

2. Failure Mode: Low Oil Pressure (and/or High Oil Temperature)

Failure cause

During engine operation, oil plays a critical role with its main functions being:

- Damping vibrations;
- Cooling;
- Cleaning;
- Sealing;
- Lubrification.

If the oil pump or oil cooler is compromised, the oil system's performance declines due to insufficient pressure or reduced density, respectively. Consequently, the engine bearings become at risk.

Failure effect

In both situations – whether due to low oil pressure or excessive temperature – the oil loses its properties, leading to increased tension on the bearings. This compromises the efficiency of the bearings and can ultimately damage the rotary components, such as the compressor or turbine.

Failure disposition

Abnormalities in engine oil samples can indicate potential problems, prompting an investigation. Therefore, periodic oil replacement, along with regular inspection and cleaning of oil system components, is essential to maintain oil quality.

3. Failure Mode: Engine Over-Speed

Failure cause

Key indicators on the control panel, such as the RPM indicator, are essential for monitoring engine performance. Exceeding the engine's RPM threshold compromises the safety of moving parts and nearby components. This can be caused by excessive fuel consumption or the disconnection of the intermediate shaft between the compressor and turbine. The increase in engine RPM results in higher centrifugal force, making rotor failure predictable and leading to a cessation of rotation.

Failure effect

The increase in engine RPM is signaled by a rapid decline in the fuel quantity indicator, an abnormal acceleration rate, and the potential activation of the main caution light. These signs point to higher-than-normal engine speed, which, if sustained, can lead to irreparable damage to the system.

Failure disposition

Periodic inspection of tip clearance, along with the compressor and turbine blades, is one of the most effective actions to prevent this failure. Typically, the first-row blades of the compressor (from the intake side) and the last-row blades of the turbine (from the exhaust side) are inspected. If the clearance is lower than normal, it may indicate over-speed in the compressor or over-speed/temperature issues in the turbine.

4. Failure Mode: Engine Gas Over-Temperature

Failure cause

Fuel combustion and gas expansion in the turbine generate significant thermal stress. If the gas temperature exceeds the normal range, it causes increased stress, leading to a higher risk of burning in the areas exposed to the gas flow. The turbine nozzle is the most susceptible to this damage.

Failure effect

Excessive expansion in the turbine, caused by high gas temperatures from combustion, leads to deformation and eventually burning of the vane areas. As a result, the streamlined flow of gases is disrupted, compromising engine performance.

Failure disposition

Due to the presence of holes in the combustion chamber for inspecting fuel and turbine nozzles, and because nozzles are crucial and may not show clear signs of wear, periodic inspection of the turbine nozzles is recommended.

5. Failure Mode: Compressor Rotor Vibration

Failure cause

The main function of the compressor rotor is to compress incoming air. The primary cause of failure is bearing failure at the rotor, which dampens vibrations. Less likely causes include loose engine installation mounts, which cause misalignment and lead to severe vibrations. An electrical fault in the vibration indicator could also occur, although the rotors would remain serviceable.

Failure effect

The illuminator on the instrument panel is activated when the frequency detected by vibration pick-ups around rotating sections, such as the compressor, exceeds a certain range.

Failure disposition

The first hypothesis for the activation of the vibration light is an electrical system failure. However, if the investigation concludes that the issue is not electrical, an engine inspection should be conducted. Finally, if the cause of the failure remains undetermined, an oil sample should be taken and analyzed to identify the defective bearing.

6. Failure Mode: Compressor Rotor Shaft Locked

Failure cause

The compressor rotor is positioned close to its casing, and excessive centrifugal forces can cause the rotor blade tips to gradually move outward, eventually leading to contact with the casing.

Failure effect

If rotor blade tips hit the casing, it reduces compressor speed and eventually causes a sudden engine halt. This results in severe damage to the blades and casing, requiring their replacement.

Failure disposition

Periodic inspection of compressor blade tip clearance is necessary to prevent failure. Due to their length, accessibility from the engine inlet, and thinner structure, only the first-row blades are inspected, and decisions are made based on these results.

7. Failure Mode: Compressor Over Temperature

Failure cause

The compressor increases the pressure and temperature of intake air and directs it to the combustion chamber at minimal speed. If the intake air temperature exceeds the specified limit due to a hotter operating environment, the compressor outlet air becomes unsuitable for combustion, leading to a compressor over-temperature failure.

Failure effect

Compressor over-temperature, caused by hotter air intake, leads to combustion over-temperature. This results in hot spots on turbine nozzles, potentially burning the vanes and significantly reducing gas turbine performance.

Failure disposition

Preventing this issue relies on closely monitoring the temperature and operating conditions, which is crucial for achieving optimal engine performance.

8. Failure Mode: Compressor Stalls

Failure cause

Stall failure, which significantly reduces gas turbine performance, occurs when the airflow inside the engine becomes distorted and forms a vortex. This can be caused by ice formation, blockages in the engine's inlet, or compressor blade damage from foreign objects, all of which disrupt the smooth flow of air or gas.

Failure effect

Stall failure, often caused by vortex flow, is typically accompanied by abnormal sounds and RPM fluctuations. If the issue persists, engine serviceability can decrease, and the operator should reduce the engine duty cycle. In severe cases, the vortex energy can bend the rotary blades.

Failure disposition

The prevention of this failure results from ensuring proper operating conditions, free from dust, sand, or foreign objects.

9. Failure Mode: RPM/Temperature Fluctuation

Failure cause

Proper combustion ensures consistent energy release. However, disruptions in the delivery of air or fuel to the combustion chamber result in incomplete combustion and reduced energy extraction. For example, leaks in the compressor reduce combustion efficiency.

Failure effect

Incomplete combustion leads to insufficient energy production, causing issues with rotary sections not receiving the necessary power. Additionally, the increase in by-products from incomplete combustion disrupts the steady flow of gas, resulting in RPM fluctuations and temperature instability in the engine.

Failure disposition

To prevent fluctuation failure, it's crucial to inspect the compressor casing for dents or deep cracks. If any are found, the casing should be replaced to prevent air leakage and ensure efficient operation.

10. Failure Mode: Flame Out

Failure cause

Gas flow in a gas turbine enables turbine rotation. Flame-out, the stoppage of gas flow into the combustion chamber, is caused by a failure in the fuel nozzle. This disrupts both the flow and power generation. Partial or total clogging of the fuel nozzle prevents fuel delivery, leading to flame-out failure.

Failure effect

Reduced gas volume in the combustion chamber lowers the energy of the gas flow hitting the turbine rotor, which in turn reduces the turbine duty cycle and generator shaft speed. This leads to an under-frequency failure in the power plant, and if the issue persists, the plant will eventually stop producing electricity.

Failure disposition

The prevention relies on inspecting the inner components of the combustion chamber. If the nozzles are obstructed, corrective measures should be taken.

11. Failure Mode: Hot Spot on Flame Tube

Failure cause

The contact between the combustion chamber's inner components and the flame causes burns. The flame tube, the main inner layer, experiences high thermal stress during engine operation. Discolored areas, known as “hot spots”, are a key indicator of combustion chamber failure.

Failure effect

The amount of burnt surfaces inside the combustion chamber depends on thermal stress and is proportional to the intensity of the incoming heat, with more intense heat causing larger discolored areas, usually purple.

Failure disposition

A portion of the intake air is used to cool the flame tube and prevent “hot spots.” Misalignment of the flame tube or higher-than-allowed intake air temperature can cause this failure. Ensuring the correct flame tube position and monitoring ambient air temperature are crucial for preventing failures.

12. Failure Mode: Flame Leakage

Failure cause

This failure occurs by RPM fluctuation, involves gas leakage through the combustion chamber casing. Instead of being directed to the turbine, the combustion gases escape through the chamber’s mating line or deep cracks, reducing the energy received by the turbine rotor.

Failure effect

Air or gas leakage from the engine, causing insufficient energy to rotate turbine blades, results in effects similar to those caused by RPM fluctuation.

Failure disposition

As a preventive measure, daily pre-operation inspections are crucial to detect any foreign body impacts or damage to the engine body, while ensuring the operational environment is free from sand, soil, and gravel. If major repairs are required, the engine and combustion chamber should be disassembled, with the casing inspected for smoothness and any dents [31].

Chapter 4

Results and Analysis

4.1 Results

This section presents the results of both the FMEA for hydrogen storage and gas turbines, following the same structure as the previous chapters. It begins with hydrogen storage and transitions into the discussion of gas turbines. In the discussion section, the author will outline potential future research and implementations that could enhance the safety and effectiveness of hydrogen combustion in gas turbines.

4.1.1 Hydrogen Storage FMEA Results

Based on the simplified risk matrix presented above (Table 3.3) and the criteria for severity and occurrence (Tables 3.1 and 3.2, respectively), the results presented in Table 7 were obtained. These results reflect the evaluation of potential risks, providing insight into their likelihood and impact within the context of the study.

Table 4.1 – Liquid Hydrogen Systems FMEA [26]

Component	Failure Modes and Cause	Severity Class	Probability Class	Risk Level
Tank	Tank rupture from crash or impact	Critical	Low	M
	Fittings fail due to material or installation error	Moderate	Medium	M
PSV	Malfunction due to extreme cold temperatures	Critical	High	H
FV	Operation failure (premature operation)	Critical	Low	M
	Operation failure (at prescribed time)	Critical	High	H
	Failure to close due to mechanical issues	Moderate	Low	L
CNL	Leakage from pump caused by seal malfunction or installation mistake	Moderate	Medium	M
	Pump activates early due to controller malfunction	Critical	Low	M
EV	Leakage from connections and pipe fittings	Moderate	Medium	M
	Rupture from crash or impact	Critical	Medium	H
Piping Lines	Leak resulting from mechanical or material failure	Moderate	Medium	M

Based on table 7, the three risk that have a highest level – highlighted in red in Table 12 – are malfunction due to extreme cold temperatures, associated to PSV, operation failure (at prescribed time), from FV and rupture from crash or impact, that happens in EV. Each one of these three risks can lead to unintended release of gaseous and liquid hydrogen, according to the release conditions [26].

4.1.2 Gas Turbine FMEA Results

The methodology presented in Chapter 3 allows for the results shown in Table 4.2, where all failure modes, their causes, respective Fuzzy RPN, and subsystem components are listed. These results provide a comprehensive overview of the identified risks and their potential impacts while also ranking them, forming the basis for further analysis and decision-making in the study [31].

Table 4.2 – Gas Turbine FMEA [31]

Subsystem Component	Failure Mode	Failure Cause	S	O	D	RPN	Fuzy RPN	Ranking
Compressor	Vibration	Faulty vibration indication	5	4	1	20	2.22312	34
		Loose mounts	6	3	3	54	3.24728	25
		Defective bearings	7	2	5	70	4.27143	11
	Shaft locked	Deformation of blades and contacting with casing	9	2	3	54	4.06024	16
	Over-temperature	Dirty compressor rotor	10	4	5	200	5.95872	3
		Foreign object damage	10	3	2	60	4.24278	13
Compressor (Stator)	Stall	Ice formation on engine inlet	6	2	1	12	2.00865	36
		Binding of variable stator vanes	7	4	3	84	3.90456	18
		Foreign object damage	6	3	2	36	2.77379	29
Compressor (Casing)	RPM or temperature fluctuation	Air leakage	4	2	4	32	2.68634	30
Combustion chamber (Fuel nozzle)	Flame-out	Partial cloggage or blockage of fuel nozzles	8	7	6	336	6.56358	2
	Instability of flame pattern	Irregular fuel-to-air ratio	6	4	6	144	4.96246	6
Combustion chamber (Flame tube)	Hot spots on flame tube	Fault in cooling of flame tube and inequality in flame distribution around it	6	2	8	96	5.34067	4

Table 4.2 – Gas Turbine FMEA (cont.)

Combustion chamber (Casing)	Flame leakage	Losing smoothness of mating areas	5	3	3	45	2.87428	27	
Turbine (Nozzle)	Over - temperature	Burnt nozzle vanes	10	3	9	270	7.56969	1	
Turbine (Rotor)	Shaft seized	Rubbing of rotor blades with turbine casing	9	3	4	108	4.82959	8	
		Vibration	Faulty vibration indication	5	4	1	20	2.22312	33
			Loose mounts	6	3	3	54	3.24728	26
		Defective bearings	7	2	5	70	4.27143	12	
Turbine (Casing)	Low power	Gas leakage	6	5	6	180	5.25284	5	
Auxiliary systems (Fuel system components)	Post - shutdown fire	Shutoff valve remains open	5	3	5	45	2.87428	28	
	Over -speed	High fuel flow	10	1	4	40	4.61403	9	
	Flame -out	Fuel contamination	7	6	1	42	3.53288	22	
	No start	Fuel shutoff valve not energized	3	1	3	9	1.54585	39	
		Air, water, or solids in fuel lines	4	2	4	32	2.68634	31	
	Under-speed	Fuel filter partial cloggage	5	7	3	105	4.03683	17	
		Low adjustments	5	5	5	125	4.40487	10	
Stall	Fuel pressure irregular	6	3	5	90	4.19622	14		
Auxiliary systems (Oil system components)	Oil contamination	Oil tank is contaminated	5	2	1	10	1.64177	38	
	No oil pressure	Sheared oil pump shaft	8	2	3	48	3.70115	20	
		Low oil level in tank	8	3	2	48	3.50798	23	
	High oil temperature	Oil cooler inoperative	7	7	1	49	3.82191	19	
Oil pressure fluctuation	Oil leakage and/or low oil level in tank	6	4	3	72	3.53695	21		
Auxiliary sys. (Electrical system components)	Faulty temperature indication	Open, short circuit in thermocouple circuit	5	5	1	25	2.50817	32	
	No RPM indication while starting	Starter inoperative	3	4	1	12	1.49077	40	
	Starter over-speed	Sheared starter drive shaft	4	3	2	24	2.04475	35	

Table 4.2 – Gas Turbine FMEA (cont.)

Auxiliary sys. (Electrical system components)	Failure to reach idle speed	Internal failure of starter components	4	6	3	72	3.37753	24
		Low electrical power	3	2	1	6	0.91928	41
	Faulty speed indication	Internal failure of tachometer	3	2	3	18	1.87194	37
	No start	Internal failure of ignition exciter	5	4	5	100	4.12335	15
		Erosion on ignition plugs	5	5	6	150	4.88086	7

The three most critical failures (with Fuzzy RPN values around 6 or higher) – highlighted in red in Table 4.2 – based on their RPN, are over-temperature (caused by burnt nozzle vanes in turbines and dirty compressor rotor) and flame-out (caused by partial clogging or blockage of fuel nozzles). Table 4.2 also helps identify the most susceptible systems where critical failures are likely to occur, enabling the prioritization of scheduled and unscheduled maintenance to ensure reliability and performance. Implementing a maintenance policy will progressively reduce the RPN through iterative failure analysis cycles.

4.2 Analysis

This section presents an analysis of the results obtained from the FMEA of hydrogen storage and the FMEA of gas turbines. Given the limited data available on hydrogen combustion in gas turbines, this study separately analyzes the failure modes of hydrogen storage and gas turbines to provide a comprehensive assessment. Additionally, this section explores key measures and policies that can be implemented to ensure the efficient and safe use of hydrogen as the primary fuel for gas turbines, from its storage to its combustion.

Before discussing maintenance policies and key safety measures applicable to the most critical cases, a brief explanation of maintenance actions will be provided for clarity. The focus of maintenance actions in GTPPS can be categorized into the following areas:

- Corrective maintenance: actions taken at component breakdown before failure; not scheduled;
- Preventive maintenance: scheduled inspections for time-independent components to detect unpredictable failures during engine operation;
- Predictive maintenance: scheduled inspections for time-dependent components to prevent predictable failures and ensure serviceability.

The key difference is that time-independent component failures are unpredictable, while time-dependent component failures can be estimated based on operational hours, stress levels, and material aging. Preventive and predictive maintenance target high-cost failures, whereas corrective maintenance is used for low-cost failures.

Periodic inspections, classified as Non-Destructive Testing (NDT), include visual inspection, dye-penetration testing, and specialized tests like turbine blade hardness evaluation [31].

Firstly, the safety measures outlined will focus on the hydrogen storage system, followed by those applicable to GTTPS.

The recommended safety measures for hydrogen storage are based on existing reports rather than this specific case. Since the exact causes of failure in some cases are unknown, certain assumptions will be made. These measures include:

- Ensuring proper installation, design, and qualification of the Pressure Safety Valve (PSV), along with the implementation of hydrogen leak sensors, ventilation systems, and a container shut-off valve, to mitigate potential hazards in case of PSV malfunction;
- Addressing the potential failure of the Air Operated Valve (FV) due to air freezing. This risk can be mitigated by temperature sensors, which help detect conditions that may lead to failure. Additionally, proper design and installation of the FV are crucial to ensuring its functionality;
- Finally, mitigating the risk of rupture due to crash or impact of the Evaporator (EV) can be achieved through the use of hydrogen sensors, proper design and installation, and ensuring compliance with crash test requirements [30][29].

In case of gas turbines, preventive maintenance can help reduce the risk of flame-out in the combustion chamber and over-temperature failures in turbine and compressor. Inspections are the most effective strategy for both cases.

Some actions that can be taken for each one of the most critical failures are:

- Over temperature (turbine nozzle): for turbine nozzle failures, by over-temperature, a Hot Section Inspection (HSI) is necessary to assess turbine component availability, typically performed at half of the engine's Time Between Overhaul (TBO).
- Flame-out (fuel nozzle of the combustion chamber): for flame-out prevention, borescope inspections at scheduled intervals allow monitoring of the combustion chamber's condition.
- Over temperature (compressor): in the case of over-temperature caused by a dirty compressor rotor, periodic cleaning of the compressor, the use of filters, and ensuring the correct operating conditions – free from sand, chemicals, pollution, and other contaminants – are the most effective measures to prevent compressor failure [32].

Therefore, and in a most general maintenance context, the results of this FMEA help the construction of a maintenance plan, which consequently decreases the RPN. Four guidelines are crucial to maintenance plan implementation:

1. Gas turbine maintenance policies are based on analyzing engine behavior over its Time Between Overhaul (TBO) period;
2. In addition to time-based inspections, some fundamental preventive tasks are carried out annually;
3. The components division rule is based in time-dependent and time-independent (commonly is condition-based components);
4. Component dependency on time-based maintenance occurs in two ways:
 - a. Failure at Specific Intervals: Some components tend to fail after a certain period. To restore their functionality, major repairs (overhauls) are performed, making them usable again;
e.g. electrical starters.
 - b. Limited Resistance to Stress: Some components fail due to their limited resistance to applied stresses. These components are assigned a Mandatory Replacement Time (MRT) for periodic replacement, as no repair can serve as a substitute;
e.g. compressor and turbine rotor disks.

Examples of actions to increase system reliability include performing periodical bore scope inspections on the combustion section as preventive maintenance and conducting comprehensive generator inspections (overhaul) after a set operational time as predictive maintenance [31]. Summarily, proper and scheduled (preventive) inspections and maintenance are the key for safe system operation, however reactive maintenance is unwise, usually. It is acceptable to operate non-critical equipment until it fails, in specific cases like redundancy in facility and component failure do not poses a safety issue [33].

The safe and effective use of hydrogen as a primary fuel in gas turbines is an area of significant interest. However, further research is necessary to ensure its long-term safety and efficient integration into turbine systems. The following discussion is based solely on findings from existing reports and safety measures implemented in various industries, both those using hydrogen and those that do not, rather than on measures specifically designed for gas turbines. Nonetheless, these general safety measures offer valuable insights into the challenges and opportunities associated with hydrogen as a fuel source.

4.3 Discussion

Research on hydrogen safety and its effective implementation in gas turbines, as an alternative to typical fossil fuels, is still in its early stages. A simpler and faster approach is to adapt existing technologies from other industries and fields, modifying them as needed for hydrogen applications. Therefore, this section discusses a few existing technologies as well as potential future advancements that could be explored for hydrogen use and

eventually implemented, ensuring its proper and efficient application. It is important to note that there are many potential failures that can occur in gas turbines and LH₂ storage systems. However, the ones discussed here are among the most common and hazardous. Key challenges related to hydrogen arise from its inert chemical properties and certain physical characteristics, including:

1. Ability to embrittle materials: hydrogen has the potential to weaken metals and other materials over time, leading to cracks or fractures;
2. Wide flammability range: hydrogen can ignite over a broad range of concentrations, making it more hazardous than many other fuels;
3. Low ignition energy: hydrogen requires very little energy to ignite, making it highly susceptible to ignition from sparks, static electricity, or other small triggers;
4. Extremely low density: This property presents challenges in storage; it can also offer advantages when compared to other gases.

While the first three properties pose significant safety concerns, hydrogen's low density can be viewed as a benefit, as it reduces the likelihood of forming hazardous concentrations in the event of a leak. This makes hydrogen less prone to causing dangerous situations compared to gases that accumulate in low-lying areas, although gaseous hydrogen (GH₂) can diffuse rapidly through certain small openings [34].

Another important consideration is the low temperature of Liquid Hydrogen (LH₂). When systems use LH₂, contamination by air or other impurities can cause freezing, potentially leading to blockages in pipes, filters, or valves. Such blockages could disrupt the flow of hydrogen or damage equipment, a concern noted in various industries handling LH₂.

In addition to the technical challenges, safety measures for systems such as GTTPS fueled by hydrogen must also account for the physical environment. For instance, the surrounding infrastructure—such as roads, ventilation for enclosed areas, and automated system shutdown—must be designed to maintain minimum safe distances between hydrogen facilities and other structures [35]. This requirement could pose challenges in terms of implementation, particularly in air transportation vehicles. Ensuring safe distances for hydrogen storage and handling within confined spaces like aircraft is a significant concern and needs careful consideration in the design process. If a leakage occurs and rapidly diffuses through small openings, it can cause asphyxiation of passengers [36].

As seen previously, tank loss presents a significant risk, so choosing suitable materials, such as aluminum or stainless steel, is crucial. Additionally, some mitigation measures can be taken, including:

- Properly designed pressure relief;
- Minimum pipework and ancillary equipment;
- Backup instrumentation;

- Water spray system;
- Availability of sufficient quantity of water/foam;
- Prevention of overfilling;
- Generous spacing between tanks [34];

Regarding these mitigation measures, some considerations should be noted. The contact between water and hydrogen does not necessarily cause a rapid phase transition, which makes it possible to control the flow or accumulation of LH₂ using sprinklers or water jets. However, this increases the vaporization rate, which, if ignited, can lead to a larger fireball [36]. Another important aspect is that all vents, including safety relief devices and purge valves, should be connected to a vent system that discharges safely into the open air [35]. The low temperature of LH₂ can cause unexpected ruptures in components such as piping, thread sealant, and valves. Therefore, special attention should be given to design and material selection, considering thermal contraction and expansion effects [37].

In terms of electrical equipment and installation, electrostatic charges can accumulate due to mechanical separation, gas flow, or material friction, creating a potential ignition risk. To prevent this, proper dissipation to the ground is essential. Delivery vehicles must be earthed before unloading, and conductive materials should be used for pumps, belts, pulleys, and protective clothing to minimize static charge buildup. Additionally, sparks, electrical arcs, and high temperatures that could ignite hydrogen must be strictly avoided during operation [35].

Hydrogen is a colorless and odorless gas, unlike other gases or fuels, which makes its leakage difficult to detect by human senses. For this reason, detection devices should be used in areas where hydrogen leakage and accumulation are likely to occur. Monitoring piping pressures, detecting flow rate changes, and enclosing hydrogen piping within another pipe while monitoring the annulus for leaks are recommended strategies. It is important to note that maintenance and recalibration of these devices should be performed every 3–6 months by qualified personnel [35][37]. These devices can enable automatic shutdown/isolation or provide alerts if hydrogen releases are detected, particularly in enclosed areas [38].

Some issues that occur during LH₂ use is related with their extremely low temperature, disregarding the issues associated with the impurities or dirties. Some future research can be done to prevent and mitigate the risks associated with LH₂ use, in field like use of composites in storage tanks and strategies for icing mitigation.

Ice formation in LH₂ systems poses a significant hazard during operations. The low temperature and impurities contained in LH₂ can freeze crucial components, such as pumps and valves, preventing the smooth movement of their movable parts and affecting

their functionality. Several strategies have been studied over the years, and some are currently used in other systems, including:

- Superhydrophobic surfaces [39]: These surfaces repel water by causing droplets to bead up and roll off, reducing ice adhesion. By altering the liquid dynamics and promoting faster droplet departure, these surfaces enhance anti-icing performance. Their low surface roughness makes it more difficult for frost or ice to stick, thereby preventing accidental damage. By hindering water accumulation, they also prevent the freezing of movable components, which could otherwise lead to malfunctions. This strategy is one of the most efficient and environmentally friendly options.
- Ultrasonic Waves for De-Icing [40]: This technology utilizes ultrasonic waves to generate shear stresses at the interface between the ice and the treated surface. If these stresses are strong enough to exceed the ice's adhesion strength, the ice layer breaks and detaches. In addition to mechanical impact, ultrasonic waves also generate thermal energy through internal damping losses, which helps to locally melt the ice, further facilitating detachment. This dual mechanism of shear and thermal energy makes ultrasonic de-icing an active, highly effective, and low-energy-consumption technique. Its primary objective aligns with that of superhydrophobic surfaces mentioned earlier.
- Electromagnetic pumps [41]: This method generates an electromagnetic field to move hydrogen. However, LH₂ must first be ionized to become electrically conductive, which presents additional challenges. Ionized hydrogen becomes more reactive, increasing the risk of ignition, making safety a primary concern. Despite these challenges, if successfully implemented, this approach could be a major advancement in LH₂ pumping, as it eliminates the need for moving parts, reducing mechanical wear and potential failure points. Further research is essential to assess its feasibility and develop safety measures to mitigate the risks associated with ionized hydrogen.

Important organizations, such as NASA, are exploring the use of advanced composite materials in cryotanks. Typically, fuel and oxidizer tanks represent 70% of the dry mass of a launch vehicle, but this can be reduced by 30% if composite materials are used, enhancing the overall performance of the vehicle [42]. Research is ongoing regarding the integration of conductive or insulating materials into composites, which would provide them with electro-mechanical properties. These new properties could allow composites to function as sensors [43]. Consequently, if a rupture or crack occurs in a tank or other system component made of such composites, the system could detect the issue automatically, without relying on inspections or external leakage detection devices. If the fissure is small enough that leakage does not occur, the composite will detect it, preventing any subsequent

leakage. However, the use of composites in other components remains under study due to their extremely low heat transfer coefficients compared to metals [44].

Finally, although these suggestions for future LH₂ system implementations appear promising and effective, further studies are needed due to hydrogen's unique properties and the challenges posed by its low-temperature liquid state. Additionally, it is crucial to assess whether the implementation of these suggested technologies is compatible with existing systems, as well as with each other.

Chapter 5

Conclusion

Concerns about the future of the planet are widely discussed among nations, and efforts to reduce greenhouse gas emissions and carbon footprints are unprecedented. The goals are ambitious, and research on new technologies seems promising. Hydrogen has emerged as a key player due to its low or zero greenhouse gas emissions. However, while hydrogen holds great potential for energy production and transportation, its implementation in existing technologies requires careful attention and effort.

Unlike other fuels, whether liquid or gaseous, hydrogen possesses unique chemical and physical properties that demand special consideration during combustion, transportation, and storage. Its tendency to embrittle materials, its ease of escape, its wide flammability range, and the low energy required for ignition all present challenges to its safe and effective use. As a result, current energy systems must be adapted to incorporate hydrogen in place of natural gas, jet fuel, or other energy sources.

Additionally, these modifications require thorough safety analysis, and this dissertation contributes to that aspect. Although hydrogen technologies are still relatively new, and data remains limited, this study provides an overall perspective on the use of LH₂ as a primary fuel in gas turbines. The FMEA presented – based on previous research and studies – identifies the main hazards associated with hydrogen use. This dissertation highlights the most critical failure modes that can occur throughout the hydrogen energy cycle, from storage to combustion and mechanical or thermal energy production, while also suggesting future research directions that could prove highly valuable if successfully implemented.

As discussed in Chapter 4, the most critical failures are associated with the extreme low temperatures and potential leakage of LH₂, which can lead to component malfunctions or tank ruptures, respectively. Regarding LH₂ combustion in gas turbines, available data remains limited. However, the primary failure causes in gas turbines are generally not related to gas combustion itself but rather to the demanding operational environment, which can lead to excessive temperatures in the turbine and compressor, as well as flameout in the combustion chamber. Although these failures can significantly impact gas turbine functionality and performance, solutions to mitigate them are well-established. Regular and scheduled inspections, along with ensuring proper operating conditions and overall operation conditions, effectively address most failure scenarios.

Future researches should be done in some fields, such as ice mitigation and tank ruptures in order to reduce even more the risks associated with hydrogen and its special properties.

Some promising measures are the use of composites and piezoresistive sensors integrated in those composites for tanks and components, and the use of superhydrophobic surfaces, electromagnetic pumps and ultrasonic waves in order to mitigate the problems associated mainly with LH2 extreme low temperature.

In conclusion, LH2 is a highly promising energy source. While its properties differ significantly from conventional fuels and its implementation in gas turbines presents challenges, the overall safety record of LH2 delivery, transfer, and storage remains impressive. Currently, hydrogen costs and production limitations still pose barriers to widespread adoption. However, as technologies advance and demand continue to rise, these obstacles will likely diminish. Ultimately, with continued research and development, the world has the potential to transition toward a more sustainable and environmentally friendly future.

References

- [1] Hannah Ritchie, Pablo Rosado and Max Roser (2020) - "Breakdown of carbon dioxide, methane and nitrous oxide emissions by sector" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/emissions-by-sector'
- [2] International Renewable Energy Agency. (2024). Renewable Energy Highlights. Published online at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/Renewable_energy_highlights_FINAL_July_2024.pdf
- [3] Duggal, H., & Hussein, M. (2022, January 20). Interactive: How much of your country's electricity is renewable?. Published online at <https://www.aljazeera.com/news/2022/1/20/interactive-how-much-of-your-countrys-electricity-is-renewable-infographic>
- [4] United Nations Framework Convention on Climate Change. (n.d.). Key aspects of the Paris Agreement. Published online at <https://unfccc.int/most-requested/key-aspects-of-the-paris-agreement>
- [5] International Air Transport Association. (2021, October 4). Zero emissão líquida de carbono até 2050. Published online at <https://www.iata.org/contentassets/dcd25da635cd4c3697b5d0d8ae32e159/2021-10-04-03-pt.pdf>
- [6] National Grid. (2023, February 23). What is hydrogen? Published online at <https://www.nationalgrid.com/stories/energy-explained/what-is-hydrogen>
- [7] Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2024). Green hydrogen: A pathway to a sustainable energy future. *International Journal of Hydrogen Energy*, 49(1), 123-134. Elsevier.
- [8] Kanade, V. (2023, August 22). What is FMEA? Meaning, types, and importance. Spiceworks. Published online at https://www.spiceworks.com/tech/tech-general/guest-article/what-is-fmea/#_002
- [9] Stamatis, D. H. (2003). *Failure mode and effect analysis: FMEA from theory to execution* (2nd ed.). ASQ.
- [10] Nguyen, J. (2023, November 7). FMEA explained: 2023 guide. Capvidia Blog.
- [11] Relyence. (2018, August 28). FMEA, DFMEA, PFMEA, and FMECA: An overview of FMEA types. Relyence. Published online at <https://relyence.com/2018/08/28/overview-fmea-types/>
- [12] Burge, S. (2010). Functional failure modes and effects analysis (FFMEA) alias system FMEA: What is it and what does it do? Burge Hughes Walsh. Published online at <https://www.burgehugheswalsh.co.uk/Uploaded/1/Documents/FFMEA-Tool-v1-2.pdf>
- [13] Carlson, C. S. (n.d.). Understanding software FMEA. Accendo Reliability. Published online at <https://accendoreliability.com/understanding-software-fmea/>
- [14] Quality-One. (n.d.). Failure Mode and Effects Analysis (FMEA). Published online at <https://quality-one.com/fmea/>

- [15] National Academies of Sciences, Engineering, and Medicine. (2020). *Advanced technologies for gas turbines*. The National Academies Press.
- [16] Langston, L. S. (2013). Turbines, gas. In *Encyclopedia of Energy Engineering and Technology*. Published online at <https://doi.org/10.1016/B978-0-12-409548-9.09044-8>
- [17] Made Easy. (2024, June 27). What is gas turbine power plant? Published online at <https://study.madeeasy.in/me/power-plant/what-is-gas-turbine-power-plant/>
- [18] Bathie, W. W. (1996). *Fundamentals of gas turbines* (2nd ed.). Wiley.
- [19] Allied Power Group. (n.d.). Gas turbine efficiency – An overview. Published online at <https://alliedpg.com/latest-articles/gas-turbine-efficiency/>
- [20] Petrotech Inc. (n.d.). Efficiency of gas turbines. Published online at <https://petrotechinc.com/efficiency-of-gas-turbines/>
- [21] Prismecs. (2024, July 2). Innovations for improved gas turbine productivity. Published online at <https://prismecs.com/blog/innovations-for-improved-gas-turbine-productivity>
- [22] Verhelst, S., & Wallner, T. (2009). Hydrogen-fueled internal combustion engines. *Energy*, 34(5), 550-558.
- [23] Giacomazzi, E., Troiani, G., Di Nardo, A., Calchetti, G., Cecere, D., Messina, G., & Carpenella, S. (2023). Hydrogen combustion: Features and barriers to its exploitation in the energy transition. *Energies*, 16(20), 7174.
- [24] Habib, M. A., Abdulrahman, G. A. Q., Alquaity, A. B. S., & Qasem, N. A. A. (2024). Hydrogen combustion, production, and applications: A review. *Alexandria Engineering Journal*, 100, 182-207.
- [25] Stępień, Z. (2021). A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. *Energies*, 14(20), 6504.
- [26] Correa-Jullian, C., & Groth, K. M. (2022). Data requirements for improving the quantitative risk assessment of liquid hydrogen storage systems. *International Journal of Hydrogen Energy*, 47(6), 4222-4235.
- [27] Powertech Labs Inc. (2016). *Hydrogen Station Equipment Performance Device (HyStEP): Summary of Failure Modes and Effects Analysis (Revision 0)*. TR00742-03-R00. Published online at <https://h2tools.org/sites/default/files/09%20-%20FMEA%20Report.pdf>
- [28] SAE International. (2001). *SAE ARP5580: Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications*. Warrendale, PA: Society of Automotive Engineers.
- [29] Stephens, D. R., Rose, S. E., Flamberg, S. A., Ricci, S. M., & George, P. E. II. (2009). *Failure modes and effects analysis for hydrogen fuel cell vehicles – Subtask 1 (Report No. DOT HS 811 075)*. National Highway Traffic Safety Administration. Published online at https://www.nhtsa.gov/sites/nhtsa.gov/files/811075_0.pdf University.
- [30] Correa-Jullian, C., & Groth, K. M. (2020). Liquid hydrogen storage system FMEA and data requirements for risk analysis. In P. Baraldi, F. Di Maio, & E. Zio (Eds.), *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and*

- Management Conference (Paper No. 5714). Published online at <https://rpsonline.com.sg/proceedings/9789811485930/pdf/5714.pdf>
- [31] Ghasemian, H., & Zeeshan, Q. (2017). Failure mode and effect analysis (FMEA) of gas turbine powerplant system (GTPPS). Advisor: Dr. Qasim Zeeshan. Eastern Mediterranean
- [32] Meher-Homji, C., Bromley, A. F., & Stalder, J.-P. (2013, March 17–20). Gas turbine performance deterioration and compressor washing. Proceedings of the 2nd Middle East Turbomachinery Symposium, Doha, Qatar. Texas A&M University.
- [33] Hydrogen Tools. (n.d.). Maintenance and inspection. H2Tools. <https://h2tools.org/bestpractices/maintenance-and-inspection>
- [34] Verfondern, K., Cirrone, D., Molkov, V., Makarov, D., Coldrick, S., Ren, Z., Wen, J., Proust, C., Friedrich, A., & Jordan, T. (2021). Handbook on hydrogen safety: Chapter on LH2 safety (Version 3.0). Pre-normative Research for Safe Use of Liquid Hydrogen (PRESLHY), European Network of Excellence on Hydrogen Safety. Published online at https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
- [35] European Industrial Gases Association. (2002). Safety in storage, handling, and distribution of liquid hydrogen (Doc 06/02/E). European Industrial Gases Association. https://h2tools.org/sites/default/files/Doc6_02SafetyLiquidHydrogen.pdf
- [36] Bernard, L., Houssin, D., Jallais, S., Jordan, T., & Cirrone, D. (2021). Novel guidelines for safe design and operation of LH2 systems and infrastructure (Deliverable No. D6.2, Version 3.0). Pre-normative Research for Safe Use of Liquid Hydrogen (PRESLHY) Project. https://hysafe.info/wp-content/uploads/sites/3/2021/04/D39_2021-01-PRESLHY_ChapterLH2-v3.pdf
- [37] H2Tools. (n.d.). Leak detection. Hydrogen Tools. <https://h2tools.org/bestpractices/hydrogen-properties-and-leak-detection-considerations/leak-detection>
- [38] H2Tools. (n.d.). Hydrogen safety checklist. <https://h2tools.org/sites/default/files/HydrogenSafetyChecklist.pdf>
- [39] Zhou, X., Sun, Y., & Liu, J. (2021). Designing anti-icing surfaces by controlling ice formation. *Advanced Materials Interfaces*, 8(17), 2100327.
- [40] Rekuvienė, R., Saeidiharzand, S., Mažeika, L., Samaitis, V., Jankauskas, A., Sadaghiani, A. K., Gharib, G., Muganlı, Z., & Koşar, A. (2024). A review on passive and active anti-icing and de-icing technologies. *Science of the Total Environment*, 901, 167061.
- [41] Zohuri, B. (2021). Electromagnetic pump. ResearchGate. https://www.researchgate.net/publication/353385701_Electromagnetic_Pump
- [42] McCarville, D. A., Guzman, J. C., Dillon, A. K., Jackson, J. R., & Birkland, J. O. (2017). Design, manufacture and test of cryotank components (NASA Technical Reports, Document No. 20170012407). NASA. <https://ntrs.nasa.gov/api/citations/20170012407/downloads/20170012407.pdf>
- [43] Costa, P., Nunes-Pereira, J., Oliveira, J., Silva, J., Moreira, J. A., Carabineiro, S. A. C., Buijnsters, J. G., & Lanceros-Mendez, S. (2017). High-performance graphene-based carbon nanofiller/polymer composites for piezoresistive sensor applications. *Composites Science and Technology*, 152, 35-44. <https://doi.org/10.1016/j.compscitech.2017.08.001>

[44] Barber-Nichols. (n.d.). Liquid hydrogen pumps. Barber-Nichols. Published online at <https://barber-nichols.com/products/pumps/cryogenic-pumps/liquid-hydrogen-pumps/>

Appendix A: Fuzzy Rule-Based Risk Number Based on Integer Risk Factors

Table A.1 – Combination modes of risk factors [31]

Severity	Occurrence	Detection	Fuzzy Rule -based RPN
10	10	10	10.000000000000
10	9	10	9.75182598539
10	10	9	9.56955204735
9	10	10	9.67986285310
10	9	9	9.30158532168
10	8	10	9.49043730670
9	10	9	9.22371921861
10	7	10	9.20004921765
9	9	10	9.41816741363
9	8	10	9.12170460573
8	10	10	9.33638327030
10	10	8	9.09321880487
10	9	8	8.82597937914
8	9	10	9.04463249995
10	8	9	9.01836702247
9	10	8	8.74811726587
7	10	10	8.96883294180
10	10	7	8.61688537659
10	8	8	8.54228452421
10	7	9	8.72407816802
10	9	7	8.35058595483
9	9	9	8.94188639559
9	8	9	8.64575430553
10	6	10	8.91632212713
8	10	9	8.86026013382
8	9	9	8.56865221223
10	7	8	8.24834825869
10	5	10	8.62291734166
7	10	9	8.49277192957
9	7	10	8.84268956971
9	6	10	8.54395419479
8	8	10	8.76075001755
8	7	10	8.46645706240
10	6	9	8.44017402190
9	10	7	8.27272902902
9	9	8	8.46564035888
7	9	10	8.67929048345

Table A.1 – Combination modes of risk factors (cont.)

7	8	10	8.39042610759
6	10	10	8.59929682428
6	9	10	8.31586136454
9	8	8	8.17005890390
5	10	10	8.24276259666
10	5	9	8.14671938924
10	4	10	8.33786847872
8	10	8	8.38427700454
9	7	9	8.36637434502
9	6	9	8.06777184665
8	9	8	8.09290681365
9	5	10	8.26433405182
10	3	10	8.04616979764
10	10	6	8.14055211991
8	8	9	8.28447930094
9	4	10	7.96644637256
10	8	7	8.06627535755
8	7	9	7.99027024481
10	9	6	7.87537275498
7	10	8	8.01689202932
7	9	9	8.20306955268
8	5	10	7.88838191029
8	6	10	8.18574104582
7	8	9	7.91421474681
9	10	6	7.79752195535
7	7	10	8.10319257118
6	10	9	8.12310560576
10	10	5	7.66421872548
6	8	10	8.02230309397
7	6	10	7.81197658724
6	9	9	7.83960538691
10	8	6	7.59032814371
10	7	7	7.77289214481
6	7	10	7.73723027275
9	9	7	7.98943394733
10	6	8	7.96414902821
5	10	9	7.76644192835
9	8	7	7.69465297098
8	10	7	7.90845277544
8	9	7	7.61742822585
5	8	10	7.66414301718
5	9	10	7.94307273183
7	10	7	7.54121795069

Table A.1 – Combination modes of risk factors (cont.)

10	5	8	7.67076926531
10	7	6	7.29770803686
10	9	5	7.40025299719
10	6	7	7.48826405647
9	7	8	7.89007095498
4	10	10	7.86550139158
9	6	8	7.59186588300
8	8	8	7.80832306699
8	7	8	7.51435155148
7	9	8	7.72705435126
7	8	8	7.43822643381
9	9	6	7.51326666505
6	10	8	7.64717454731
10	4	9	7.86162785736
6	9	8	7.36349056449
10	5	7	7.19513493008
3	10	10	7.50320015836
4	9	10	7.58637278080
5	10	8	7.29014370627
9	5	9	7.78803470565
10	3	9	7.56969272169
9	4	9	7.48994271943
9	7	7	7.41378132733
8	5	9	7.41187488222
8	6	9	7.70936261805
10	4	8	7.38555657413
9	8	6	7.21953464800
7	7	9	7.62674805734
6	8	9	7.54581569628
7	6	9	7.33548938647
6	7	9	7.26078610153
9	6	7	7.11631210184
9	10	5	7.32240886228
5	8	9	7.18776507776
5	9	9	7.46656565256
9	5	8	7.31179693029
10	3	8	7.09343096164
10	2	10	7.75927122389
8	10	6	7.43278628372
8	8	7	7.33231288129
4	10	9	7.38899783295
9	3	10	7.68569094600
10	1	10	7.46998692196

Table A.1 – Combination modes of risk factors (cont.)

8	4	10	7.61144449274
9	2	10	7.38939040450
3	10	9	7.02650790318
4	9	9	7.10990675059
7	5	10	7.52772723076
8	3	10	7.31062654566
8	7	7	7.03877460233
6	6	10	7.44584264387
7	4	10	7.23369536638
8	9	6	7.14221474196
9	4	8	7.01369422436
5	7	10	7.36579077345
6	5	10	7.15859690371
10	2	9	7.28281184138
4	8	10	7.28757159937
5	6	10	7.08533113254
7	9	7	7.25130133767
3	9	10	7.21118511645
4	7	10	7.01241285943
8	5	8	6.93562807566
8	6	8	7.23305163082
2	10	10	7.13663129651
3	8	10	6.92814325005
1	10	10	6.76548796540
2	9	10	6.84583496043
7	8	7	6.96252259457
9	3	9	7.20929089967
10	1	9	6.99322500732
9	1	10	7.10691395785
7	7	8	7.15047004757
7	10	6	7.06574835986
6	8	8	7.06955908751
7	6	8	6.85923269195
8	4	9	7.13506063903
9	2	9	6.91251123510
6	10	7	7.17157498449
8	1	10	6.73345752630
8	2	10	7.03493622750
10	8	5	7.11441320636
6	7	8	6.78450794256
10	10	4	7.18788539677
5	8	8	6.71145387787
5	9	8	6.99031886829

Table A.1 – Combination modes of risk factors (cont.)

7	5	9	7.05109411213
8	3	9	6.83370764656
10	9	4	6.92507367033
7	2	10	6.65586743313
7	3	10	6.95298291475
6	9	7	6.88755611339
4	10	8	6.91274929673
9	10	4	6.84723587821
6	6	9	6.96903778537
7	4	9	6.75681426273
10	7	5	6.82272969127
6	4	10	6.87009170709
9	9	5	7.03712918327
10	8	4	6.63847780664
9	8	5	6.74463384370
8	10	5	6.95723922861
10	6	6	7.01251816733
5	7	9	6.88889170024
6	5	9	6.68183112061
8	9	5	6.66720171864
5	10	7	6.81387492074
6	3	10	6.58023865611
10	10	3	6.71155209649
7	10	5	6.59043335706
3	10	8	6.54993096930
4	9	8	6.63348326396
5	5	10	6.78916182213
4	8	9	6.81065583654
5	6	9	6.60875819512
10	6	5	6.53687738512
3	9	9	6.73433018910
4	7	9	6.53602670831
10	5	6	6.71986243387
10	7	4	6.34779453226
4	6	10	6.71019330510
5	4	10	6.50657120325
9	7	6	6.93750527230
9	6	6	6.64116184491
2	10	9	6.65991472981
3	8	9	6.45130800705
8	8	6	6.85646998550
8	7	6	6.56358916507
10	4	7	6.90970149178

Table A.1 – Combination modes of risk factors (cont.)

7	9	6	6.77584873538
7	8	6	6.48714455730
9	5	7	6.83563833943
10	3	7	6.61748337705
6	10	6	6.69635525720
4	5	10	6.43486510272
9	4	7	6.53781781450
6	9	6	6.41182805702
1	10	9	6.28816454519
2	9	9	6.36868729439
8	5	7	6.45976064705
8	6	7	6.75683973149
5	10	6	6.33763942489
10	5	5	6.24493491669
3	7	10	6.63318612334
7	7	7	6.67443522631
9	9	4	6.56099803959
6	8	7	6.59363915091
7	6	7	6.38331205112
10	2	8	6.80654127052
10	4	6	6.43409389922
10	9	3	6.44962348821
6	7	7	6.30847189601
3	6	10	6.35381019347
9	3	8	6.73299072838
10	1	8	6.51660082523
5	8	7	6.23524023211
5	9	7	6.51445162281
8	4	8	6.65869289330
9	2	8	6.43580752685
4	10	7	6.43687254891
9	7	5	6.46123938642
7	5	8	6.57455728973
8	3	8	6.35697700210
3	10	7	6.07356049800
4	9	7	6.15713621892
6	6	8	6.49238447627
7	4	8	6.28010927205
5	7	8	6.41217449443
6	5	8	6.20520437371
10	2	7	6.33054601713
4	8	8	6.33392732401
7	9	6	6.77584873538

Table A.1 – Combination modes of risk factors (cont.)

7	8	6	6.48714455730
9	5	7	6.83563833943
10	3	7	6.61748337705
6	10	6	6.69635525720
4	5	10	6.43486510272
9	4	7	6.53781781450
6	9	6	6.41182805702
1	10	9	6.28816454519
2	9	9	6.36868729439
8	5	7	6.45976064705
8	6	7	6.75683973149
5	10	6	6.33763942489
10	5	5	6.24493491669
3	7	10	6.63318612334
7	7	7	6.67443522631
9	9	4	6.56099803959
6	8	7	6.59363915091
7	6	7	6.38331205112
10	2	8	6.80654127052
10	4	6	6.43409389922
10	9	3	6.44962348821
6	7	7	6.30847189601
3	6	10	6.35381019347
9	3	8	6.73299072838
10	1	8	6.51660082523
5	8	7	6.23524023211
5	9	7	6.51445162281
8	4	8	6.65869289330
9	2	8	6.43580752685
4	10	7	6.43687254891
9	7	5	6.46123938642
7	5	8	6.57455728973
8	3	8	6.35697700210
3	10	7	6.07356049800
4	9	7	6.15713621892
6	6	8	6.49238447627
7	4	8	6.28010927205
5	7	8	6.41217449443
6	5	8	6.20520437371
10	2	7	6.33054601713
4	8	8	6.33392732401
5	6	8	6.13226228198

Table A.1 – Combination modes of risk factors (cont.)

2	7	10	6.27063896309
2	8	10	6.55814025021
3	9	8	6.25764295981
4	7	8	6.05964288265
9	8	4	6.26977868714
2	10	8	6.18332137380
3	8	8	5.97449513143
9	5	6	6.35957009207
10	3	6	6.14195313691
9	6	5	6.16639633925
1	10	8	5.81088527367
2	9	8	5.89157593681
9	3	7	6.25683635946
10	1	7	6.04022314042
9	1	8	6.15373532280
9	1	9	6.63027561131
1	8	10	6.18948228523
1	9	10	6.48505570764
8	8	5	6.38078652256
8	1	9	6.25610177795
8	2	9	6.55854521162
7	2	9	6.17852803393
7	3	9	6.47626686655
9	4	6	6.06243579490
9	10	3	6.37179053776
8	10	4	6.48171728281
6	4	9	6.39302261847
8	7	5	6.08877705059
8	4	7	6.18235435786
9	2	7	5.95941769973
6	3	9	6.10305227501
5	5	9	6.31187636207
4	6	9	6.23282814261
5	4	9	6.02967450928
7	1	10	6.37891657582
4	5	9	5.95839476472
6	2	10	6.29514661377
3	7	9	6.15587792729
3	6	9	5.87699034962
5	3	10	6.21339122101
8	5	6	5.98439734400
8	6	6	6.28075908923
2	7	9	5.79331856458

Table A.1 – Combination modes of risk factors (cont.)

2	8	9	6.08102568955
4	4	10	6.13365038084
7	9	5	6.30068252283
8	1	8	5.77879161926
8	2	8	6.08217271733
3	5	10	6.05592411892
2	6	10	5.98021241951
1	8	9	5.71184993667
1	9	9	6.00827145133
7	5	7	6.09819294221
8	3	7	5.88058306043
1	7	10	5.90651527820
6	1	10	6.00250316139
7	7	6	6.19872332466
8	9	4	6.19223076974
7	8	5	6.01207721357
7	1	9	5.90228184960
6	8	6	6.11816648601
7	6	6	5.90783796058
7	2	8	5.70123348922
7	3	8	5.99956786650
6	6	7	6.01600234445
7	4	7	5.80371924363
6	10	5	6.22149767617
10	10	2	6.23521872378
6	4	8	5.91598633224
10	8	3	6.16244895456
6	7	6	5.83275751388
7	10	4	6.11515082085
10	9	2	5.97367629213
5	2	10	5.92820728185
5	7	7	5.93578260610
6	5	7	5.72882628633
9	10	2	5.89584546635
6	3	8	5.62590391242
6	2	9	5.81795528048
6	9	5	5.93629686438
4	6	8	5.75550898842
5	4	8	5.55280289697
5	5	8	5.83463335778
4	8	7	5.85753370696
5	6	7	5.65590416342
5	8	6	5.75915605437

Table A.1 – Combination modes of risk factors (cont.)

5	9	6	6.03908869046
10	7	3	5.87263348845
5	1	10	5.63856646487
4	5	8	5.48193047073
10	8	2	5.68624875881
9	9	3	6.08483416842
3	9	7	5.78125564182
4	7	7	5.58326835476
3	4	10	5.78001462268
4	2	10	5.55815195394
4	3	10	5.85592598035
3	7	8	5.67861319126
9	8	3	5.79468473105
10	6	4	6.06125870621
5	10	5	5.86143576196
4	10	6	5.96148984514
3	3	10	5.47970077397
8	10	3	6.00606421833
5	3	9	5.73583188539
4	4	9	5.65591164756
8	9	3	5.71703973167
3	6	8	5.40012186375
10	5	4	5.77021295868
2	5	10	5.69625697782
3	5	9	5.57819459266
7	10	3	5.63969853093
9	7	4	5.98497572049
2	10	7	5.70694838266
3	8	7	5.49777019001
9	6	4	5.69186006337
3	10	6	5.59752002965
4	9	6	5.68091117571
8	8	4	5.90519813017
8	7	4	5.61418733808
2	4	10	5.40321292487
10	6	3	5.58552457309
7	9	4	5.82568698418
2	7	8	5.31589956219
2	8	8	5.60394593979
10	4	5	5.95872234710
7	8	4	5.53719494558
2	6	9	5.50268070490
6	10	4	5.74685587417

Table A.1 – Combination modes of risk factors (cont.)

9	5	5	5.88358807108
10	3	5	5.66690601622
6	9	4	5.46088292292
9	4	5	5.58762605519
1	10	7	5.33377941178
2	9	7	5.41460721739
5	10	4	5.38525102710
8	5	5	5.50961757617
8	6	5	5.80483047023
1	6	10	5.61446266727
7	7	5	5.72338526394
6	8	5	5.64321157466
7	6	5	5.43288075548
10	2	6	5.85491657317
10	4	4	5.48349138834
6	7	5	5.35741546223
1	8	8	5.23408785008
1	9	8	5.53150725595
5	8	5	5.28322174702
5	9	5	5.56430951908
9	3	6	5.78087560803
10	1	6	5.56423950612
1	7	9	5.42936997988
4	10	5	5.48667900466
8	4	6	5.70606226725
9	2	6	5.48352973013
7	5	6	5.62210422508
8	3	6	5.40472750186
3	10	5	5.12194658737
4	9	5	5.20485880634
6	6	6	5.54005374712
7	4	6	5.32783284234
5	7	6	5.45991087481
6	5	6	5.25284578859
9	1	7	5.67737043122
10	2	5	5.37971055669
1	5	10	5.32868840257
10	10	1	5.75888540168
4	8	6	5.38167558800
5	6	6	5.17976631551
10	5	3	5.29538331225
8	1	7	5.30166052908
8	2	7	5.60583343655

Table A.1 – Combination modes of risk factors (cont.)

3	9	6	5.30534788148
4	7	6	5.10691493443
2	10	6	5.23092772717
3	8	6	5.02124622572
7	2	7	5.22411514471
7	3	7	5.52293592970
1	10	6	4.85707006125
2	9	6	4.93796460970
10	7	2	5.39691644796
6	4	7	5.43907892584
9	5	4	5.40765738438
10	3	4	5.19228275091
6	3	7	5.14890494920
5	5	7	5.35755711739
4	6	7	5.27837054970
5	4	7	5.07602995068
9	1	6	5.20128595290
7	1	8	5.42561695898
4	5	7	5.00549017692
3	7	7	5.20151918975
3	6	7	4.92322550218
6	1	9	5.52489296123
9	7	3	5.50870078703
9	3	5	5.30513897712
10	1	5	5.08881353526
6	2	8	5.34067822543
2	7	7	4.83842400800
2	8	7	5.12700301110
1	8	7	4.75625134083
1	9	7	5.05482203568
5	3	8	5.25815009837
9	4	4	5.11331840628
4	4	8	5.17803256095
3	5	8	5.10032563888
9	9	2	5.60858993174
8	1	6	4.82493890201
8	2	6	5.12954715306
9	6	3	5.21720369810
8	9	2	5.24130691566
8	10	2	5.53008851904
9	8	2	5.31900295638
2	6	8	5.02502931631
5	2	9	5.45092744577

Table A.1 – Combination modes of risk factors (cont.)

8	4	5	5.22983592673
9	2	5	5.00835199025
7	1	7	4.94893479786
1	7	8	4.95214358884
5	1	9	5.16095318548
8	5	4	5.03534978251
8	6	4	5.32903519692
8	8	3	5.42955994089
6	1	8	5.04715525016
4	3	9	5.37916511296
10	9	1	5.49706835520
7	10	2	5.16382836635
4	2	9	5.08025245347
4	1	10	5.27748695257
3	4	9	5.30338803850
7	2	6	4.74739972684
7	3	6	5.04645722996
3	3	9	5.00173203576
1	4	10	5.04036101269
2	2	10	4.82741238594
2	3	10	5.12246124290
3	1	10	4.90467718508
3	2	10	5.20630555313
2	5	9	5.21897469237
7	5	5	5.14640558858
8	3	5	4.92963386802
1	3	10	4.75193667141
8	7	3	5.13948111622
2	4	9	4.92539193219
7	7	4	5.24837517452
1	6	9	5.13674166386
7	9	3	5.35060203519
1	5	9	4.85123213861
9	10	1	5.41923601554
7	8	3	5.06221572929
6	4	6	4.96246615808
1	1	10	4.57017488311
1	2	10	4.59166178552
2	1	10	4.59746465647
6	6	5	5.06471868966
7	4	5	4.85265918941
6	8	4	5.16871090826
7	6	4	4.95837705584

Table A.1 – Combination modes of risk factors (cont.)

5	2	8	4.97355308454
6	10	3	5.27210102928
4	1	9	4.80041685829
6	3	6	4.67224764111
6	7	4	4.88240009525
10	8	1	5.20982071685
6	2	7	4.86335201253
5	7	5	4.98477527125
6	5	5	4.77742799151
5	5	6	4.88086218222
6	9	3	4.98540757517
5	3	7	4.78039807137
5	1	8	4.68309727037
10	7	1	4.92037039652
4	4	7	4.70007295745
9	9	1	5.13222581416
5	8	4	4.80741895148
5	9	4	5.09004251414
10	6	2	5.10950623569
4	8	5	4.90657531331
5	6	5	4.70394024918
9	8	1	4.84244473675
3	2	9	4.72996966806
4	6	6	4.80164534774
5	4	6	4.59948265300
8	10	1	5.05363172910
5	10	3	4.90905640906
8	9	1	4.76476631322
4	3	8	4.90236153391
7	10	1	4.68733516653
3	5	7	4.62237669652
10	6	1	4.63306417332
4	5	6	4.52910479020
3	7	6	4.72481562156
4	10	4	5.01236990010
10	5	2	4.81998073818
3	9	5	4.83011881064
4	7	5	4.63060093140
9	7	2	5.03239813706
9	6	2	4.74190838497
8	8	2	4.95365687976
7	8	2	4.58672057230
7	9	2	4.87504142910

Table A.1 – Combination modes of risk factors (cont.)

8	7	2	4.66415494214
6	10	2	4.79674475730
3	6	6	4.44635586471
4	2	8	4.60205606222
6	9	2	4.50960531380
5	10	2	4.43280892072
2	6	7	4.54730927264
3	1	9	4.42678661842
10	4	2	4.53249022451
10	4	3	5.00818679144
3	10	4	4.64691605121
4	9	4	4.72900718299
2	10	5	4.75540573498
3	8	5	4.54509669162
3	4	8	4.82670584132
9	5	3	4.93169983311
10	3	3	4.71777868175
2	7	6	4.36100264791
2	8	6	4.65037297727
9	4	3	4.63915193826
7	7	3	4.77345733217
8	5	3	4.56122593878
8	6	3	4.85327746534
6	8	3	4.69433797857
7	6	3	4.48400085949
3	3	8	4.52345327725
6	7	3	4.40747656919
5	8	3	4.33165311881
5	9	3	4.61591951984
1	10	5	4.38109931193
2	9	5	4.46192949351
10	2	4	4.90487605370
4	10	3	4.53820186440
10	5	1	4.34355384630
9	3	4	4.82959900085
10	1	4	4.61403582881
3	10	3	4.17227799557
4	9	3	4.25330067134
2	5	8	4.74151251017
2	3	9	4.64542994200
1	7	7	4.47487068146
8	4	4	4.75368604206
9	2	4	4.53399985951

Table A.1 – Combination modes of risk factors (cont.)

1	8	6	4.27848614333
1	9	6	4.57831743683
7	5	4	4.67116041556
8	3	4	4.45542593288
10	2	3	4.43014599710
6	6	4	4.59009684812
7	4	4	4.37831406945
2	4	8	4.44728891518
5	7	4	4.51049538073
6	5	4	4.30266430638
9	1	5	4.72559836258
4	8	4	4.43235599354
5	6	4	4.22847661853
8	1	5	4.34897999274
8	2	5	4.65333594569
3	9	4	4.35567868135
4	7	4	4.15434810750
9	7	1	4.55605419593
7	2	5	4.27143483212
7	3	5	4.57026404362
2	10	4	4.28046341562
3	8	4	4.06952823335
6	4	5	4.48640226459
1	10	4	3.90627478547
2	9	4	3.98683713439
2	2	9	4.34958648183
6	3	5	4.19622670989
5	5	5	4.40487753050
1	6	8	4.65875760548
4	6	5	4.32568988671
5	4	5	4.12335563418
9	1	4	4.25037213824
7	1	6	4.47226920139
9	5	2	4.45559908867
10	3	2	4.24278217628
4	5	5	4.05282163274
9	6	1	4.26547071223
3	7	5	4.24883930017
3	6	5	3.96963243912
6	2	6	4.38607291094
2	7	5	3.88387792617
2	8	5	4.17432574447
6	1	7	4.56934438731

Table A.1 – Combination modes of risk factors (cont.)

5	3	6	4.30271335000
1	8	5	3.80111133080
1	9	5	4.10214924153
8	8	1	4.47728028755
4	4	6	4.22219050156
1	5	8	4.37356297176
1	4	9	4.56283585950
3	5	6	4.14450439142
2	6	6	4.06965500356
8	7	1	4.18772036925
1	7	6	3.99764233364
9	4	2	4.16440215606
5	2	7	4.49612449901
7	1	5	3.99569418524
6	1	6	4.09160360852
5	1	7	4.20495794620
7	9	1	4.39863041992
4	3	7	4.42553346326
4	2	7	4.12351288683
1	3	9	4.27438207243
3	4	7	4.34995871124
3	3	7	4.04481240485
2	4	7	3.96885649983
2	5	7	4.26384020815
1	6	7	4.18046628571
1	5	7	3.89564516746
8	5	2	4.08650730684
8	6	2	4.37736476686
7	7	1	4.11030297997
4	1	8	4.32320704832
3	2	8	4.25363321749
9	3	3	4.35411430374
10	1	3	4.13972677302
7	7	2	4.29815843582
6	10	1	4.32031321178
8	1	4	3.87420473238
8	2	4	4.17721202051
3	1	8	3.94853025442
2	2	8	3.87140997605
2	3	8	4.16823463504
1	4	8	4.08503071852
1	3	8	3.79654060122
6	8	2	4.21943731154

Table A.1 – Combination modes of risk factors (cont.)

7	6	2	4.00909780472
4	1	7	3.84583410899
6	9	1	4.03321858272
1	1	8	3.61053239876
1	1	9	4.09069527451
1	2	8	3.63686387163
1	2	9	4.11436720984
2	1	8	3.64397509390
2	1	9	4.12076018279
6	7	2	3.93217351839
6	2	5	3.90905166112
5	2	6	4.01874785920
5	10	1	3.95646693167
7	2	4	3.79663466263
7	3	4	4.09451394571
5	8	2	3.85573449892
5	9	2	4.14120150878
8	4	3	4.27759141206
9	2	3	4.06024459350
4	10	2	4.06345093633
10	4	1	4.05609287201
7	5	3	4.19624305937
8	3	3	3.98185830582
6	4	4	4.01119016170
6	6	3	4.11599061487
7	4	3	3.90456793010
5	3	5	3.82539707197
3	10	2	3.69745106627
4	9	2	3.77752430953
6	3	4	3.72119336461
5	7	3	4.03683411912
6	5	3	3.82837350366
4	8	3	3.95877355257
5	6	3	3.75327500128
5	5	4	3.92999515597
3	9	3	3.88180891000
4	7	3	3.67816522767
5	1	6	3.72651905320
2	10	3	3.80594016251
3	8	3	3.59462427336
4	6	4	3.85092897381
5	4	4	3.64788084640
10	2	2	3.95498433642

Table A.1 – Combination modes of risk factors (cont.)

3	2	7	3.77729621034
9	5	1	3.97924235289
10	3	1	3.76656007988
1	10	3	3.43276106404
2	9	3	3.51282289389
4	5	4	3.57669713596
4	4	5	3.74473040072
9	3	2	3.87840114152
10	1	2	3.66519219382
4	3	6	3.94872884763
3	7	4	3.77399158239
3	6	4	3.49327674678
9	4	1	3.68820059786
8	4	2	3.80147016741
9	2	2	3.58620211340
9	1	3	3.77547944955
3	5	5	3.66705167319
4	2	6	3.64460315676
2	7	4	3.40749924770
2	8	4	3.69918295517
3	1	7	3.46978107740
7	5	2	3.72116794295
8	3	2	3.50798256250
1	8	4	3.32471832761
1	9	4	3.62650311407
3	4	6	3.87314293089
8	5	1	3.61030834651
8	6	1	3.90106641405
6	6	2	3.64163626428
7	4	2	3.43053356087
2	6	5	3.59236087331
8	1	3	3.40078307904
8	2	3	3.70115118473
3	3	6	3.56578877238
2	3	7	3.69081844835
7	7	1	3.82191117010
7	1	4	3.51934699382
5	7	2	3.56287517165
6	5	2	3.35385514595
1	7	5	3.52065799677
2	5	6	3.78594580080
7	2	3	3.32316646377
7	3	3	3.61927054346

Table A.1 – Combination modes of risk factors (cont.)

6	8	1	3.74322319259
7	6	1	3.53288350193
2	4	6	3.49007589951
6	4	3	3.53695214753
6	1	5	3.61424655559
4	8	2	3.48488464572
5	6	2	3.27794729249
6	7	1	3.45592593280
2	2	7	3.39276111763
6	3	3	3.24728941953
1	6	6	3.70185018600
6	2	4	3.43267890945
5	5	3	3.45637332919
5	8	1	3.37943569020
5	9	1	3.66500259626
1	5	6	3.41746453368
3	9	2	3.40766468127
4	7	2	3.20200796938
1	4	7	3.60684840913
4	6	3	3.37753413356
5	4	3	3.17315195424
5	2	5	3.54165566227
4	5	3	3.10075409632
4	10	1	3.58724928991
5	3	4	3.34900742144
4	1	6	3.36828871400
1	3	7	3.31831263242
3	7	3	3.30043452821
2	10	2	3.33121524909
3	8	2	3.11996391422
5	1	5	3.24785368767
3	6	3	3.01758322723
3	10	1	3.22148123743
4	9	1	3.30132538839
1	1	7	3.12945353858
1	2	7	3.15908067139
2	1	7	3.16708193770
4	4	4	3.26833251276
3	2	6	3.30095857230
2	7	3	2.93246394248
2	8	3	3.22507448640
4	3	5	3.47205271206
1	10	2	2.95972789665

Table A.1 – Combination modes of risk factors (cont.)

2	9	2	3.03920389840
3	5	4	3.19065420921
4	2	5	3.16541631425
3	1	6	2.99036064782
10	2	1	3.47874851591
3	4	5	3.39627525288
9	3	1	3.40211942967
10	1	1	3.18929290719
8	4	1	3.32518802807
9	2	1	3.11042156686
2	6	4	3.11597249472
7	5	1	3.24513822809
8	3	1	3.03224224778
1	8	3	2.85009322417
1	9	3	3.15145403003
6	6	1	3.16578046563
7	4	1	2.95475496963
3	3	5	3.08647577886
5	7	1	3.08711478083
6	5	1	2.87795976986
2	3	6	3.21310137108
4	8	1	3.00914115443
5	6	1	2.80185662322
3	9	1	2.93185958122
4	7	1	2.72574651176
9	1	2	3.30042625515
2	10	1	2.85527003189
3	8	1	2.64431339055
2	5	5	3.30788348308
1	7	4	3.04428736497
8	1	2	2.92785767210
8	2	2	3.22505997302
1	10	1	2.48474148410
2	9	1	2.56397838976
2	2	6	2.91346888589
7	2	2	2.85018657890
7	3	2	3.14421288743
2	4	5	3.01103208077
9	1	1	2.82440182506
6	4	2	3.06307123826
6	3	2	2.77379952083
5	5	2	2.98321363080
4	6	2	2.90464010997

Table A.1 – Combination modes of risk factors (cont.)

5	4	2	2.69869650566
1	6	5	3.22298855447
1	4	6	3.12815234442
4	5	2	2.62487756227
3	7	2	2.82735064380
7	1	3	3.04341004956
3	6	2	2.54256827904
2	7	2	2.45880531354
2	8	2	2.75134520533
1	8	2	2.37727986165
1	9	2	2.67662381643
6	2	3	2.95747388767
8	1	1	2.45291524031
8	2	1	2.74878507376
1	5	5	2.93908521539
6	1	4	3.13785457231
5	3	3	2.87428630945
7	1	2	2.56789349992
4	4	3	2.79384729794
3	5	3	2.71615687893
2	6	3	2.64121503641
1	3	6	2.83955824140
7	2	1	2.37522191338
7	3	1	2.66840021378
1	7	3	2.56902176606
5	2	4	3.06527885166
6	1	3	2.66320032394
5	1	4	2.76928348358
4	3	4	2.99569973554
6	4	1	2.58773883391
6	2	2	2.48346553977
4	2	4	2.68634590660
3	4	4	2.91942939628
3	3	4	2.60728436463
2	5	4	2.82989172464
6	3	1	2.29862670249
5	5	1	2.50817557666
2	4	4	2.53209885679
4	1	5	2.89061296147
1	6	4	2.74423009115
3	2	5	2.82462048351
5	3	2	2.40127511013
4	6	1	2.42971048689

Table A.1 – Combination modes of risk factors (cont.)

5	4	1	2.22312961535
1	5	4	2.46078937835
3	1	5	2.51003102910
2	3	5	2.73497677606
4	5	1	2.14873068105
3	7	1	2.35234353281
2	2	5	2.43330521652
4	4	2	2.32132219422
5	2	3	2.59019017059
3	6	1	2.06710064236
1	4	5	2.64876043298
4	1	4	2.41299198358
2	1	6	2.69004117760
1	2	6	2.68091516451
1	1	6	2.64712331310
1	3	5	2.36009080942
3	5	2	2.24360681775
2	7	1	1.98422825987
2	8	1	2.27607468737
5	1	3	2.29166967546
1	1	5	2.16306678349
1	2	5	2.20222222444
2	1	5	2.21279675800
1	8	1	1.90325782386
1	9	1	2.20090397242
2	6	2	2.16812896489
4	3	3	2.51992860923
4	2	3	2.20844576707
1	7	2	2.09488863124
3	4	3	2.44280265891
7	1	1	2.09209650276
3	2	4	2.34828259135
3	3	3	2.12931495859
6	2	1	2.00865885457
2	5	3	2.35260903680
6	1	2	2.19032692380
5	3	1	1.92712316958
4	4	1	1.84748943112
2	4	3	2.05427724905
3	1	4	2.02853597246
3	5	1	1.76975766483
2	6	1	1.69392785500
5	2	2	2.11642158917

Table A.1 – Combination modes of risk factors (cont.)

1	6	3	2.26650851771
1	7	1	1.61999999722
5	1	2	1.81633328981
6	1	1	1.71626545871
4	3	2	2.04475379367
2	3	4	2.25632979938
4	2	2	1.73333231720
1	5	3	1.98333263365
3	4	2	1.96669774423
2	2	4	1.95202450562
3	3	2	1.65425543826
2	5	2	1.87701484249
4	1	3	1.93592155178
2	4	2	1.57910265206
1	4	4	2.16847654932
1	6	2	1.79125603754
5	2	1	1.64177232858
3	2	3	1.87194664195
1	5	2	1.50787395388
1	3	4	1.87970938154
3	1	3	1.54585637791
5	1	1	1.34181018928
2	3	3	1.77715187870
4	1	2	1.46016208878
4	3	1	1.56918117045
2	2	3	1.46960844465
1	4	3	1.68728607544
2	1	4	1.73527904543
1	1	4	1.67669350170
1	2	4	1.72282147222
4	2	1	1.25921401772
1	3	3	1.39839897402
3	4	1	1.49077917566
3	3	1	1.18023506571
2	5	1	1.40202362151
1	1	3	1.18779319981
1	2	3	1.24264865688
2	1	3	1.25746322307
2	4	1	1.10487333250
3	2	2	1.39561531135
1	6	1	1.31688529008
1	5	1	1.03312881342
3	1	2	1.06300794946

Table A.1 – Combination modes of risk factors (cont.)

2	3	2	1.29789827624
4	1	1	0.98487080231
2	2	2	0.98703056198
1	4	2	1.20596638073
3	2	1	0.91928565702
1	3	2	0.91695616013
3	1	1	0.58086171979
1	2	2	0.76284106248
2	1	2	0.77978841901
1	1	2	0.70008829765
2	3	1	0.81895943139
2	2	1	0.50512572239
1	4	1	0.72518412038
1	3	1	0.43606405915
2	1	1	0.30564266254
1	2	1	0.29217331070
1	1	1	0.24229892070