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MASTER'S THESIS

Development of a Methodology for the Resilience Assessment of Alternative Maritime Fuel Transport and Port Infrastructure

Submitted by

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Abstract

The implementation of alternative fuel options in the maritime sector is essential, not only from the perspective of emissions and environmental pollution reduction, but also from supply resilience. In this sense, methanol and ammonia are two of the most promising and studied alternatives. However, experience in their utilization as maritime fuels is still limited. Therefore, it is essential to work towards their safe and successful deployment, considering the risks associated with them.

Resilience assessment methods provide the opportunity to analyze system performance and reliability in a comprehensive manner, as they focus not only on pre-failure scenarios, but also post-failure phases. Within the existing quantitative resilience assessment methods, one of the most widely used in literature are Bayesian Networks (BNs), which stand out for their ability to handle causalities between different variables in probabilistic terms, as well as for their adaptability and capacity to evaluate system behavior over time.

In this context, the main objective of this work was to develop a methodology to quantitatively analyze the resilience of the ammonia and methanol transport, storage and bunkering stages of the supply chain for the maritime sector based on the creation of a BN model. This was achieved via the derivation of a bow-tie (BT) model, from which indicators for possible disruptions to the systems, as well as for their resilience attributes (i.e., their absorption, adaptation and restoration capacities) were identified. All of these elements were incorporated into two BN models: one for methanol- and another for ammonia-based systems.

While the developed models still require the input of the prior and conditional probabilities of the elements included within them before being able to be applied, they constitute a base that can be utilized to structure and program the BNs using software solutions, allowing to perform probabilistic resilience assessments in the future. The derivation of the models also led to the identification of central disruptions that the analyzed systems might incur into, with fuel releases standing out as the most prominent within them, especially when originating from damages to the fuel transfer or storage infrastructure. Additionally, it was possible to understand the differences and similarities between methanol- and ammonia-based systems, as well as to generate recommendations for improving their resilience based on the analysis of their attributes.

Compared to the existing work in literature, the methodology presented offers the advantage of incorporating processes from multiple stages of the supply chain, whereas previous analyses have been limited to specific processes or supply chain stages, such as fuel bunkering or storage only. Additionally, it was developed specifically for resilience assessment, rather than risk assessment, which focuses exclusively on pre-disruption stages.

Future lines of work for the models include their application to analyze specific case studies of interest; to consider possible interdependencies between different supply chain stages; to convert the models from static to dynamic by incorporating a temporal dimension as well as the learning capacity of the system; and lastly to explore the use of artificial intelligence (AI) and machine learning (ML) tools to enhance the resilience assessment of the systems.

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Declaration of originality

I hereby certify that I have written this thesis myself and that I have not used any sources other than those specified and have not made use of any unauthorized external help. Furthermore, the work was not produced using unrecognizable generative AI. Furthermore, I assure that I have followed the general principles of scientific / academic work and publication as laid down in the guidelines of good academic practice of the University of Oldenburg.

I further declare that the work has not yet been submitted in the same or a similar form to any examining authority.

Oldenburg, 22nd of September 2025 Juan Sebastián Márquez Torres

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LIST OF CONTENTS

LIST OF CONTENTS 6
LIST OF FIGURES 8
LIST OF TABLES 10
LIST OF EQUATIONS 10
LIST OF ABBREVIATIONS 11
1. INTRODUCTION 12
1.1. General context and motivation.. 12
1.2. Scope of work and objectives... 14
2. THEORY 16
2.1 Methanol as an alternative maritime fuel 16
Methanol description and production methods........................... 16
Methanol as an alternative maritime fuel & key considerations .. 17
2.2 Ammonia as an alternative maritime fuel................................. 19
Ammonia description and production methods 19
Ammonia as an alternative maritime fuel & key considerations.. 20
2.3 Quantitative Resilience Assessment through Bayesian Networks 23
Definition of Resilience and its importance............................... 23
Quantitative Resilience Assessment Methods and Bayesian Networks 25
Main considerations of Bayesian Networks for quantitative resilience assessment.. 26
Creation of Bayesian Networks for Resilience Assessment 29
Assignment of weighting factors for deriving CPTs................... 30
3. METHODOLOGY 33
3.1 Definition of the system 33
3.2 Conceptualization of the resilience assessment model.............. 37
3.3 Derivation of the BT and BN models.. 42
3.4 Method for the assignment of weighting factors within the BNs 50
4. RESULTS 54
4.1 Fault trees 54
4.2 Event trees 68
4.3 Restoration measures 95
4.4 BN Models... 99
4.5 Assignation of weighting factors to the BN 110

5. DISCUSSION 113

5.1 Requirements and insights for the application of the model to case studies 113

5.2 Comparison with existent models 115

5.3 Main insights derived from the models 116

5.4 Exclusions and possible extensions to the model 121

5.5 Outlook and future work 123

6. CONCLUSIONS 126

7. REFERENCES 128

LIST OF FIGURES

Figure 1. Summary of the main methanol production pathways.. 17
Figure 2. Summary of the main ammonia production pathways.. 20
Figure 3. Transient resilience model. 24
Figure 4. Simplified BN model for quantitative resilience assessment...................................... 28
Figure 5. Supply Chain Scope of the model.. 35
Figure 6. Example of the identification of a top event as a way to trace its basic and intermediate causes. 44
Figure 7. Example of the analysis of the sequence of events involving response mechanisms to a disruption.. 46
Figure 8. Considerations for the transformation of the BT model into the BN model................ 49
Figure 9. Flow chart of the method for assigning weighting factors to the parent nodes based on the FAHP.. 51
Figure 10. Fault tree for methanol transport processes. 54
Figure 11. Fault tree for methanol transfer processes - Part 1 of 2. 56
Figure 12. Fault tree for methanol transfer processes - Part 2 of 2. 59
Figure 13. Fault tree for methanol storage processes - Part 1 of 2... 60
Figure 14. Fault tree for methanol storage processes – Part 2 of 2. 61
Figure 15. Fault tree for ammonia transport processes. 62
Figure 16. Fault tree for ammonia transfer processes - Part 1 of 3. 64
Figure 17. Fault tree for ammonia transfer processes - Part 2 of 3. 65
Figure 18. Fault tree for ammonia transfer processes - Part 3 of 3. 66
Figure 19. Fault tree for ammonia storage processes - Part 1 of 2... 67
Figure 20. Fault tree for ammonia storage processes - Part 2 of 2... 68
Figure 21. Event tree for methanol transport processes - Part 1 of 2. 69
Figure 22. Event tree for methanol transport processes - Part 2 of 2. 71
Figure 23. Event tree for methanol transfer processes - Part 1 of 6. 72
Figure 24. Event tree for methanol transfer processes - Part 2 of 6. 74
Figure 25. Event tree for methanol transfer processes - Part 3 of 6. 75
Figure 26. Event tree for methanol transfer processes - Part 4 of 6. 76
Figure 27. Event tree for methanol transfer processes - Part 5 of 6. 77
Figure 28. Event tree for methanol transfer processes - Part 6 of 6. 78
Figure 29. Event tree for methanol storage processes - Part 1 of 5.. 79
Figure 30. Event tree for methanol storage processes - Part 2 of 5.. 80
Figure 31. Event tree for methanol storage processes - Part 3 of 5.. 82
Figure 32. Event tree for methanol storage processes - Part 4 of 5.. 83
Figure 33. Event tree for methanol storage processes - Part 5 of 5.. 84
Figure 34. Event tree for ammonia transport processes - Part 1 of 2. 85
Figure 35. Event tree for ammonia transport processes - Part 2 of 2. 86
Figure 36. Event tree for ammonia transfer processes - Part 1 of 5. 87
Figure 37. Event tree for ammonia transfer processes - Part 2 of 5. 88
Figure 38. Event tree for ammonia transfer processes - Part 3 of 5. 89
Figure 39. Event tree for ammonia transfer processes - Part 4 of 5. 90
Figure 40. Event tree for ammonia transfer processes - Part 5 of 5. 90
Figure 41. Event tree for ammonia storage processes - Part 1 of 4.. 91
Figure 42. Event tree for ammonia storage processes - Part 2 of 4.. 92
Figure 43. Event tree for ammonia storage processes - Part 3 of 4.. 93
Figure 44. Event tree for ammonia storage processes - Part 4 of 4.. 94

Figure 45. Restoration measures identified for fuel transport processes. 95
Figure 46. Restoration measures identified for fuel transfer processes. 96
Figure 47. Restoration measures identified for fuel storage processes. 98
Figure 48. Disruption node of the BN for methanol-based systems. Part 1 of 2: fuel transport and transfer processes. 100
Figure 49. Disruption node of the BN for methanol-based systems. Part 2 of 2: fuel storage processes. 101
Figure 50. Absorption node of the BN for methanol-based systems. 102
Figure 51. Adaptation node of the BN for methanol-based systems. 103
Figure 52. Restoration node of the BN for methanol-based systems. 105
Figure 53. Disruption node of the BN for ammonia-based systems. Part 1 of 2: fuel transport and transfer processes. 106
Figure 54. Disruption node of the BN for ammonia-based systems. Part 2 of 2: fuel storage processes. 107
Figure 55. Absorption node of the BN for ammonia-based systems. 108
Figure 56. Adaptation node of the BN for ammonia-based systems. 109
Figure 57. Restoration node of the BN for ammonia-based systems. 110
Figure 58. Weighting factors obtained for the parent nodes contributing to the disruptions during methanol transport processes. 112
Figure 59. DBN model for quantitative resilience assessment. 125

LIST OF TABLES

Table 1. Main characteristics of ammonia and methanol as alternative maritime fuels. 22
Table 2. Example of a CPT for a child node with 3 parent nodes.. 30
Table 3. Saaty Scale with linguistic explanation and applicable TFNs for applying the FAHP. 31
Table 4. Sequence of fuel transport, transfer and storage processes throughout the supply chain stages analyzed. 36
Table 5. Description of the main nodes of the BN. 41
Table 6. Color convention to illustrate the state of functionality of the final outcome of the event trees. 47
Table 7. Color convention to show the characteristics of the intermediate events of the event trees. 48
Table 8. Example of a pairwise linguistic comparison between 5 different parent nodes. 51
Table 9. Pairwise comparisons of the parent nodes contributing to the disruptions during methanol transport processes. 112

LIST OF EQUATIONS

Equation 1. Calculation of the synthetic extent values of the TFN components of the parent nodes. 52
Equation 2. Calculation of the fuzzy weights of each parent node. 53

LIST OF ABBREVIATIONS

ABS	American Bureau of Shipping
AI	Artificial Intelligence
ARMS	Ammonia Release Mitigation System
BN	Bayesian Network
BT	Bow-Tie Model
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPT	Conditional Probability Table
ECE	Economic Commission for Europe
ESD	Emergency Shutdown System
FAHP	Fuzzy Analytic Hierarchy Process
GHG	Greenhouse Gas
H_2	Hydrogen
IEA	International Energy Association
IMO	International Maritime Organization
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
ML	Machine Learning
PPE	Personal Protection Equipment
PRV	Pressure Relief Valve

1. INTRODUCTION

This chapter presents the general context and motivation of the work, as well as its scope and objectives.

1.1. General context and motivation

The maritime sector is responsible for approximately 80% of international freight transport, making it an essential pillar of the world's trade and connectivity (IEA 2023b). However, the majority of ships currently rely on conventional fossil fuels, mainly heavy fuel oil (HFO) and marine diesel oil (MDO), which is why maritime shipping also accounts for approximately 2.9% of global Carbon Dioxide (CO_2) emissions (IEA 2023a). However, this has begun to change in order to align with global initiatives and goals, such as the International Maritime Organization's (IMO) Net-zero Framework, approved by the Marine Environment Protection Committee (MEPC 83) in April 2025 (DNV 2025). This has reinforced various relevant aspects in the pursuit of the decarbonization and long-term sustainability of the maritime sector. Namely, new requirements on the greenhouse gas (GHG) fuel intensity for maritime ships, in combination with a pricing and reward mechanism that will begin to take effect from 2028. The designation of new Emission Control Areas (ECAs) has also been agreed (DNV 2025).

Consequently, it is of great importance to analyze and implement alternative fuel options that can allow to transition away from the use of conventional, fossil-based fuels. This is positive not only from the perspective of emissions and environmental pollution reduction, but also from supply resilience, as adopting a broader mix of fuels stimulates production and the development of infrastructure. Ultimately, this would allow to develop a diversified and sufficiently capable fuel supply ecosystem (Spiegelenberg 2025).

Two of the most promising alternative fuels for the maritime sector are methanol and ammonia. Firstly, both of them can be produced via renewable or low-carbon pathways, as synthetic fuels derived from hydrogen produced from renewable energy or incorporating Carbon Capture and Storage (CCS) technologies (DNV 2024; Kazemi Esfeh et al. 2022). This makes them suitable fuels to comply with GHG emissions standards, such as the ones enforced in the European Union by the FuelEU Maritime

Regulation (DNV 2024). Additionally, both of these chemicals are already extensively traded for industrial use, meaning that there is existing know-how and infrastructure for handling them. This makes them attractive options as alternative fuels, which is why their demand for the maritime sector is expected to further increase the share traded globally in the coming years (DNV 2023).

Nevertheless, experience with methanol- and ammonia-fueled ships is still quite limited (Wissner et al. 2023). Therefore, it is essential to take the necessary precautions to pave the way for their safe and successful deployment. This, on one hand, begins with safety regulations, which is why the IMO has developed interim guidelines for the use of methanol (IMO 2020) and ammonia (IMO 2025b) as alternative maritime fuels. Performing risk assessments is also highly relevant in order to identify potential dangers and guide ship and port infrastructure design and operation. Consequently, these types of analyses have started to emerge within literature. For instance, Wang (2024) analyzed the risk of methanol leakage in methanol dual-fuel powered ships, concluding that a considerable part of the leakage risks come from human and management factors. Complementarily, Fan et al. (2022) performed a quantitative risk assessment for ammonia ship-to-ship bunkering, which showed that toxicity has the greatest impact on the risks associated with the process. Meanwhile, Zhang et al. (2024) analyzed the potential risks of liquid ammonia tanks for storage, evidencing that human errors during the production or maintenance of the tanks, as well as component wear down due to corrosion, are the main causes of liquid ammonia leakage.

However, when trying to gather more comprehensive views of system performance and supply chain reliability, resilience assessment methods can be considered. In particular, quantitative resilience assessments not only allow to get an overall understanding of a system’s behavior when it is exposed to disruptions, but also to estimate the probability of consequences occurring given a specific disruption (known as forward causal reasoning) or, when applied reversely, to track down the probable causes of an observed outcome (known as backward diagnostic reasoning) (Wang et al. 2024b). Moreover, resilience assessment focuses not only on pre-failure scenarios, but also considers the post-failure phase; i.e., if and how systems are able to sustain or return to a normal operational state after disruptions occur, thus providing a comprehensive image of system reliability, which is highly relevant in energy supply applications (Tong et al. 2020).

While there exist various quantitative resilience assessment methods, as discussed by authors such as Ghaljahi et al. (2025), the development and application of Bayesian Networks (BN) is one of the most widespread in literature. This can be attributed to the fact that they are data-based and allow to link events and dependencies clearly and intuitively via the use of conditional probabilities (Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020). Given that this type of analysis has still not been applied to the use of methanol and ammonia as alternative maritime fuels, this master thesis presents the development of a methodology which can be used to analyze the resilience of transport and port infrastructure using ammonia and methanol as maritime fuels, focusing on the transport, storage and bunkering stages of the supply chain. This will be achieved through the structuration of BNs that could be utilized to simulate and understand the behavior of these systems. The formulated models constitute a base that could be used to analyze case studies of interest in the future.

1.2. Scope of work and objectives

Main Objective:

Develop a Bayesian Network model that can be utilized as a base to quantitatively analyze the resilience of ammonia and methanol transport, storage and bunkering systems for the maritime sector.

Specific Objectives:

- Based on literature review, define indicators that can be used to quantitatively analyze the resilience of the ammonia and methanol system under investigation. Namely, the transport, storage and bunkering stages of ammonia and methanol for their use as alternative fuels in the maritime sector.
- Identify fuel transport and port infrastructure vulnerabilities to understand potential disturbances to the system's operation, with the goal of analyzing and enhancing its ability to cope with threats and hazards.
- Understand which inherent traits or response mechanisms are present in this type of systems in order to address potential disruptive situations and how they can allow them to maintain or restore a high state of functionality.

- Develop a BN model that incorporates the identified resilience indicators. This constitutes a base that could be used to analyze case studies of interest, subject to the provision and incorporation of the probabilities of the specific events involved in them.
- Set the basis for a resilience assessment model that could be further developed to incorporate a temporal component, allowing to perform dynamic resilience assessments for this type of systems.

The work presented here starts with a theorical background covered throughout chapter two. First, methanol and ammonia as alternative maritime fuels are discussed, describing their main characteristics, implications for their use and state of the art. Then, a definition of resilience which is used to base the development of the model is presented, alongside an overview of quantitative resilience assessment methods, focusing on the use BNs as a tool to perform them. Afterwards, during chapter three, the methodology followed to derive and structure the BN model is discussed, including a proposal for assigning weighting factors to the elements that make part of it. Subsequently, in chapter four, the results of the work are presented. This encompasses the derivation of all the elements of the model, as well as the structure of the final models themselves. Later, in chapter five, the main implications and findings of the work are discussed. And lastly, during chapter six, a set of conclusions and final remarks are shown.

2. THEORY

The theoretical background relevant to the development of this work includes three main points: 1) a contextualization of methanol and ammonia as alternative maritime fuels; 2) a review on quantitative resilience assessment in general; and 3) a deep dive on the use of BN models as a tool to perform quantitative resilience assessment. These will all be presented as part of this chapter.

2.1 Methanol as an alternative maritime fuel

Methanol description and production methods

Methanol, also known as methyl alcohol, is the simplest form of alcohol, defined chemically as CH_3OH or MeOH (ABS 2021). It is an important and widely used chemical, with around 110 million tons produced per year worldwide (Wissner et al. 2023). It is a colorless and water-soluble compound that is also flammable and highly volatile. Additionally, it is in liquid state at ambient temperature and pressure, making it easier to store compared to other alternatives considered for the maritime sector, such as ammonia, liquified natural gas (LNG) or liquid hydrogen (LH_2) (ABS 2021; ITOPF 2024).

Methanol has the highest hydrogen-to-carbon ratio of any liquid fuel, which is a significant aspect increasing the appeal for its use on the maritime sector over other similar compounds, as the CO_2 emissions resulting from its combustion are the lowest when compared to other hydrocarbons. Additionally, from an environmental point of view, methanol is generally expected to generate lower impacts in the event of a leakage compared to other fuels, as it is readily biodegradable in aquatic environments (ABS 2021; ITOPF 2024).

Currently, methanol is most commonly produced from natural gas via steam reforming, which generates a synthesis gas mixture of Carbon Monoxide (CO), hydrogen (H_2) and CO_2, from which methanol is synthesized via a catalytic and exothermic reaction. This type of methanol is referred to as grey methanol and has high CO_2 emissions associated to its production process (Gielen et al. 2022; Kazemi Esfeh et al. 2022). Nevertheless, there exist alternative renewable and low-carbon production pathways for methanol, yielding what is referred to as green and blue methanol respectively (ITOPF 2024).

Green methanol is produced when combining renewable hydrogen (i.e. hydrogen produced from renewable electricity via water electrolysis) with a renewable carbon source, which can either be CO_2 extracted from the air via Direct Air Capture (DAC) or derived from biomass gasification or reforming. Meanwhile, blue methanol can be produced either via natural gas reforming, but incorporating CCS technologies to reduce CO_2 emissions, or by combining renewable hydrogen with a non-renewable CO_2 source (such as a stream of industrial waste gases) (Gielen et al. 2022; Kazemi Esfeh et al. 2022).

Figure 1 presents a summary of the most relevant methanol production pathways.

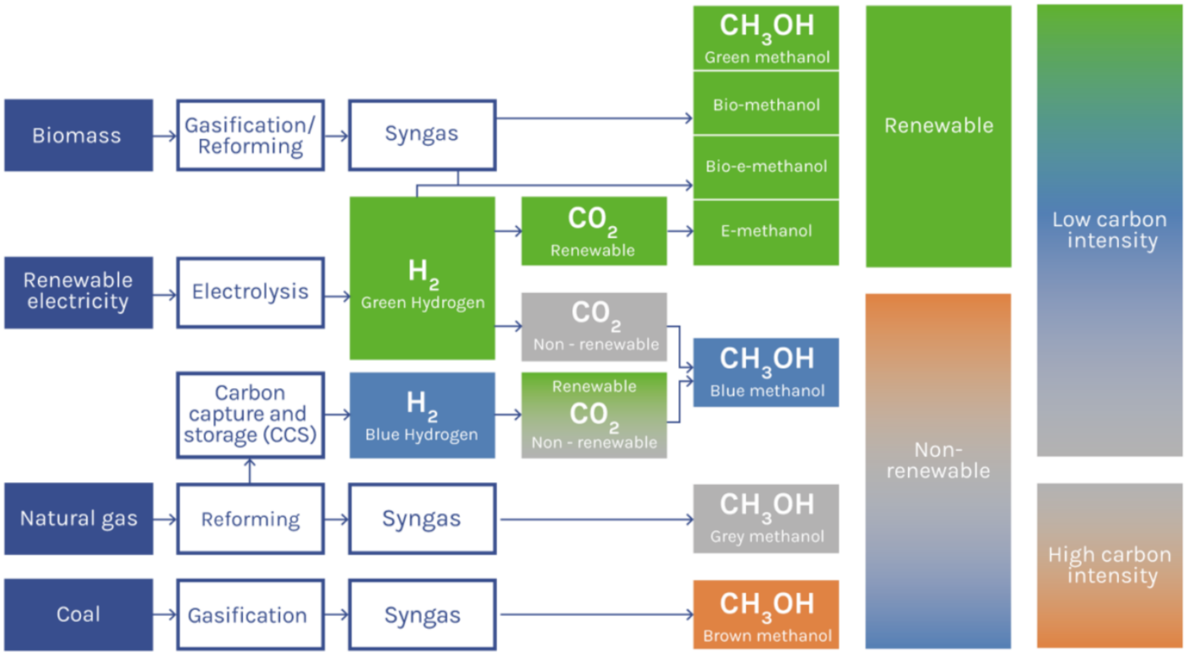

Figure 1. Summary of the main methanol production pathways. Source: Gielen et al. (2022)

Methanol as an alternative maritime fuel & key considerations

Methanol's uptake and utilization as a maritime fuel is a relatively recent development, as it was only approved to be included in the IMO's Interim Guidelines for Low Flash Point Fuels in November 2020 (ABS 2021). However, the number of ships capable of using methanol as an alternative fuel has grown steadily ever since, with 62 ships in operation as of May 2024, as well as a further 207 placed orders. This implies that methanol-fueled ships account for 0.09% of the world fleet tonnage in operation and 9.68% of the tonnage ordered (DNV 2024).

The key considerations associated to the operation of methanol-fueled or methanol-transporting ships are the flammability, toxicity, and corrosivity of the fuel (ITOPF 2024; Wissner et al. 2023). In terms of flammability, it is important to consider that the flammability range of methanol vapor to air is between 6% to 36.5% volume. Additionally, methanol's flash point at atmospheric pressure is 12°C, meaning that highly flammable methanol vapors can be easily produced above this temperature (ABS 2023).

While it is true that vapor formation can be avoided completely if the temperature of methanol is kept below its flashpoint at all times, this is generally more costly compared to controlling the vapor formation inside the tank, as well as the vapor emissions from it (Methanol Institute 2017a). Consequently, it is necessary to incorporate various safety features to counteract the risk of excessive vapor formation and the creation of flammable atmospheres, such as water screens for preventive cooling, inerting systems to displace oxygen with nitrogen-enriched air, and sufficient ventilation capacity for dissipating vapor releases (IMO 2020).

As for its toxicity, methanol is hardly toxic for fish, invertebrates, algae and microorganisms in the short term and is easily biodegradable. Consequently, the main risks associated to it are the consequences of human exposure, both acutely (due to accidental contact) and chronically (due to continued long-term exposure) (Wissner et al. 2023). Notably, acute exposure to methanol can cause effects such as the depression of the Central Nervous System, blurred vision, irritation to the eyes, skin and respiratory tract, metabolic acidosis, irreversible blindness, coma, damage to the liver, and even death (Wissner et al. 2023; WHO 1997). In contrast, chronic effects could include skin dermatitis, a broad range of ocular effects, and potential liver or kidney damage (WHO 1997). Therefore, it is essential to avoid the exposure of workers with the use of adequate personal protection equipment (PPE) for both, regular operations, as well as emergency situations. Additionally, contingency equipment, such as emergency showers, must also be provided on ships transporting the fuel (IMO 2020).

Lastly, the risk of corrosivity must be addressed with the use of methanol corrosion resistant materials, especially for components expected to come in contact with the fuel, as well as with mitigation systems capable of dealing with either vapor or liquid methanol leakages (IMO 2020).

2.2 Ammonia as an alternative maritime fuel

Ammonia description and production methods

Ammonia (NH_3) is an important and well-known chemical compound comprised of nitrogen and hydrogen, with an estimated annual production of 180 million tons worldwide (Kobayashi et al. 2019). It is mainly used for the production of fertilizers, but it has also gained increased attention as a potential energy source and hydrogen carrier (Kazemi Esfeh et al. 2022). It is a colorless gas at atmospheric conditions and has a very characteristic pungent smell (Cames et al. 2021). However, it is typically transported in liquid state, as this allows to carry larger volumes and reduces the risk of leaks. This can be achieved either by compression, refrigeration or a combination of the two. When storing ammonia at atmospheric pressure, it requires a cryogenic temperature of −33°C in order to become liquid. In contrast, for fully pressurized storage at room temperature, a pressure of approximately 10 bar is required (Hammer and Leisner 2025; Kobayashi et al. 2019).

While ammonia is a toxic compound, posing risks not only to humans, but also to maritime and terrestrial environments, it is also an attractive fuel from the perspective of decarbonization, as it is carbon-free and, consequently, does not generate CO_2 emissions upon its usage (Dawson et al. 2022). Another advantage of using ammonia as a maritime fuel is that the storage conditions are very similar to those of liquefied petroleum gas (LPG). Therefore, even though there exist ammonia-dedicated vessels, LPG carriers may also be used for transporting ammonia, which can facilitate a faster uptake on its usage (Cames et al. 2021). This is also one of the reasons why cryogenic storage at atmospheric pressure is preferred for its use in the maritime sector, as it builds on existing experience and infrastructure.

Currently, most of the commercial production of ammonia is done based on hydrogen produced from natural gas or lignite reforming, as well as nitrogen separated from the air, in a process known as Haber-Bosch (Kobayashi et al. 2019). However, this route is CO_2 intensive, and is thus responsible of approximately 1.6% of the global total emissions (Lucentini et al. 2021). Therefore, alternative renewable and low-carbon production methods are also being explored.

One such option is the production of green ammonia, which is achieved by using hydrogen derived from water electrolysis powered by renewable energy or, alternatively, from renewable biomass gasification, while the air separation process also consumes electricity from renewable sources (Cames et al. 2021; Fahnestock et al. 2021). Another alternative is the production of low-carbon ammonia, also known as blue ammonia. This consists on incorporating CCS systems into the current fossil-based Haber-Bosch processes (Fahnestock et al. 2021; Kazemi Esfeh et al. 2022).

Figure 2 shows an overview of the most important ammonia production pathways.

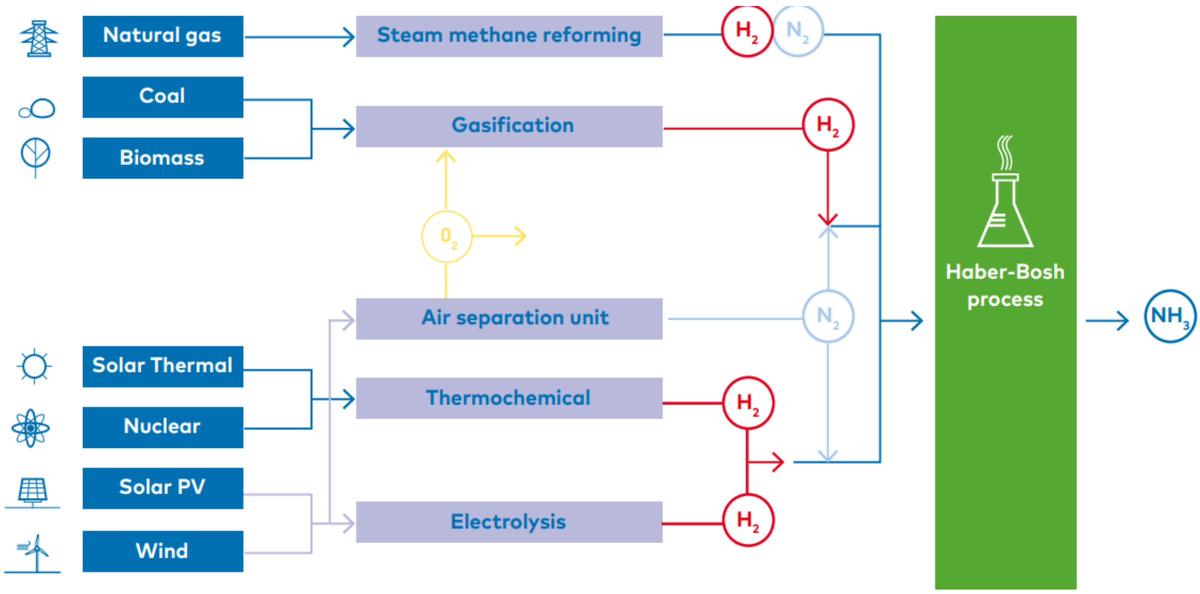

Figure 2. Summary of the main ammonia production pathways. Source: Fahnestock et al. (2021)

Ammonia as an alternative maritime fuel & key considerations

Ammonia's utilization as a maritime fuel is a more recent development than in the case of methanol, reflected by the fact that the IMO interim guidelines for the utilization of ammonia as an alternative maritime fuel were only published in 2025 (IMO 2025b). Nevertheless, significant efforts towards the deployment of ammonia-fueled and ammonia-ready vessels have been identified. As of December 2024, the Ammonia Energy Association (AEA) has tracked 26 ammonia-ready vessels in operation, which includes ammonia carriers, bulk carriers, oil carriers, container vessels, and supply vessels. There are also 4 ammonia-fueled vessels in operation, consisting on a couple of supply vessels and tug boats, which entered the water in 2023 and 2024. Lastly, in terms of global announcements, a total of 322 vessels have been identified, with 129 being ammonia-fueled and 193 ammonia-ready (Nironen and Blackmore 2025).

In terms of key considerations for the use of ammonia in the maritime sector, the toxicity of the fuel, as well as its storage conditions, stand out. In terms of the toxicity of ammonia, the consequences of an accidental release into the environment, as well as of human of exposure, are both highly relevant. Regarding the former, ammonia has been found out to be very toxic to various freshwater and marine animal species, both acutely and chronically (Cames et al. 2021). In particular, ionized ammonia is threatening to various species. For example, it can cause gill damage to fish and affect the development of both fish and shellfish. Very high concentrations can also be lethal to different forms of wildlife, including fish, birds and marine mammals (Dawson et al. 2022). Conversely, ammonia is not toxic to algae, aquatic plants or microorganisms. In fact, it can be degraded by them to be used as a source of nitrogen. However, this can lead to an uncontrolled growth of these species, causing a phenomenon known as eutrophication, which ultimately causes the depletion of oxygen levels in the water, as well as the release of toxins by algae. These events can therefore be highly detrimental to maritime ecosystems and must be prevented at all costs (Cames et al. 2021; Dawson et al. 2022).

Regarding the effects on human health, upon acute exposure, ammonia can cause various adverse symptoms. These include immediate irritation in eyes, nose, and throat; increased respiratory rate; coughing and chest pain; chemical and cryogenic burns; eye damage; and even death due to pulmonary edema, asphyxiation or cardiac arrest, among other effects (Cames et al. 2021; UK Health Security Agency 2024). There can also be chronic sequels due to long-term exposure, such as bronchitis, pneumonia, reduced lunge function, cataracts on eyes, glaucoma, corneal ulceration, and potential kidney or liver damage (UK Health Security Agency 2024).

For these reasons, it is essential for ships transporting or utilizing ammonia as a fuel to incorporate mechanisms that minimize the risk or impact of leakages, such as gas and liquid detectors or drip trays to safely contain leaks. Similarly, the availability of adequate PPE for protecting workers, as well as mechanisms to isolate potentially toxic areas, such as airlocks, must also be guaranteed (IMO 2025b).

In terms of the storage requirements for ammonia, cryogenic systems are generally preferred for large-scale transport, since it allows to have a liquid fuel at atmospheric pressure, which is safer compared to pressurized gas storage. This is especially relevant when considering potential fuel release scenarios, as losses of containment occur at a much smaller rate compared to pressurized storage systems and fuel flashing (which refers to the rapid vaporization of the liquid fuel upon its release) is also minimized (Ng et al. 2023). Additionally, the storage solutions are much more space-efficient (Ehlers et al. 2022).

As a result, one key factor to consider is the constant generation of boil-off gas (BOG) within storage tanks, which demands the use of reliquefication systems in order to avoid pressure build-up due to fuel vaporization (IMO 2025b). Thermal isolation is also essential, as the exposure of ship components not intended for ammonia storage to low temperatures could generate material embrittlement or losses of function. Additionally, it prevents an active thermal exchange between the ammonia-holding infrastructure and the surrounding environment, which would otherwise result in an excessive amount of BOG generation (Hammer and Leisner 2025). Lastly, and similarly to methanol, ammonia can also be corrosive, meaning that compatible materials must also be considered for system design (IMO 2025b).

Table 1 presents a summarized comparison of the main characteristics of ammonia and methanol for their use as alternative maritime fuels.

Table 1. Main characteristics of ammonia and methanol as alternative maritime fuels. Source: own elaboration based on ABS (2021), Cames et al. (2021), Dawson et al. (2022), Hammer and Leisner (2025), ITOPF (2024), Kobayashi et al. (2019) and Wissner et al. (2023)

	Methanol	**Ammonia**
Chemical formula	CH_3OH	NH_3
Main associated risks	Higher flammability and volatility	Higher toxicity and corrosivity
Storage conditions	Ambient temperature and atmospheric pressure	Cryogenic temperature (≈ -33°C) and atmospheric pressure or ambient temperature and high pressure (≈10 bar)
Main advantage for its use in the maritime sector	Highest Hydrogen-to-Carbon ratio amongst all liquid fuels	Lack of CO_2 emissions due to a no-carbon structure
Environmental impact upon release	Low. Easily biodegradable	High due to toxicity to sea fauna and risk of eutrophication
Toxicity upon human exposure	High for both, acute and long-term exposure	High for both, acute and long-term exposure

2.3 Quantitative Resilience Assessment through Bayesian Networks

Definition of Resilience and its importance

Reliability and resilience in operations are fundamental for every industry and economic sector, which also applies to maritime transport. At the same time, the desire and need to incorporate alternative maritime fuels, not only to decarbonize the shipping sector, but also to reliably meet its increasing energy needs, is a pressing issue. However, this must be done in a way that guarantees that their use is safe and reliable, as well as without any adverse consequences to the environment or human health.

To this end, one conventional approach is to perform risk assessments, which allow to identify hazards and formulate adequate system design and operation requirements, in the form of preventive and protective mechanisms. Nonetheless, traditional risk assessments historically focus on pre-failure scenarios and system vulnerability only (i.e. their likelihood to be affected by disruptions and the effects which they generate). Therefore, they tend not to consider their capacity to recover afterwards, which could allow for a much more comprehensive assessment (Hosseini and Barker 2016; Tong et al. 2020). It is within this context that the concept of resilience can be highly valuable.

The term "resilience" was first utilized by Canadian ecologist Crawford Holling in the context of ecosystem studies. It described their ability to absorb external disruptions while maintaining their original state (Zinetullina et al. 2020). When applied in the context of any system of interest, it can be defined as its ability to maintain normal functioning when exposed to external threats, or to recover to a state of equilibrium after a disturbance occurs. Therefore, resilience as a system property can be split into three key attributes: the absorption, adaptation and restoration capacities (Hosseini and Barker 2016; Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020).

Absorption refers to the inherent ability of a system to resist (absorb) a disruption. This can be achieved, for example, through an inherently safer system design. Adaptation is defined as the ability of the system to accommodate to a disruptive situation and maintain its performance without needing any sort of external intervention (i.e., utilizing internal resources only). One example could be the use of pressure relief valves in storage tanks to avoid overpressure. Lastly, restoration is the ability of the system to accept external interventions which allow it to regain its operational capacity after it had been lost. This could be done, for example, by performing maintenance labors or repairing system components (Tong et al. 2020; Zinetullina et al. 2020).

As a complement to these definitions, authors such as Tong et al. (2020) and Zinetullina et al. (2020) have proposed to adopt the concept of state of functionality. The functionality of a system refers to its ability to perform its prescribed function. With this in mind, the resilience of a system could also be defined as its ability of sustaining a high-functionality state, or recovering to a high-functionality state from a low-functionality state, during and after the occurrence of disruptions in its operation (Tong et al. 2020).

Figure 3 presents a visual representation of the transient resilience model, which refers to the evaluation of the state of functionality over time as a way to quantify resilience (Zinetullina et al. 2020).

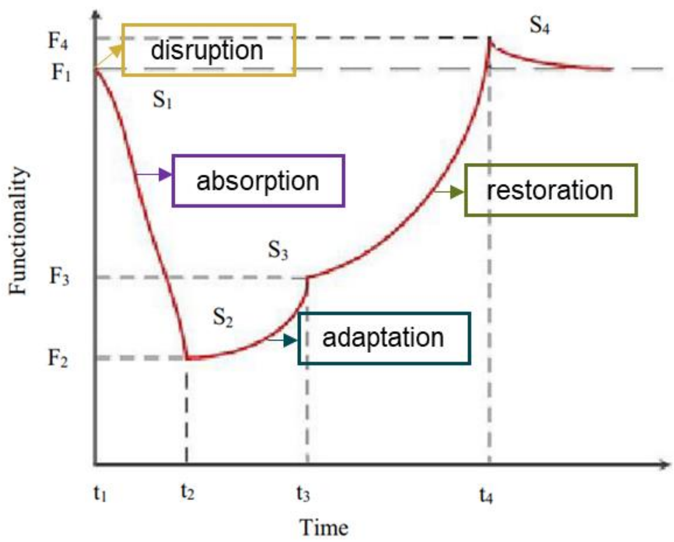

Figure 3. Transient resilience model. Source: adapted from Zinetullina et al. (2020)

In this diagram, four different states of resilience can be identified. S_1 represents the transition from the initial state of high-functionality at the normal operating conditions (functionality F_1 at time t_1) to the state of low-functionality that is caused by the disruption (functionality F_2 at time t_2). Here it is important to note that the extent to which the functionality of the system decreases depends on its absorption capacity. Then, S_2 represents the transition from F_2 to the still low- (but higher) state of functionality after the adaptation of the system has taken place (functionality F_3 at time t_3). Meanwhile, S_3 represents the transition to from F_3 to the new state of high-functionality after the restoration phase is finished (functionality F_4 at time t_4). Lastly,

S_4 represents the transition to the new normal high-functionality conditions (Tong et al. 2020; Zinetullina et al. 2020).

Quantitative Resilience Assessment Methods and Bayesian Networks

The aforementioned definitions of resilience have been used as a basis to formulate resilience assessment methods. These can be either qualitative, quantitative or a mix of both (Hosseini and Barker 2016; Tong et al. 2020). Quantitative resilience methods are particularly interesting, since they allow to construct and use data-based models to perform probabilistic assessments of the systems of interest and, consequently, more clearly identify what are the most critical disruptions or system components. Some of the most notable analyses that can be performed in this sense are casual reasoning, diagnostic reasoning and sensitivity analysis (Wang 2024; Wang et al. 2024b). Casual reasoning, also known as forward reasoning or top-down reasoning, refers to inferring the probabilities of different possible outcomes based on known evidence, as well as analyzing the factors that influence these outcomes. This could take the form of analyzing the consequences of a specific disruption of interest, such as a ship collision. On the other hand, diagnostic reasoning, also known as reverse or bottom-up reasoning, allows to determine what are the most probable causes of an observed event. For example, identifying the causes of a fuel leakage during storage processes. Lastly, sensitivity analysis consists of examining the impact of changes in parameters on a target object. This could encompass analyzing the effect of changes to the probabilities connected to a target event of interest, such as the causes of a fire during fuel transport (Wang 2024; Wang et al. 2024b).

From the existing quantitative resilience assessment methods, one of the most widely used in literature are Bayesian Networks. A Bayesian Network (BN) is an acyclic, directed probabilistic graph that consists of nodes and arcs. Nodes represent variables, while arcs illustrate the dependency between them. BNs can be used in failure analysis by connecting disruptions with their consequences via conditional probabilities (Tong et al. 2020; Zinetullina et al. 2020). Within BNs, there are parent nodes (which can be interpreted as causes) and child nodes (which can be interpreted as consequences). Additionally, nodes without parent nodes are called root nodes, nodes with both parent and child nodes are called intermediate nodes, and nodes without child nodes are called leaf nodes (Hosseini and Barker 2016).

Bayesian Networks have been found to be one of the most common quantitative resilience assessment methods due to their ability to estimate the probability and uncertainty of resilience. This means that they are especially suited to deal with the uncertainties that arise from the possible paths of the evolution of disruptions. Additionally, they stand out for their adaptability and dynamism (Ghaljahi et al. 2025). Nevertheless, some of their disadvantages and limitations when compared to other methods, such as Data Development Analysis (DEA) and Fuzzy Cognitive Maps (FCM), include the need to perform complex calculations, that they require a substantial amount of data to be structured and that they may also be susceptible to incorporate subjective assessments (Ghaljahi et al. 2025).

Main considerations of Bayesian Networks for quantitative resilience assessment

A fundamental characteristic of BNs used for quantitative resilience assessment is that their probabilistic structure consists of prior probabilities and conditional probabilities. The formers refer to the probability of occurrence of the basic (or root) nodes, which are typically obtained by analyzing and sorting historical data, such as failure reports and accident records, or are derived directly from expert opinion (Hosseini and Barker 2016; Wang 2024; Wang et al. 2024b; Zhang et al. 2024). Conditional probabilities, on the other hand, refer to the probability of events happening considering whether other events linked to them have occurred or not. Therefore, in the case of BN models, all the possible combinations between the parent nodes linked to the same child node should be considered (Zhang et al. 2024).

As stated by Tong et al. (2020), conditional probabilities for real-world cases should also ideally be derived from historical data or expert opinion. However, when this is not possible due to a lack of sufficient data or existing experience, alternative approaches can be considered. One such approach, adopted not only by Tong et al. (2020) themselves, but also Zhang et al. (2024) is to calculate the conditional probabilities as the weighting factors assigned to the parent nodes that contribute to the same child node. These aim to represent the impact of the different parent nodes on their respective child nodes and could be estimated with methodologies such as the Fuzzy Analytical Hierarchy Process (FAHP), as will be described in more detail later. Another possible approach, which can be applied when dealing with incomplete datasets, is the use of algorithms such as Expectation-Maximization (EM) in order to transform incomplete data into complete data, as was done by Wang et al. (2024b). Similarly, the Noisy-OR method is also commonly applied in literature. This one allows to simplify the requirements of the input parameters by assuming that all parent node variables are independent of each other. That is, that they can cause the child node event to happen without the influence of the others (Wang 2024). However, it is also assumed that even if a parent node is true (i.e., would cause the child event to happen), there is also a chance that "noise" coming from hidden factors (i.e., not considered in the model) or the other parent nodes prevents it from doing so. This is represented by what is known as a leak probability, which is defined for the purposes of the model (Hosseini and Barker 2016; Hossain et al. 2020). This makes it so that it is not necessary to derive the conditional probabilities of child nodes considering all the parent nodes at once, but rather that only the probability of each parent node causing the child node on its own is needed.

Nevertheless, independent of the method utilized to derive the conditional probabilities, they are always assigned to the child nodes via the use of Conditional Probability Tables (CPTs). These are a tool that contain the probability causalities between a child node and all of its parent nodes (Qiu et al. 2018; Tong et al. 2020; Wang 2024; Zhang et al. 2024).

Bayesian Networks can be applied to quantitatively analyze resilience based on two key concepts presented before. First, the definition of resilience as a system property comprised of absorption, adaptation and restoration capacities. And second, the ability to use the state of functionality of a system as an indicator of its resilience at a given point (Hosseini and Barker 2016; Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020). Following this logic, a Bayesian Network can be structured in which the state of functionality of the system is a leaf node of the entire system, while the absorption, adaptation and restoration capacities are parent nodes connected to it. Similarly, potential system disruptions, which threaten to have a negative effect on the state of functionality, would be another of the system's parent nodes. In this way, the model could be applied to assess the effect of potential disruptions on the system's absorption, adaptation and restoration capacities, subsequently allowing to determine the state of functionality and, ultimately, quantify the system's resilience. Figure 4 presents a simplified representation of such a model (Hosseini and Barker 2016; Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020).

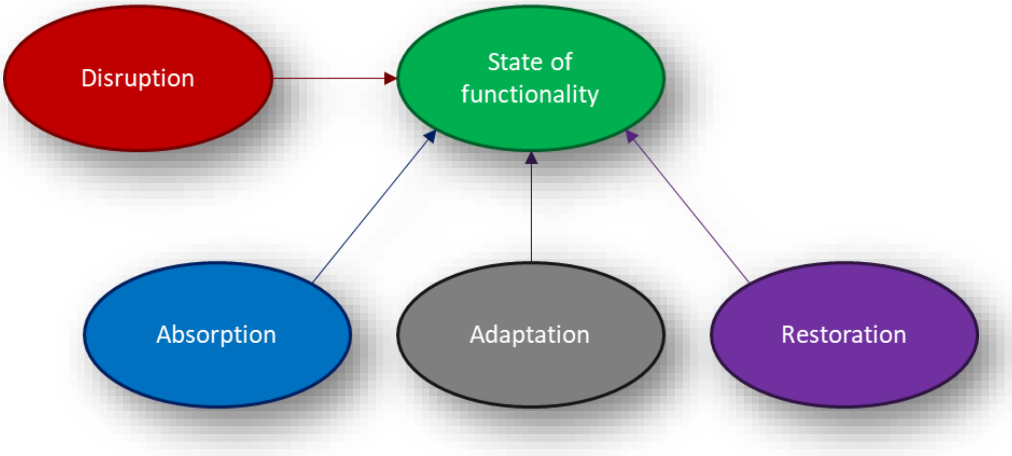

Figure 4. Simplified BN model for quantitative resilience assessment. Source: own elaboration based on Tong et al. (2020), Wang et al. (2024b) and Zinetullina et al. (2020)

It is important to note that various authors, such as the aforementioned (Hosseini and Barker 2016; Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020), have employed Dynamic Bayesian Networks (DBNs) instead of static BN models, such as the one that is intended to be developed as a result of this work. The main difference between a static and a dynamic BN model is the inclusion of a temporal dimension. This has the objective of analyzing the temporal evolution of the probability of events over a discretized time domain. Consequently, in a DBN, the status of a node at a time "t" does not only depend on its parent nodes at the same time step, but also on its previous state (at time "t-1") and the state of its parent nodes at the previous time step (Tong et al. 2020).

In line with the introduction of the temporal component, quantitative resilience assessments with DBNs also tend to include an additional resilience attribute: the learning capacity of the system. This refers to its ability to learn from past experiences, improving its capacity to respond to future disruptions (Tong et al. 2020; Zinetullina et al. 2020). Consequently, the learning capacity can potentially have an impact in all of the absorption, adaptation and restoration capacities of the system.

It is acknowledged that the work presented here should evolve towards the development of a DBN, as will be discussed further in Section 5.5 (Outlook and future work). However, this requires detailed knowledge of the behavior of the systems over time, which is more likely to be achieved when further experience on their operation can be gathered. Therefore, it was decided that the model presented here will not incorporate a learning dimension, nor a temporal component, to simplify its derivation.

Creation of Bayesian Networks for Resilience Assessment

Once the basic structure of the BN is defined, it is necessary to identify all the elements that will be part of the model. That is, all the nodes connected to the disruption, absorption, adaptation and restoration components. One approach widely used in literature for both quantitative and qualitative risk assessment is the creation of a bow-tie model, from which a BN can be derived afterwards (Wang 2024; Zhang et al. 2024; Zinetullina et al. 2020).

A bow-tie (BT) model is a risk analysis and management method that consists of the combination of a fault tree and an event tree. These are used to comprehensively analyze the causes of an event, as well as its possible consequences, with the end goal of identifying risk factors and mitigation measures (Wang 2024; Zhang et al. 2024). The bow-tie representation of a disruption, for example an accident, helps to understand the combination of events that led to it and which type of escalations could lead to a particular consequence. In the context of resilience assessment, the fault tree consists on the identification of the root and intermediate causes of malfunctions to the system. Meanwhile, the event tree assesses the consequences of the identified malfunctions, considering all the safety barriers and responses triggered by them that aim to avoid or mitigate their impact (Zinetullina et al. 2020). Examples of the derivation of fault and event trees for quantitative resilience assessments will be presented in the methodology section.

Once a BT model is stablished, it can be converted into a BN by following two stages: structure transformation and Conditional Probability Table (CPT) assignment (Qiu et al. 2018). Structure transformation refers to the conversion of the BT model into a BN according to the correspondence rules. These indicate that the basic events of the fault and event trees are transformed into root nodes, while the intermediate events are transformed into intermediate nodes and, lastly, the top events into child nodes (which could be leaf nodes or not) (Wang 2024). Meanwhile, in order to assign the CPTs to the child nodes, it is necessary to include all the possible combinations of the identified parent nodes that are connected to the them. In particular, all child nodes will have 2^n conditional probabilities, where “n” is the number of parent nodes they have (Zhang et al. 2024). Table 2 shows an example of this for a child node "C1" with 3 parent nodes "X_1", "X_2" & "X_3". All of them are dichotomous variables with "1" and "0" as their possible values. There it can be seen that the CPT considers a total of eight combinations (2^3) and that the probability of the child node to have a specific value varies depending on the values of its parent nodes (Zhang et al. 2024).

Table 2. Example of a CPT for a child node with 3 parent nodes. Source: Zhang et al. (2024)

X_1	X_2	X_3	$P(C_1=1 \mid X_1,X_2,X_3)$	$P(C_1=0 \mid X_1,X_2,X_3)$
1	1	1	1.00	0.00
1	1	0	0.86	0.14
1	0	1	0.76	0.24
1	0	0	0.62	0.38
0	1	1	0.38	0.62
0	1	0	0.24	0.76
0	0	1	0.14	0.86
0	0	0	0.00	1.00

Assignment of weighting factors for deriving CPTs

As mentioned during the description of BNs for quantitative resilience assessment, one possible approach to derive the conditional probability tables of the model, especially when not enough data is available, is to assign weighting factors to the parent nodes that contribute to the same child node (Tong et al. 2020; Zhang et al. 2024). This is done as a means to represent the relative importance and impact of each element, allowing to prioritize some of them in relation to the rest. To this end, expert opinion is typically considered, as it is deemed as a solid basis for establishing priorities. Consequently, methods such as the Fuzzy Analytic Hierarchy Process (FAHP) come into consideration (Hosseini and Barker 2016; Tong et al. 2020; Zhang et al. 2024).

The FAHP in particular is a method that can be used to go from an assessment of the relative importance of factors to defining numerical weights for each of them based on a pairwise comparison. This is done by applying Saaty's nine-point scale for evaluating relative importance. Table 3 presents the aforementioned scale, alongside an equivalent linguistic valuation and the Triangular Fuzzy Numbers (TFNs) that need to be input as part of the calculation process of the weights, as will be described later (Huang et al. 2025; Palak et al. 2023; Wang et al. 2019; Zhang et al. 2024).

Table 3. Saaty Scale with linguistic explanation and applicable TFNs for applying the FAHP. (Source: own elaboration based on Huang et al. (2025), Palak et al. (2023), Wang et al. (2019) and Zhang et al. (2024)

Level of importance in the Saaty Scale	Linguistic explanation	TFNs
1	Both factors have equal importance	(1,1,1)
3	Factor “x” is moderately more important compared to factor “y”	(2,3,4)
5	Factor “x” is strongly more important compared to factor “y”	(4,5,6)
7	Factor “x” is very strongly more important compared to factor “y”	(6,7,8)
9	Factor “x” is absolutely more important compared to factor “y”	(8,9,9)
2	Intermediate value between 1 and 3	(1,2,3)
4	Intermediate value between 3 and 5	(3,4,5)
6	Intermediate value between 5 and 7	(5,6,7)
8	Intermediate value between 7 and 9	(7,8,9)

The TFNs are triplets of numbers with a (a,b,c)-type structure where “a” represents the smallest likely value within the Saaty scale (lower bound), “b” represents the most probable or most representative value (mean), and “c” the largest possible value (higher bound). This means, for example, that an evaluation of (4,5,6), when comparing factor “x” to factor “y” implies both of the following (Huang et al. 2025; Palak et al. 2023; Wang et al. 2019; Zhang et al. 2024):

- That factor “x” is considered strongly more important compared to factor “y”
- That the lower bound in the Saaty scale of importance is 4, the most probable value is 5 and the higher bound is 6

All of the factors of interest must be compared to each other, allowing to build a matrix from which the weights representing their relative importance can ultimately be calculated. This will be presented in detail in the methodology section.

The FAHP incorporating TFNs has been utilized by researchers in literature to assign numerical weights to groups of elements of interest, while accommodating for fuzziness and uncertainty (Palak et al. 2023). Additionally, it is a method that allows to handle qualitative and quantitative criteria at the same time, making it especially useful for systems with both types of elements (Wang et al. 2019). It is precisely because of these reasons that it has also been used for assigning weighting factors in BNs to derive the CPTs for quantitative risk and resilience assessments, especially when not enough data or experience is available to do so (Tong et al. 2020; Wang 2024). This could be relevant for the systems analyzed as part of this work, as experience with ammonia and methanol as alternative maritime fuels is still limited.

3. METHODOLOGY

This chapter covers all of the steps followed to derive the BN models for the resilience assessment of the systems of interest. That includes the definition of the scope of analysis; the conceptualization of the model (i.e., the definition of its components); the derivation of the BT models and, subsequently, the BN models; and lastly, the development of a method that can be used to assign weighting factors to the parent nodes of the model.

3.1 Definition of the system

As introduced before, the objective of the work is to formulate a model that can be used to analyze the resilience of a system encompassing the transport, storage and bunkering of ammonia and methanol as alternative fuels for the maritime sector. Therefore, a brief description of the supply chain stages covered will be presented in this section in order to clearly outline the scope of analysis.

In terms of the system boundaries, however, it is important to highlight that the potential implications of incidents on elements external to the system will not be considered within the model. One such example could be the environmental consequences of a fuel spill caused by a leakage during transport or bunkering operations. It is acknowledged that these incidents can have significant repercussions. For instance, an ammonia spill would represent a significant threat to maritime ecosystems because of its toxicity to sea fauna, as well as the risk of causing eutrophication, as described before (Cames et al. 2021; Dawson et al. 2022). However, since these elements are not part of the methanol or ammonia transport, storage and bunkering systems, their resilience in the face of disruptions will not be evaluated. This will instead be limited to the infrastructure and processes that are part of the supply chain stages defined next. Namely, transport, storage at port and bunkering.

Transport to port of destination

This covers the process of transporting ammonia or methanol from a production site to a storage site at a port of destination. The production processes of the fuels themselves are not considered within the scope of analysis. Additionally, the transport is assumed to be carried out via methanol- or ammonia-tanker / carrier vessels respectively. These vessels are assumed not to run on these fuels but only used as a means to transport them.

In terms of the storage conditions within the ships, for the case of methanol, it is assumed to be at ambient temperature and atmospheric pressure. It is also assumed that all the tanks utilized for methanol storage comply with the safety features mandated by the IMO's Interim Guidelines for the Use of Methanol as a Maritime Fuel, which will be expanded upon later when deriving the fault and event trees of the system (IMO 2020).

Meanwhile, in the case of ammonia, it is considered that the storage is performed in cryogenic conditions. That is, at a temperature of −33°C and atmospheric pressure (Hammer and Leisner 2025; Kobayashi et al. 2019). Similarly, the storage tanks are assumed to comply with the IMO's Interim Guidelines for the Safety of Ships Using Ammonia as Fuel (IMO 2025b).

Lastly, it is important to consider the transfer of the fuel from the production site to the carrier vessels and, afterwards, to the storage tanks at port. This is assumed to be done via bunkering systems that comply with the regulations stated by the IMO's Interim Guidelines for methanol and ammonia as alternative maritime fuels (IMO 2020, 2025b).

Storage at port of destination

This refers to the storage of the fuels at the receiving port. The storage conditions are assumed to be the same as within the ships utilized for fuel transport. Namely, methanol at ambient temperature and atmospheric pressure and ammonia at -33°C and atmospheric pressure.

Bunkering to off-taker vessel

This stage covers three main processes. First, delivering the fuel from the storage facility at port to a bunkering vessel. Second, transporting the fuel with the bunkering vessel from the port to a final off-taker ship. And third, bunkering (or delivering the fuel to) a final methanol- or ammonia-fueled ship. Therefore, the bunkering process is conducted using a ship-to-ship scheme (ABS 2024b; ClassNK 2025). This aligns with the procedure that was followed in two already successful methanol bunkering processes in the ports of Amsterdam (Port of Amsterdam 2025) and Antwerp (Port of Antwerp 2024).

It is also assumed that the bunkering systems employed in both cases comply with the

IMO's Interim Guidelines (IMO 2020, 2025b). Additionally, the storage conditions within the bunkering vessels are assumed to be the same as in the previous stages.

Figure 5 presents a visual representation of the supply chain processes within the scope of analysis, beginning with the fuel transfer process to the tanker vessel and finishing with the transfer process to the off-taker ship, as highlighted by the red box.

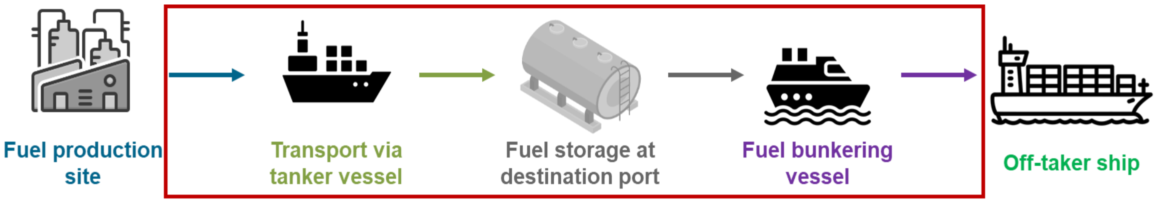

Figure 5. Supply Chain Scope of the model. Source: own elaboration

Given the configuration of the system of study, three different types of processes can be identified:

1. **Fuel transport processes**: which occur from the production site of the fuels to the storage site at port (via the tanker vessels), as well as from there to the final off-taker ships (via the bunkering vessels).
2. **Fuel transfer processes**: from the fuel production site to the tanker vessels, then to the storage facility at port, subsequently to the bunkering vessels, and lastly to the off-taker ships.
3. **Fuel storage processes**: on board of the tanker vessels transporting the fuels from the production site to the storage at port, at the storage port facility itself, and on board of the bunkering vessels transporting the fuel to the off-taker ships.

This classification of processes will be considered when deriving the fault and event trees, as well as the restoration measures of the system later. For the case of the fuel transfer processes, it is important to note that the bunkering infrastructure is assumed to change depending on where it occurs. More specifically, for the fuel transfer processes from the fuel production site and from and to the fuel storage facility at port, a combination of bunkering pipelines and hoses is assumed to be used. In contrast, for the fuel transfer process from the bunkering vessel to the final off-taker ship, only bunkering hoses are considered.

Table 4 presents a breakdown of the sequence of fuel transport, transfer and storage processes that occur during the supply chain stages analyzed, highlighting relevant assumptions or considerations for each of them.

Table 4. Sequence of fuel transport, transfer and storage processes throughout the supply chain stages analyzed. Source: own elaboration

Supply chain stage	Type of supply chain process	Origin and destination	Relevant assumptions or considerations
Transport to port of destination	Fuel transfer	From the fuel production site to the methanol- or ammonia-tanker vessel	The fuel transfer process uses a combination of bunkering pipelines and hoses
	Fuel storage and transport	From the fuel production site to the port of destination	The fuel, which has been stored in the tanker vessel, is transported to the port of destination
	Fuel transfer	From the fuel tanker vessel to the storage tanks at port	The fuel transfer process uses a combination of bunkering hoses and pipelines
Storage at port of destination	Fuel storage	Fuel remains stored in the port facility	None
Bunkering to off-taker vessel	Fuel transfer	From the storage facility at port to the bunkering vessel	The fuel transfer process uses a combination of bunkering pipelines and hoses
	Fuel storage and transport	From the port of destination to the off-taker vessel	The fuel, which has been stored in the bunkering vessel, is transported to the off-taker vessel
	Fuel transfer	From the bunkering vessel to the off-taker vessel	The fuel transfer process uses a system of bunkering hoses only

This allows to see that, throughout the different stages of the supply chain of interest, there are multiple fuel transport, transfer and storage processes involved. It is precisely for this reason that it was decided to derive the fault trees, event trees and restoration measures based on the types of supply chain processes rather than the supply chain stages. Nevertheless, it was also considered whether the processes could have different implications depending on the specific situations being analyzed. For instance, the assumption that the fuel transfer process from the bunkering to the off-taker vessel utilizes a hose-only system, while the others also incorporate bunkering pipelines and, consequently, the risks associated to them must also be accounted for.

It is also worth noting that, in the sequence of events presented in Table 4, fuel transport processes are always grouped together with storage processes. This is because fuel storage is also a part of fuel transport. That will be relevant for the derivation of the event trees of the fuel transport processes, as in order to facilitate the work and avoid redundancies, the events that correspond to response mechanisms that deal with disruptions associated with the storage tanks were not presented. Instead, they were derived and included within the fuel storage processes. As a result, the event trees for the fuel transport processes, and subsequently their representation in the BN models, only focus on the additional elements associated to the process of moving the fuels, rather than the storage processes on board of the transporting ships.

3.2 Conceptualization of the resilience assessment model

With the scope of analysis clearly defined, a BN wants to be created as a tool that can be utilized to perform the resilience assessment. The base structure will be the one previously presented in Figure 4: a BN where the state of functionality is the leaf node of the whole system, while the absorption, adaptation and restoration capacities are all parent nodes connected to it. In order to serve as a guiding principle for the structuration of the network, a brief description of all the main nodes is presented first.

State of functionality node

As described in the theory section, the state of functionality of a system refers to its ability to perform its prescribed function (Tong et al. 2020). In this case, this encompasses the ability to safely and reliably transport and store methanol and ammonia, as well as bunker (deliver) them to the off-taker ships. This node can then be defined as a dichotomous variable: the state of functionality can be considered “high” when operations are able to be carried out without any disruption forcing them to stop, while it will be “low” when disruptions cause an unmitigable impact to the system which makes it unable to operate safely or operate at all.

Consequently, the state of functionality of the system will be “high” in the events in which there are no disruptions affecting it or, alternatively, if the absorption, adaptation, or restoration capacities enabled it to continue operating safely, in spite of the occurrence of disruptions.

Disruptions node

The disruptions node will be comprised of the disturbances that threaten to negatively affect the state of functionality of the system. This includes all the root and intermediate causes of malfunctions that will be identified via the derivation of the fault tree, as will be presented later (Zinetullina et al. 2020). Disruptions can also be defined as dichotomous variables, with “yes” meaning that the they are occurring and “no” that they are not.

Absorption capacity node

The absorption capacity node includes all the features and measures within the system that prevent disruptions from affecting it to the point of triggering or demanding a reaction or intervention (Tong et al. 2020). They will be derived as part of the event tree of the system, corresponding, on one side, to inherent characteristics that passively prevent the effect of disruptions. For instance, the thermal resistance of system components within the ammonia storage system, which could prevent material embrittlement or loss of equipment functions, even in the face of a slight loss of thermal insulation (IMO 2025b). Preventive system monitoring coupled with proactive responses will also be considered within this node. This is because the combination of the two would make it possible to respond to potentially disruptive situations before they can occur and affect the system, therefore having a similar effect to the inherent absorption traits.

Elements that are part of the absorption capacity node can be defined as dichotomous variables with two possible values: “successful” and “unsuccessful”. “Successful” meaning that the element in question is able to successfully prevent the system from being affected by the disruption it provides protection against. This could happen either because it was able to prevent the effects of the disruption it responds to, or because it was not tested at all and is thus still available to protect the system. On the contrary, the element would be “unsuccessful” if it was tested by a disruption that it is supposed to provide protection against, but its capacity was exceeded and thus the disruption is able to cause further effects onto the system (Hosseini and Barker 2016; Zinetullina et al. 2020). Similarly, for preventive monitoring and proactive responses, the measures would be "successful" if they allowed to identify potentially disruptive situations anticipatedly and respond to them before any affectation to the system occurs, or if a potentially disruptive situation never occurred in the first place. In contrast, they would be "unsuccessful" if such a situation did happen, but it was not possible to detect it with enough time to respond to it and it was thus able to further affect the system.

Following this logic, the absorption capacity as a whole can also be defined as a dichotomous variable, with either a "high" or a "low" value. It would be "high" on the event that it was able to prevent the system from being affected by an occurring disruption, or if the system was not affected by any disruption in the first place. Meanwhile, it would be "low" if the system was affected by a disruption that it was not able to control and is thus causing further consequences.

Adaptation capacity node

Complementarily, the adaptation capacity node covers internal mechanisms that are triggered after a disruption could not be contained by the absorption capacity and whose goal is to stop further negative effects to the system, so that it can continue operating under safe conditions (Hosseini and Barker 2016; Zinetullina et al. 2020). For the purposes of the proposed model, internal mechanisms are defined as features or characteristics that are part of the system of interest. That is, elements that already belong to the methanol and ammonia transport, storage and bunkering systems, as stipulated by the IMO interim guidelines for methanol and ammonia as maritime fuels (IMO 2020, 2025b).

The elements that belong to this node can be defined similarly to the ones in the absorption capacity. That is, they can be either "successful" or "unsuccessful". "Successful" when the element in question is able to successfully handle the disruption it responds to. This could happen either because it was able to control it, avoiding further negative effects on the system, or because it was not triggered at all. Hence, it is still readily available. In contrast, the element would be "unsuccessful" if it was triggered by a disruption that it is supposed to control, but its capacity was exceeded and therefore the system goes on to experience further negative consequences (Hosseini and Barker 2016; Zinetullina et al. 2020).

Similarly, the adaptation capacity as a system entity can also be defined as a dichotomous variable, having either a “high” or a “low” value. It would be “high” if: 1) it was able to control a disruption that was starting to affect the system, 2) if the absorption capacity was previously able to prevent any disruptions from affecting the system, or 3) if the system was never affected by a disruption at all. In contrast, it would be “low” if the system was affected by a disruption that was unable to be stopped and goes on to have further negative effects on the system.

Restoration capacity node

Lastly, the restoration capacity node includes mechanisms external to the analyzed system that attempt to restore its operational capacity following the effects of an uncontrolled disruption (Hosseini and Barker 2016; Zinetullina et al. 2020). That is, it covers measures that are not part of the original methanol and ammonia transport, storage or bunkering systems.

The elements within this node are also defined as dichotomous variables that can be “successful” or “unsuccessful”. They will be “successful” when they are able to successfully restore the operation of the system following an uncontrolled disruption that exceeded the adaptation capacity, or when they never had to be utilized and are thus still available. On the other hand, the mechanisms would be “unsuccessful” if they were activated but did not manage to restore the operational capacity of the system.

Likewise, the restoration capacity as a whole will also be dichotomous, having either a “high” or a “low” value. It will be “high” in either of the following scenarios: 1) it was able to restore the operational capacity of the system following an uncontrolled disruption, 2) if the disruptions affecting the system could be controlled by the absorption or adaptation capacities beforehand, or 3) if the system was never affected by any sort of disruption. In contrast, it would be “low” if a disruption to the system could never be controlled and the restoration measures were also not able to return it to a high state of functionality.

As a consequence of the previously defined parameters, it follows that the state of functionality of the system will only end up as “low” when a disruption affecting the system could not be controlled neither by the absorption, nor the adaptation capacity and the operational capacity could also not be recovered by the restoration measures.

Table 5 presents a summarized description of the main nodes of the BN, as well as a proposal for the indicators of their status (i.e., whether they are high or low, or present or absent) and the status of their elements (i.e., whether they are successful or unsuccessful, or present or absent, depending on the case). This by considering a binary system with 1 and 0 as the possible values.

Table 5. Description of the main nodes of the BN. Source: own elaboration

Name of the node	**Description**	**Indicators for the status of the node**	**Indicators for the status of its elements**
State of functionality	Ability of the system to perform its prescribed function (i.e., to safely and reliably transport, store and bunker methanol or ammonia to off-taker ships).	- **1**: the state of functionality is high - **0**: the state of functionality is low	See the description of the other nodes
Disruption	Disturbances that threaten to negatively affect the state of functionality of the system.	- **1**: there are disruptions present in the system - **0**: there are no disruptions in the system	- **1**: the disruption in question is occurring - **0**: the disruption is not occurring
Absorption	Features and measures of the system that prevent disruptions from having an effect on it, avoiding the need for any sort of reaction or intervention. This includes both, inherent traits that passively protect the system, as well as preventive system monitoring coupled with proactive responses.	- **1**: the absorption capacity is high (is still protecting the system) - **0**: the absorption capacity is low (has been exceeded)	- **1**: the element is protecting or is still able to protect the system from the disruption it responds to - **0**: the element's capacity has been exceeded and is no longer able to protect the system
Adaptation	Internal mechanisms triggered after a disruption that aim to stop and/or mitigate	- **1**: the adaptation capacity is high (is still protecting the system)	- **1**: the element has successfully handled or is still able to

Name of the node	**Description**	**Indicators for the status of the node**	**Indicators for the status of its elements**
	repercussions to the system, allowing it to continue operating under safe conditions.	- **0**: the adaptation capacity is low (has been exceeded)	respond to the disruption it protects the system from - **0**: the element's capacity has been exceeded and is no longer able to protect the system
Restoration 	Mechanisms external to the system that attempt to restore its operational capacity following the effects of an uncontrolled disruption.	- **1**: the restoration capacity is high (is still able to attempt to restore the operational state of the system if needed) - **0**: the restoration capacity is low (was unable to restore the operational capacity of the system after it was tested	- **1**: the element was able to successfully restore the operational capacity of the system or is still able to do so - **0**: the element was triggered, but unable to restore the operational capacity of the system

3.3 Derivation of the BT and BN models

As previously discussed in the theory section, a systematic and widespread method for deriving BNs for resilience assessment is to construct BT models first. This itself involves the derivation of both, a fault tree and an event tree (Wang 2024; Zhang et al. 2024; Zinetullina et al. 2020). The fault tree is based on identifying the root and intermediate causes of malfunctions to the system. In contrast, the event tree explores the consequences of the identified malfunctions, and incorporates all the safety barriers and responses triggered by them in order to avoid or mitigate their impact (Zinetullina et al. 2020). The methodology and sources utilized for deriving the fault and event trees are introduced next.

Elaboration of the fault trees

The derivation of the fault trees was done by identifying the basic events (root causes) and their consequences (intermediate causes) which would test the resilience of the system. This was achieved by considering what could be the final outcome of accidents within the systems of interest and tracing them back to their intermediate and basic causes, assuming that no safety or response mechanism was able to stop or mitigate them along the way. Within risk and resilience assessment literature, this approach has been referred to as identifying the top events of the fault tree (Qiu et al. 2018; Zinetullina et al. 2020).

Figure 6 shows an example of the application of this method, performed by Zinetullina et al. (2020). There, they analyzed the resilience of a separator system, which is a component of an oil production system, operating under extreme arctic conditions. The top event identified in that case was the failure of the self-regulating electric heat tracing, as it can lead to a rapid decrease in the operating temperature. That in turn causes wax and hydrate formation, which ultimately disrupts the system's operation and creates blockages in piping (Zinetullina et al. 2020).

In order to construct the fault tree of the system, the leading causes of the failure were identified through literature review, as well as an interview with an experienced operator. These included the outage of the main power and the standby generators, as well trips to the overcurrent protection and the residual current device. The causes were then further reasoned by intermediate events to finally end up with the root causes (Zinetullina et al. 2020).

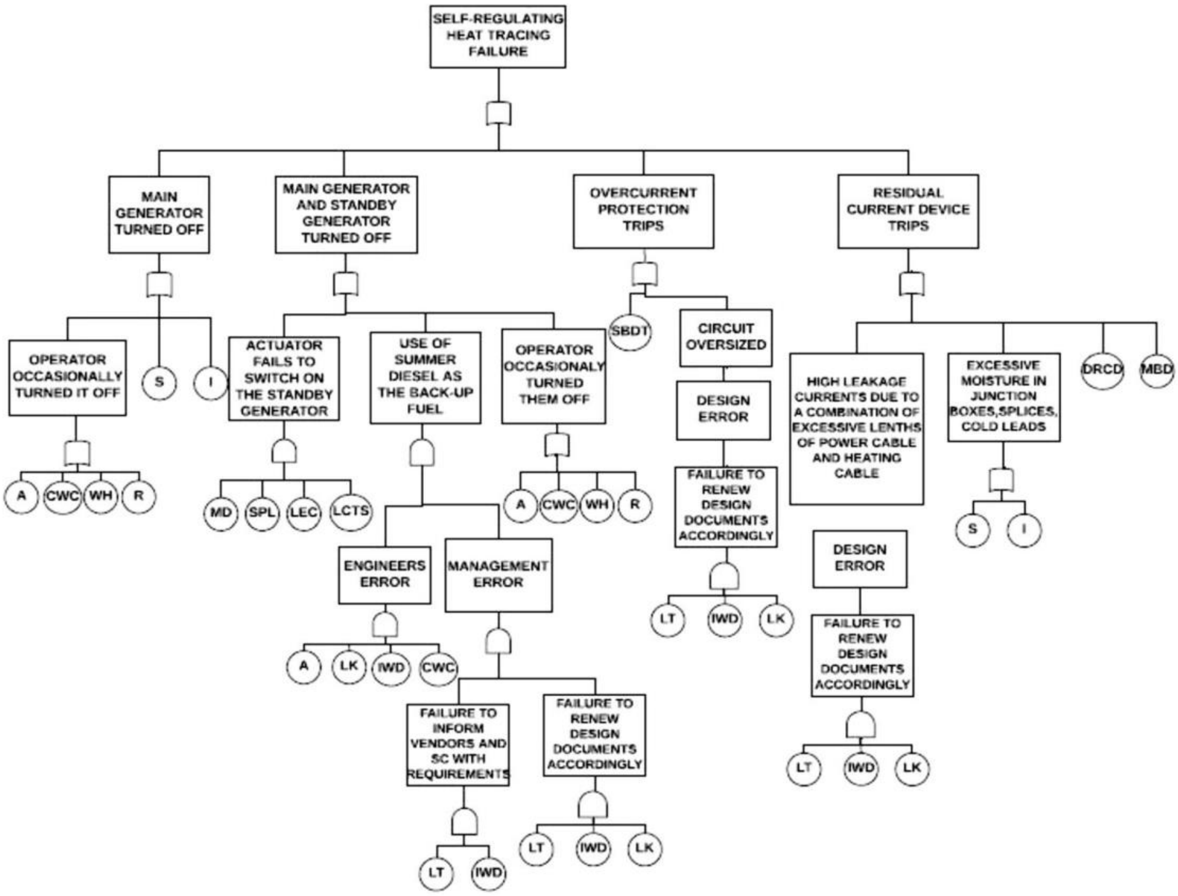

Figure 6. Example of the identification of a top event as a way to trace its basic and intermediate causes. Source: Zinetullina et al. (2020)

The main references considered as a base to identify the top events in the systems of interest, as well as tracing back their causes, were the IMO's Interim Guidelines for the Use of Methanol as a Maritime Fuel (IMO 2020) and Interim Guidelines for the Safety of Ships Using Ammonia as Fuel (IMO 2025b). This is because they include descriptions of the main hazards associated with the use of both fuels in the maritime sector, as well as the safety and response mechanisms that must exist in order to avoid or mitigate them, which are in turn responding to the events, either basic or intermediate, that can cause them. Both Interim Guidelines were also developed as a result of co-construction processes with relevant actors from multiple sectors, such as shipowners, seafarers, and experts from the maritime transport sector, as well as other industries (BIMCO 2025) (IMO 2025a). This means that they consolidate an accurate and comprehensive assessment of the use of both chemicals as alternative maritime fuels. Nevertheless, additional sources were also consulted when further clarifications or justifications of specific processes or mechanisms were required.

Additional literature that was used to cross-check and validate the risks and response mechanisms associated with the use of ammonia and methanol as alternative maritime fuels includes the likes of Cames et al. (2021) and Wissner et al. (2023), who analyze ammonia and methanol respectively. For bunkering processes specifically, the guidelines from the American Bureau of Shipping (ABS) (2024a) for ammonia and from Bureau Veritas (2025), the Economic Commission for Europe (ECE) (2024) and, once again, ABS (2024b) for methanol were considered. And regarding the transport operations, the guidelines and requirements from ClassNK for ammonia (ClassNK 2025) and methanol (ClassNK 2023) ships were also incorporated. All of this was further complemented by extensive peer discussions.

The final result of the derivation of the fault trees included events applicable to systems of either fuel, as well as exclusive to ammonia or methanol. These were presented for each of the types of supply chain processes identified (i.e., fuel transport, transfer and storage).

Elaboration of the event trees

Complementarily to the fault trees, event trees for systems utilizing the analyzed fuels were also derived. This was done by considering the root and intermediate events identified within the fault trees as a starting point. From there, all the systems that would respond to them, either from a proactive or reactive point of view were identified. This was achieved by considering the sequence of possible events following decision trees. That is, to consider whether a response mechanism was successful or not and what the follow-up consequence (final state) or action (further response mechanism) would be. This approach has been applied by authors such as Qiu et al. (2018) and Zinetullina et al. (2020).

An example illustrating this concept, performed by Zinetullina et al. (2020) is presented in Figure 7. There, a series of safety barriers and restoration measures following the top event described before (the failure of the self-regulating electric heat tracing in a separator operating under extreme arctic conditions) are presented. Using decision trees, it is analyzed whether a response mechanism (either a safety barrier or restoration measure) is successful or not. That can either lead to a follow up response mechanism or to a final consequence to the system, which are enumerated from C1 to C11 (Zinetullina et al. 2020).

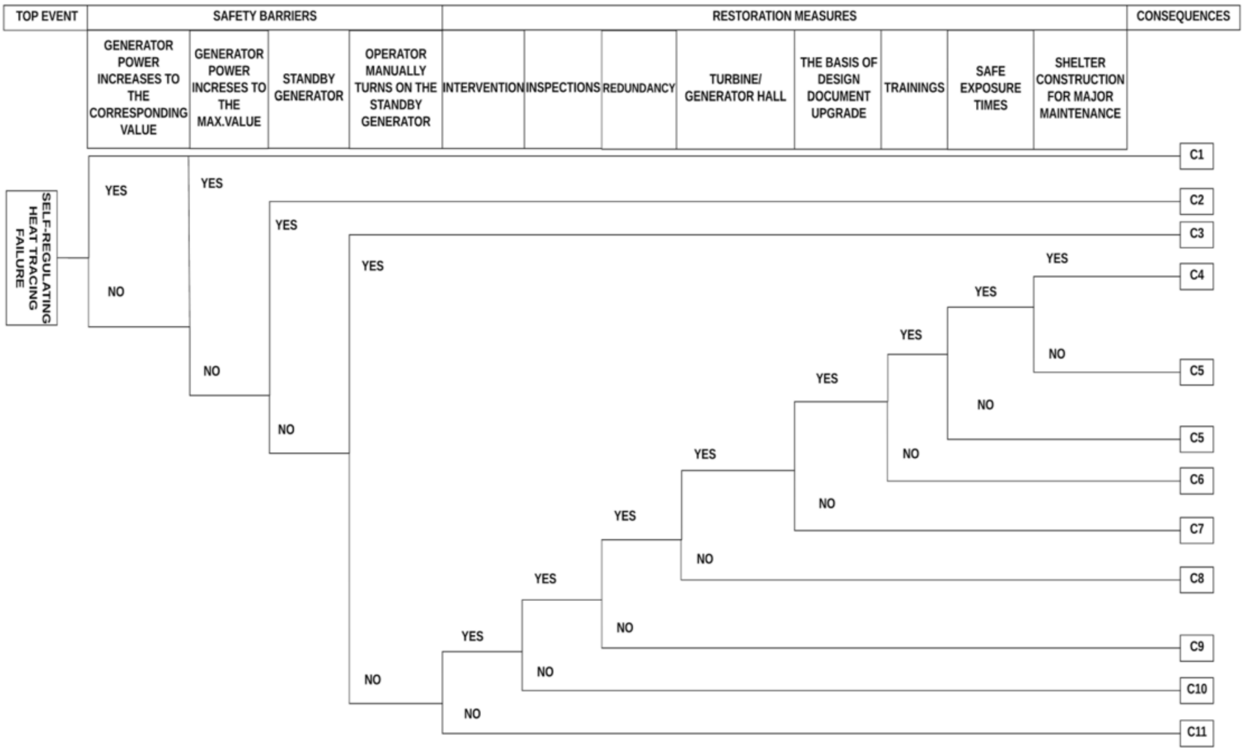

Figure 7. Example of the analysis of the sequence of events involving response mechanisms to a disruption. Source: Zinetullina et al. (2020)

As a result of conducting a similar process on the systems analyzed in this work, event trees for them could be constructed. Similar to the fault trees, these included events shared by a system utilizing either fuel, or exclusive to ammonia or methanol. They were also segregated by the type of supply chain process in order to facilitate understanding.

It is important to consider that the state of the system at the end of an event tree could correspond to different states of functionality: either fully functional with no further risks associated, functional but with further risks present or non-functional. To illustrate this, a color scale convention for the text boxes in which they are presented was implemented, as shown in Table 6.

Additionally, for the specific case of vapor and liquid fuel releases, which are a key disruption that will be discussed afterwards, it is important to note that they could be more easily controlled or not depending on their origin. Therefore, their effect on the functionality of the system considers two possible scenarios:

- On one hand, leakages could be caused as a result of accidents which do not lead to damages to the infrastructure of the system. Hence, the adaptation mechanisms could allow to adequately respond to them and operations could be restored quickly afterwards, to the benefit to the system's functionality.

- Alternatively, leakages could be caused as a result of infrastructural damages, such as a tank rupture or a loss of pipeline tightness. In these situations, while the adaptation mechanisms could still allow to adequately respond to the emergency, operations would not be able to be resumed promptly afterwards. Instead, it will be necessary to consider restoration mechanisms, such as the replacement of damaged components, if possible.

To account for both possibilities, as they have different implications, the use of a star mark convention was also adopted and described in Table 6.

Table 6. Color convention to illustrate the state of functionality of the final outcome of the event trees. Source: own elaboration.

Text box convention	Meaning
Green	The final outcome of the sequence of actions in the event tree is a fully functional state with no further risks associated. This means that the disruptive situation could be successfully controlled.
Yellow	The final outcome of the event tree is a fully functional state, but with risks associated to it. These risks remain potential threats to the state of functionality of the system further down the line. However, depending on the case, they could still be answered by other adaptation mechanisms.
Green or yellow with star mark	The final outcome of the sequence of actions in the event tree is a fully functional state (either with or without further risks associated) only if the fuel release was caused by accident and not due to infrastructural damage. If it was not, then the final outcome is a non-functional state.
Red	The final outcome of the event tree is a non-functional state, which would or should force an interruption of the operations. However, the operational capacity of the system could still be recovered afterwards, following restoration mechanisms.

Similarly, for the intermediate events of the trees, a color convention was adopted and implemented to show whether they correspond to proactive or reactive response mechanisms, or if they are an important condition to determine what the outcome of the event tree is. This last situation alludes, for example, to whether the presence of an ignitable atmosphere occurs within an enclosed space or not, as the former translates into a higher risk of explosion, while the latter implies a higher risk of fire (ABS 2021). The color convention in question is presented in Table 7.

Table 7. Color convention to show the characteristics of the intermediate events of the event trees. Source: own elaboration.

Text box color	Meaning
Dark yellow	Proactive response mechanism. It addresses a potentially disruptive situation before it occurs. For example, the proactive monitoring of the pressure inside the fuel storage tank.
Light yellow	Reactive response mechanism. It answers a disruptive situation once it has already occurred. For example, a fuel gas leakage detection system.
Orange	The presence or absence of this condition is relevant to the outcome of the event tree. For example, the presence of an ignition source.

Derivation of restoration measures

The last series of events that needed to be derived in order to construct the BN model were the restoration measures. This was done by identifying actions that could be performed to restore the operational capacity of the system once it had either been compromised due to the effects of an uncontrolled disruption or interrupted by the adaptation measures for safety reasons. Therefore, it includes actions ranging from replacing damaged equipment, to using backup systems or reactivating interrupted operations. These were also identified per type of process (i.e. fuel transport, transfer and storage) and as a simple sequence of events, going from the initial disrupted status to the action performed to restore operations.

Structure transformation & BN construction

Once the fault and event trees, as well as the restoration measures were derived, the corresponding BNs could be constructed following a set of considerations, which are also illustrated in Figure 8.

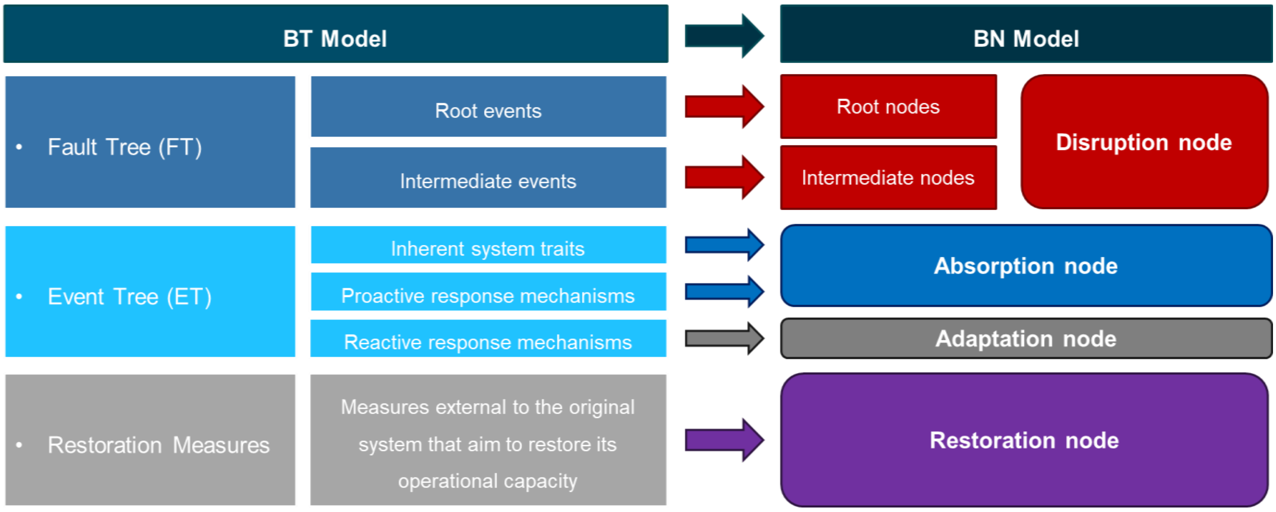

Figure 8. Considerations for the transformation of the BT model into the BN model. Source: own elaboration.

- The fault trees were utilized to construct the disruption node of the BN. The basic events were transformed into root nodes, while the intermediate events became intermediate nodes.

- The absorption node of the BN was derived from a subsection of the event trees. Specifically, from the measures or safety mechanisms that prevented disruptions from affecting the system to any extent. This could either be from a proactive control and response point of view (e.g. pressure monitoring and early corrective actions), or due to inherent system traits (e.g. high thermal resistance of the equipment surrounding ammonia storage or transfer infrastructure) and corresponds to the elements in the event trees presented with a dark yellow color, as previously shown in Table 7.

- The adaptation node was derived from the remaining subsection of the event trees, corresponding to measures or mechanisms attempting to stop, control or mitigate the consequences of disruptions to the system in order to allow it to continue operating. For example, the use of drip trays that can safely store accidental leaks during a bunkering process. These correspond to the elements in the event trees represented with a light yellow color, as presented in Table 7.

- Lastly, the restoration mode was structured from the identification of measures external to the system that could be performed in order to attempt to restore its operational capacity, once it had been compromised due to an uncontrolled disruption or interrupted for safety reasons. For example, the replacement of damaged equipment.

As a result of this process, separate BN models for methanol and ammonia systems could be derived. Each of them includes all the events from the stages of the supply chain covered within the scope of analysis.

3.4 Method for the assignment of weighting factors within the BNs

Once the BNs were fully structured, an additional complement to consolidate the models was to formulate a method that can be used to assign weighting factors to the parent nodes of the systems, in order to reflect an assessment of their relative importance. This could be useful as an approach to derive the conditional probabilities required to perform quantitative resilience assessments with BNs, considering that the experience with methanol and ammonia as alternative maritime fuels is still limited and, consequently, a lack of sufficient historical data to feed all the elements of the models could be expected. Therefore, having a tool that allows to achieve this task by incorporating expert judgement instead could facilitate the application of the methodology in the short term.

The assignment of weights to the parent nodes should be done considering aspects such as how seriously they could disrupt the system operation on the event that they occurred, whether they could impact other components of the system (or even other stages of the supply chain) and how significant their consequences could be. For example, a fuel leakage caused by the structural collapse of the storage tank should be given a higher weight compared to a small leakage of residual fuel left on a bunkering hose after a fuel transfer process, as the latter would be much less impactful and easier to control.

It is proposed to perform the assignment of the weighting factors by applying the FAHP, taking into consideration its ability to incorporate qualitative and quantitative criteria and accommodate for uncertainty, as well as the precedent on its use for quantitative and qualitative risk assessments using BNs (Tong et al. 2020; Wang 2024). To this end, the scale of relative importance presented previously in Table 3 was considered. However, it was opted not to utilize intermediate values in order to facilitate the application of the method, as this allows for a good balance between granularity and simplicity. Figure 9 presents a flow chart summarizing the procedure.

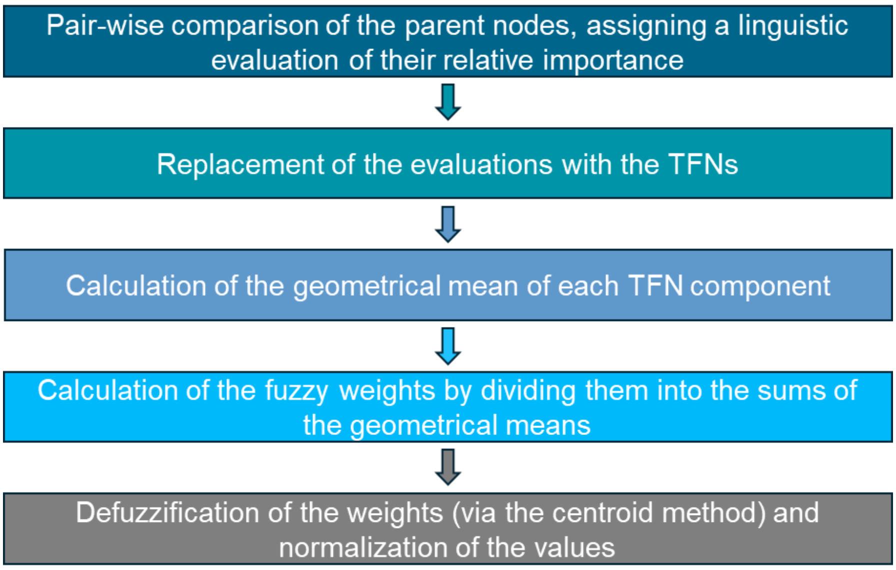

Figure 9. Flow chart of the method for assigning weighting factors to the parent nodes based on the FAHP. Source: own elaboration.

The first step is to perform a pairwise comparison of all the parent nodes contributing to the same child node. This consists on evaluating each parent node against all others one-on-one, initially assigning a linguistic valuation of the relative importance of one against the other. In this way, a n*n matrix can be constructed, where "n" represents the number of parent nodes analyzed. This process must be replicated for all the parent nodes that want to be analyzed in order to construct all the required matrixes (Huang et al. 2025; Palak et al. 2023; Wang et al. 2019; Zhang et al. 2024). An example of how a pairwise comparison looks is presented in Table 8. There it is being applied to 5 elements, or PNs, which stands for parent nodes.

Table 8. Example of a pairwise linguistic comparison between 5 different parent nodes.

Source: own elaboration

	PN1	PN2	PN3	PN4	PN5
PN1	equal	moderate	moderate	absolute	moderate
PN2	none	equal	strong	absolute	moderate
PN3	none	none	equal	absolute	none
PN4	none	none	none	equal	none
PN5	none	none	strong	absolute	equal

Here, a couple of things should be noted. First, that the values in the diagonal of the matrix are always set to "equal", as it corresponds to the evaluation of a parent node with itself. Meanwhile, the valuations present in the other fields should be interpreted from the perspective of the row that is being analyzed. For example, cell PN1-PN4, where the value is set to “absolute”, means that PN1 is considered absolutely more important compared to PN4. Then, to facilitate the application of the method, the value of the reciprocal cell (in this case PN4-PN1) is set to “none” temporarily. However, if the element on the row is considered to be less important than the element in the column (such as in the case of cell PN3-PN5), then the value is temporarily set to “none” and instead the valuation is placed on the reciprocal cell (in this case, cell PN5-PN3). This configuration means that PN5 is considered strongly more important than PN3.

After this is done, the linguistic valuation matrixes are transformed by assigning the TFNs that correspond to each value, as presented in Table 3. As for the cells that were assigned a “none” value temporarily, they are replaced by the reciprocal TFN of their reciprocal cell. This means that if a cell is assigned the TFN (a, b ,c), then its reciprocal cell should be set to (1/a, 1/b ,1/c) (Wang et al. 2019). The next step is to apply Chang’s Extent Analysis, which consists of three main processes: 1) calculating the synthetic extent values for each parent node, 2) calculating the degree of possibility for each type of TFN component considering all parent nodes, and 3) deriving a fuzzy weights vector (Chang 1996).

The synthetic extent values are calculated as the geometrical means of the TFN components for each parent node. This means that for all of the lower, middle and upper values of each parent node, the following formula is applied (Helmy et al. 2021):

$$r_i = (\prod_{j=1}^{n}(l_{ij}, m_{ij}, u_{ij}))^{\frac{1}{n}} = \left((\prod_{j=1}^{n} l_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} m_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} u_{ij})^{\frac{1}{n}} \right)$$

Equation 1. Calculation of the synthetic extent values of the TFN components of the parent nodes. Source: adapted from Helmy et al. (2021)

Where “r_i” represents the synthetic extent values of a parent node i; “l_{ij}”, “m_{ij}” and “u_{ij}” are the lower, mean and upper values of its TFNs respectively and “n” is the total number of parent nodes evaluated.

In other words, the geometrical mean for each of the lower, mean and upper values of the TFNs are calculated as the product of the values of all the different pairwise comparisons, which are then elevated to the power of 1/n. As a result, a geometric mean triplet is obtained for each parent node.

Afterwards, the degree of possibility of each type of TFN component is calculated as the sum of the geometric means of that component from all parent nodes, which were calculated previously. As a result, one value is calculated per type of TFN component. That is, one using all of the lower values ($\sum l_i$), one using all of the mean values ($\sum m_i$) and another using all of the upper values ($\sum u_i$) (Chang 1996; Helmy et al. 2021). Then, a triplet of fuzzy weights for each parent node (w_i) is derived by dividing its geometrical means (l_i, m_i and u_i) by the corresponding degree of possibility, as seen in Equation 2.

$$w_i = (\frac{l_i}{\sum u_i}, \frac{m_i}{\sum m_i}, \frac{u_i}{\sum l_i})$$

Equation 2. Calculation of the fuzzy weights of each parent node. Source: adapted from Helmy et al. (2021).

Here it can be noted, however, that the geometric means of the lower bound values (l_i) must be divided by the degree of possibility calculated with the upper bound values ($\sum u_i$) and vice versa for the upper bound values (u_i), which are divided by the degree of possibility calculated with the lower bound values ($\sum l_i$). Meanwhile, the geometric means of the mean values (m_i) are still divided by the degree of possibility calculated with the mean values ($\sum m_i$). As a result of this process, a triplet of fuzzy weights is obtained for each parent node (Chang 1996; Helmy et al. 2021).

Subsequently, the weights are defuzzified by calculating the mean value of the fuzzy weights triplets, which is known as the centroid method (Więckowski et al. 2022). Lastly, each defuzzied weight is normalized by dividing it into the sum of all of weights. The outcome of the whole process is a final weighting factor for each of the analyzed parent nodes (Więckowski et al. 2022).

It is important to note that all of the steps described after the linguistic pairwise evaluation can be carried out via with a Python script named “FAHP_BN_weights.ipynb”, which will be available for consult alongside this manuscript.

4. RESULTS

The results derived as part of this work include all of the following: 1) the derivation of the fault and event trees, as well as the restoration measures for the systems of interest; 2) the final BN models for the ammonia and methanol-based systems; and 3) an example on how to apply the method designed for assigning weights to the parent nodes of the system. These are all presented in detail during this chapter.

4.1 Fault trees

As discussed in the methodology section, the fault trees were derived separately for ammonia and methanol, as well as for each type of supply chain process (i.e. fuel transport, transfer and storage). The results obtained for each of them are presented in this section. For each figure, the sources that were considered to derive the identified events will be discussed.

Fault trees for methanol transport processes

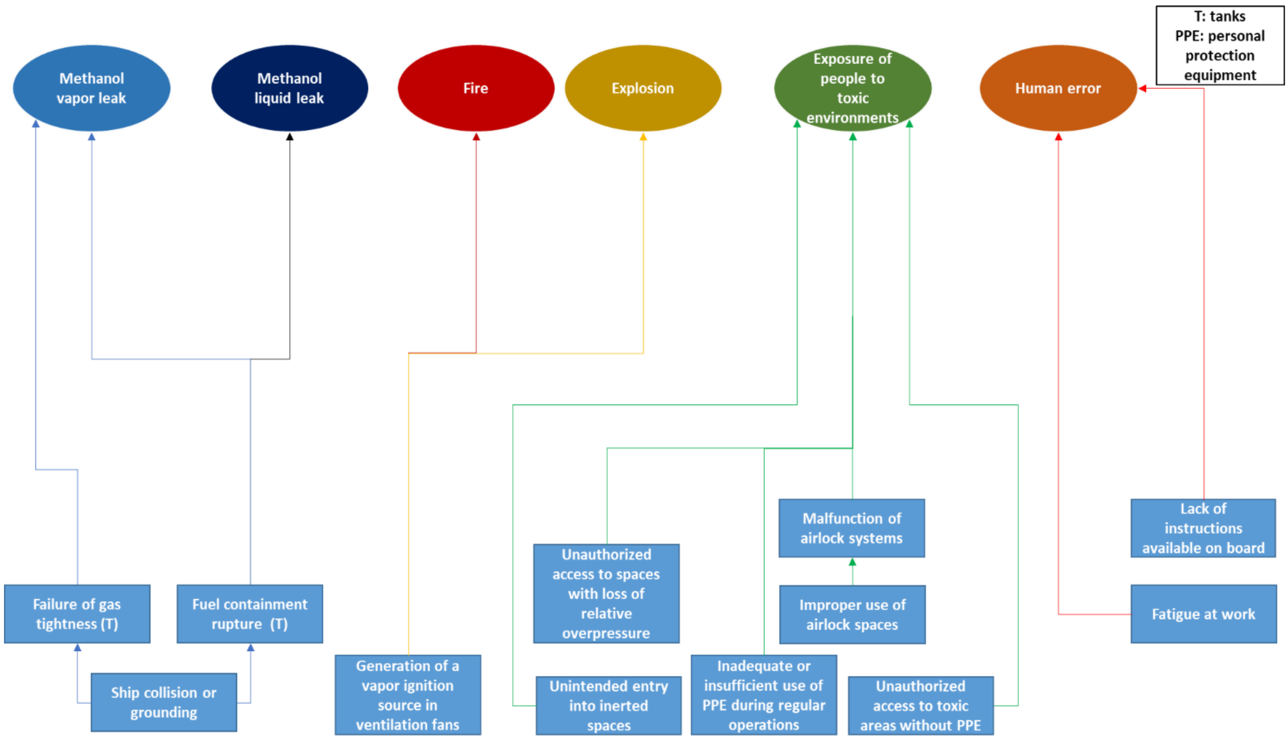

Figure 10. Fault tree for methanol transport processes. Source: own elaboration.

The first event considered is a collision or grounding event on the ship. This can cause either a failure of gas tightness in the storage tank (due to partial breaches in the vapor space area of the tanks or the deformation of seals, gaskets or flanges) or a full tank rupture, leading to liquid and gaseous releases, due to the constant formation of methanol vapors at temperatures above its flashpoint (Gyenes et al. 2017). **The second event identified is the generation of a source of vapor ignition in the ventilation fans**. This would be the result of an incorrect ventilation system design, or an undesired failure within the fans themselves, and it is a situation that the IMO explicitly encourages to avoid (IMO 2020).

Other series of significant events are the ones that could lead to the **exposure of crew members to toxic areas or environments**. These include multiple causes, starting with the **unintended entry of personnel into inerted spaces**. Inerting refers to the introduction of nitrogen-enriched air to reduce the oxygen level of an atmosphere or space, decreasing the risk of combustion. This should be done regularly in methanol-transporting ships in order to reduce the risk of fires or explosions (Indian Register of Shipping 2025a). However, the unintended entry of ship personnel into inerted areas must be prevented, as it can have negative effects on their health due to a risk of oxygen deficiency (IMO 2025b). Similarly, the **entry of personnel to spaces with a loss of relative overpressure** must also be avoided. This alludes to the fact that hazardous areas (i.e., spaces containing methanol, and thus potential methanol vapors) must be kept at a relative underpressure compared to non-hazardous areas, in order to prevent the diffusion of toxic vapors. Therefore, the ship crew working on a methanol-transporting ship must also avoid entering to non-hazardous spaces that adjoin hazardous spaces if there has been a loss of relative underpressure on the latter (IMO 2020). Another possible cause for the exposure of people to toxic environments is the **inadequate or insufficient use of Personal Protection Equipment (PPE)**, either for conducting regular operations or for entering toxic spaces when required (IMO 2025b). Lastly, the **improper use of airlock spaces** could compromise their adequate operation, to the detriment of the protection from toxic gases that they should provide to the ship crew.

Airlocks are spaces enclosed by gastight bulkheads with two gastight doors which are self-closing and should not ever be left open. They are located next to hazardous areas or spaces and are mechanically ventilated to maintain an overpressure relative to them (IMO 2020). This prevents toxic gases from entering safe areas, offering protection to the ship crew. Airlocks are also typically equipped with gas sensors and a warning system with visual and auditive alarms that activate if more than one door is opened or if there is a loss of pressure, alerting the crew of potential losses of containment (Bureau Veritas 2025). For this reason, they are explicitly forbidden of being used for any purpose other than the transit between zones. One especially noteworthy situation, which is explicitly addressed in the IMO guidelines, is the use of these spaces as storerooms. This is because objects present in the room could impede an adequate ventilation or obstruct sensors or alarms, compromising the integrity and function of the system (IMO 2020).

Finally, **potential sources of human error** were also considered. The first one is **fatigue at work**, which has also been proposed and incorporated by authors such as Wang et al. (2024b), as it can lead to unintentional mistakes during operations. The last factor considered is the occurrence of **errors due to a lack of instructions available on board**, as this is another situation that must be explicitly avoided according to the IMO Guidelines (IMO 2020). More specifically, it is stated that information related to the description and maintenance procedures for all the methanol related installations must be available on board at all times. This could also be extended to operational procedures for which the crew members could require or would benefit from having additional and readily available resources to consult.

Fault trees for methanol transfer processes

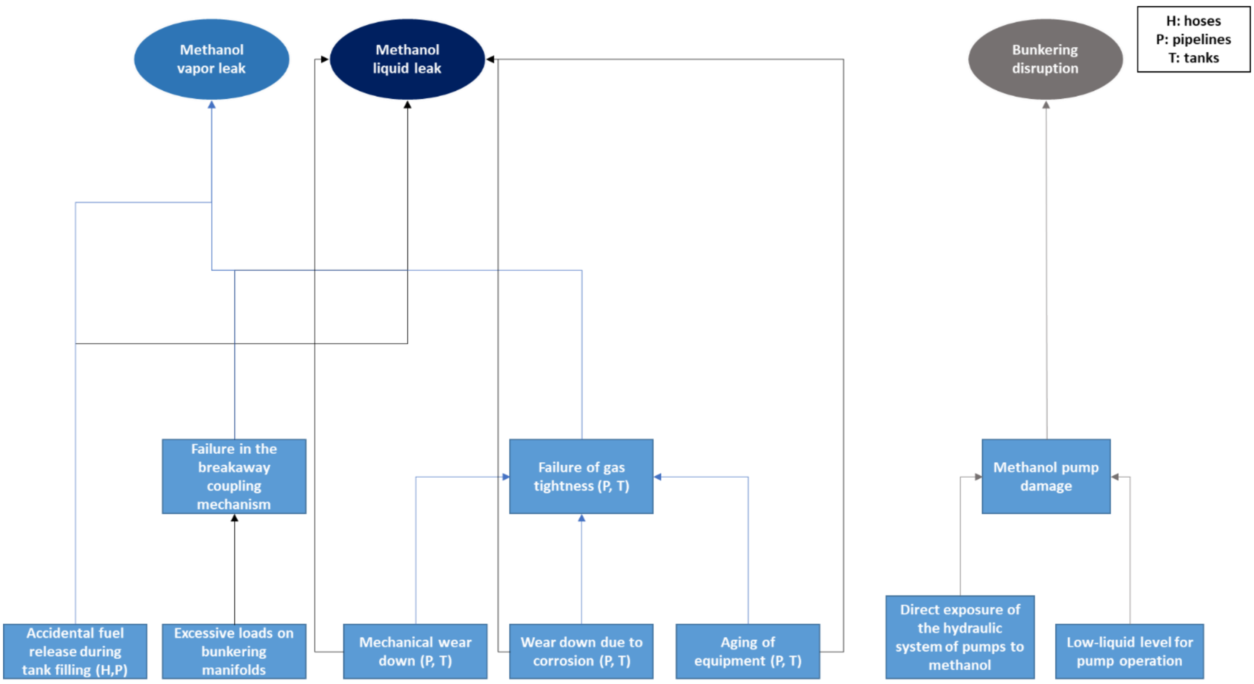

Figure 11. Fault tree for methanol transfer processes - Part 1 of 2. Source: own elaboration.

As for potential faults during methanol transfer processes, **one initially identified factor is the accidental fuel release from either hoses or pipelines during bunkering procedures**. This is considered to cause not only a liquid leakage, but also a vapor leakage due to the vaporization of the fuel. However, it must be noted that this process does not happen as quickly at ambient temperature and pressure as it does with other liquefied fuels, meaning the concentrations of vapors should not be expected to be significantly high (ABS 2021). A disruption with similar implications would be the **leakages caused by failures in the breakaway coupling mechanism following excessive loads in the bunkering manifolds**, which is another situation that needs to be prevented according to the IMO Guidelines (IMO 2020).

This refers to the fact that the coupling that connects the fuel transfer hoses to the system's manifolds are of the breakaway type. That means that they are held together by bolts or other mechanisms calibrated to withstand a specific maximum force during the bunkering processes. If the limit is exceeded due to the occurrence of an external force on the manifold, the coupling is designed to separate or "break off" in a controlled manner (ABS 2024a). Additionally, the breakaway system also automatically seals the ends of the hose and manifold, keeping the fuel inside and minimizing the risk of leakages, achieving what is called a dry disconnect (IMO 2020). However, if the breakaway mechanism fails to disconnect the system, the excessive force can result in the rupture of the bunkering hose or the manifold itself, causing a loss of containment. Additionally, leakages may also occur if the valves inside the coupling do not seal the system fully or were mechanically damaged as a result of the incident (Driplex Engitech 2024).

Furthermore, vapor and liquid leaks could also be caused by the **wear down of the bunkering pipelines or the receiving storage tanks**. This includes **mechanical wear down, material wear down caused by corrosion and the aging of equipment**. The former refers to damages to the physical integrity of the pipelines or tanks caused by repeated impacts or collisions, as well as, in the case of the fuel tanks from the receiving vessels, the continuous vibration of the ship during its operation (Wang et al. 2024a). Meanwhile, material wear down could also be caused by means of methanol corrosion, as certain equipment, such as seals and gaskets, could be degraded over time, especially if compatible materials were not used in their design (Sustainable Ships 2023). Lastly, the aging of equipment, such as pipelines, valves or gaskets, could also compromise their functional integrity (Bragatto and Milazzo 2016). All of these wear down mechanisms could manifest themselves as either the loss of the gas tightness of the equipment or as direct liquid leakages.

Another set of considerations is related to the **pumping equipment utilized for the bunkering processes**. In this sense, two particular threats were identified: the direct **exposure of the hydraulic system of the pumps to methanol**, as well as a **low-liquid level for the pumping operations**. Both of these situations are relevant, as they could result in damage to the pumping equipment, disrupting the bunkering process. Regarding the former, the IMO Guidelines state that hydraulically powered pumps that are submerged in fuel tanks must be provided with double barriers that prevent the hydraulic system serving the pumps from being directly exposed to methanol, as this could have significant negative effects (IMO 2020). On one side, methanol could degrade seals or other materials that were designed to withstand hydraulic oil, but not alcohols, which could then lead to leaks or failures in the pumping system (Indian Register of Shipping 2025a). Additionally, since hydraulic oil is also combustible, a mixture with methanol could be volatile and hazardous, which is another dangerous condition that must be avoided (ABS 2021).

Meanwhile, the low-liquid level for pump operations refers to guaranteeing that the pumps in the bunkering system that operate submerged are protected against running dry (i.e., in the absence of fuel), as this could also cause damage to the system. It is for this reason that the pumping systems must be provided with sensors that can alert of low-liquid levels, as well as shutdown mechanisms to avoid dry operations (IMO 2020).

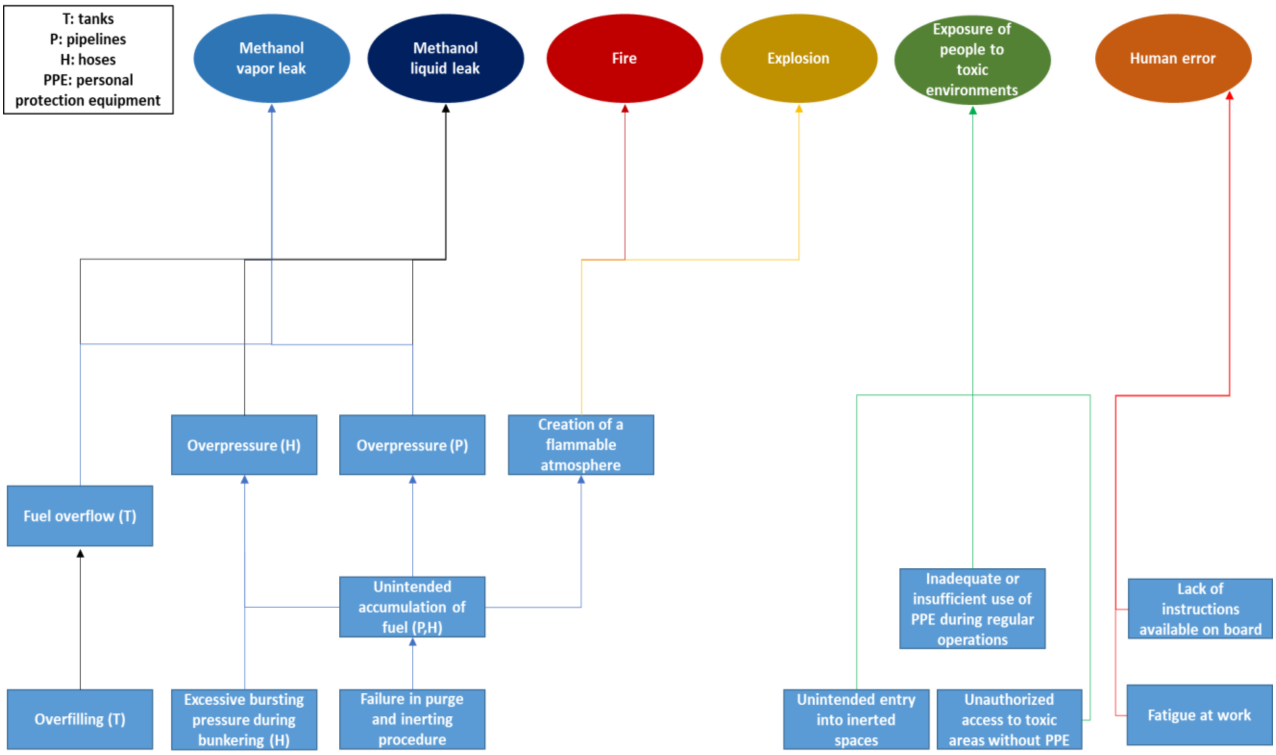

Figure 12. Fault tree for methanol transfer processes - Part 2 of 2. Source: own elaboration.

Further disruptions related to methanol bunkering processes are the **risk of overfilling the storage tanks**, since this could also lead to a fuel leak. This is the reason why the tanks must have visible and calibrated level indicators, as well as high liquid alarm systems that can help to prevent overflow situations (IMO 2020). Additionally, the **bunkering hoses could be subject to stress due to excessive bursting pressures during fuel transfer processes**. This is the reason why they must be designed with a bursting pressure of at least 5 times their specified maximum working pressure at the upper and lower extreme service temperatures, as well as hydrostatically tested at a pressure that is at least 1.5 times their specified maximum working pressure, but lower than 2/5 of their bursting pressure (IMO 2020). If the limit of the hose is exceeded, however, it could lead to a rupture and, consequently, a fuel leak.

Two further disruptive situations could arise from failures in the purging procedure of the bunkering system. Existing advisory guidelines for methanol bunkering processes from organizations such as the American Bureau of Shipping (ABS 2024b) and the Economic Commission for Europe (ECE 2024) recommend that bunkering systems are purged and inerted before and after the fuel transfer operations. This process consists of two stages. First, draining the bunkering lines (i.e., hoses and pipelines) to remove the remaining fuel liquid or vapor. And second, purging the system using inert gas to ensure that no leftovers are left behind, as well as to reduce the risk of the creation of flammable atmospheres (ABS 2024b).

Failures during these procedures would lead to the unintended accumulation of fuel in the bunkering pipelines or hoses, which in turn has two possible consequences. First, a pressure build-up, which could eventually lead to a fuel leakage due to overpressure. And second, a risk of fire or explosion due to the unexpected presence of methanol in liquid or vapor form.

Similar to the fuel transport processes, there could also be situations leading to the **exposure of crew members to toxic environments**. In particular, the **entrance into inerted spaces**, as fuel bunkering facilities are also regularly inerted (Indian Register of Shipping 2025a). The **inadequate or insufficient use of PPE for bunkering operations or access to toxic areas** also represents a risk. Lastly, the **factors leading to potential human errors**, namely fatigue at work and a lack of instructions available on board, could also be present during bunkering operations.

Fault trees for methanol storage processes

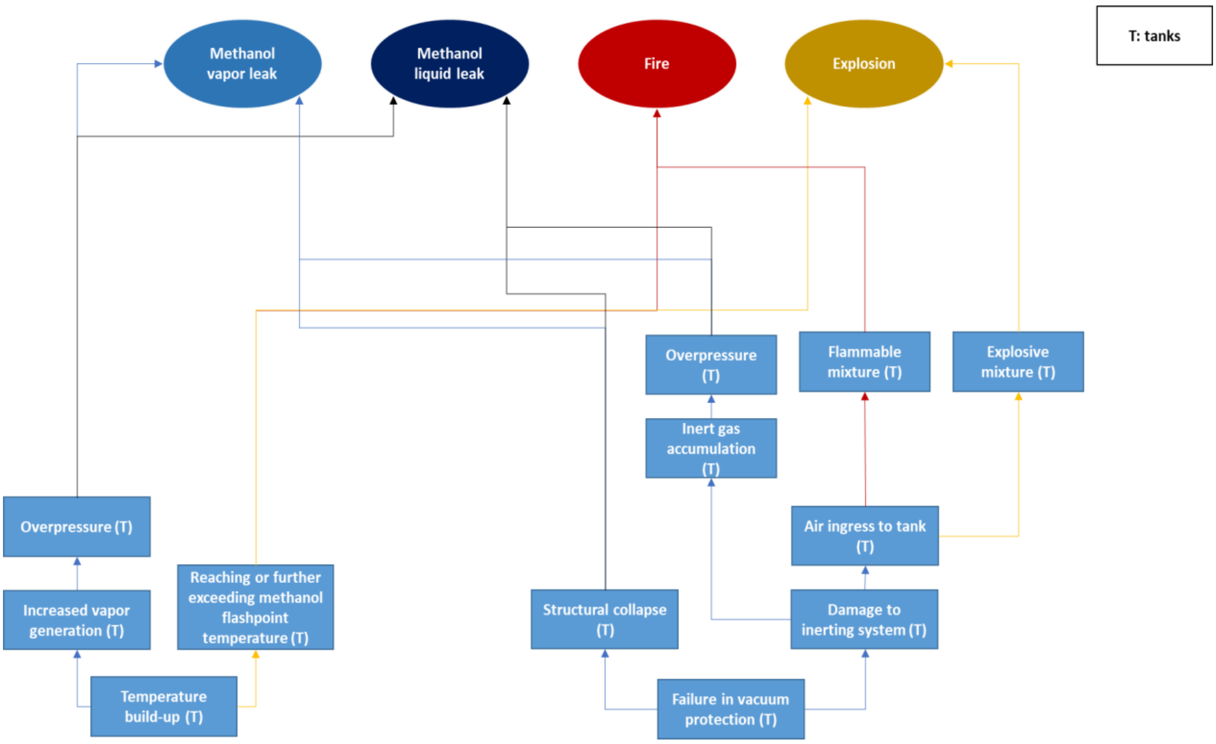

Figure 13. Fault tree for methanol storage processes - Part 1 of 2. Source: own elaboration.

Regarding the storage processes, the initial factor that was identified was the **risk of temperature build-up within the storage tanks**. This can lead to the increase of the methanol's vapor pressure, causing additional vapor generation and accumulation inside the tank and, ultimately, raising the risk of overpressure (Methanol Institute 2020). Another risk associated with temperature-build up would be **reaching or further exceeding the flashpoint temperature of methanol** (12°C), which increases the likelihood of methanol-related fires or explosions (ABS 2021; Methanol Institute 2020). Potential **failures in the tank's vacuum protection systems** could also lead to various negative consequences. On one hand, it could make the tanks susceptible to the effect of external pressures, which could end up causing a structural collapse, and thus a vapor and liquid fuel leakage (Indian Register of Shipping 2025a). Alternatively, it could compromise the integrity of the storage inerting system, which could have two further ramifications. First, it could lead to the accumulation of inert gas, which increases the risk of overpressure in the tank (ClassNK 2023). And second, it could allow the ingress of air into the tank, forming flammable mixtures that could cause fires or explosions (Indian Register of Shipping 2025a).

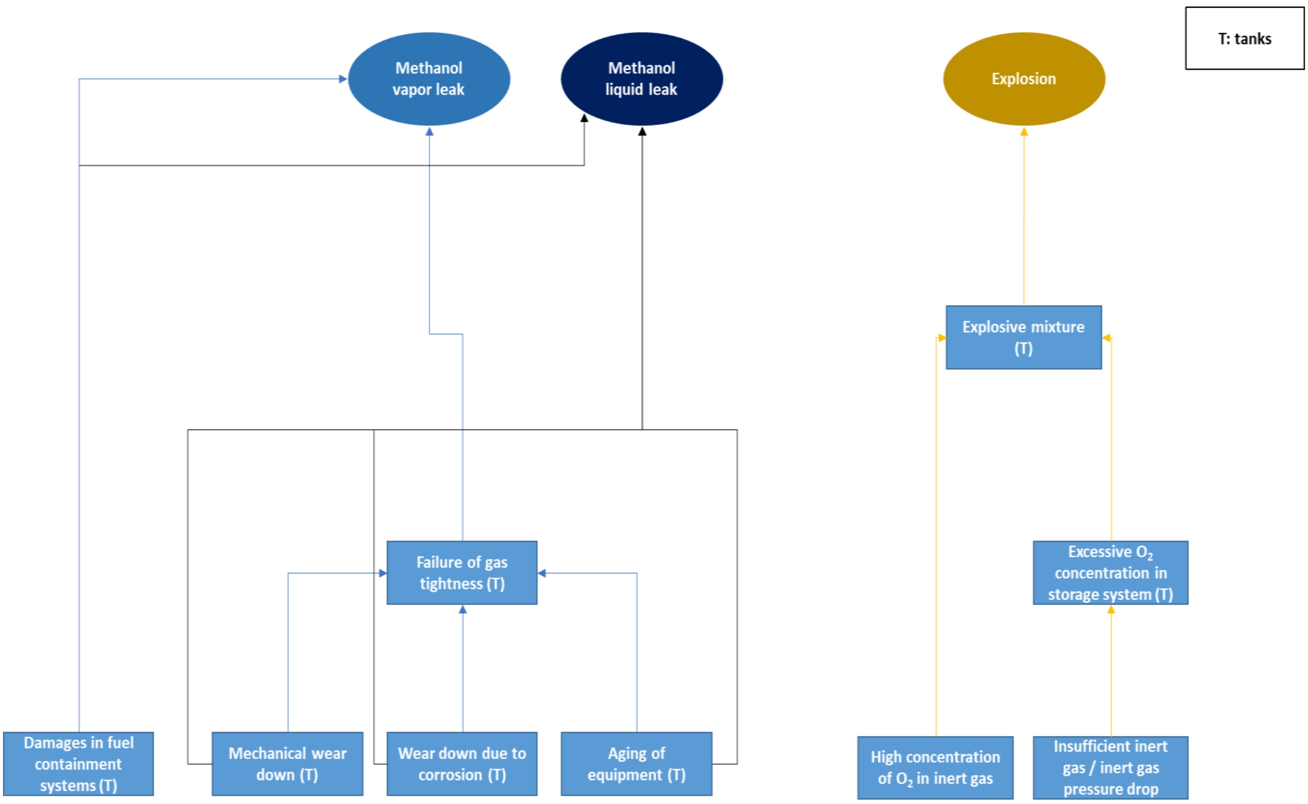

Figure 14. Fault tree for methanol storage processes – Part 2 of 2. Source: own elaboration.

Another potential risk associated to methanol storage would be **damages to the fuel containment tanks** which, similar to an overfilling episode, would result in a liquid and vapor fuel leakage (IMO 2020). The failure of gas tightness or the occurrence of liquid fuel leaks due to the **wear down of the storage equipment** (i.e. mechanical wear down, wear down due to corrosion and aging) could also be present (Bragatto and Milazzo 2016; Sustainable Ships 2023; Wang et al. 2024a). Lastly, **failures associated with the operation of the inerting system** for the storage infrastructure must be considered. On one hand, this could correspond to a **high oxygen content within the inert gas**, which should never exceed a concentration of 5% by volume (IMO 2020). On the other hand, there could also be a **lack of sufficient inert gas to protect the storage system**, which is evidenced by a drop of the inert gas pressure. This situation would also lead to an oxygen concentration higher than desired around the storage infrastructure (Indian Register of Shipping 2025a). Both of these conditions would cause the formation of a flammable atmosphere, most notably increasing the risk of explosions, as it would be embedded within enclosed spaces (ABS 2021).

Fault trees for ammonia transport processes

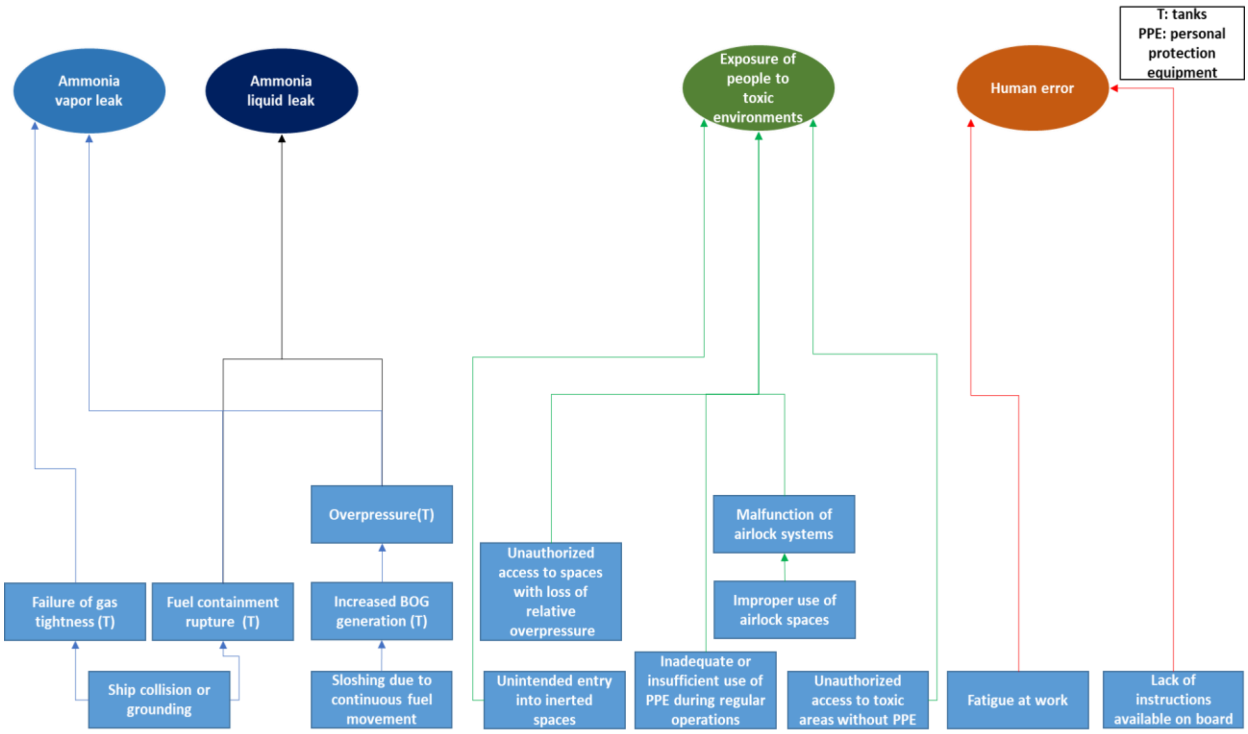

Figure 15. Fault tree for ammonia transport processes. Source: own elaboration.

The majority of the fault events identified for ammonia transport processes were also present in methanol transport processes. One exception, however, is the generation of a vapor ignition source in the ventilation fans, which is not considered in ammonia-based systems, as the risks of fires or explosions are much lower (Cames et al. 2021). Consequently, this potential disruption is not mentioned in the IMO interim guidelines for ammonia shipping systems (IMO 2025b), unlike in the case of methanol systems (IMO 2020).

In contrast, one event that is highly relevant for ammonia transport, but not as much for methanol systems, is the **sloshing of the fuel due to the continuous movement of the tanks**. Sloshing refers to the creation of waves and surges of liquid inside the storage tank as a result of ship motions. This, on one hand, causes an increased probability of high-pressure impacts inside the tank, which must be accounted for and managed as part of the storage system design, independent of the fuel in question. However, it is particularly relevant for the transport of saturated liquids, such as liquified ammonia, because it also has the thermodynamic effect of increasing temperature and, consequently, the generation of BOG emissions (Seatrade Maritime News 2023; Vijay 2023). This, in turn, has the potential to increase the pressure within the storage task, which is a risk that must be managed, as it could ultimately lead to fuel releases due to overpressure.

Another important distinction to keep in mind between methanol and ammonia systems is that since ammonia is stored and handled in cryogenic conditions, liquid fuel leakages would vaporize much more quickly when in contact with the surrounding external environment. This means that ammonia liquid leakages would generate much higher concentrations of vapors (Hammer and Leisner 2025).

Fault trees for ammonia transfer processes

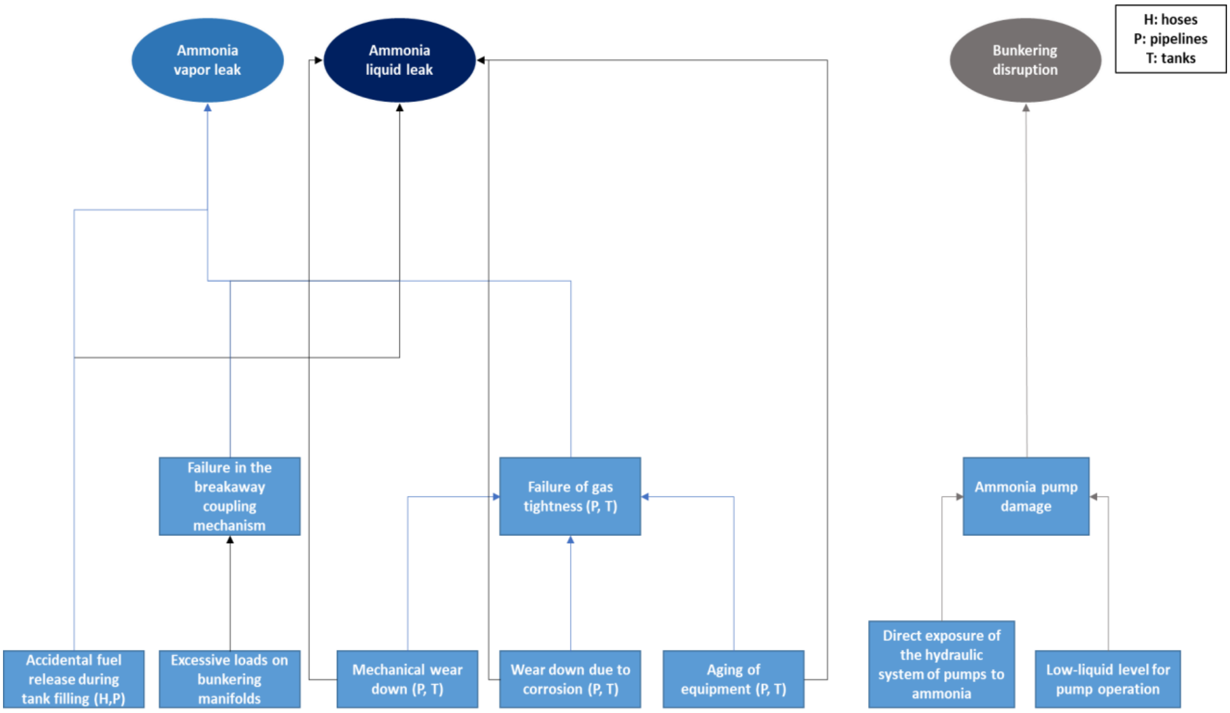

Figure 16. Fault tree for ammonia transfer processes - Part 1 of 3. Source: own elaboration.

For the ammonia transfer processes, the first set of events identified were also identical to the ones for methanol. However, it must be noted that the pumping system in this case will be cryogenic and would be threatened by the direct exposure to liquified ammonia. This could cause a series of negative effects leading to pump damage. One of them is material corrosion, as condensed ammonia is much more aggressive to a broader range metals compared to methanol (Grünhagen Romanelli et al. 2014). Furthermore, there could also be consequences related to the exposure of equipment to very low temperatures. In particular, material embrittlement, seal and gasket failures, thermal contraction of metals and mechanical stress. Not to mention that any existing moisture could also freeze rapidly, potentially leading to blockages and interfering with moving parts (AESSEAL 2025; Bright 2023; Goodrich 2020).

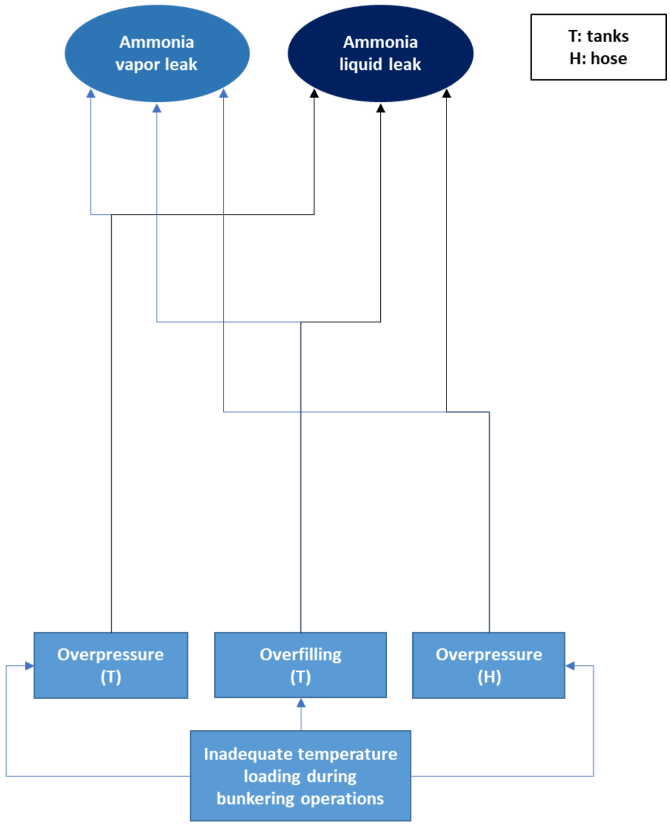

Figure 17. Fault tree for ammonia transfer processes - Part 2 of 3. Source: own elaboration.

A group of events exclusive to ammonia transfer systems would be the **consequences of inadequate temperature loading during bunkering operations**. This refers to fact that ammonia bunkering systems must follow a loading limit curve that indicates the maximum allowable fill level of the tank at specific temperatures (IMO 2025b). That is essential because of two main reasons. First, the condition that the ammonia density will change with temperature, being higher at lower temperatures and vice versa. Thus, the fill limit at lower temperatures will be higher because ammonia occupies less space, but as temperature increases, the liquid expands, taking up more room in the storage tank (ABS 2023). Consequently, an incorrect application of the loading curve could potentially lead to tank overfilling problems. Another reason is to prevent the risk of overpressure in the storage tanks and bunkering hoses. This could happen if the tank was being filled at a low temperature, but then the ammonia warmed up due to ambient conditions or heat ingress. The expanding liquid could exert additional pressure on both, the bunkering hose and the fuel containment tank (IMO 2025b).

Additionally, it must also be kept in mind that there will be a continuous generation of boil-off gas during the bunkering process, which must be handled via the tank's reliquefaction system. Therefore, the generation of excessive BOG due to a temperature build-up caused by heat ingress, as well as failures in the boil-off reliquefaction system itself could also lead to a risk of tank overpressure. However, this will be analyzed and modeled as part of the fuel storage processes, as it affects and is dealt with mechanisms of the storage infrastructure itself.

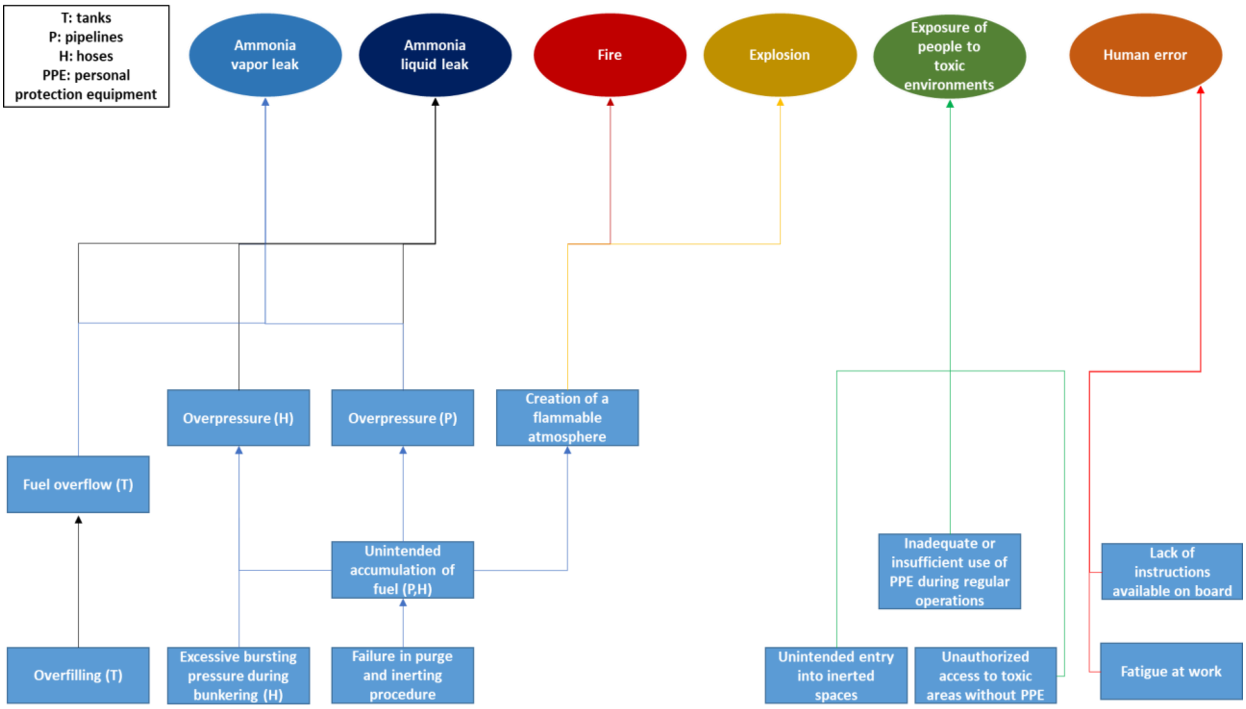

Figure 18. Fault tree for ammonia transfer processes - Part 3 of 3. Source: own elaboration.

The last set of potential disturbances during ammonia transfer processes are also identical to the ones identified for methanol. In terms of potential causes of ammonia vapor or liquid leaks, there is the risk of overfilling, the unintended accumulation of fuel in either hoses or pipelines due to a failure in the purge and inerting procedure, which are also recommended for ammonia bunkering processes (ABS 2024a), and excessive bursting pressures on hoses during bunkering. The unintended accumulation of fuel could also lead to the creation of a flammable atmosphere due to the unexpected presence of liquid or gaseous ammonia, which in turn generates a risk of fire or explosion. Regarding the exposure of people to toxic environments, the unintended entry into inerted spaces and the inadequate or insufficient use of PPE for performing regular operations or entering into toxic areas can all be present. Lastly, for the potential sources of human error, there can also be fatigue at work or a lack of instructions available on board.

Fault trees for ammonia storage processes

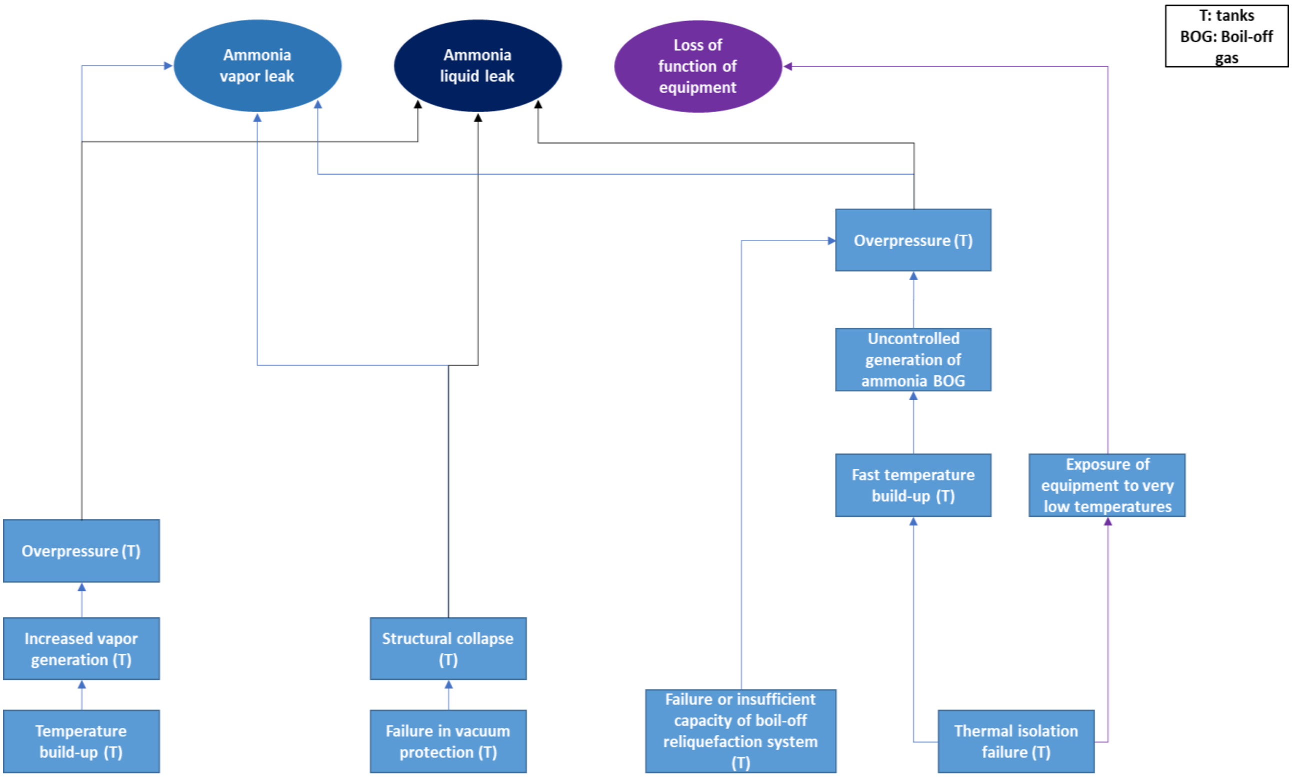

Figure 19. Fault tree for ammonia storage processes - Part 1 of 2. Source: own elaboration.

Regarding ammonia storage processes, one main difference compared to methanol storage is the absence of an inerting system, as inerting procedures are only recommended for the fuel transfer processes (ABS 2024a; ECE 2024). Instead, ammonia storage systems are not mandated to have permanent inerting processes (IMO 2025b). Therefore, the consequences of failures in the tank's vacuum protection are limited to liquid and vapor leakages due to a structural collapse. Additionally, the risks related to reaching or exceeding the flashpoint temperature of the fuel are not present. Instead, a critical aspect to consider is the integrity of the thermal isolation system of the tank. This is because failures in this regard, as well as any other source of **temperature build-up within the tank, would lead to an increased generation of ammonia BOG**, which could be another contributor to tank overpressure (Hammer and Leisner 2025). BOG refers to the gas that is generated due to the vaporization of liquid ammonia during its storage and transport. BOG can increase the pressure in tanks or pipelines, which is why ammonia storage solutions must always be coupled with boil-off reliquefaction systems (ClassNK 2025). These are responsible for receiving the evaporated fuel and recondensing it via cooling or compression (IMO 2025b).

Consequently, the storage system could be threatened either by an excessive generation of BOG due to temperature-build up within the tank or in case of **failures to the boil-off reliquefaction system** itself. **Failures in the thermal isolation system** could also cause further effects due to the exposure of surrounding equipment to very low temperatures, leading to potential losses of function (IMO 2025b).

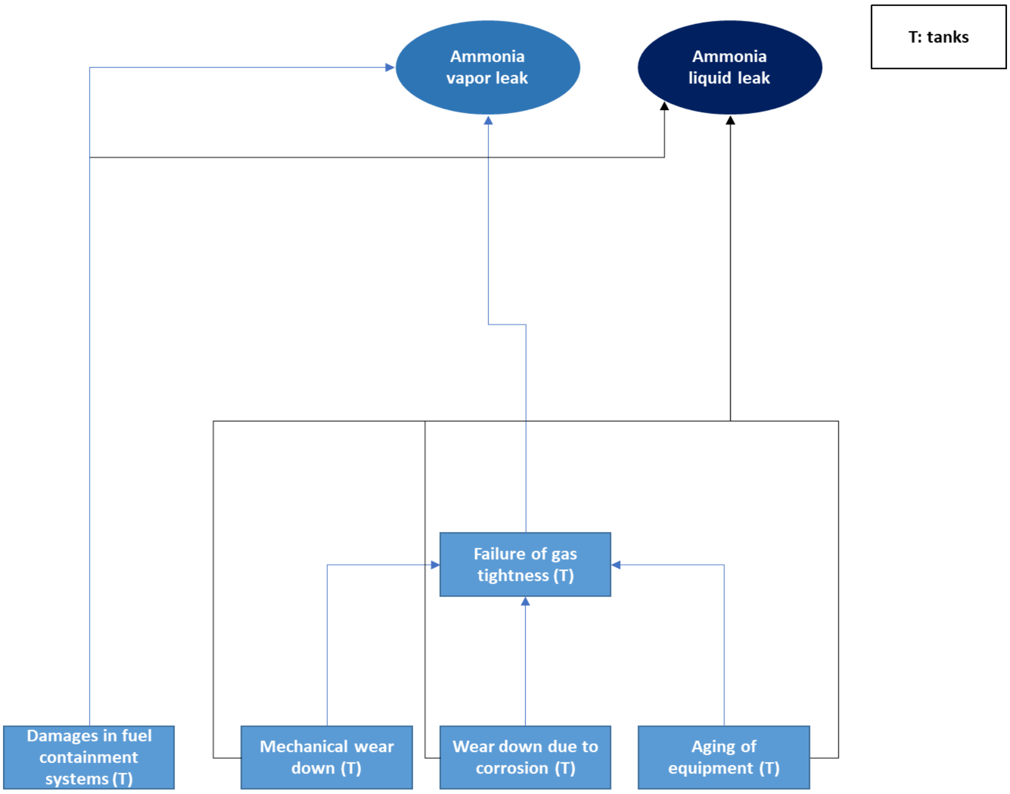

Figure 20. Fault tree for ammonia storage processes - Part 2 of 2. Source: own elaboration.

The last set of disturbances identified for ammonia storage processes are also commonly shared with methanol storage systems. These are other potential sources for vapor or liquid leaks, including damages to the fuel containment system, as well as component wear down due to mechanical stress, corrosion, or aging (Bragatto and Milazzo 2016; Grünhagen Romanelli et al. 2014; Sustainable Ships 2023).

4.2 Event trees

Similar to the fault trees, the event trees for ammonia and methanol systems were derived separately for the fuel transport, transfer and storage processes. They consist of a series of decision trees which begin with a disruptive situation and analyze all the possible response mechanisms that could allow to avoid or mitigate their impact. Depending on whether a response mechanism is successful or not, it could lead to a final state of the system or a further response mechanism. To illustrate that the state of the system at the end of the event tree could correspond to different states of functionality, the color scale convention for the text boxes in which they are presented, described previously in Table 6, was implemented. Likewise, the color convention to illustrate the nature of the intermediate events (whether they correspond to proactive response mechanisms, reactive response mechanisms or conditions relevant to the outcome of the event tree) presented in Table 7 was also utilized. Regarding the derivation of the event trees for fuel transport processes, it is also important to keep in mind that they do not cover events related to the storage tanks, as previously discussed in Section 3.1. Instead, these were derived and included within the event trees for fuel storage processes.

With these considerations in mind, the results obtained are presented in detail, alongside the sources that were considered to derive all the events.

Event trees for methanol transport processes

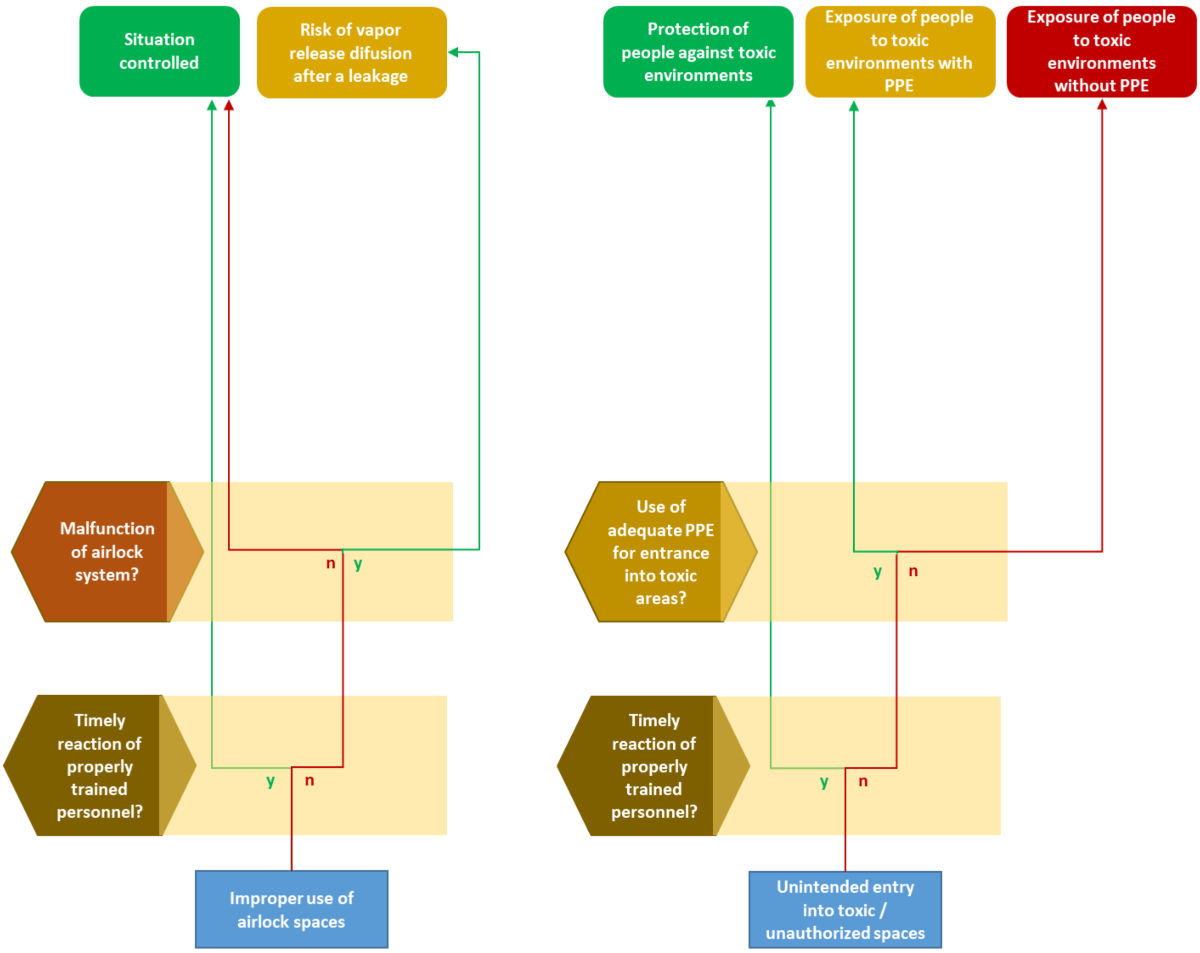

Figure 21. Event tree for methanol transport processes - Part 1 of 2. Source: own elaboration.

Beginning with methanol transport processes, the first event to consider is the **improper use of airlock spaces**. As described during the derivation of the fault tree, airlock spaces must not be used for any sort of additional purpose, such as goods storage, as this could compromise their operational integrity (IMO 2020, 2025a). In this sense, two paths of action that could allow to avoid the impact of this situation were identified. First, an opportune reaction from the ship crew, correcting any misuse of the airlock spaces. And second, the operational tolerance of the airlock itself. That is, the fact that the airlock system could still operate and provide protection to the ship crew, in spite of any objects located inside it. Nevertheless, should none of these conditions be met, the airlock system would be left at risk of not being able to guard the ship personnel in the event that a methanol vapor release occurs.

A second disruptive situation that could be responded to is the **unintended entry of personnel into toxic or unauthorized (inerted) spaces**. Initially, an opportune reaction of other crew members could prevent this event from happening at all. However, should it still occur, the availability and use of adequate PPE could protect people from experiencing negative consequences to their health. In case none of these conditions are met, and a crew member is exposed to toxic environments without using any type of PPE, operations should be interrupted until the wellbeing of the person is assessed and preventive or responsive assistance is provided, as will be described later during the restoration measures analysis.

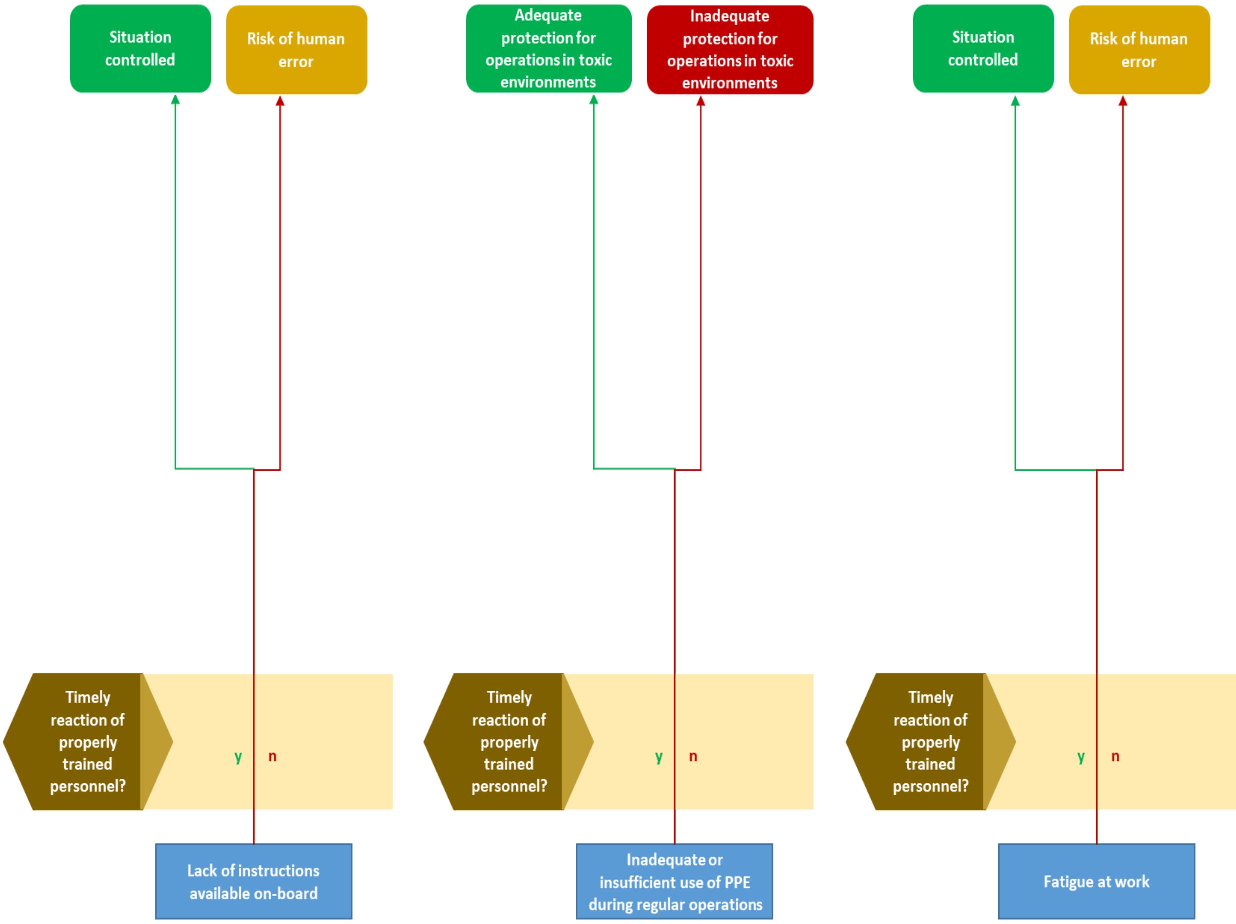

Figure 22. Event tree for methanol transport processes - Part 2 of 2. Source: own elaboration.

Another set of disruptive situations associated with methanol transport processes are the **occurrence of human errors due to either fatigue at work or a lack of instructions available on board**. Both these events could be prevented by the timely intervention of other crew members to correct inadequate or wrong actions. This is also the case for the performance of regular operations without adequate or sufficient PPE. However, should this conduct not be corrected by the proactive reaction of ship personnel, operations should be similarly interrupted until the wellbeing of the exposed workers is assessed and the corresponding actions are taken.

Event trees for methanol transfer processes

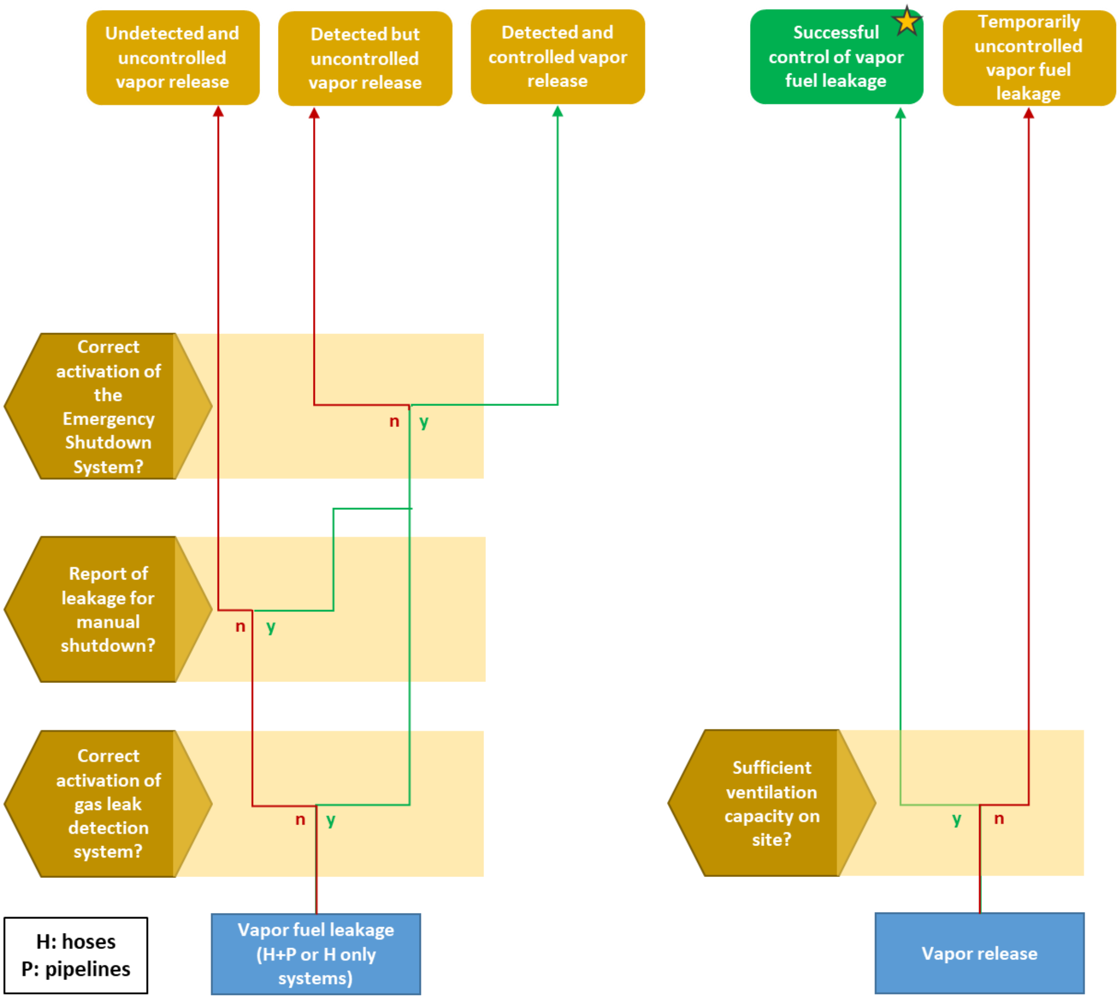

Figure 23. Event tree for methanol transfer processes - Part 1 of 6. Source: own elaboration.

Regarding the methanol transfer processes, an initial disruptive situation to consider is a **vapor fuel leakage from the fuel conduction infrastructure**. This could correspond to either a bunkering hose + pipeline arrangement or a hose-only system. The former applies to the fuel transfer processes from the production site to the tanker vessel, as well as to and from the storage tanks at port, since the use of a combination of bunkering pipelines and hoses is assumed. In contrast, a hose-only system is assumed for the ship-to-ship transfer from the bunkering vessel to the final off-taker ship. However, independent of the type of system, the first response to this event is the gas leak detection system, which should be part of any type of bunkering system and allow to identify methanol vapor leaks as soon as they occur by measuring its concentration in the surrounding air before it disperses (IMO 2020). Upon its activation, the Emergency Shutdown System (ESD) of the fuel transfer infrastructure should also be triggered, interrupting the operations with the objective of minimizing spillage (Port of Gothenburg 2022).

The ESD consists of two stages. First is the controlled shutdown of the methanol transfer process, via the deactivation of the pumps, and the second is the decoupling of the transfer system. The latter is accompanied by quick acting valves that store the methanol contained in any part the fuel transfer line (i.e., the bunkering pumps, pipelines or hoses), allowing to achieve what is known as a dry disconnection or dry break of the system (Indian Register of Shipping 2025b). Should the gas leak detection system fail, however, there is also the possibility of the operation crew identifying and reporting the leakage to manually trigger the system shutdown. This should be done via a manual stop valve located in the bunkering line, close to the connection point (IMO 2020).

The fuel vapor releases will be easier or more difficult to control depending on whether the gas detection system and the ESD mechanisms were triggered or not. The former will determine if the vapor leakage could be detected or not, and the latter whether the vapor release will be controlled (i.e., expected to stop promptly) or not.

Independent of this outcome, **all vapor releases in the system will be handled via its ventilation capacity** (IMO 2020). In the case of open deck or open air located systems, this corresponds to the natural ventilation on site. Meanwhile, for closed or semi-enclosed locations, a mechanical ventilation system must be made available (IMO 2020). Should the ventilation capacity on site at the moment of the methanol vapor release not be enough to safely disperse it, there is the option of activating additional ventilation capabilities, as will be shown next in Figure 24. Conversely, if the fuel vapor leakage could be successfully dissipated, the functionality of the system at the end of the event would depend on the origin of the leakage: functional when the release was accidental and non-functional when it was the result of infrastructural damage (in this case, to either the bunkering hoses or pipelines).

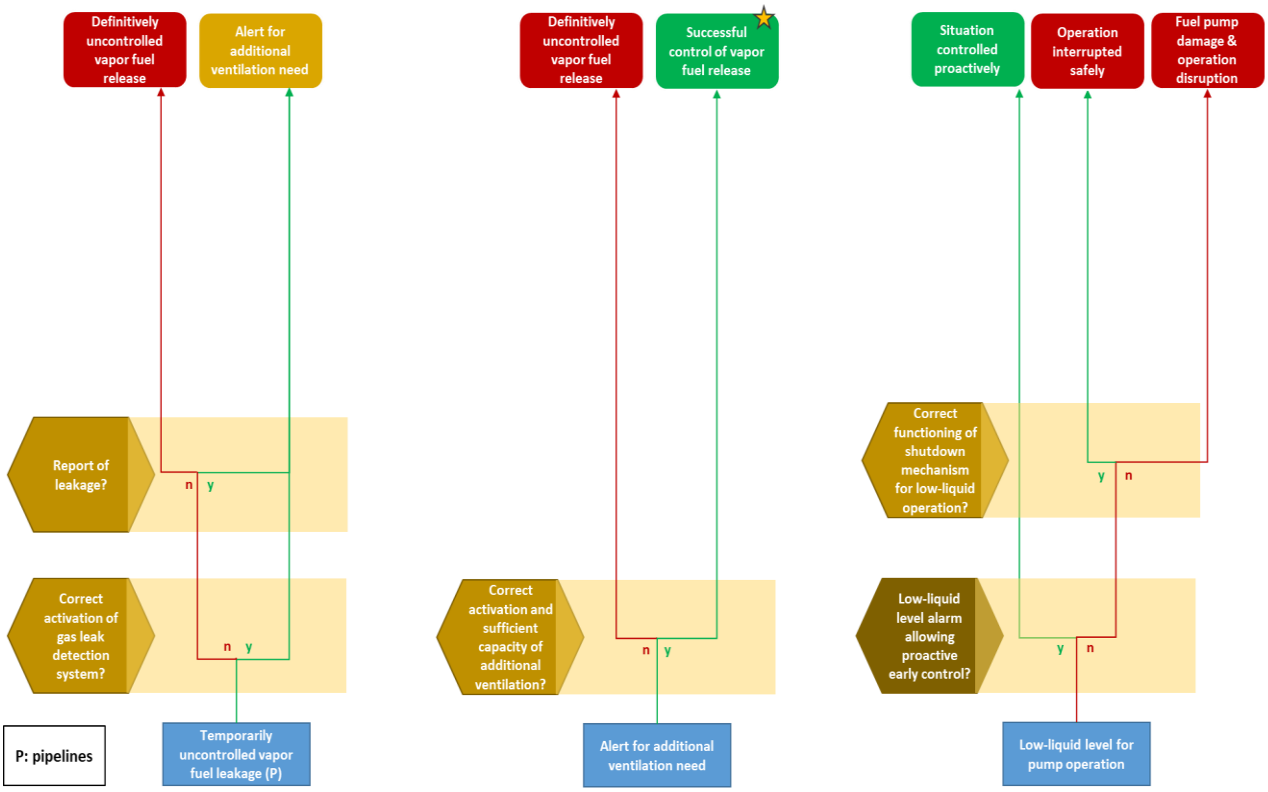

Figure 24. Event tree for methanol transfer processes - Part 2 of 6. Source: own elaboration.

In the event that a methanol vapor release could not be controlled by the ventilation capacity on site, either the activation of the gas leak detection system or a manual report of the leakage could allow to generate an alert for the activation of additional ventilation. If none of these conditions are met, the fuel vapor release would be definitely uncontrolled, posing a threat to the state of functionality of the system and the surrounding environment. On the contrary, **if the alert for additional ventilation needs was generated** and this was sufficient to safely disperse the methanol vapors, the situation can be considered fully controlled. However, the resulting state of functionality of the system would depend on the nature of the causes of the fuel release, as illustrated by the star sign convention. Alternatively, the situation would be definitely uncontrolled in case the additional ventilation capacity was still not sufficient to respond to the emergency.

Another potentially disruptive situation during fuel transfer processes is a **low-liquid level for the operation of submerged methanol pumps**. Should this event take place, an alert should be generated by a low-liquid level alarm system, which could allow to correct the situation before it can impact the pumps (IMO 2020). If the parameter is monitored proactively, a slightly but not critically low-liquid level could be corrected by increasing the inflow of methanol to the pump, without needing to cause any interruptions to the bunkering operation. However, should the low-liquid level exceed a determined threshold, the alarm system would automatically trigger the shutdown of the motors to prevent any type of damage to the pump, temporarily disrupting the bunkering operations, and hence leaving it in a non-operational state (IMO 2020). In case the low-liquid level shutdown mechanism did not activate properly, the pumps could be subject to damage, forcing a longer interruption of the operations.

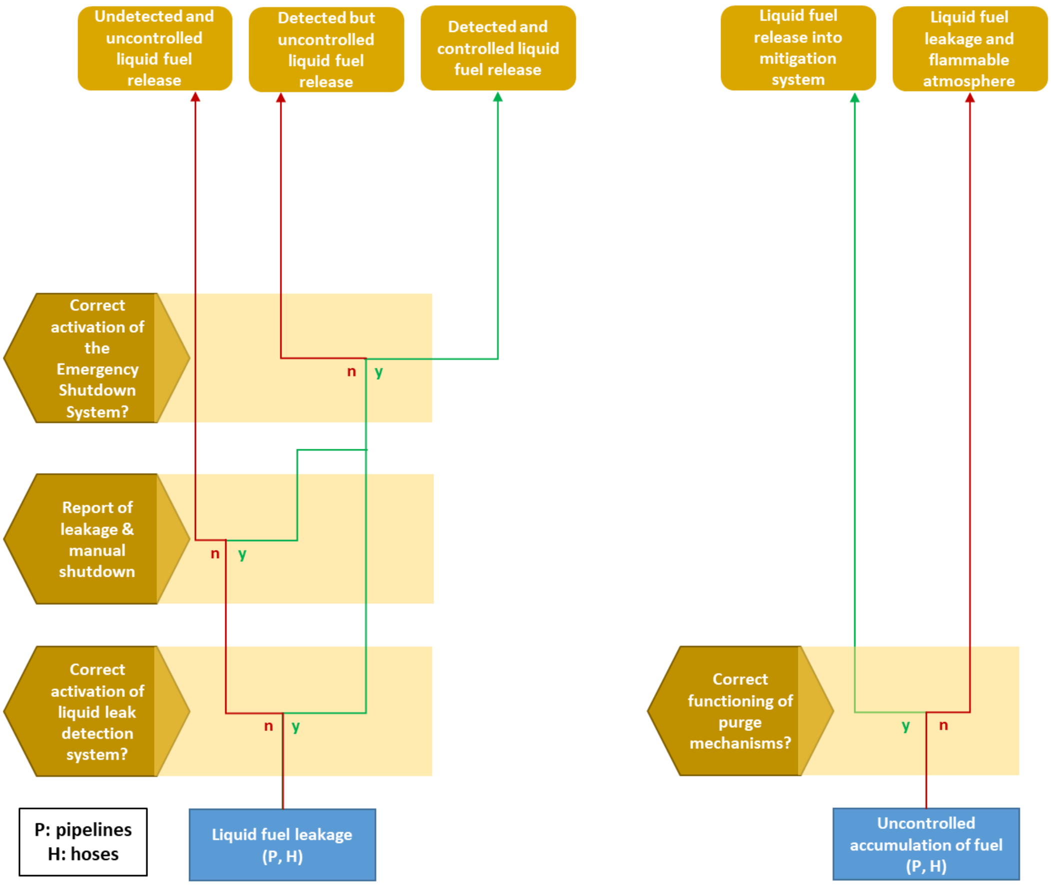

Figure 25. Event tree for methanol transfer processes - Part 3 of 6. Source: own elaboration.

Liquid methanol leakages from the bunkering hoses or pipelines are also a highly relevant disruptive event that can occur during fuel transfer operations. Similar to the vapor leakages, the first line of response against them are liquid leak detection systems (Indian Register of Shipping 2025b). Should a liquid methanol leakage be detected, it will also trigger the Emergency Shutdown System (ESD) of the fuel transfer processes (Port of Gothenburg 2022). In the event of a failure of the leak detection system, there is also the possibility of the personnel identifying and reporting the leakage in order to manually trigger the safety measures.

An additional disruptive event could be **the unintended accumulation of fuel within the bunkering hoses or pipelines**. This could occur as a consequence of methanol not being properly drained at the end of bunkering operations or after a safety shutdown was triggered (Indian Register of Shipping 2025b). In order to respond to this potential threat, fuel piping systems can make use of their purge mechanisms (IMO 2025b). These should allow to safely release the excess methanol into dedicated holding tanks (IMO 2020). However, it could also generate the risk of the holding tanks being overwhelmed as a result of future fuel releases into them, which is why the final state of the system is presented with a yellow text box. In contrast, if the purge mechanisms do not work properly, it could lead to overpressure in the equipment, which could ultimately cause a fuel leakage. Additionally, there would be risks associated to the creation of a flammable atmosphere, for which the bunkering system has no further response mechanisms.

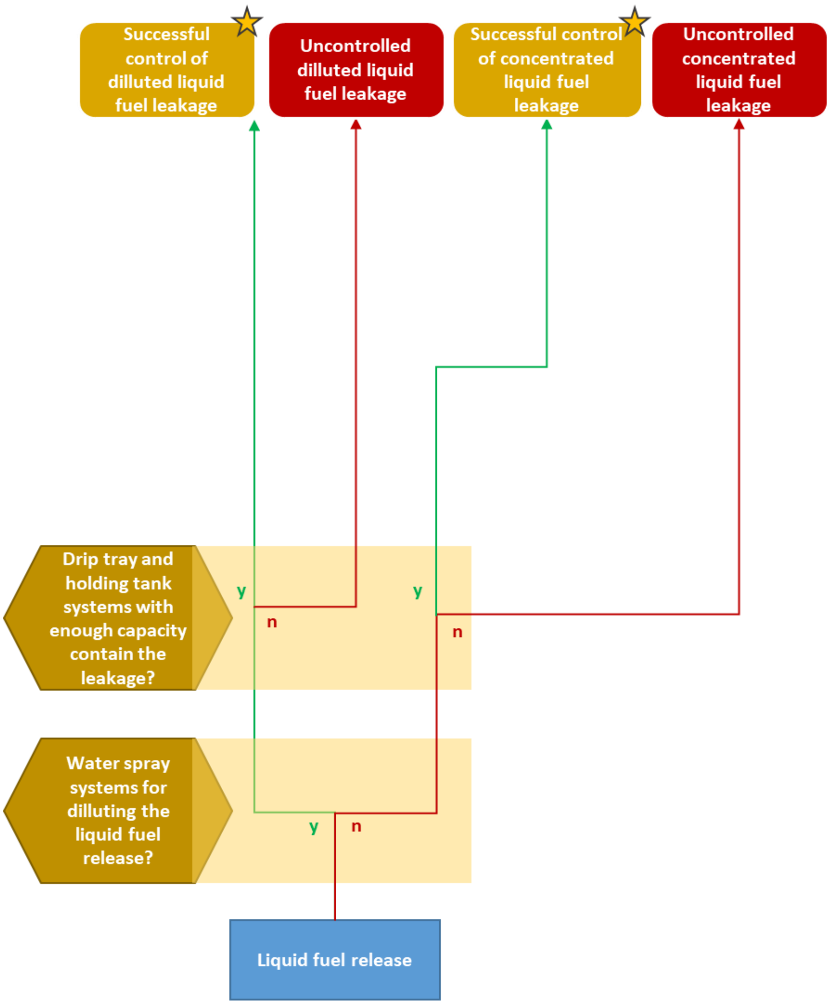

Figure 26. Event tree for methanol transfer processes - Part 4 of 6. Source: own elaboration.

Liquid methanol releases are handled via the use of two main safety mechanisms, namely water spray and drip tray systems. The water spray systems would be triggered automatically following the activation of the liquid leak alarm but could also be triggered manually by the operations crew. Their objective is to dilute spills. This not only helps to reduce vapor concentrations below flammable levels, but also decreases the toxicity of the leaks, to the benefit of people protection (IMO 2020). Nevertheless, even if the water screen systems are not activated, liquid leakages will always be conducted to a drip tray system, which itself leads to a holding tank, capable of safely containing the leaks. As long as its capacity is not exceeded, this should allow to successfully control the leakage (which is why a yellow text box was used to represent the final state of the system) (IMO 2020). It is also important to note that the nature of the origin of the liquid fuel release would determine whether the final state of the system is still operational or not, as illustrated by the use of the star symbol.

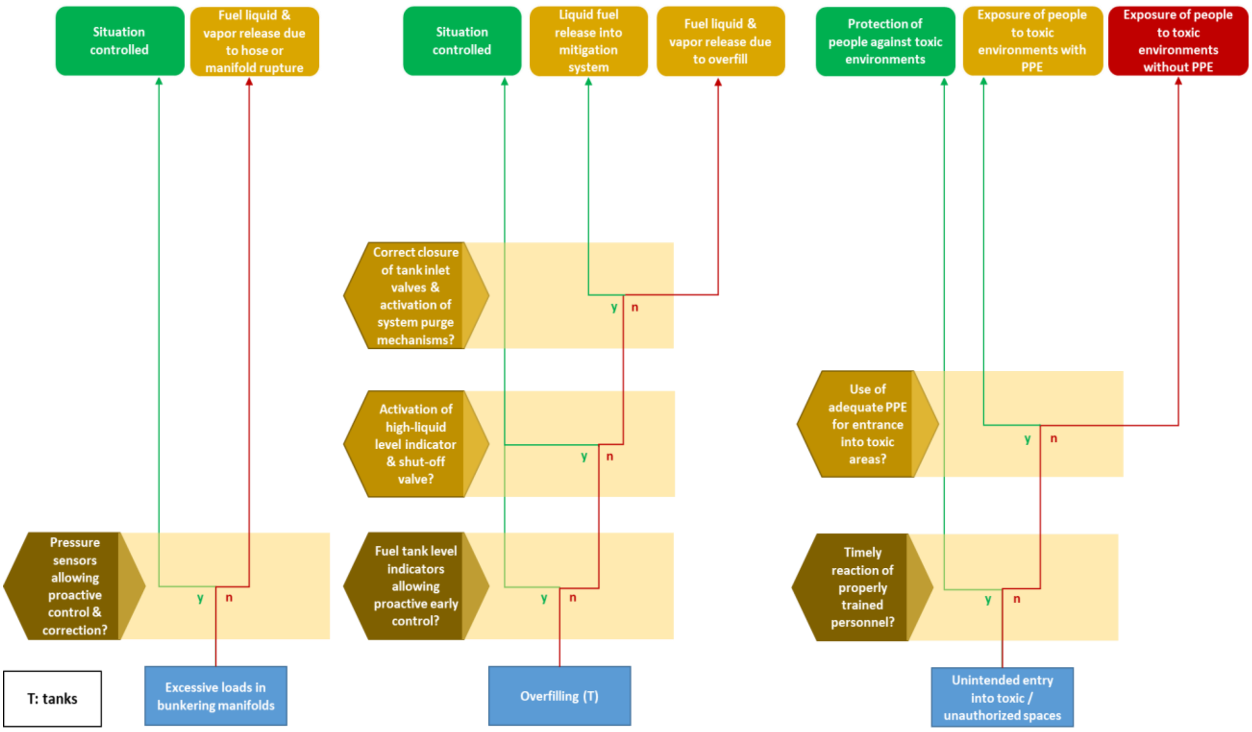

Figure 27. Event tree for methanol transfer processes - Part 5 of 6. Source: own elaboration.

Another disruptive situation relevant to methanol transfer processes is the **occurrence of excessive loads on the bunkering manifolds**. Here, a proactive monitoring of the pressure sensors of the manifolds could allow to avoid this risk (IMO 2020). **The overfilling of the receiving tank** is also a potential threat that can and must be responded to. This can be accomplished at an initial stage by proactively monitoring the fuel tank level indicators, which are components required to be installed in the system (IMO 2020). In addition to this, however, the tanks should also have a high-liquid level alarm system coupled with a shut-off valve, which would be triggered once the tank level reaches a threshold value (IMO 2020). Should this mechanism fail, a further safety action is to close the inlet valve of the tanks, avoiding further ingress of fuel into it, as well as to activate the tank's own purge mechanism, which can be used when the liquid level of the tanks needs to be lowered (IMO 2020). In case this last measure fails, the tank would overflow, causing a fuel release.

Similar to what was previously described for the methanol transport systems, another disruptive situation that can be controlled is the **ingress of personnel into unauthorized or toxic areas**. This can be achieved either by an opportune reaction of other crew members or the use of adequate PPE to protect workers.

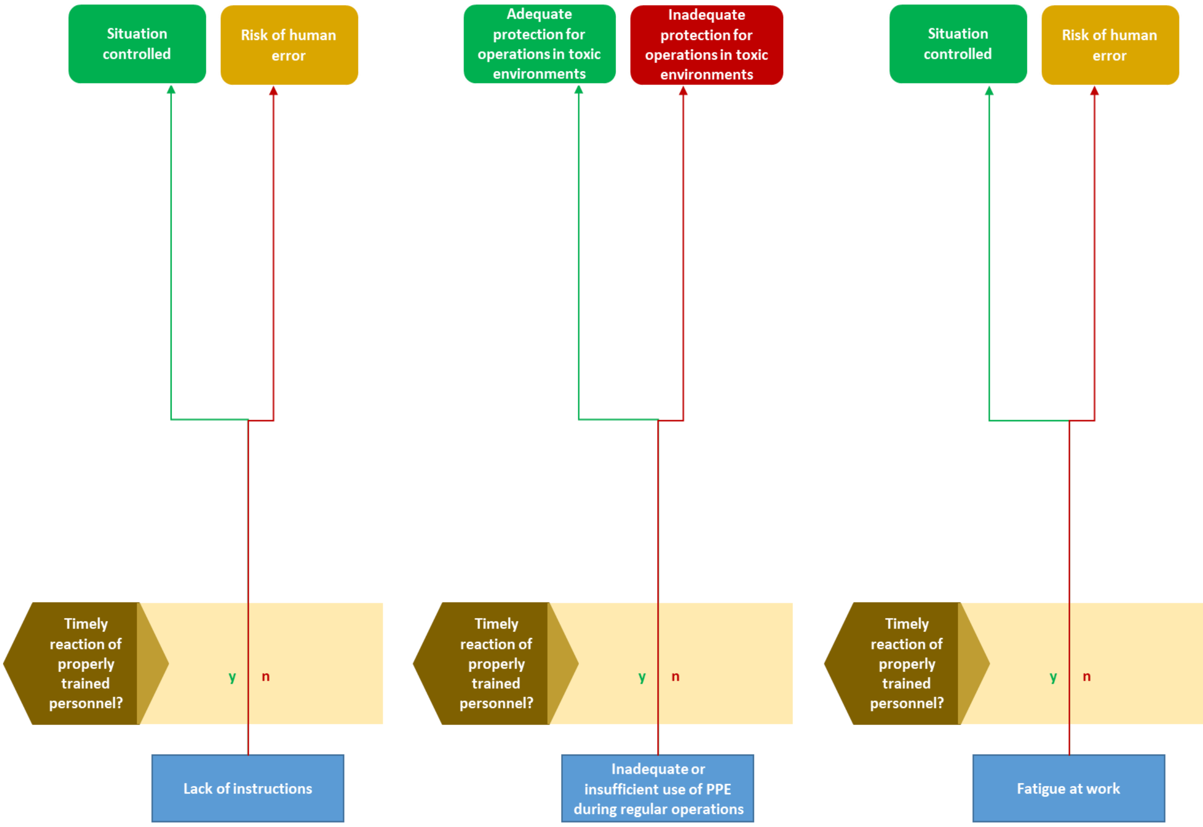

Figure 28. Event tree for methanol transfer processes - Part 6 of 6. Source: own elaboration.

The last set of disruptive situations during methanol transfer processes are the occurrence of human errors due to either fatigue at work or a lack of instructions, as well as the inadequate or insufficient use of PPE to perform regular operations. Just as it was described for the transport processes, all of these events could be prevented by the timely intervention of other crew members.

Event trees for methanol storage processes

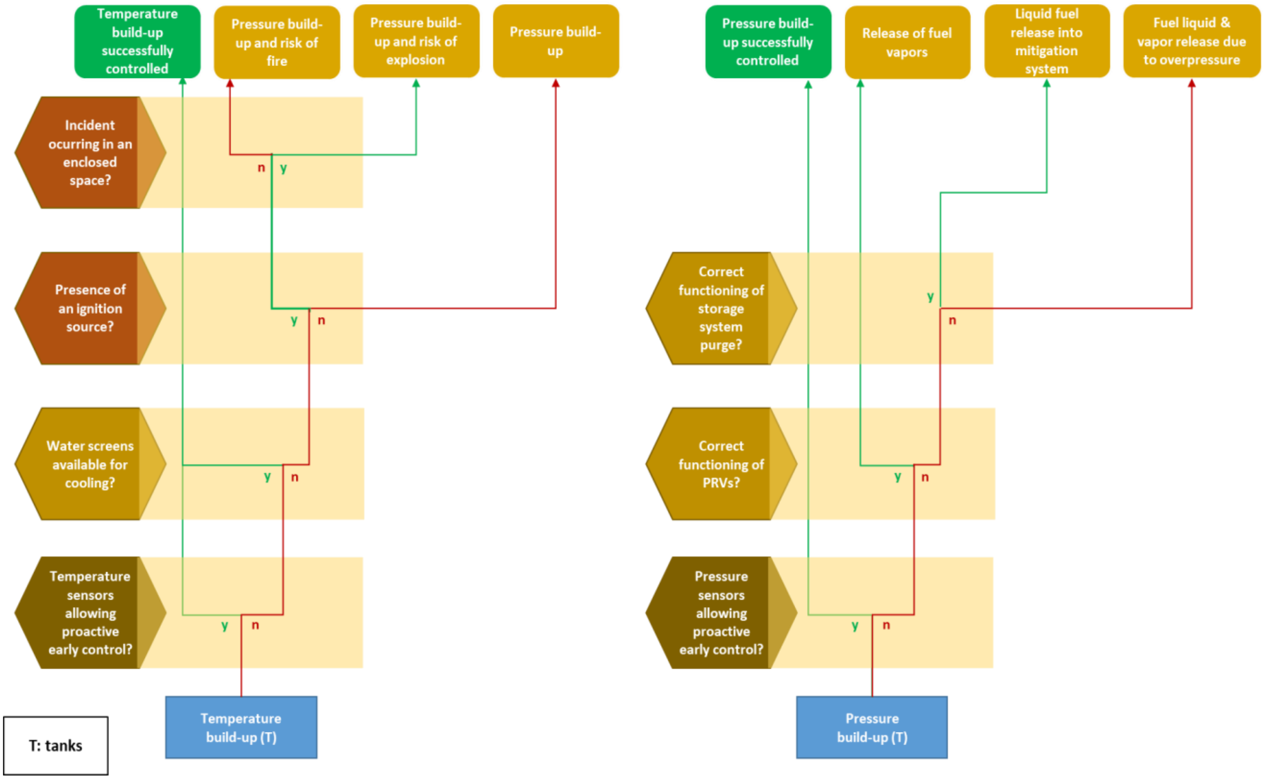

Figure 29. Event tree for methanol storage processes - Part 1 of 5. Source: own elaboration.

Regarding methanol storage processes, the first disruptive situation to consider is a **temperature build-up in the fuel tank**. At a first instance, this can be addressed proactively by monitoring the temperature sensors that should be installed in the tank (IMO 2020). That is, adjusting operational parameters in a way that they allow to reduce the tank's temperature before any of the response mechanisms need to be triggered. Should this not be possible, however, methanol storage systems, both at ports and ships, should be equipped with water screens that can be utilized to cool down the storage tanks (IMO 2020). If these fail, and a high temperature of the tank persists, it will result in an increased generation of methanol vapors, which would create an ignitable atmosphere. Therefore, if an ignition source was also present, this could trigger the occurrence of a fire, mostly if the incident occurs in an open area, or an explosion, should the storage tank be located in an enclosed space (ABS 2021). In case there are no ignition sources present, the temperature build-up would nonetheless result in a pressure build-up within the tank because of the increased vapor generation.

A **pressure build-up** itself could also be controlled proactively by constantly monitoring the pressure sensors of the fuel tank and adjusting operational parameters to keep it within the intended values. If this is not sufficient, the tanks' pressure relief valves (PRVs) could come into action. These are valves that can be used to release fuel vapors in a controlled manner so that the pressure inside the tank decreases. This means that a successful activation of the PRVs results in the release of methanol vapors, which would need to be controlled by the ventilation capacity of the system, as described before (IMO 2020). In case the PRVs cannot be successfully activated, however, a further response mechanism is the purge system of the tank. This means that some of the tank's content would be released into the methanol mitigation system in order to reduce the pressure. If this safety action is not successful either, it would lead to an uncontrolled overpressure in the tank and could ultimately cause a fuel release.

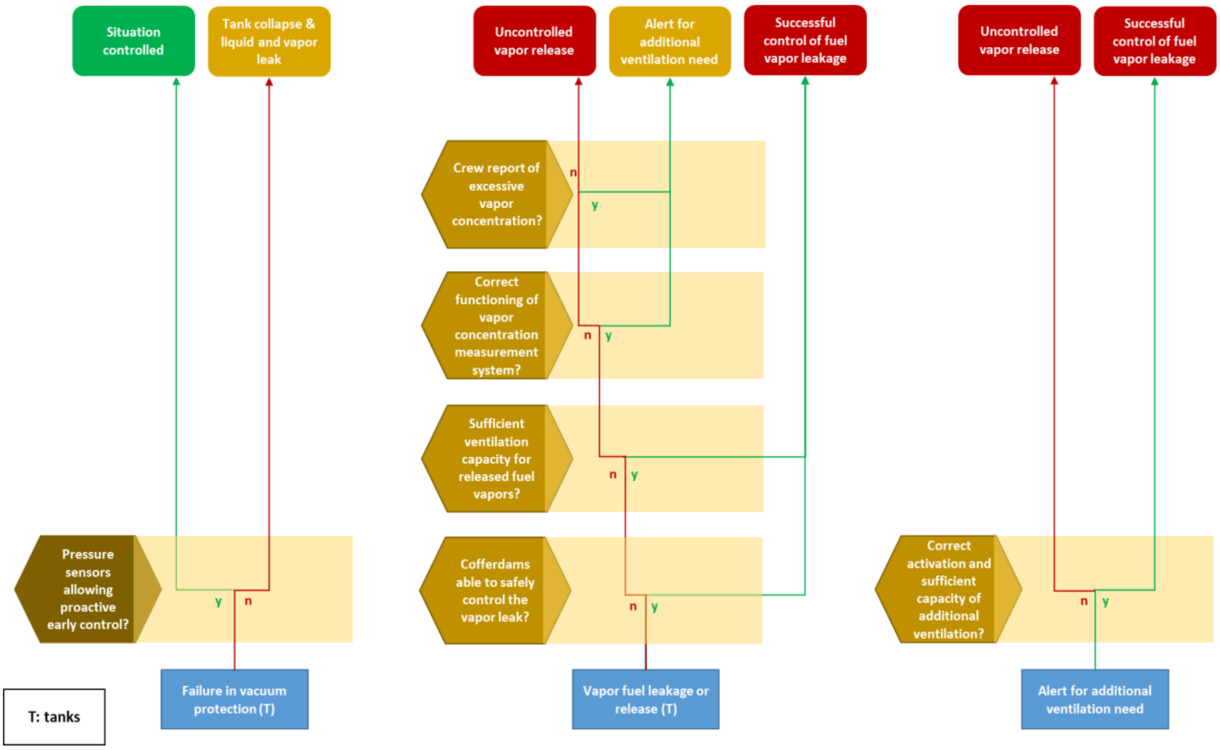

Figure 30. Event tree for methanol storage processes - Part 2 of 5. Source: own elaboration.

Another disruptive event for methanol storage would be **failures in the tanks' vacuum protection systems** (Indian Register of Shipping 2025a). This could be monitored proactively via the pressure sensors of the tanks, by checking that no type of vacuum is being generated and thus the relief systems are not at risk of being overloaded or, alternatively, that the tanks would collapse in the event that they cannot respond appropriately.

Vapor fuel leakages from the storage tanks are another disruptive event with multiple response mechanisms available to them. The first of them are cofferdams, which are structural spaces that surround the tanks, providing an additional layer of gas and liquid tightness protection in the event of leaks (IMO 2020). Should the capacity of the cofferdams be exceeded, however, and similar to the leakages that occur during fuel transfer processes, methanol vapor releases would be handled via the ventilation capacity on site. This would also be applicable to the releases coming from the tank's PRVs. If the ventilation capacity on-site would not be enough, there are two possible ways to generate an **alert for additional ventilation needs**. The first is the vapor concentration measurement system, which would activate at a fuel vapor concentration of 20% of the lower explosion limit (LEL) of methanol, generating a visual and audible alarm (IMO 2020). The second, in case the vapor detection system does not work properly, is the reporting of excessive vapor concentration by the crew members. However, if none of this was necessary and the vapor leakage could be handled either by the cofferdams or the ventilation capacity on site, the situation can be considered controlled. The same would be true if the alert for additional ventilation needs was successful and the capacity was sufficient to safely disperse the vapors. In case this did not happen, the fuel vapor leakage would be considered uncontrolled.

Nevertheless, it is important to note that leakages that occur during storage processes would always lead to a non-functional state at the end, as they can only be caused by infrastructural damage. Namely, a tank rupture or collapse, as well as due to overpressure. It is for this reason that they were represented using red boxes. This is also applicable to liquid fuel leakages, which are presented in Figure 31 next.

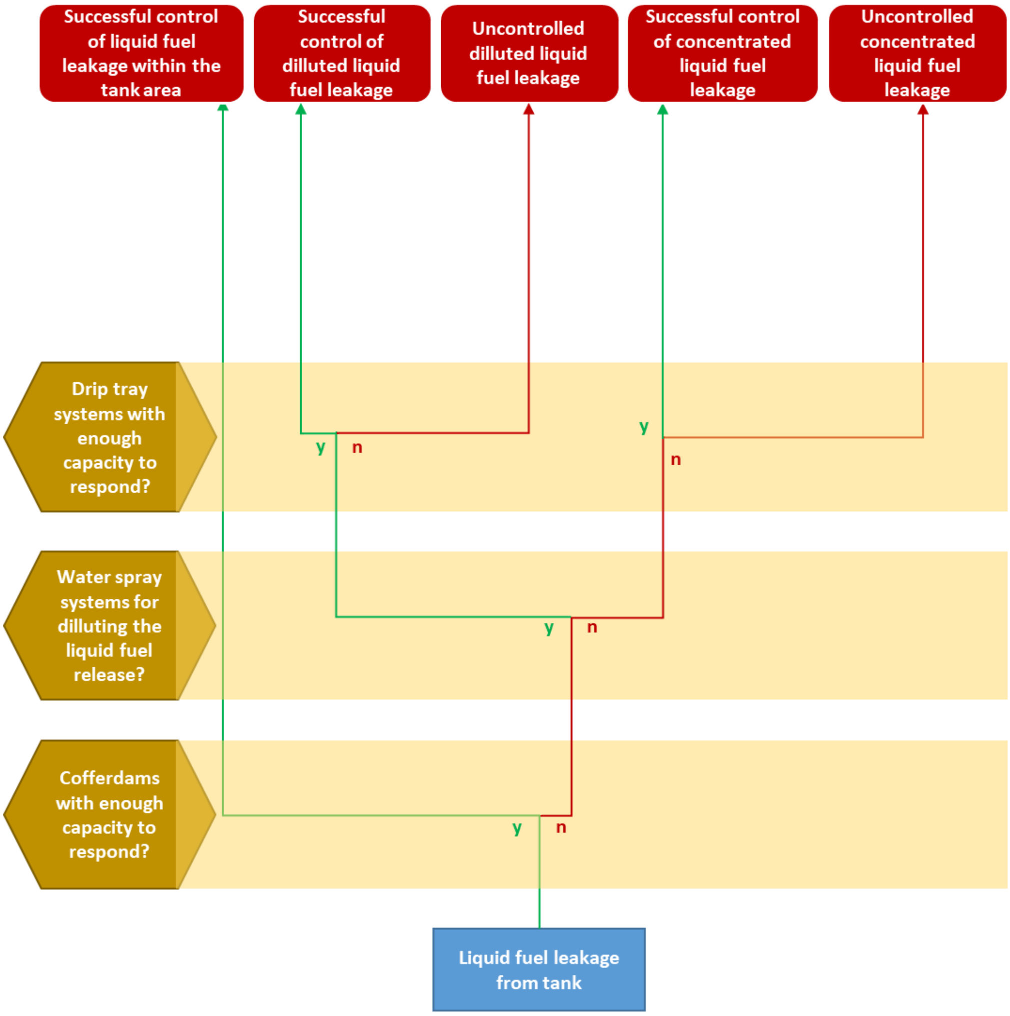

Figure 31. Event tree for methanol storage processes - Part 3 of 5. Source: own elaboration.

Similar to vapor the fuel leakages, the first safety response mechanism for **liquid leakages** are the tank's cofferdams (IMO 2020). Should their capacity be exceeded, methanol storage systems should also be equipped with water spray systems to dilute leakages, reducing flammability and toxicity risks (IMO 2020). Afterwards, independent of whether the water screens were triggered or not, the leakages would be conducted to the drip tray + holding tanks systems, where they would be stored safely (IMO 2020). Thus, the situation could be considered controlled, unless the capacity of the holding tanks is exceeded and the leakage still remains a threat to the crew and the surrounding infrastructure. Nevertheless, all of the possible outcomes correspond to non-functional states, as the leakages would always be caused by infrastructural damage to the tank.

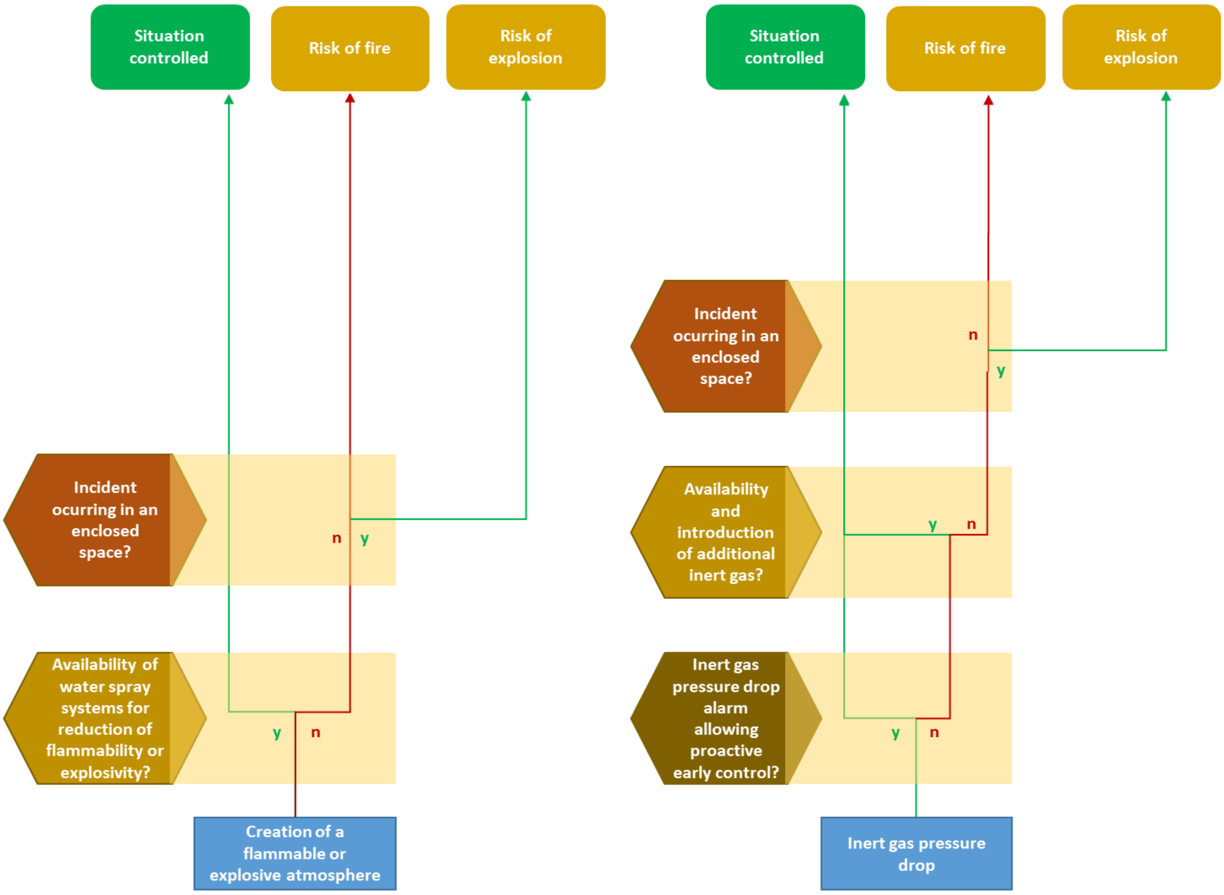

Figure 32. Event tree for methanol storage processes - Part 4 of 5. Source: own elaboration.

Other disruptive situations that could be responded to are related to the generation of ignitable atmospheres within the storage system. First is the **creation of flammable or explosive atmospheres due to the presence of methanol vapors within its ignitable range**. This can be responded to via the use of the water spray systems, which not only have a cooling function, but also aim to reduce the risk of flammability or explosivity (IMO 2020). In case they cannot be activated successfully, it would then be relevant to consider if the storage system is located in an enclosed space or not, leading to a risk of explosions or fires, respectively (ABS 2021).

Another similar situation is a **lack of inert gas to reduce the risk of ignition in the system**. This will be evidenced by a drop in the inert gas pressure, which should be monitored constantly (IMO 2020). Therefore, if a slight, but not critical drop in the inert gas pressure is noticed, the situation could be corrected before any response mechanism must come into action. Once a more significant pressure drop is experienced, however, the introduction of additional inert gas to the system should be triggered. In case this measure is successful, and the inert gas pressure can be safely reinstated, the situation can be considered fully controlled. If this is not the case, there would be a risk of fire or explosion associated, as described before.

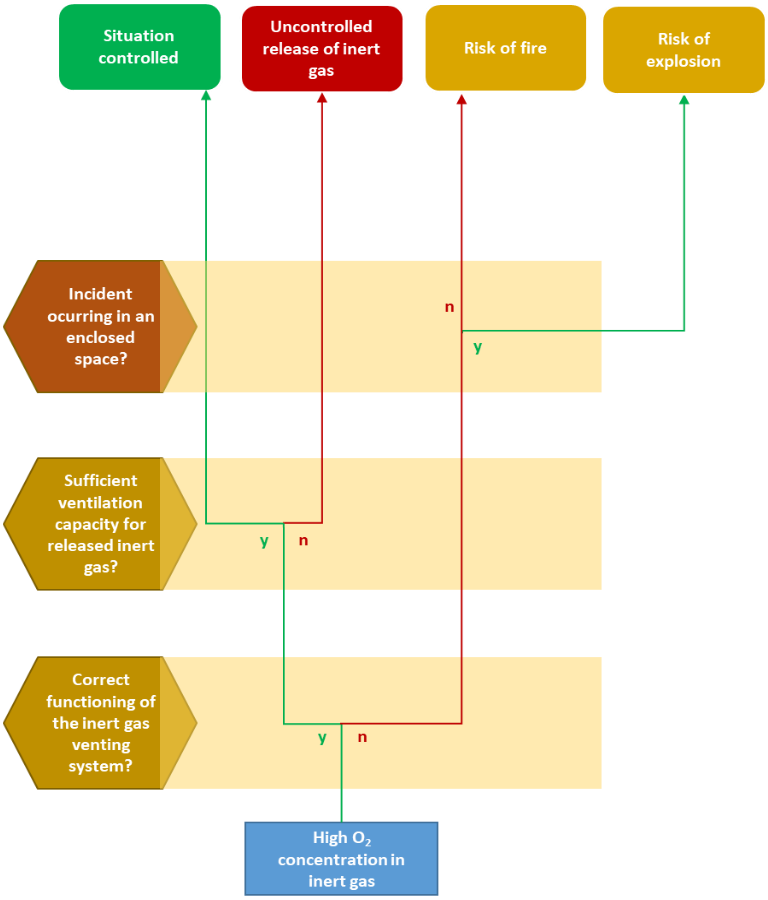

Figure 33. Event tree for methanol storage processes - Part 5 of 5. Source: own elaboration.

The last disruption related to methanol storage processes is **a high concentration of oxygen in the inert gas**. This is because the storage system should always be able to maintain an atmosphere with an oxygen content not higher than 8% by volume in any part of the fuel tank (IMO 2020). If this condition is not met, it will be necessary to vent the oxygen-rich inert gas. In case the venting system is working properly and the gas is released, it is then important to assess whether there is enough ventilation capacity on site to safely evacuate it or not, as the inert gas would still be a safety hazard for the operators (IMO 2025b). To this end, it would also be possible to make use of the additional ventilation capacity of the system (as illustrated in Figure 30). However, if this is still not enough, the release of the inert gas should be considered uncontrolled. On the contrary, if the inert gas venting system did not respond properly, this would lead to the creation of an ignitable atmosphere and, consequently, to a risk of fire or explosion.

Event trees for ammonia transport processes

Regarding ammonia transport processes, it was found that the event trees would include all of the elements derived for methanol, since all considerations, in terms of the response mechanisms to possible disruptions, are applicable to systems using either fuel. The only difference is the addition of the generation of BOG due to the sloshing of ammonia during the transport of the fuel, which will be covered next in Figure 34.

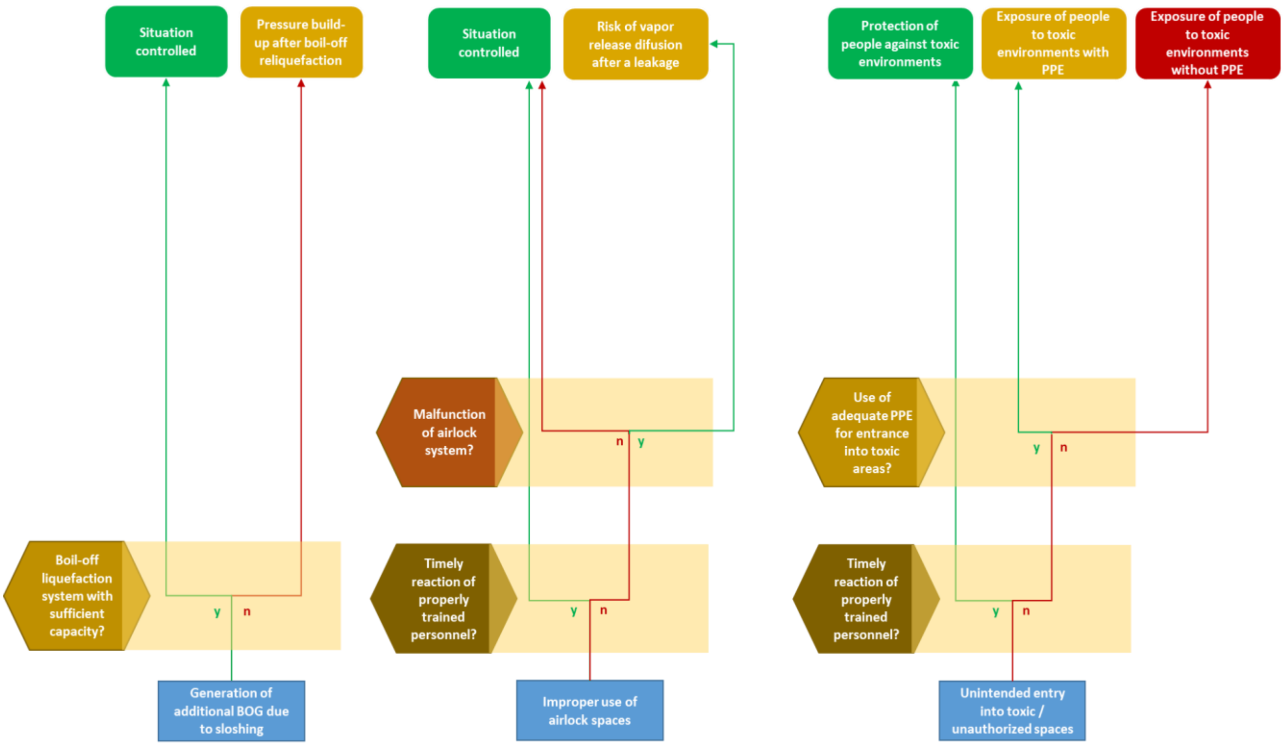

Figure 34. Event tree for ammonia transport processes - Part 1 of 2. Source: own elaboration.

The generation of additional BOG due to the sloshing of the fuel will be responded to by the fuel tank's boil-off reliquefaction system. However, in case its capacity is exceeded, it will lead to an uncontrolled pressure build-up. The response mechanisms available to respond to this situation will be presented later, as part of the storage systems event tree (Figure 42).

Additionally, there is the inadequate use of airlock systems, which, as in the case of methanol-based systems, must also be present in ammonia systems and should not be used for any sort of different purpose (such as goods storage). Similarly, there can also be the unintended entry of personnel into toxic or authorized spaces (IMO 2025b).

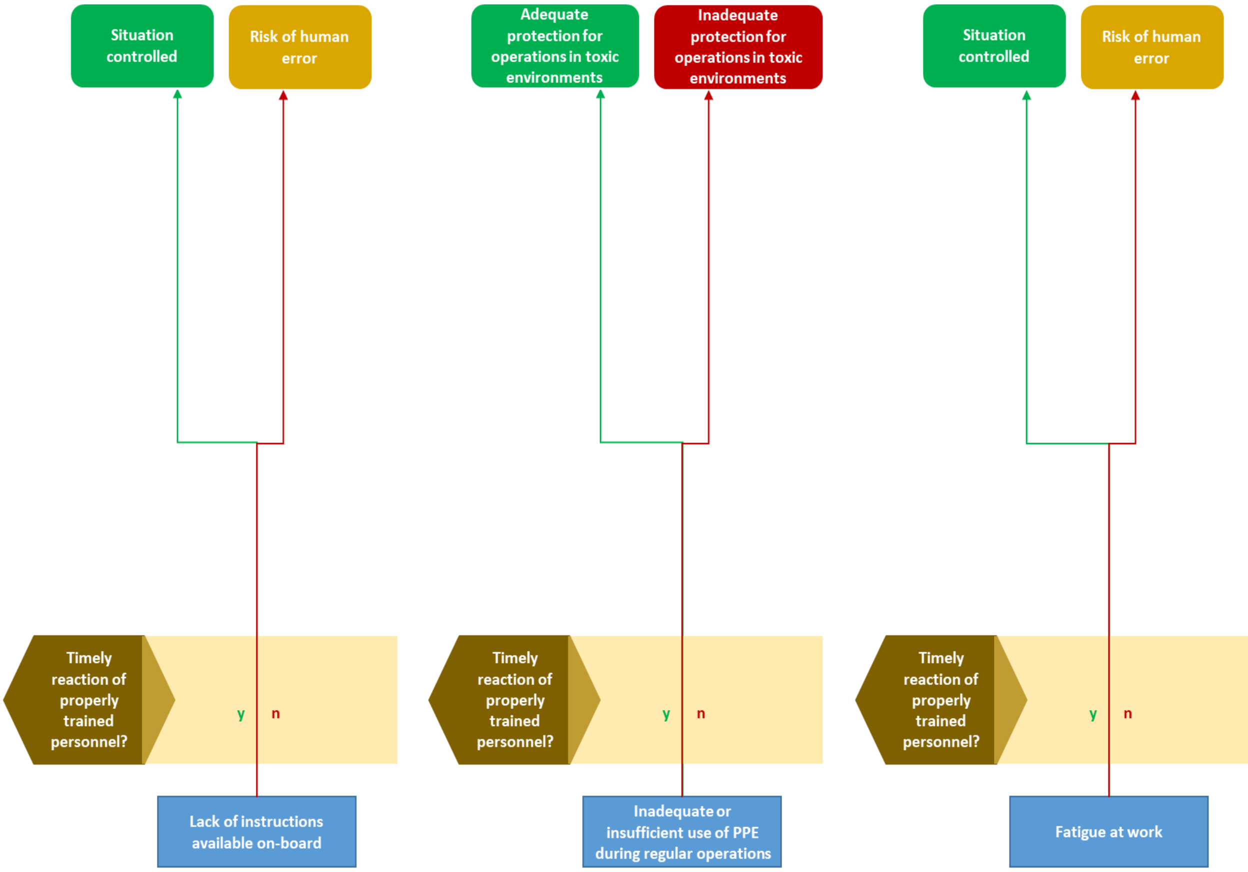

Figure 35. Event tree for ammonia transport processes - Part 2 of 2. Source: own elaboration.

Meanwhile, the occurrence of human errors due to fatigue at work or a lack of instructions available on board could also be present and responded to, as well as the inadequate or insufficient use of PPE for performing regular operations. However, it is important to highlight that PPE requirements for ammonia-handling processes are more demanding than for methanol-handling processes. Concerning the transport of the fuels, for example, respiratory protection should always be mandatory for ammonia systems (International Enviroguard 2021). This is not the case for methanol, since respiratory protection is required only if vapors are present and the concentration of methanol in air exceeds 200 ppm (Methanol Institute 2017b).

Event trees for ammonia transfer processes

In the case of the ammonia transfer processes, while some of the potential disruptions identified in the fault trees were different compared to methanol's, a lot of the available response mechanisms for both type of systems, and consequently the range of situations that can be answered to, remain the same. One notable difference, however, are the procedures to deal with vapor and liquid fuel leakages. This is due to two key characteristics of ammonia. First, that ammonia releases are more toxic to crew members than methanol releases, meaning that there must be less tolerance with high environmental concentrations. It is for this reason that it is strongly recommended not to allow direct releases of ammonia vapors into the air, unlike in the case of methanol-based systems, where it is possible (ClassNK 2025). And secondly, that since liquified ammonia is a saturated liquid, it is also advised against diluting it with water, as this would increase its evaporation rate, creating a more dangerous gas cloud (Corruchaga and Casal 2015). Both of these differences will be addressed in Figure 36 and Figure 38 respectively.

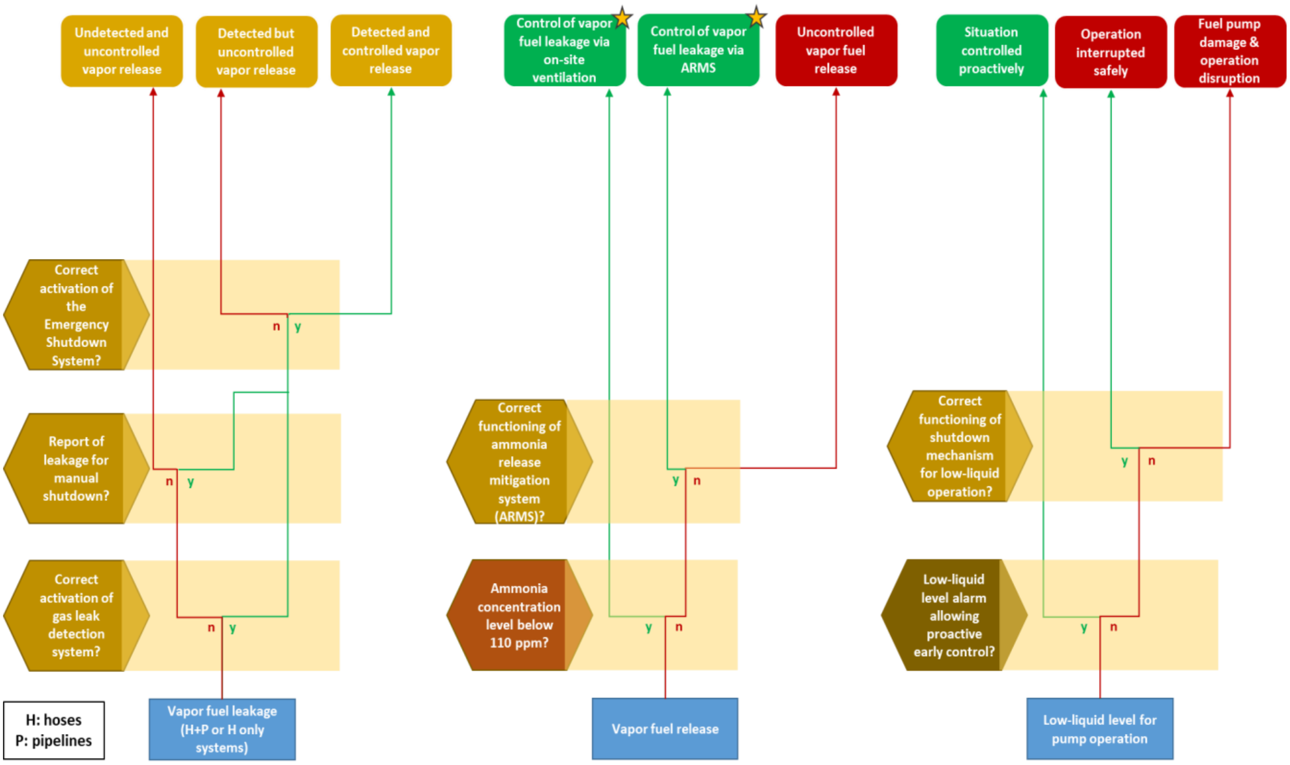

Figure 36. Event tree for ammonia transfer processes - Part 1 of 5. Source: own elaboration.

Firstly, ammonia transfer processes are susceptible to **vapor fuel leakages**, which could initially be detected via a concentration-based system or reported by the crew, just as in the case of methanol-based systems (IMO 2025b). However, it is strongly recommended that releases of ammonia into the air do not lead to environmental concentrations higher than 110 ppm, in order to protect workers. If concentrations are below this threshold, the leakage can be left to be handled by the ventilation capacity on-site. If this is not the case, however, it will be necessary to activate the ammonia release mitigation system (ARMS). The ARMS has the ability to consume, collect or disperse ammonia either via thermal oxidation, catalytic oxidation or dissolution in air or water. Its objective is to reduce the ammonia concentration until the defined safety threshold is achieved (ClassNK 2025). Nonetheless, for the systems analyzed as part of this work, it is advised against the use of solutions based on dissolution in water, as ammonia vapor releases could be coupled or be the result of liquid releases that are being vaporized. Therefore, it would be counterproductive and dangerous to mix them with water, as described before (Corruchaga and Casal 2015). Additionally, it is important to keep in mind that the leakages can only be considered fully controlled if their causes are accidental rather than by infrastructural damage. This also applies to all other paths leading to ammonia releases during fuel transfer processes.

Complementarily, and just as in the case for methanol-based systems, ammonia systems should have a monitoring and alarm arrangement to avoid **low-liquid levels during pumping operations** (IMO 2025b).

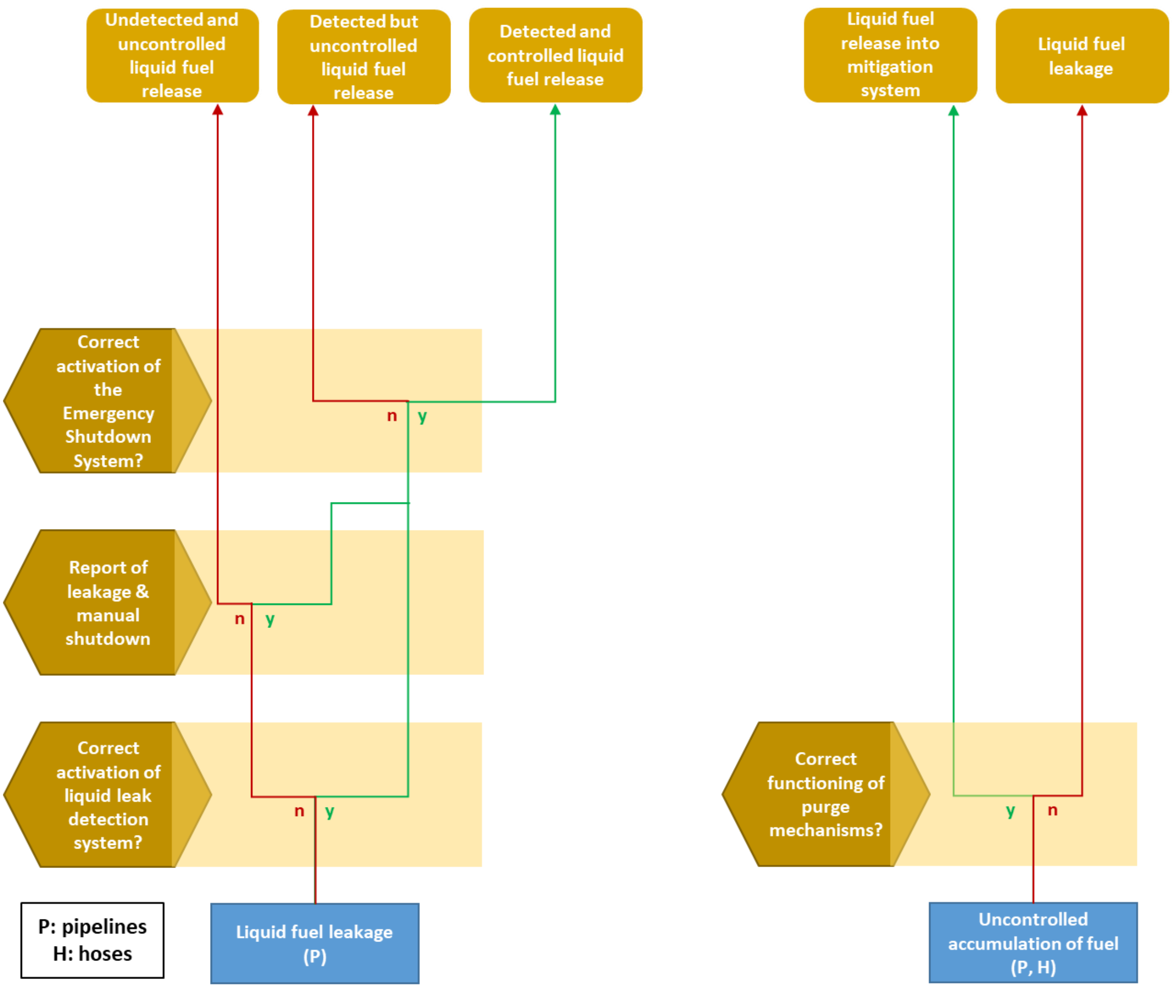

Figure 37. Event tree for ammonia transfer processes - Part 2 of 5. Source: own elaboration.

Similarly, they could also be prone to experiencing liquid fuel leakages, which would be identified via the liquid leak detection system or following a report from the crew. Then, the ESD mechanism would be activated (IMO 2025b). Additionally, the unintended accumulation of fuel could also be handled via the purge mechanism of the fuel conduction system (IMO 2025b).

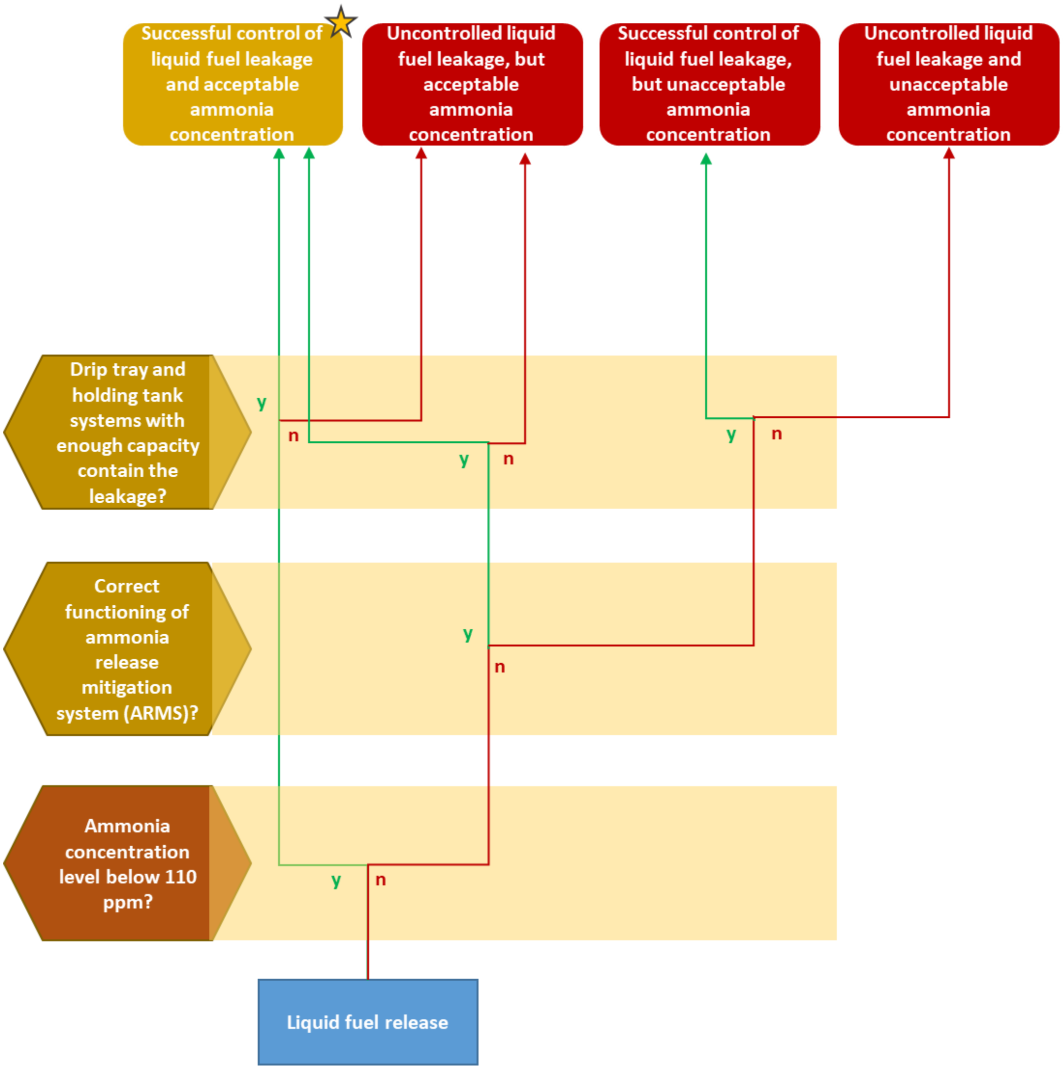

Figure 38. Event tree for ammonia transfer processes - Part 3 of 5. Source: own elaboration.

As for liquid fuel releases, it would first be necessary to evaluate whether the environmental concentration of ammonia due to the leakage is below the 110-ppm threshold or not. If it is not the case, the ARMS would need to be activated to attempt to control it. This sequence of events would determine if the resulting ammonia concentration is acceptable or not. Independent of this, however, all liquid fuel leakages would be directed to the drip tray + holding tank arrangements with the goal to safely contain them (IMO 2025b).

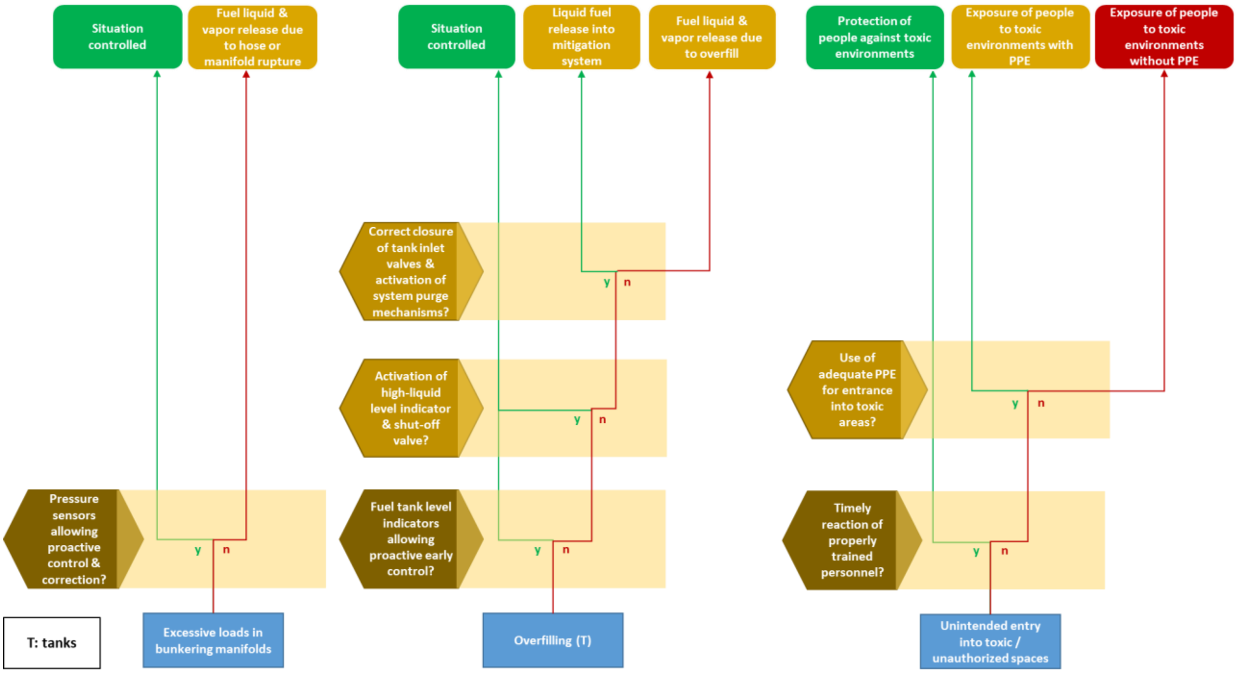

Figure 39. Event tree for ammonia transfer processes - Part 4 of 5. Source: own elaboration.

Ammonia bunkering processes could also be subject to the occurrence of excessive loads in the bunkering manifolds, the overfilling of the fuel tank or the unintended entry of personnel into toxic or unauthorized spaces. The response mechanisms for all of them would be identical to the ones in methanol-based systems (IMO 2025b).

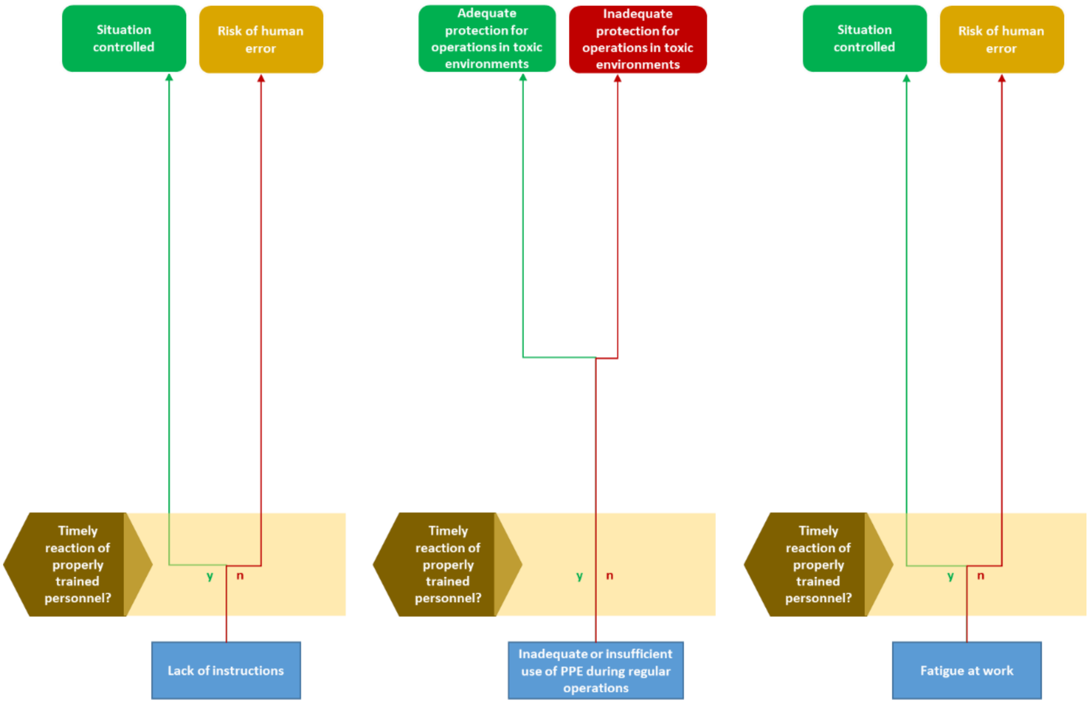

Figure 40. Event tree for ammonia transfer processes - Part 5 of 5. Source: own elaboration.

Lastly, there could also be an occurrence of human errors due to a lack of instructions available or fatigue at work, as well an insufficient or inadequate use of PPE to perform regular operations. Regarding this last aspect, it is also worth to highlight that PPE requirements for ammonia transfer processes are also much stricter than for methanol transfer processes. For the former, it is recommended that workers always utilize a type 1 chemical-resistant suit (Dräger Safety 2025), while for the latter, the use of chemical-resistant clothing is generally enough and full suits are only required in the event of large spills, where there are high risks of exposure to liquids or vapors (Methanol Institute 2017b).

Event trees for ammonia storage processes

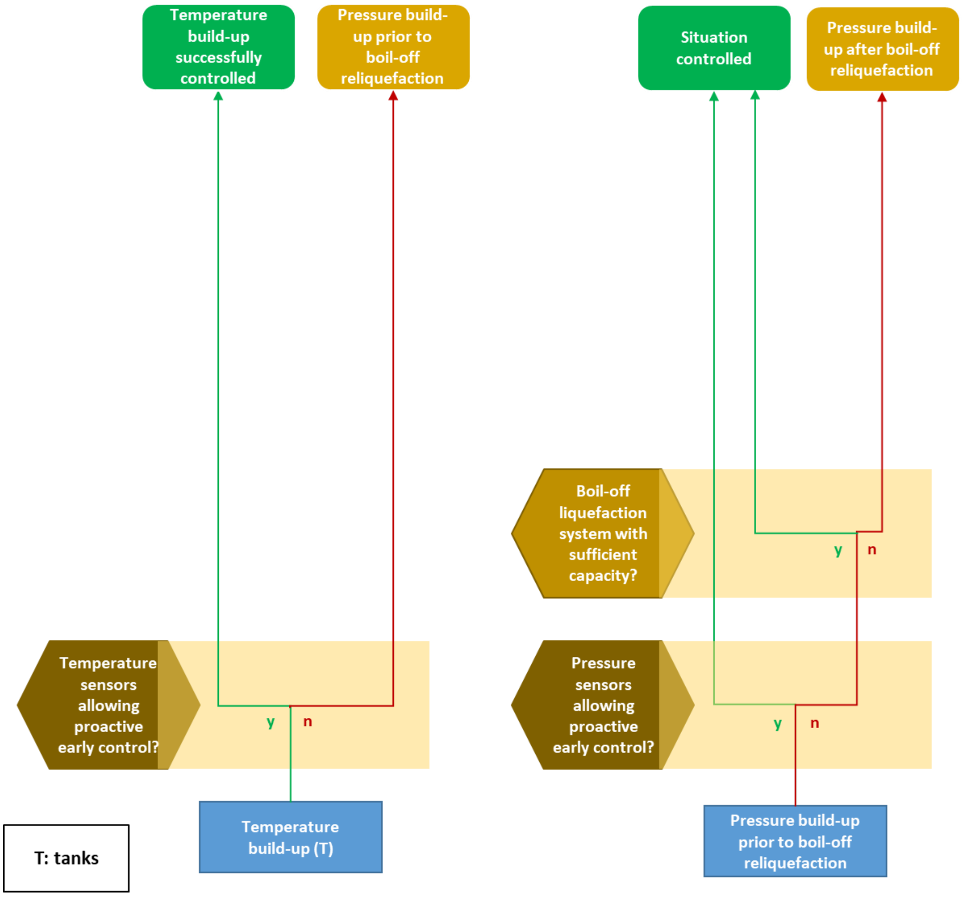

Figure 41. Event tree for ammonia storage processes - Part 1 of 4. Source: own elaboration.

Regarding ammonia storage processes, the first events identified are a **temperature or pressure build-up within the storage tank**. Similar to what was described previously for methanol, the first line of action to respond to them is a proactive monitoring via the tank's temperature or pressure sensors (IMO 2025b). Unlike in the case of methanol, however, ammonia storage systems do not use water screens for cooling down the tanks. Instead, the tanks' temperature and pressure are initially controlled via the boil-off reliquefaction system (IMO 2025b). This is because decreasing the amount of boil-off gas in the tank and reintroducing liquified ammonia instead helps to decrease both the temperature and pressure (ClassNK 2025; Hammer and Leisner 2025). However, in case the capacity of the reliquefaction system is not sufficient to bring the system down to safe operational temperatures or pressures, it will be necessary to consider further response mechanisms.

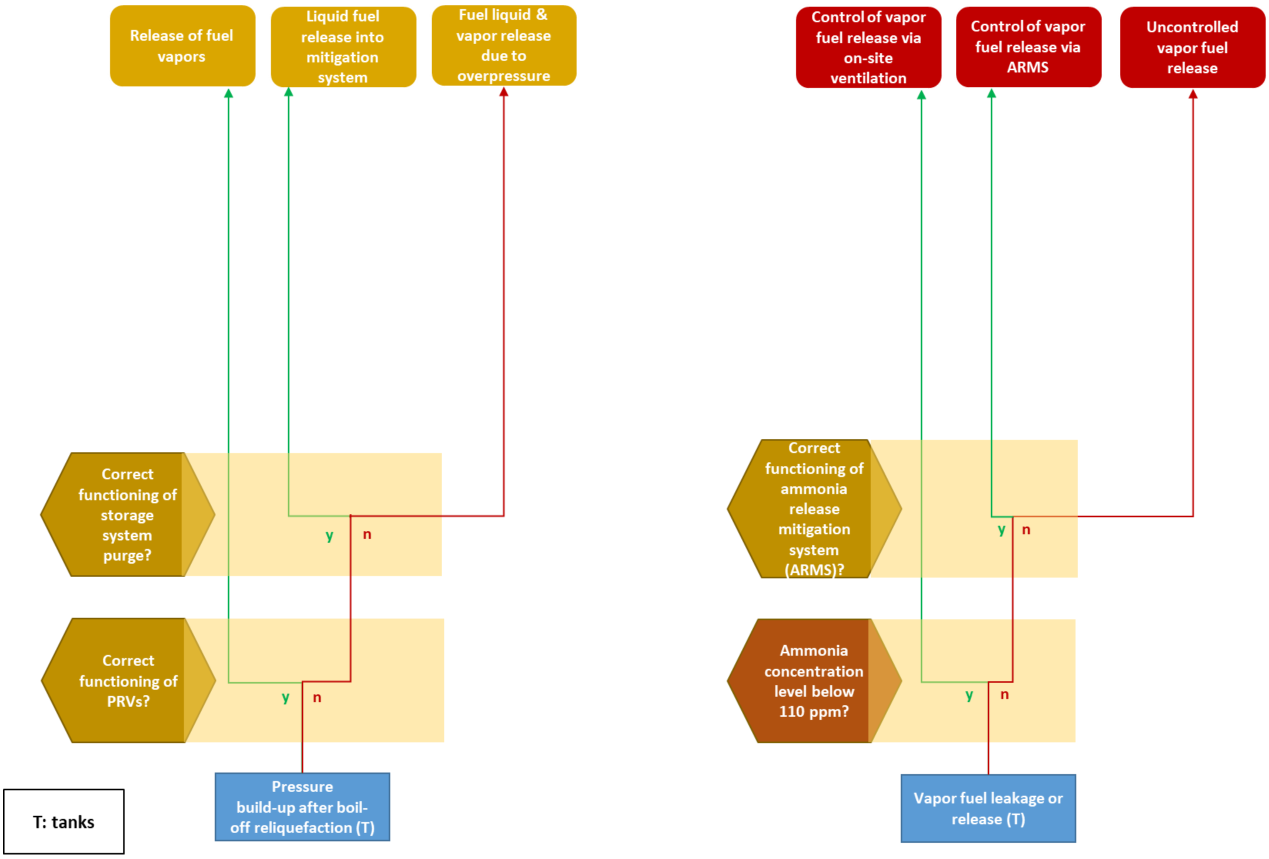

Figure 42. Event tree for ammonia storage processes - Part 2 of 4. Source: own elaboration.

This specifically refers to two systems that were also present in methanol storage: PRVs and the fuel tank purge mechanism. The PRVs would come into action first, should a pressure-build-up in the tank exceed the capacity of the BOG reliquefaction system. When activated, they would also release ammonia vapors that need to be handled via the ARMS, should the environmental concentration exceed 110 ppm (ClassNK 2025; IMO 2025b). In case the PRVs do not work properly or offer enough release capabilities, the last response mechanism would be to purge the storage tank, as retrieving part of its content would allow to reduce the internal pressure (IMO 2025b). If this would fail or be insufficient, it would lead to a fuel release from the tank due to uncontrolled overpressure.

Similar to what occurs during the fuel transfer processes, **ammonia vapor leakages or releases** would be handled via the on-site ventilation capacity, in case the environmental concentration is below 110 ppm, or with the addition of the ARMS, in case it is higher. Nevertheless, independent of whether a release could successfully be responded to or not, the system would end up in a non-functional state since, in the case of storage processes, they would always be caused by infrastructural damage to the tanks.

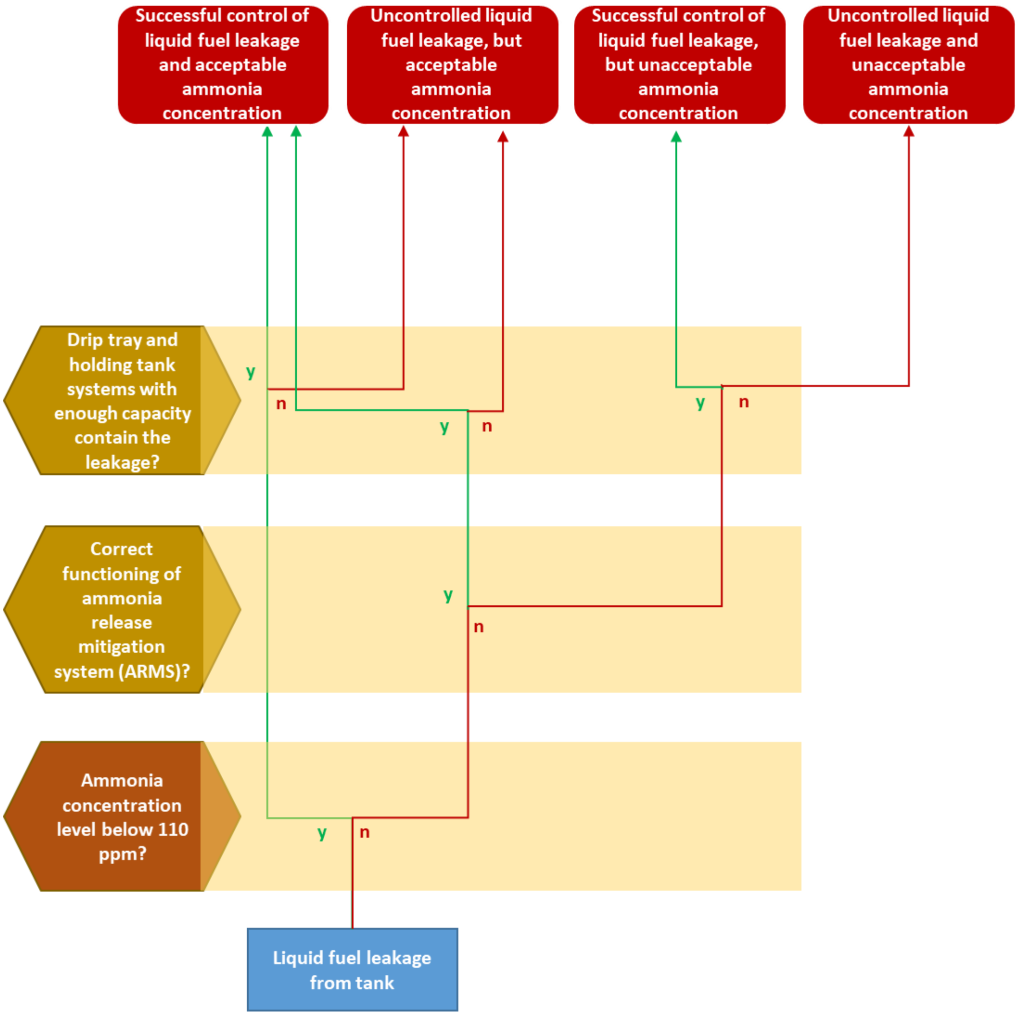

Figure 43. Event tree for ammonia storage processes - Part 3 of 4. Source: own elaboration.

Regarding liquid fuel leakages from the storage tank, the response mechanisms would be the same as the ones described for fuel transfer processes (Figure 38). The difference is that the resulting state of functionality would always be low, as the fuel releases would originate from infrastructural damage.

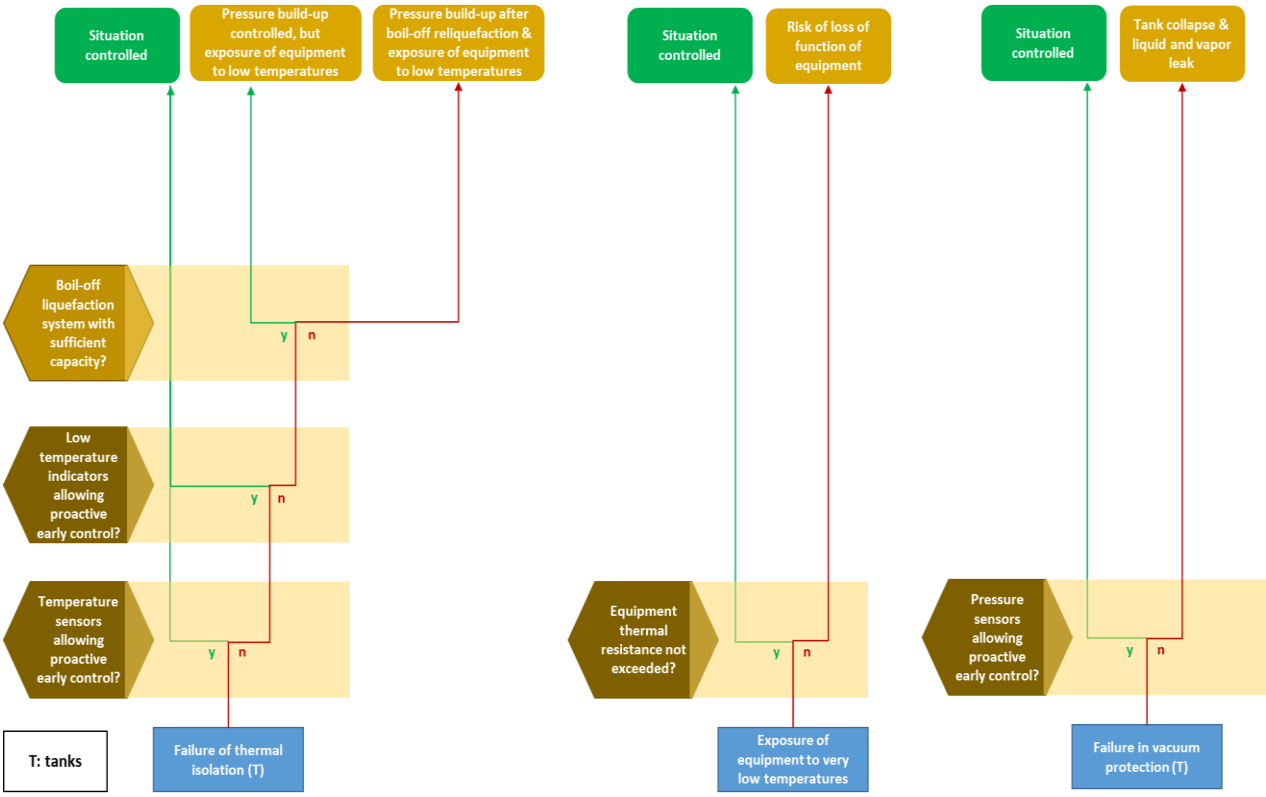

Figure 44. Event tree for ammonia storage processes - Part 4 of 4. Source: own elaboration.

A series of events exclusive to ammonia storage systems are derived from the **potential failure of the tanks' thermal insulation**. In this sense, a first response mechanism is a proactive monitoring of the temperature sensors located in the spaces surrounding the ammonia tanks, allowing to identify and potentially correct the occurrence of slightly low temperatures before they can reach more critical values (IMO 2025b). If this would not be the case, however, ammonia systems should also have dedicated low temperature indicators, which generate an alert whenever temperatures surrounding the tanks are unusually low, offering another layer of protection in temperature monitoring (IMO 2025b). Should none of these instances allow a proactive control of the situation, there would be an excessive generation of BOG in the tanks due to a temperature increase caused by the loss of thermal isolation. This would need to be handled, at least initially, by the boil-off reliquefaction system (ClassNK 2025; Hammer and Leisner 2025). Moreover, **the equipment surrounding the storage tank would end up exposed to very low temperatures**, prompting the risk of a loss of their functions. In this respect, it will be important to assess whether their thermal resistance was exceeded or not (IMO 2025b).

The last disruptive situation for ammonia storage processes that could be responded to would be the failure of the tanks' vacuum relief systems, which could be controlled proactively by checking the pressure sensors in the tank, as described for the methanol-based systems (IMO 2025b).

4.3 Restoration measures

The last essential component to structure the BN models was the derivation of the restoration measures. This was done by identifying actions that could help to restore the operational capacity of the systems after it had been compromised by the effects of an uncontrolled disruption or interrupted as part of the adaptation measures.

It is important to highlight that not all the events that could not be controlled up to the adaptation capacity can be responded to by the restoration capacity. On the contrary, there are some situations that, should they occur, mean that the system's state of functionality is already compromised and cannot be restored anymore. For example, the occurrence of a fire or explosion. There are also other situations which could not be responded to quickly and would rather need a lengthy and detailed assessment or intervention before the system would be able to operate again. For example, a storage tank or bunkering pipeline rupture.

With these considerations in mind, an analysis of situations that could be responded to, as well as what the measures would be, is presented for all of the fuel transport, transfer and storage processes. Since it was found that they would be applicable to systems using either fuel, they will only be presented once.

Restoration measures for fuel transport processes

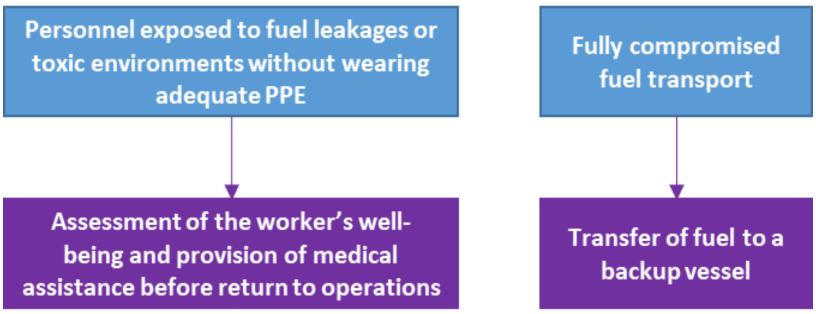

Figure 45. Restoration measures identified for fuel transport processes. Source: own elaboration.

First are the restoration measures for fuel transport processes. Here, two main situations were identified. The first is the **exposure of personnel to fuel leakages or toxic environments without the use of adequate PPE**. In response to this, a health evaluation should be given to the affected workers in order to assess their wellbeing and provide them with any medical assistance they need before operations are resumed. The second situation corresponds to when **fuel transport is fully compromised, for example following a ship grounding episode**. Here, the transfer of the fuel to a backup bunkering vessel could be considered, if available and possible.

Restoration measures for fuel transfer processes

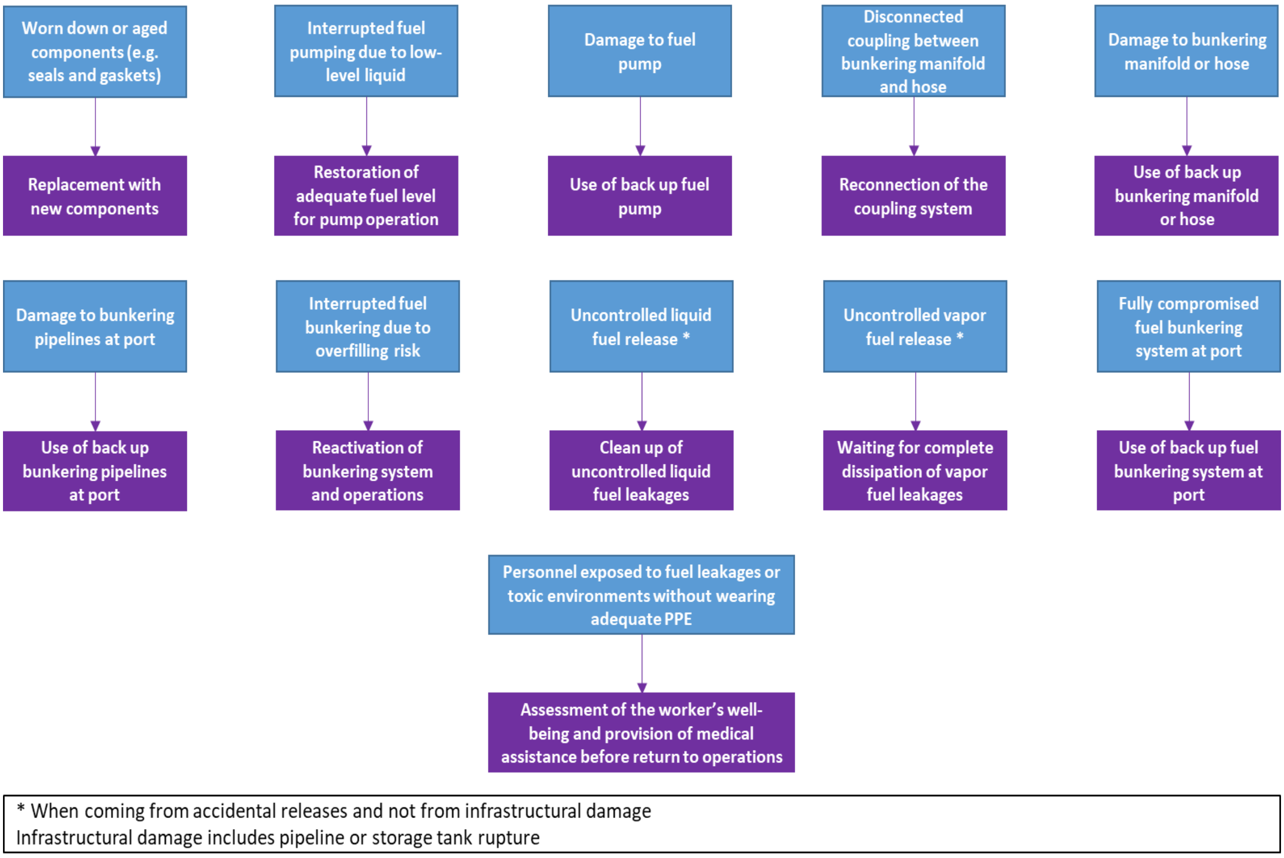

Figure 46. Restoration measures identified for fuel transfer processes. Source: own elaboration.

During fuel transfer processes is where the largest number of potential restoration measures were identified. First is the **replacement of worn down or aged components**, such as seals and gaskets from tanks or pipelines. This would be applicable to cases where leakages were caused exclusively by a failure of these components, rather than a rupture of the fuel transfer or storage equipment (i.e. bunkering hoses or pipelines, or the fuel storage tank). Therefore, operations could be expected to be resumed in a relatively short period of time, following the replacement of the required pieces. Then is the **restoration of an adequate fuel level for pump operation**, following an enforced interruption due to the activation of the low liquid level system (IMO 2020, 2025b). Similarly, there is the prospect of **utilizing a backup fuel pump**, if available, upon a failure or damage to then one that was being utilized.

Regarding the fuel transfer lines, there could be a **reconnection of the coupling system between the bunkering hoses and manifolds, following a forced breakaway** caused by excessive external forces (ABS 2024a). This should be done once the operational parameters (for example the flow rate) have been adjusted to avoid experiencing excessive loads again. In contrast, **in case either the hose or manifold sustained damages, it would be possible to replace them using back up equipment**, if available. Moreover, in the case of bunkering at port specifically, if there is **damage to the bunkering pipelines, the use of a backup system** could also be a possibility.

Another instance in which **bunkering operations could be resumed** would be **after an enforced interruption due to a risk of tank overfilling**. Once the situation would be successfully controlled, the bunkering processes could be restarted. In terms of uncontrolled fuel releases, if they were caused accidentally and are not the result of infrastructural damage, it would be possible to respond to them externally. In the case of **liquid leakages**, this could involve performing **clean-up operations** of the liquid fuel that could not be safely contained in the drip tray + holding tank systems. Meanwhile, in the case of **vapor leakages**, a possible solution would be to **interrupt operations for a longer period of time so that they can be fully dissipated** before resuming activities. Additionally, and also in the case of bunkering at port, if the bunkering system was fully compromised and restorative measures could not be applied easily, there could be the opportunity to **use a backup bunkering system if available**.

Lastly, there can also be the **exposure of personnel to fuel leakages or toxic environments without wearing adequate PPE**. Just as in the case of the transport processes, it would be necessary to assess the workers' wellbeing and provide them with any medical assistance they may need before returning to operations.

Restoration measures for fuel storage processes

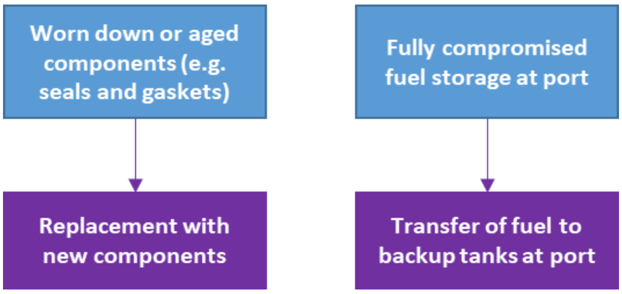

Figure 47. Restoration measures identified for fuel storage processes. Source: own elaboration.

Regarding fuel storage processes, two possible restoration measures were identified. The first is, as previously described for the fuel transfer processes, to **replace any worn down or aged components of the storage tanks** (such as seals or gaskets) when these were the cause of a fuel leakage, but the integrity of the tanks themselves was not compromised. Finally, in the case of fuel storage at port, if the system that was being used is fully compromised, it could be transferred to a **backup tank, if available**.

It is important to acknowledge that the technological components that are exclusive to methanol- and ammonia-based systems are essential to their functioning. For this reason, no restoration measures around them were identified, seeing as damages to these systems would force an interruption of the operations, but at the same time, it would not be possible to restore them quickly. This is because the components are so indispensable that it must be guaranteed that they can operate safely and reliably at all times, meaning that any reparations or interventions to them should be done with enough time and thoroughness.

The component that falls under this situation in the case of methanol is the inerting system, including all of the aspects that allow for its safe and reliable operation, such as the ability to vent inert gas with high O_2 concentrations. Meanwhile, for ammonia, the essential components are the boil-off reliquefaction and thermal isolation systems, which must operate correctly at all times. If the aforementioned elements are not working properly, operations of the systems with either fuel would not be viable. In the case of methanol, the risk of causing fires or explosions would be too high, while in the case of ammonia, it would not be possible to handle the generation of BOG, which needs to be done constantly to control the pressure and temperature within the storage tanks.

4.4 BN Models

Once the BT models were fully derived, it was possible to construct the BN models for the analyzed systems. One BN was structured for the methanol-based systems and another for the ammonia-based systems. Each of them is composed of a disruption, absorption, adaptation and restoration node, as described before. While all of them are connected to the node of the state of functionality, as illustrated in Figure 4, they will be presented separately in order to more easily show all of their components.

BN for methanol fuel systems

First, the disruption node of the BN is presented. The components related to methanol transport and transfer processes are presented in Figure 48, while Figure 49 covers the methanol storage processes. As a general clarification, the disruption nodes were derived from the sequences of events shown in the fault trees, and the last parent nodes (i.e., the ones that are connected directly to the disruption node) are the base events that are responded to in the event trees (i.e., they are their starting points).

Another important consideration for all the BNs presented is that it was carefully analyzed whether events shared common causes or consequences, in order to link them to each other. This is because one of the objectives of performing quantitative resilience assessments with BNs is to conduct backward analyses in order to track down the probable causes of an observed event. Thus, it is indispensable to link all the child nodes with the parent nodes that can cause them (Wang et al. 2024b).

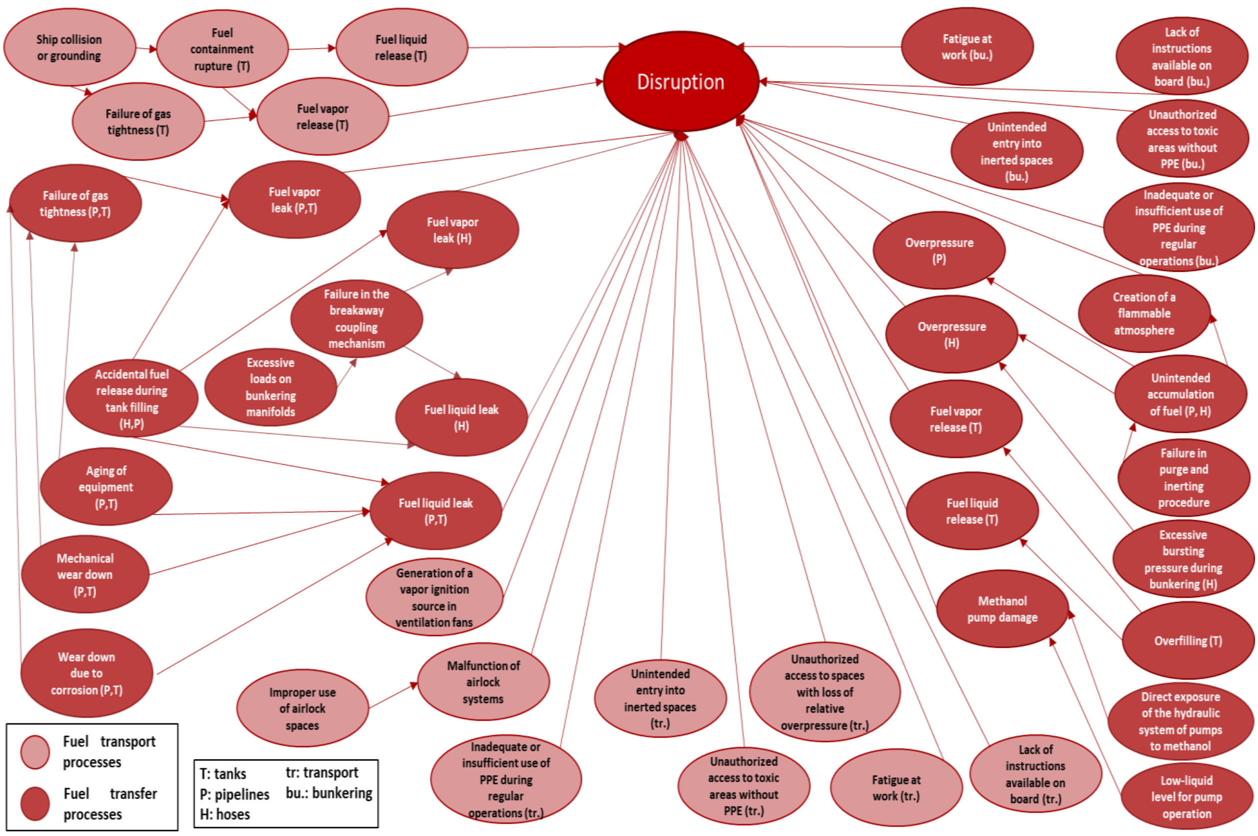

Figure 48. Disruption node of the BN for methanol-based systems. Part 1 of 2: fuel transport and transfer processes. Source: own elaboration.

An initial noteworthy observation for this part of the BN is that a ship collision could cause a fuel vapor release from the tank during transport due to two possible causes: a tank rupture or a loss of the gas tightness. Similarly, during fuel transfer processes, various events could lead to fuel vapor or liquid releases from the bunkering pipes or hoses as well as the receiving storage tanks, which is shown in the diagram accordingly. Damage to the methanol pump also has two possible causes: either a low-liquid level for its operation or a direct exposure of the hydraulic system to the fuel. Lastly, overpressure in the bunkering hose could be attributed either to the unintended accumulation of fuel or to excessive bursting pressures during the fuel transfer.

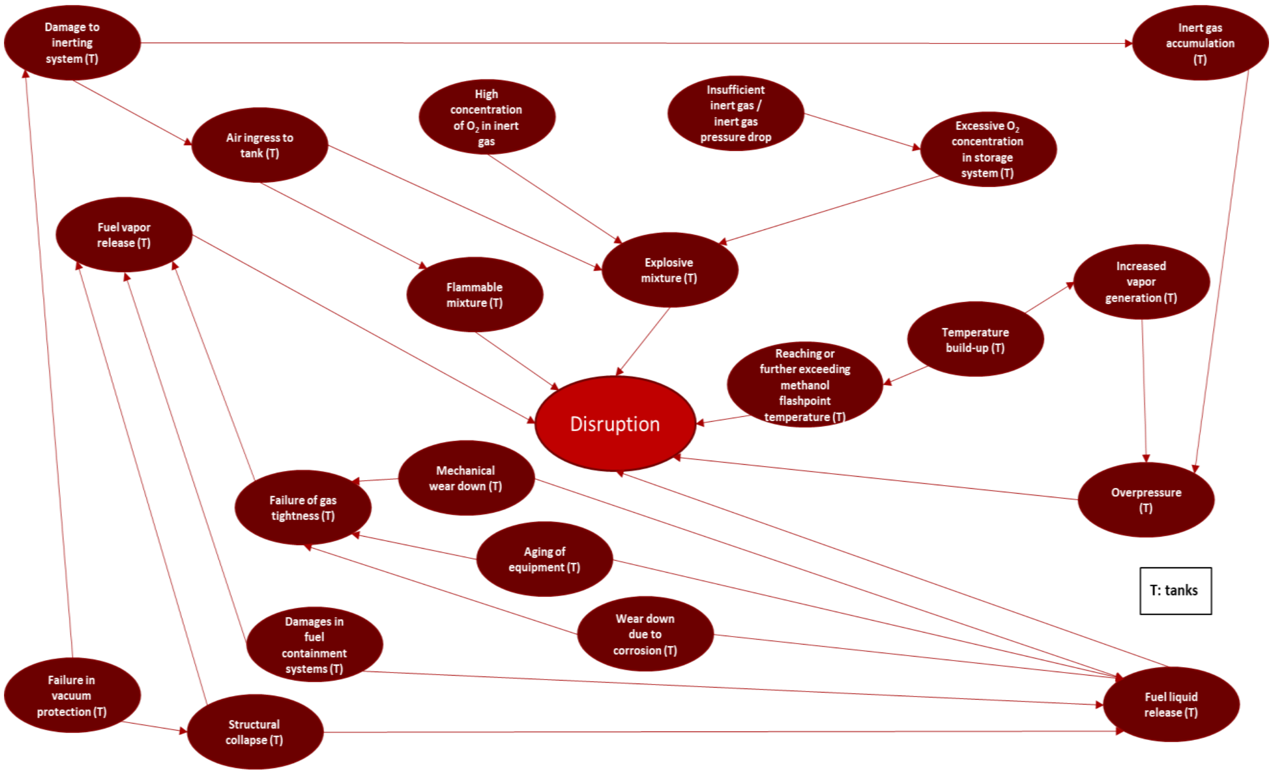

Figure 49. Disruption node of the BN for methanol-based systems. Part 2 of 2: fuel storage processes. Source: own elaboration.

As for the fuel storage processes, it can be highlighted that methanol vapor or liquid releases from the tank can also have multiple causes. Similarly, failures in the vacuum protection systems have two possible implications: either a fuel release due to a structural collapse of the tank or damage to the fuel inerting system, which can itself lead to air ingress to the tank or inert gas accumulation. The latter is one of the possible causes of overpressure in the tank, alongside increased vapor generation due to temperature build-up. Lastly, the creation of an explosive atmosphere within the tank has 3 possible causes: either air ingress to the tank, a high concentration of oxygen in the inert gas or a lack of sufficient inert gas itself.

As for the other components of the BN, Figure 50 presents the absorption node, Figure 51 the adaptation node and Figure 52 the restoration node.

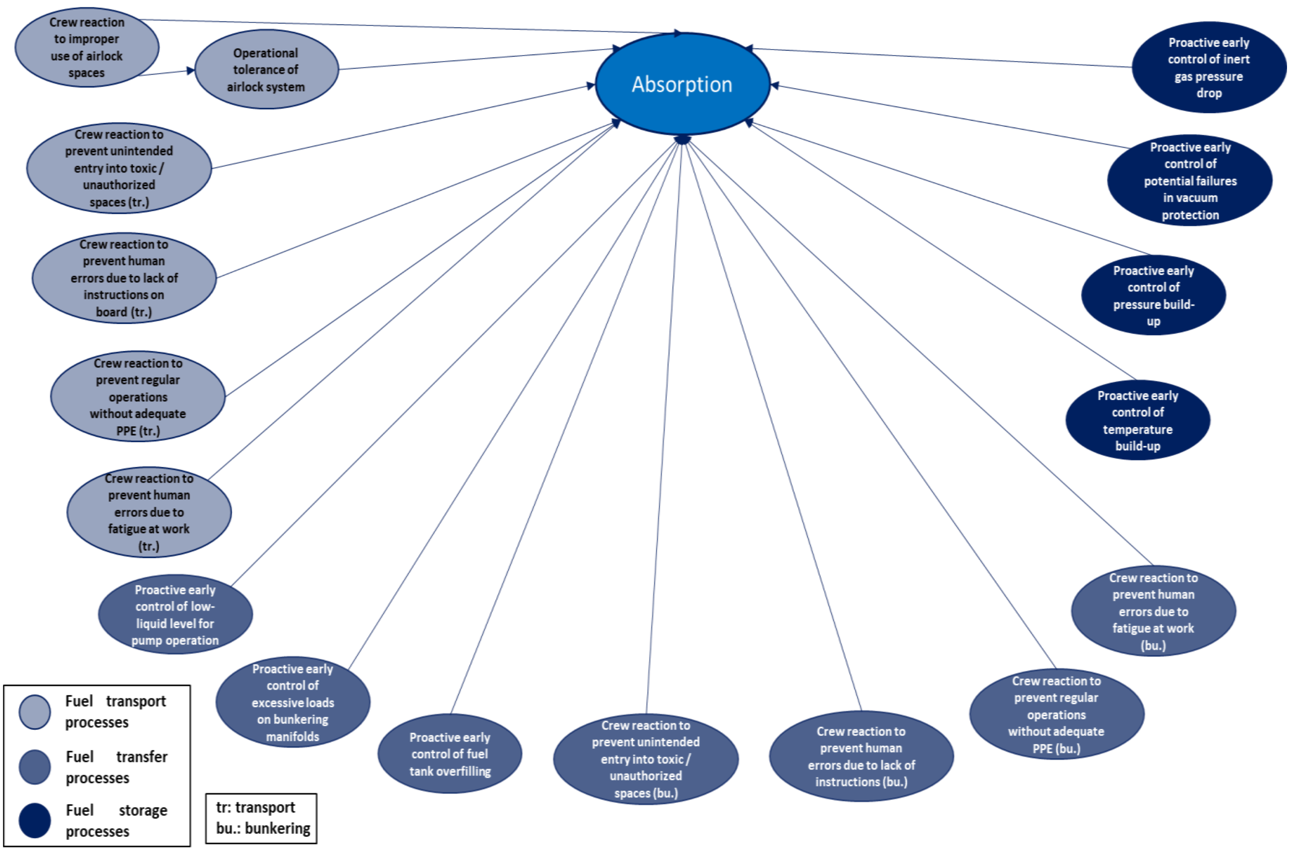

Figure 50. Absorption node of the BN for methanol-based systems. Source: own elaboration.

The absorption node is made up of the proactive response mechanisms identified in the fault trees, represented there with a dark yellow text box, as described in Table 7. All of them, except the improper use of airlock spaces, are directly connected to the absorption capacity node. This is because that is the only event in which two separate instances of the absorptive capacity are present (i.e., not only can the crew members correct the situation, but the airlock system itself also has an innate tolerance level). The rest of them are limited to being proactive mechanisms that respond to their respective disruptions.

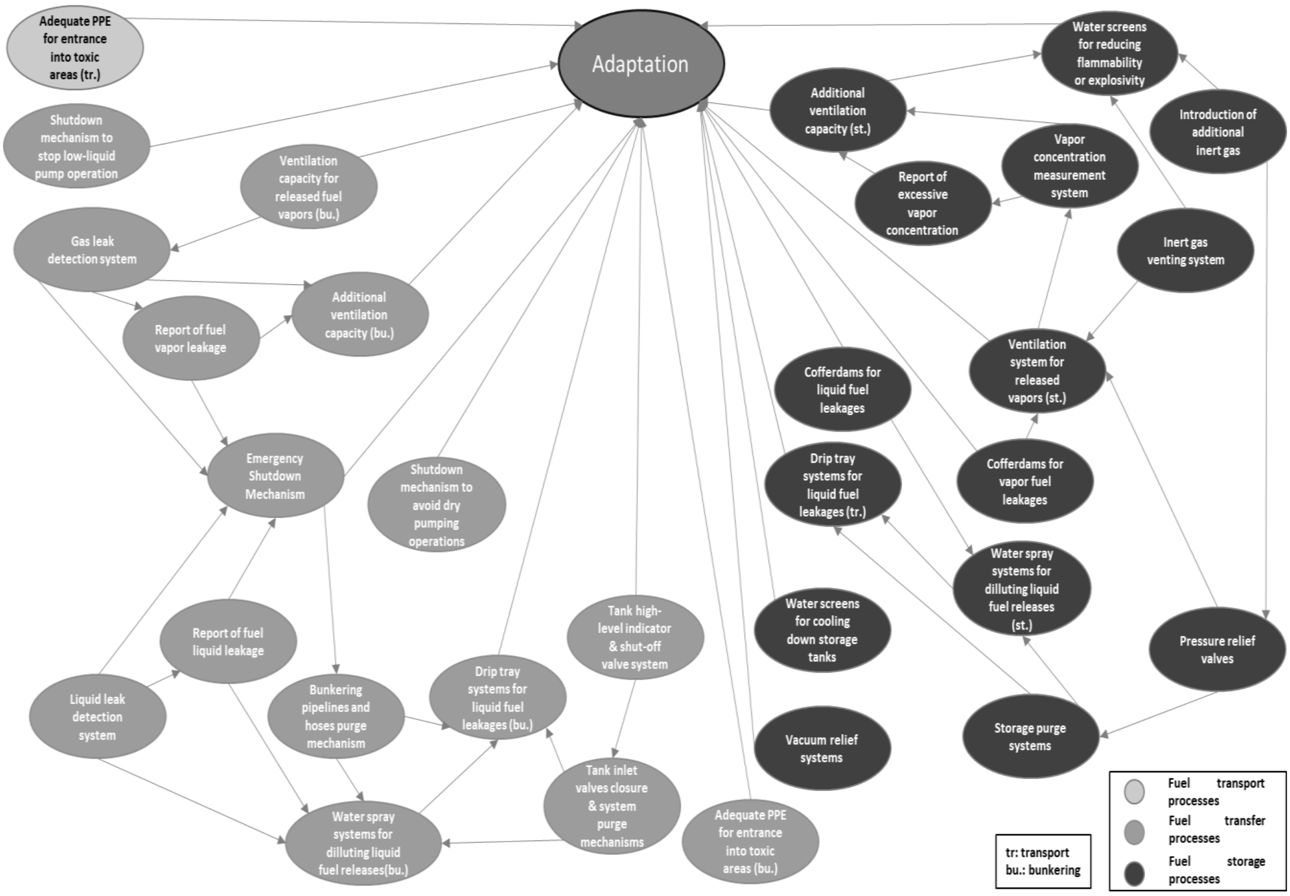

Figure 51. Adaptation node of the BN for methanol-based systems. Source: own elaboration.

As for the adaptation node, this was formed by the rest of the response mechanisms, which were classified as reactive and represented with light yellow text boxes within the event trees (as described in Table 7). It is also important to note that many more connections between the nodes were made here, since the functions of the system components are related to each other. Additionally, nodes that are directly connected to the adaptation capacity are mechanisms with the ability to provide the system flexibility to keep operating despite the occurrence of disruptions, or that are able to control the disruptive situations themselves.

Regarding fuel transfer processes, it can be highlighted that the gas leak detection system can trigger both the fuel transfer emergency shutdown and the additional ventilation capacity. Should this fail, a manual report of vapor leakage by the crew members could also activate both. Likewise, the ventilation capacity on site could control a fuel vapor leakage on its own or rely on the gas leak detection system or a manual report from the crew to activate the additional ventilation capabilities.

A similar situation occurs with the liquid leak detection systems, as they can trigger the block valves of the bunkering systems, as well as the dry disconnect of the bunkering manifolds (which are both part of the ESD). In case this fails, the mechanisms can also be activated following a report from the operations personnel. Independent of this, all liquid leakages would initially be attempted to be diluted using the water screen system. This also includes leakages caused by an overfilling of the storage tank or an overpressure in the bunkering pipelines or hoses, following an improper functioning of the purge mechanisms. However, if both of these systems do work properly, the purged methanol would be conducted to the drip tray systems, which is also the case for all the liquid leakages that were tried to be diluted beforehand. Last for the fuel transfer processes, the tank's high-level indicator and shut-off valve can control risks of overfilling on their own or, in case they fail, it would lead to the tank's inlet valve closure and purge.

Moving onto the fuel storage processes, first it can be noticed that the tank's purge system is connected from the pressure relief valves because it would be triggered in case the latter failed. Conversely, it connects to the drip tray systems for the scenario that a purge process is successful, but also to the water screens for leakage dilution when it is not (as an unsuccessful purge attempt might mean that there is a fuel leakage from the tank due to unhandled overpressure). Also regarding liquid fuel leakages, cofferdams are directly connected to the adaptation node because they could handle them on their own, but are also connected to the water spray system for when they would fail or be overwhelmed. Something similar happens with the cofferdams dealing with vapor fuel leakages, as they could handle them themselves, or if not, the system would rely on the on-site ventilation capacity to safely disperse them.

The ventilation capacity on-site is also key for handling any vapor releases coming from the pressure relief valves, including the ones potentially triggered by the introduction of additional inert gas to the system. Additionally, whenever any of the measures for reducing the flammability of the gas mixture in the tank fail (i.e., introducing additional inert gas, venting inert gas with a high oxygen content or triggering additional ventilation capacity to dissipate a high concentration of methanol vapors), the water screens would come into action. Lastly, whenever the ventilation capacity on site is not enough to safely dissipate vapors, the additional ventilation capacity could be activated either following an alert from the vapor concentration measurement system or a report from the operations crew.

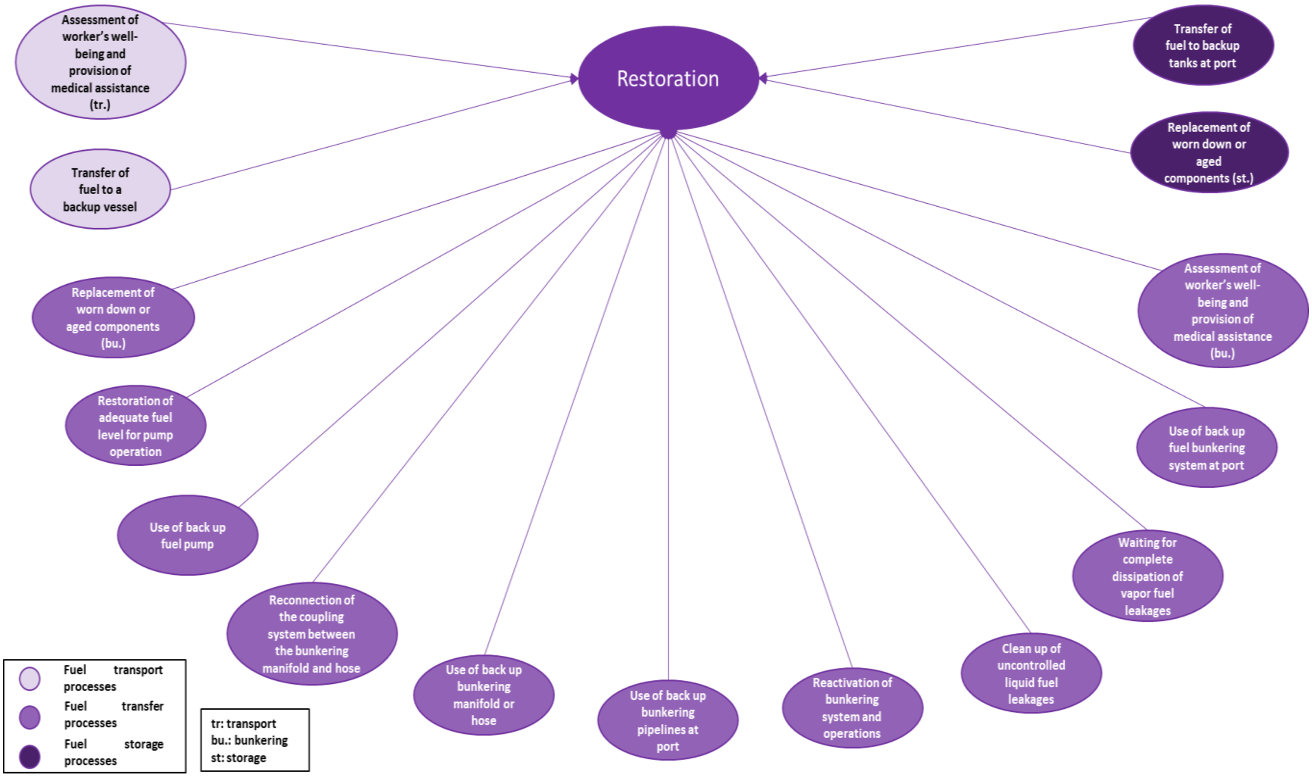

Figure 52. Restoration node of the BN for methanol-based systems. Source: own elaboration.

Finally, for the restoration node, the BN is essentially a one-on-one translation of the restoration measures identified (Figure 45, Figure 46 and Figure 47). All of them are connected directly to the restoration capacity node since 1) there are no intermediate events associated, and 2) all of them can have a direct impact on it.

BN for ammonia fuel systems

Similar to the methanol fuel systems, the components of the disruption node of the BN will be presented first. Figure 53 covers the fuel transport and transfer processes, while Figure 54 includes fuel storage.

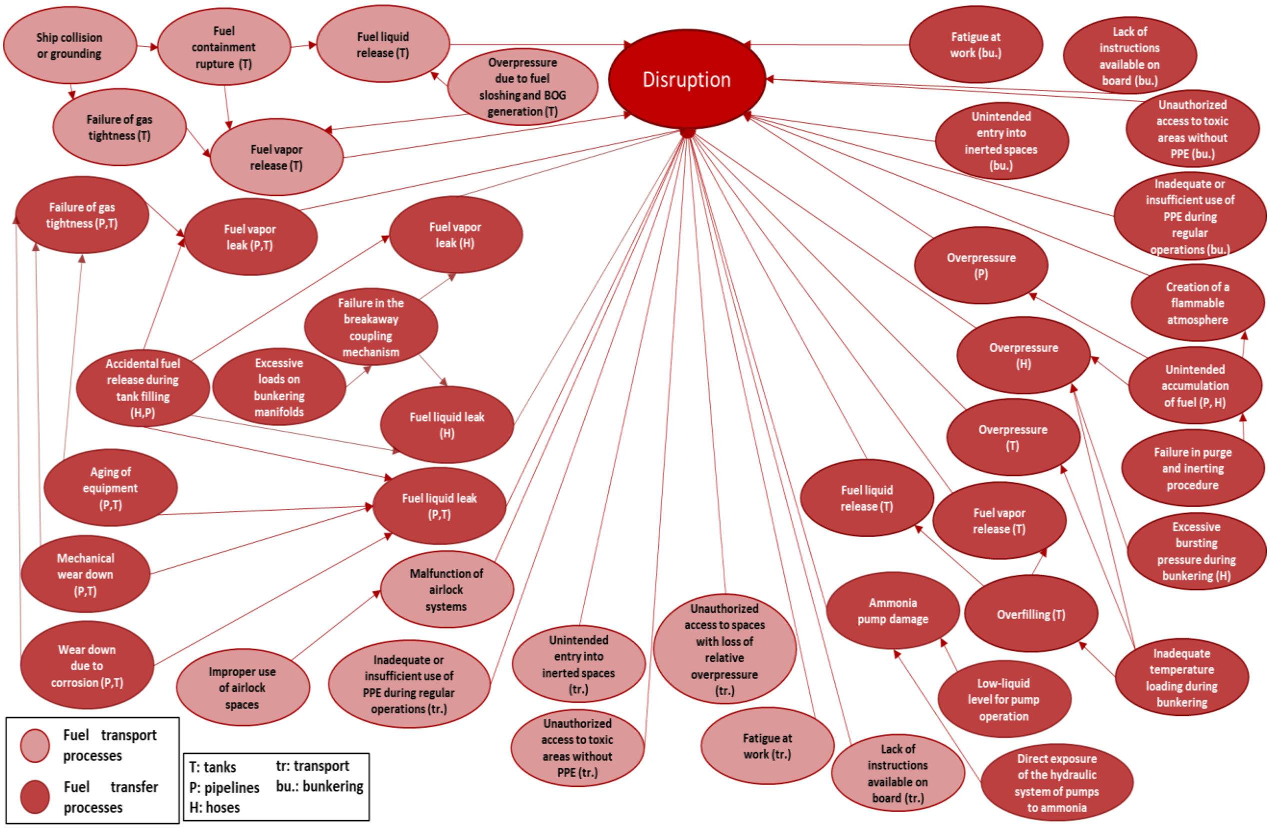

Figure 53. Disruption node of the BN for ammonia-based systems. Part 1 of 2: fuel transport and transfer processes. Source: own elaboration.

As described during the derivation of the fault trees, three key differences between methanol and ammonia transport and transfer processes are 1) that the risk of the generation of ignition sources during transport is not considered for ammonia systems, 2) that the sloshing of the fuel during transport processes can also lead to the occurrence of releases due to overpressure and 3) that ammonia bunkering requires following a temperature loading curve carefully. Therefore, these discrepancies are also reflected in the BN model. It is also important to note that the inadequate temperature loading during fuel transfer is not only another possible cause of overpressure in the bunkering hose, but also of unintentional overfilling of the tank.

The rest of the elements that are part of this section of the BN are identical to the ones present in the model for methanol-based systems.

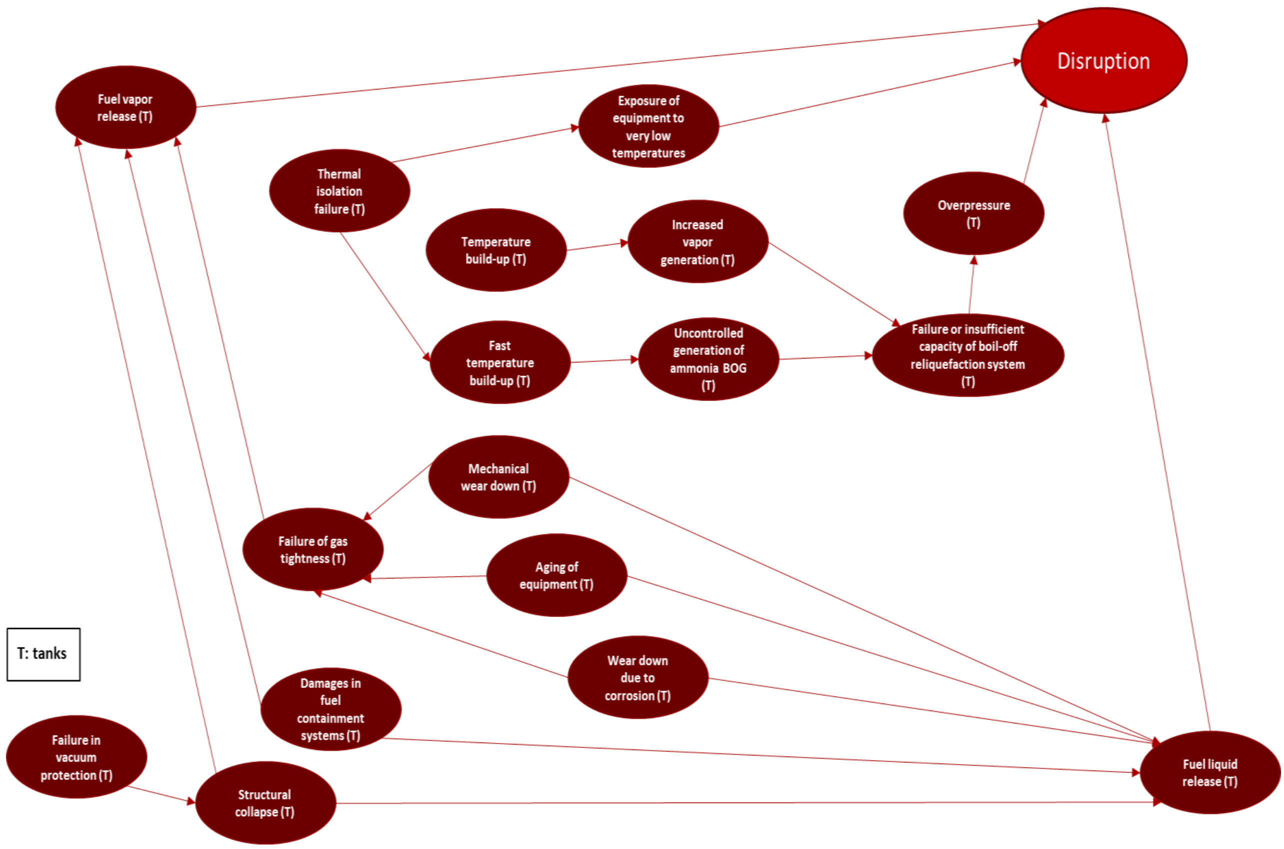

Figure 54. Disruption node of the BN for ammonia-based systems. Part 2 of 2: fuel storage processes. Source: own elaboration.

Meanwhile, for the storage processes, and also in line with what was described during the derivation of the fault trees, the main differences between ammonia and methanol systems are that the former do not have an inerting system, nor are at a significant risk of the formation of flammable or explosive atmospheres. Instead, they must consider events related to the potential failures of the thermal isolation and boil-off reliquefaction systems. This has a series of implications. First, that a failure in the vacuum protection system is only responsible for a structural collapse of the tank. Second, that the risk of overpressure is preceded by the protection provided by the boil-off reliquefaction system. Third, that the boil-off reliquefaction system can be tested either by a slight temperature build-up within the tank or a more significant temperature build-up due to failures in the thermal isolation. And lastly, that a loss of thermal isolation also poses the risk of exposing surrounding equipment to very low temperatures.

In contrast, similar to the case of the methanol storage systems, it is shown how vapor and liquid fuel releases from the tank have multiple possible causes.

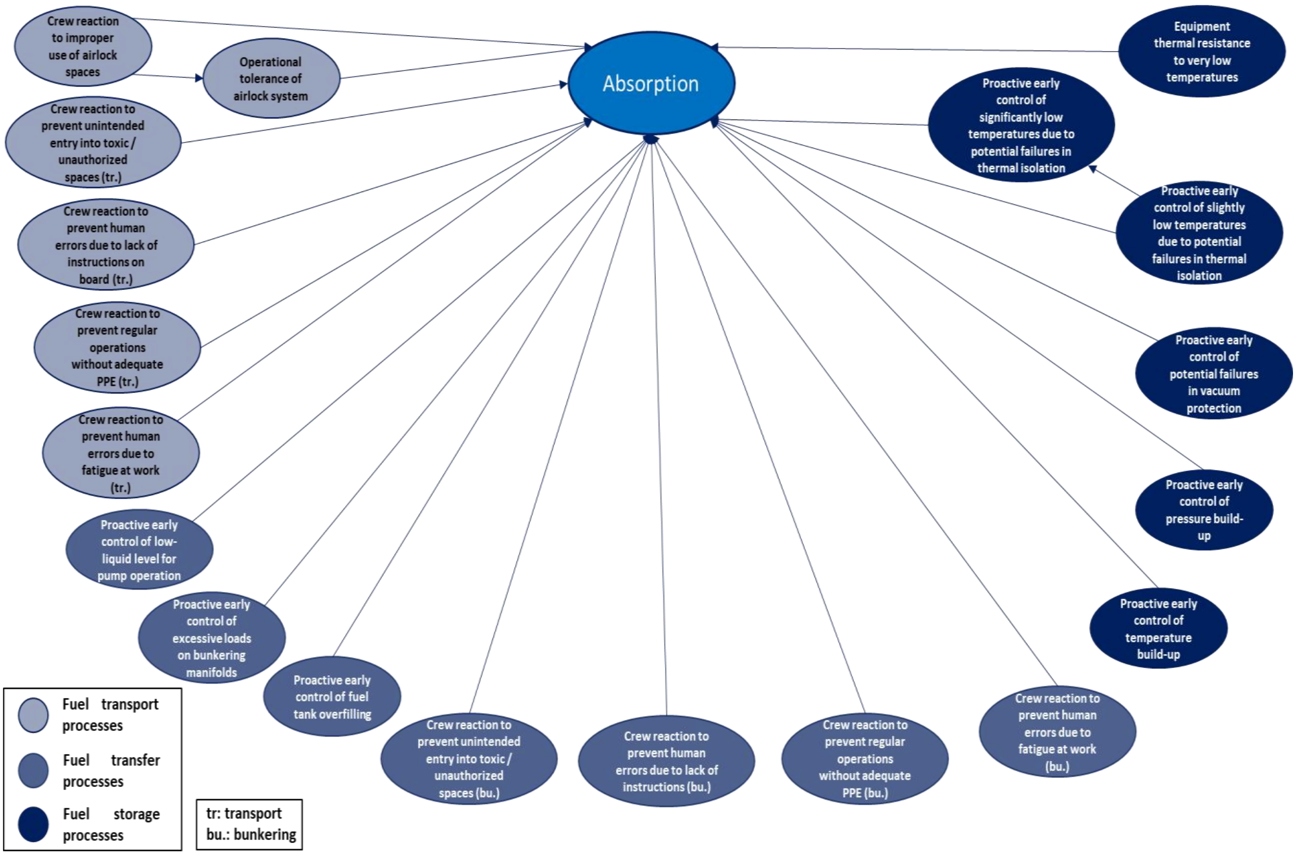

Figure 55. Absorption node of the BN for ammonia-based systems. Source: own elaboration.

As for the absorption capacity node, the elements related to fuel transport and transfer processes are identical to the ones for methanol-based systems. The differences are present in the fuel storage section, which no longer contains the monitoring of inert gas pressure drops, but instead the proactive control of slightly or significantly low temperatures outside the storage tank, as well as the thermal resistance of surrounding equipment.

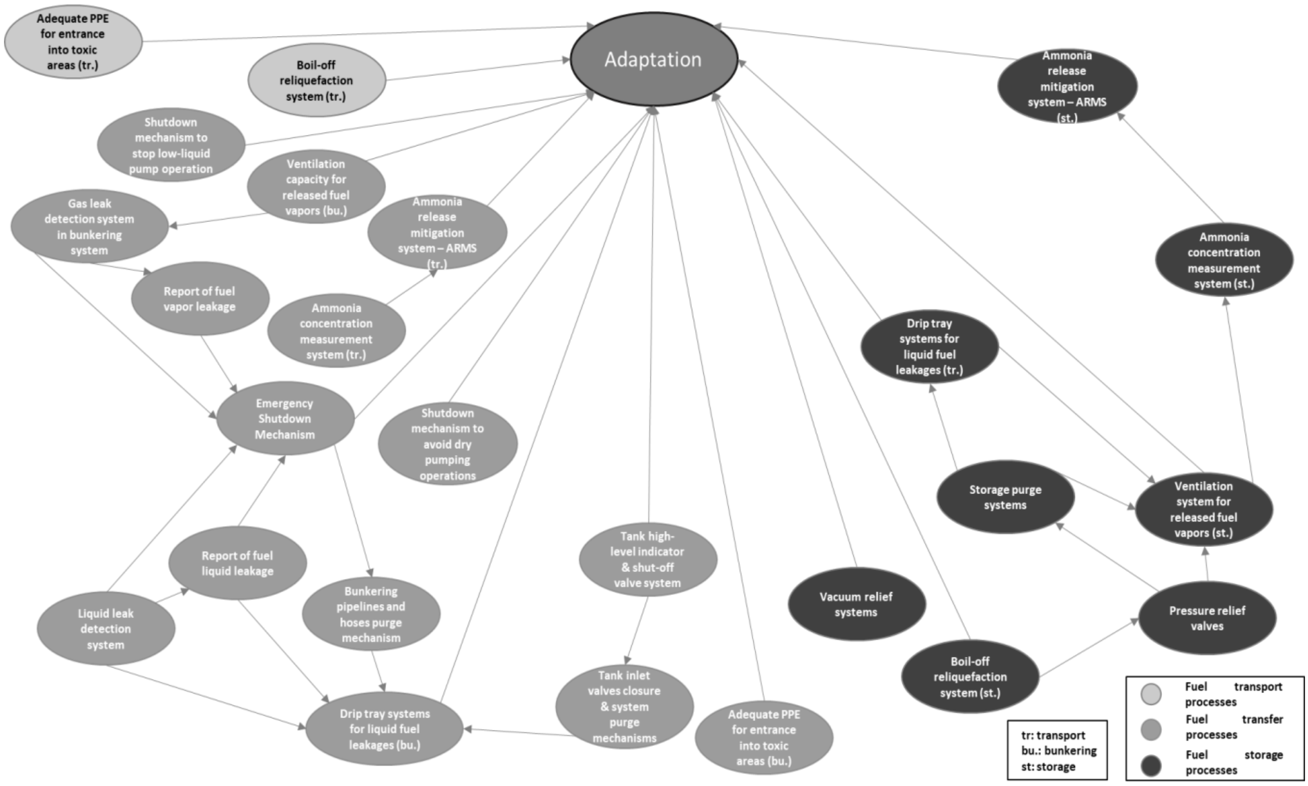

Figure 56. Adaptation node of the BN for ammonia-based systems. Source: own elaboration.

For the adaptation capacity node, some differences between ammonia- and methanol-based systems can be observed for all the different types of processes. In the case of fuel transport, there is the addition of the boil-off reliquefaction system, which is tasked with handling the BOG generation that originates from the sloshing of the fuel. Additionally, there are a couple of differences that apply to both, transfer and storage processes. The first is that ammonia vapor releases are not only handled via the ventilation capacity on-site, but also with the help of the ARMS, which is itself activated by the ammonia concentration measurement system. The second difference is that water spray systems are not used to dilute liquid ammonia releases, but these are instead directly led to the drip tray + holding tank arrangements.

There are also some additional differences exclusive to the fuel storage processes. Namely, that nor the events associated with flammability of explosivity, neither the cofferdam systems are present in ammonia-based systems. Instead, there is the boil-off reliquefaction system, which can help to deal with excessive ammonia vapor generation within the storage tank. However, in case it fails, or its capacity is exceeded, the system would need to rely on the pressure relief valves, or ultimately the purge system to decrease the tank pressure.

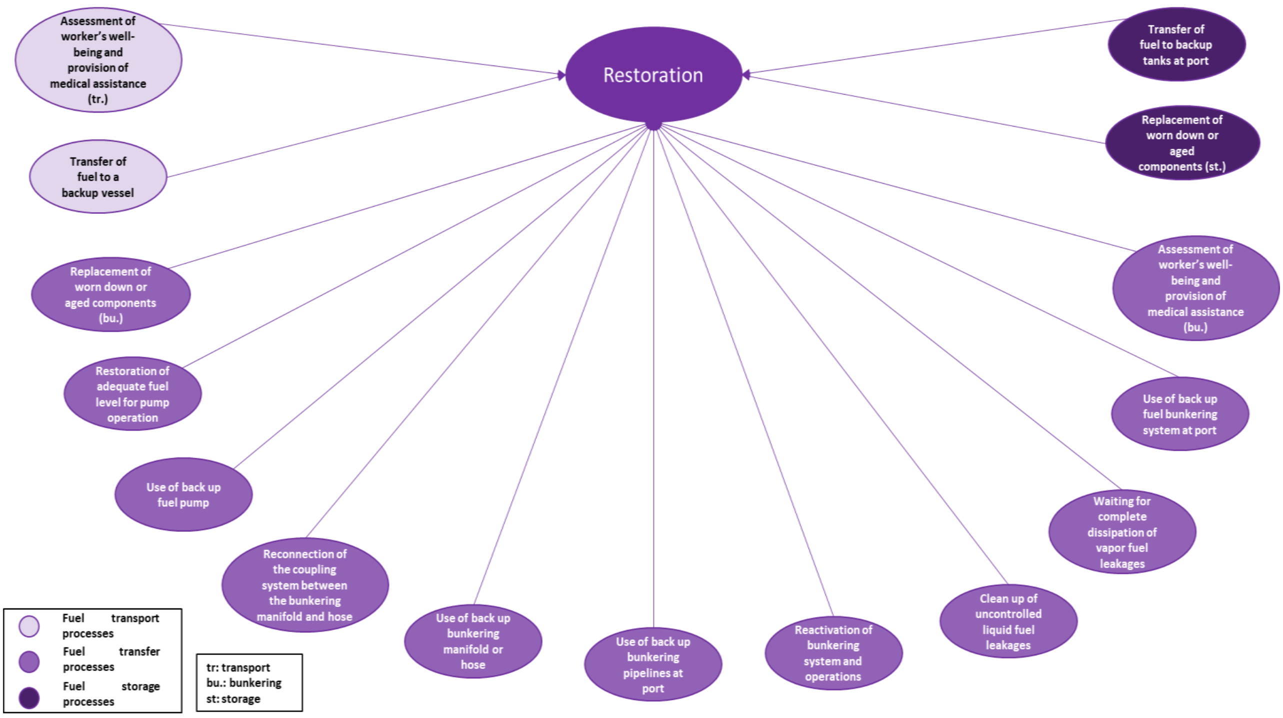

Figure 57. Restoration node of the BN for ammonia-based systems. Source: own elaboration.

Finally, regarding the restoration node, it is identical to the one presented for methanol systems since the same restoration measures were identified for both, as described before. Nevertheless, the BN node is presented again for clarity purposes.

4.5 Assignation of weighting factors to the BN

With the BN models fully stablished, weighting factors can then be assigned to the parent nodes if desired as a method to derive the conditional probabilities of child nodes, as described before. In order to do this more clearly and easily, an Excel file was created in which the pairwise comparisons can be organized and presented. This document, titled "Weight_assignment_BN_model.xlsx", is available to consult alongside this manuscript. The same applies to the Python script that can be used to take the pairwise comparisons and calculate the weighting factors, titled "FAHP_BN_weights.ipynb".

It is important to remark that the weight assignation approach is only one possible method to derive the conditional probabilities and, in reality, it should be seen as a backup option for when they cannot be obtained either from historical data or direct expert consultation (Tong et al. 2020; Zhang et al. 2024). Some examples of databases cited in literature for obtaining historical data include the ones from the UK health and safety exclusive (HSE), the International Association of Oil and Gas Producers (IOGP) and the Offshore Reliability Data (OREDA). All of these were referenced by Fan et al. (2022), in the context of a quantitative risk assessment for ammonia ship-to-ship bunkering, as possible sources for the probabilities of Loss of Containment (LOC) as well as other basic events they considered. Similarly, Wu et al. (2021) referenced the Trends in Risk Levels in the Petroleum Activity (RNNP) reports from the Norwegian Petroleum Safety Authority when performing a quantitative risk assessment for LNG bunkering and storage at ports. Meanwhile, Zhang et al. (2024), in the context of a quantitative risk assessment of liquid ammonia storage tanks, referred to the Guidelines for Quantitative Risk Assessment of Chemical Enterprises from the State Administration of Work Safety of the Chinese government, as well as OREDA once again.

Having clarified this, an example for the assignation of weighting factors will be presented in this section. This will cover the parent nodes connected directly to the disruption node for methanol transport processes. It is important to note that these are not intended to be definitive when applying the model. On the contrary, it is encouraged that stakeholders utilizing the method to define weighting factors when analyzing specific case studies modify them according to the characteristics of their system, as well as their corresponding priorities. Additionally, the method could also be applied to derive the conditional probabilities of parent nodes connected to intermediate nodes if desired. This means that it is not limited to the nodes that are connected directly to the disruption, absorption, adaptation or restoration nodes.

The values presented were derived considering a generalized system covering the supply chain stages of interest, as previously shown in Figure 5, with the corresponding infrastructure and equipment, as described in the derivation of the fault and event trees, as well as the restoration measures. Table 9 presents the example of the pairwise comparisons of the parent nodes that directly contribute to the disruption node during methanol transport processes. The justifications for the linguistic valuations assigned are available to be consulted in the aforementioned Excel file.

Table 9. Pairwise comparisons of the parent nodes contributing to the disruptions during methanol transport processes. Source: own elaboration.

	PN1	PN2	PN3	PN4	PN5	PN6	PN7	PN8	PN9	PN10
PN1	equal	moderate	moderate	absolute	moderate	strong	moderate	very_strong	very_strong	very_strong
PN2	none	equal	strong	absolute	moderate	strong	moderate	very_strong	very_strong	very_strong
PN3	none	none	equal	absolute	none	moderate	none	strong	strong	strong
PN4	none	none	none	equal	none	none	none	none	none	none
PN5	none	none	strong	absolute	equal	strong	none	very_strong	strong	strong
PN6	none	none	none	absolute	none	equal	none	moderate	strong	strong
PN7	none	none	strong	absolute	moderate	very_strong	equal	very_strong	very_strong	very_strong
PN8	none	none	none	very_strong	none	none	none	equal	strong	strong
PN9	none	none	none	strong	none	none	none	none	equal	strong
PN10	none	none	none	strong	none	none	none	none	none	equal

Meanwhile, Figure 58 presents the weighting factors that were obtained after applying the FAHP, as described before.

```
Final normalized weights for disruptions during methanol transport processes
| Child Node                                                             |   Weight |
|------------------------------------------------------------------------|----------|
| Fuel liquid release (T)                                                |    0.252 |
| Fuel vapor release (T)                                                 |    0.214 |
| Generation of a vapor ignition source in ventilation fans             |    0.078 |
| Malfunction of airlock systems                                         |    0.01  |
| Inadequate or insufficient use of PPE during regular operations (tr.) |    0.131 |
| Unintended entry into inerted spaces (tr.)                            |    0.055 |
| Unauthorized access to toxic areas without PPE (tr.)                  |    0.179 |
| Unauthorized access to spaces with loss of relative overpressure (tr.) |    0.037 |
| Fatigue at work (tr.)                                                  |    0.025 |
| Lack of instructions available on board (tr.)                          |    0.018 |
Sum of weights: 1.0000
```

Figure 58. Weighting factors obtained for the parent nodes contributing to the disruptions during methanol transport processes. Source: own elaboration.

In this example, the disruption that was assigned the highest weighting factor was a liquid fuel release (with a value of 0.251), since it not only poses a direct threat to the ship crew and the surrounding infrastructure, but it also results in the generation of methanol vapors. It is followed by a fuel vapor release (0.213), which is also a direct risk for the workers, as well as a flammability hazard. The two other highly relevant disruptions are the unauthorized access to toxic areas without PPE (0.194) and the inadequate or insufficient use of PPE during regular operations (0.119), since both of them are related to the potential exposure of workers to liquid or gaseous methanol without sufficient protection. The rest of the disruptions have lower weighting factors, considering that they represent less direct risks. This is best evidenced with the case of the malfunction of airlock systems, which was assigned the lowest value (0.01) because, even if it occurs, the probability of it leading to the exposure of methanol vapors to unprotected personnel is much lower.

5. DISCUSSION

This chapter covers a series of discussion points derived from the results of this work. These include the requirements and insights for the application of the model to case studies, the comparison of the derived models with existent ones in literature, the main insights drawn from the creation of the models, some of the exclusions and possible extensions to the models and a discussion of the outlook and future work prospects.

5.1 Requirements and insights for the application of the model to case studies

One initial consideration to discuss is that the developed model still requires some key inputs before being able to be applied for evaluating case studies. The most central are the prior and conditional probabilities of all the elements within the model. As described during the theory section, the formers refer to the probability of occurrence of the root nodes on their own, which are normally derived from historical data or direct expert opinion (Hosseini and Barker 2016; Wang 2024; Wang et al. 2024b; Zhang et al. 2024). This is also the case for the conditional probabilities, which are the probability of intermediate events occurring depending on whether the events linked to them have occurred or not, and are normally presented in the form of CPTs (Qiu et al. 2018; Tong et al. 2020; Wang 2024; Zhang et al. 2024). The derivation of these probabilities was left out of the scope of the present work for a couple of reasons. First, that this requires a more in-depth consideration of all the elements and sub elements of the processes covered within the scope of analysis and would also benefit from more experience and knowledge in the use of ammonia and methanol transport, storage and bunkering systems for their application as alternative fuels in the maritime sector, which is still limited. And second, that the probabilities will also depend on the specific characteristics of the system that is being studied.

However, once all the necessary probabilistic inputs are gathered, the model structure presented here could be used to program the BN. To this end, possible software alternatives include specialized solutions such as GeNIE Modeler (BayesFusion 2025), which has been used by authors such as Qiu et al. (2018), Wang et al. (2024b) and Zinetullina et al. (2020) to structure BN models for quantitative resilience or risk assessments and compute results. Free access alternatives could include the PyBNesian package in Python (Atienza et al. 2022).

Another central point for the application of the model concerns the definition of weighting factors, in case this approach is considered. As previously described during Section 4.5., the examples of values presented as part of this work are only intended to be a point of reference and are instead actively encouraged to be checked and adapted to the analyzed case studies. Moreover, one key factor to consider when defining weights is that some of the variables included in the model (i.e., the nodes) are of a qualitative nature, while others can be quantified. An example of the former, in the context of the disruption node for either methanol or ammonia systems, is fatigue at work from operators. Meanwhile, an example of the latter could be a fuel liquid release from a bunkering hose, as the volume of the leakage is quantifiable. Therefore, when analyzing the potential impact of this event, a lower weighting factor could be used in the case of a mild fuel release. In contrast, a higher weighting factor could be considered if the leakage volume is higher and thus it could have a greater impact on the system.

An additional way in which the specific characteristics of the analyzed system could influence the definition of the weighting factors is the availability of resources and infrastructure. For example, if the bunkering system has backup pumps available, the event of a damage to the pump could be given a lower weight compared to a system where there is no backup equipment, as the impact on the latter case would be much more significant.

It is also important to remark that the definition of weighting factors is not the only alternative approach for deriving the conditional probabilities of intermediate events. Other options identified in literature include the adoption of a Noisy-OR model (see for example Hossain et al. (2020), Hosseini and Barker (2016) or Wang (2024)) or the use of an Expectation-Maximization algorithm (as done by Wang et al. (2024b)).

Lastly, while the derivation of disruptions to the systems, as well as the response mechanisms, was based on intensive literature research and peer discussion, the model could be adapted to add new components or remove elements that are not relevant to or not present in specific case studies of interest.

5.2 Comparison with existent models

As discussed during the introduction section beforehand, quantitative analyses for the safe and reliable use of ammonia and methanol as alternative maritime fuels have started to emerge in literature. Examples include Fan et al. (2022), Wang (2024) and Zhang et al. (2024), all of whom also utilize BN models. However, these correspond to quantitative risk assessments rather than resilience assessments. Thus, the focus of these analyses is on assessing the probability of potential risks to occur. This means that they are not considering the absorption, adaptation or restoration capacities of the system, but are instead focusing on pre-disruption stages only. In contrast, the model presented here also aims to include the post-failure phase, which would allow to determine the probability of the systems to maintain or return to a normal operational state, following the occurrence of disruptions (Tong et al. 2020). As a matter of fact, resilience assessment has been stated to be more suitable than risk assessment when dealing with complex systems with uncertain disruptions. This is because it is able to deal with both, uncertain hazards as well as failure propagation following a disruption (Tong et al. 2020). For this reason, authors such as Park et al. (2013) have suggested than risk analyses on their own are not sufficient to ensure the safety of complex engineered systems, especially in the face of emerging disruptions. This is relevant to the analyzed systems since, as it could be evidenced when deriving the BN models, plenty of disruptive events, as well as response mechanisms, are linked to one another, making it a very complex and intricate system.

Additionally, the existing risk assessments in literature only concern themselves with specific processes within the supply chain. Zhang et al. (2024), for example, focus on liquid ammonia storage only. Meanwhile, Fan et al. (2022) cover the ammonia bunkering stage, considering a ship-to-ship model. Similarly, Wang (2024) addresses the risk of leakage in the methanol fuel system of dual-fuel powered ships. In contrast, the models proposed cover multiple stages of the supply chain, incorporating all of the infrastructure and processes that are needed to supply methanol or ammonia as alternative maritime fuels to ships, beginning with the transport of the fuels from a production site all the way to delivering them to the final off-takers.

Lastly, the concept of utilizing BN models to perform quantitative resilience assessments considering the absorption, adaptation and restoration capacities of systems has been applied before (Hosseini and Barker 2016; Tong et al. 2020; Wang et al. 2024b; Zinetullina et al. 2020). However, it was yet to be done for the specific applications and supply chain stages covered in this work.

5.3 Main insights derived from the models

This section covers a couple of insights related to the use of ammonia and methanol as alternative maritime fuels that were identified following the derivation of the models for quantitative resilience assessment.

Fuel releases as a central disruption to the systems

Following the derivation of the fault and event trees, as well as the BNs themselves, it was realized that fuel releases, either as liquid or vapor, are one of the most central disruptions to the analyzed systems for multiple reasons. First is that they can occur during any of stages of the supply chain that were covered as part of this work. That is, either at fuel transport, transfer or storage processes. Moreover, they have multiple possible causes, including tank, pipeline or hose ruptures, component damage, overpressure and accidental releases.

In addition to this, their impact is not only profound, but also diverse. This is because they bring further significant risks with themselves. One applicable to both fuels is the toxicity to workers (Cames et al. 2021; Wissner et al. 2023). In the case of methanol, there are also significant risks of flammability and explosivity (ABS 2021). Meanwhile, for ammonia systems, there is the risk of exposure of personnel and surrounding infrastructure to very low temperatures (Hammer and Leisner 2025).

It is also important to highlight that fuel releases caused by infrastructural damage are particularly impactful, since they pose a very significant threat to the state of functionality of the system. This is because while there are multiple response mechanisms to address and safely contain the releases, operations could potentially take a long time to be restored, especially if no backup equipment is available to use. This scenario would be even more likely on board of transporting ships.

For all of the aforementioned reasons, it is essential for systems deployed towards the use of ammonia and methanol as alternative maritime fuels to manage the risk of fuel releases in a very robust and comprehensive manner. To this end, a series of recommendations on how to improve the resilience of the analyzed systems, not only for this disruptive situation, but also for various others that were identified, will be presented later. These will consider all of the resilience attributes that were studied.

Key differences between methanol and ammonia systems

As a result of analyzing systems for both, methanol and ammonia as alternative maritime fuels, it was also possible to identify what the main differences between them are regarding the specific infrastructure that they demand, as well as the response mechanisms to manage the risks associated with them. From the side of methanol systems, the most relevant differences have to do with managing the flammability and explosivity of the fuel. This is reflected in two main components of the system. First is the inerting system, which addresses this risk from a preventive point of view, as its mission is to reduce the oxygen concentration in the spaces surrounding the methanol infrastructure, decreasing the probability of ignition (Indian Register of Shipping 2025b). The second is the use of the water screens, which are also not present in ammonia systems. These are used not only to dilute potential fuel leakages (IMO 2025b), but also to reduce the risk of fires or explosions. This is done both, preventively by cooling down the system when there is a temperature build-up, but also reactively by reducing the flammability and explosivity of methanol liquid or vapor fuel releases (IMO 2020).

In contrast, for the case of ammonia systems, two main differences are due to the cryogenic storage conditions of the fuel. This is manifested in the need for a boil-off reliquefaction system, as well as thermal insulation for all the ammonia-related infrastructure. The boil-off reliquefaction system is essential in order to re-condensate the BOG that is continuously generated during the storage and transport of the fuel. Thus, it is key for managing any temperature and pressure build-ups within the storage tanks (ClassNK 2025; Hammer and Leisner 2025). Thermal insulation is also necessary not only to limit the amount of BOG that is generated, but also to protect surrounding infrastructure and operators from very low temperatures (IMO 2025b). Additionally, there is the need to follow a temperature loading curve during the bunkering operations in order to avoid accidental overfillings due to reductions in the fuel density caused by higher temperatures (ABS 2023).

Two other significant differences between ammonia and methanol systems arise from the higher toxicity of the former. On one side, this is evidenced by the inclusion of the ARMS, as there is much less tolerance for high concentrations of ammonia vapors in the environment, meaning it cannot be relied on the on-site ventilation capacity only to deal with them (ClassNK 2025). In a similar line, ammonia transport and transfer processes demand a much stricter use of PPE. For instance, respiratory protection should always be mandatory in any ammonia handling process, while in the case of methanol it is only required if vapors are present and their concentration in air exceeds 200 ppm (International Enviroguard 2021; Methanol Institute 2017b). Similarly, for ammonia bunkering processes, it is recommended that workers always utilize a type 1 chemical-resistant suit (Dräger Safety 2025), while for methanol, the use of chemical-resistant clothing is generally considered enough and full suits are only required in the event of large spills, as there are high risks of exposure to liquids or vapors (Methanol Institute 2017b).

Similarities between the systems and opportunity to learn from one another

In spite of the differences presented in the previous section, it is also important to note that systems for ammonia and methanol also share various similarities in terms of the required infrastructure and safety mechanisms. Therefore, the implementation, development and improvement of systems for one fuel can also benefit systems for the other. This is positive for the development of the alternative maritime fuel sector and highlights the importance of knowledge and experience exchange between system manufacturers and project developers regarding best practices and lessons learned. Some of the elements that are present in systems using either ammonia or methanol as alternative maritime fuels include:

- The adequate maintenance and replacement of equipment to prevent leaks associated to the wear down of components.
- The performance of inerting procedures after fuel bunkering processes.
- The constant monitoring of measuring equipment to prevent failures in the pumping and vacuum protection systems, as well as tank overfilling and pressure or temperature build-ups.
- The safe storage of fuel bunkering hoses and the adequate use of airlock spaces within transporting ships.
- The development and deployment of key safety infrastructure, including gas and liquid leakage detection systems, ESDs, breakaway-type couplings between bunkering hoses and manifolds, the ventilation capacity at ship and port facilities, purge systems for bunkering pipelines and fuel tanks, drip tray + holding tank arrangements and PRVs.

This observation also holds true for all of the restoration measures proposed and discussed as part of this work, since they are also common to both types of systems.

Recommendations for enhancing the resilience of the analyzed systems

Having analyzed the resilience of the target systems from the perspective of their different resilience attributes, it was also possible to generate a set of recommendations to enhance them in a holistic manner.

Starting with the **potential disruptions** to the systems, an initial recommendation is to focus on the prevention of events that can have multiple possible consequences. In the case of fuel transport processes, this could be the occurrence of ship collision or grounding incidents. Meanwhile, for fuel transfer processes, examples could include the wear down of system components, the occurrence of excessive loads on bunkering manifolds, and failures in purge and inerting procedures. And lastly, for fuel storage processes, situations could include temperature build-ups, in the case of methanol-based systems, or failures in the thermal isolation system, in the case of ammonia-based systems. This is because these events could have the potential to cause multiple disruptions simultaneously, meaning they could have a greater impact on the state of functionality of the system and put higher pressure on the available response mechanisms.

From the side of the **absorption capacity**, one key element to consider is the emphasis on adequate and extensive crew training. This is because properly prepared personnel can help to detect and prevent many potentially disruptive situations. Those can include the improper use of airlock spaces, the entry of people into toxic or unauthorized spaces, the performance of operations without adequate PPE or the occurrence of human errors due to fatigue at work or a lack of instructions available on site. This can also be extended to the proactive control of key operational parameters. In particular, the liquid level for pumping operations, the pressure levels on bunkering manifolds, and the liquid level, pressure and temperature of the storage tanks. For the case of methanol systems specifically, there is also the inert gas pressure of the system, while for ammonia-based systems, there are the low temperature indicators (IMO 2020, 2025b). When crew members are trained and instructed to monitor these parameters with a proactive and preventive approach, they can also make a significant contribution to correct undesired situations in early phases, thus increasing the absorption capacity of the systems. It is also worth noting that this proactive and preventive monitoring of operational parameters could also be implemented from a technological point of view by incorporating alarm systems that trigger not only when parameters are close to or have surpassed critical thresholds, but that also when undesirable trends are being observed. For example, continuous temperature and pressure increases in fuel storage tanks, even if they are still not close to posing a threat to the system.

Human capital can also have a positive effect on the **adaptation capacity**, as crew members could be able to manually report disruptive situations in the event that the automatic detection systems fail, as well as to activate manual emergency responses. This could be the case with reporting undetected liquid or vapor fuel leakages or excessive vapor concentrations, as well as activating manual shut-off mechanisms. Additionally, as a general consideration regarding crew training, it is encouraged to include safety-related recommendations specific to the use of ammonia and methanol as alternative maritime fuels within the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STWC) from the IMO (IMO 2025c).

Other potential points of improvement for the adaptation capacity of the systems include guaranteeing the use of adequate PPE for both, regular operations and emergency situations. Additionally, it is recommended that all the response mechanisms that were presented as part of this work are included in systems designed in the future and are also inspected and tested regularly to make sure that they will be able to operate properly when required.

Lastly, in terms of the **restoration capacity**, proper training on the effects of methanol or ammonia exposure in people must also be provided to crew members in order for them to be aware of potential consequences to their health, as well as to facilitate opportune assistance whenever a worker is affected. Likewise, the ability to incorporate backup components and infrastructure could be beneficial to a quick recovery of the operations in the event of disruptions. However, the extra costs and effort that this would imply should also be taken into consideration.

As a final reflection, it should also be kept in mind that enhancing the absorption capacity of the system will reduce the pressure on the adaptation and restoration mechanisms and, similarly, that improving both, the absorption and adaptation capacity will translate into a lesser demand for the restoration mechanisms.

Potentially key role of the adaptation capacity

One last insight derived from the structuration of the final models is that the adaptation capacity could potentially be the most important contributor to the system's resilience. While this would and should be able to be assessed for certain by applying the model to case studies, there is an indication that this could be the case, aligning with the findings of previous authors in literature. In particular, Abimbola and Khan (2019), who also developed a BN model for quantitative resilience assessment, applied it to a case study of a nuclear power plant accident and found that the adaptation capacity contributed the most to the system resilience, followed by the absorption capacity and, lastly, the restoration capacity.

Interestingly, when analyzing the final version of the derived models it can be seen that the adaptation nodes have the highest number of elements (30 in the case of methanol systems and 25 for ammonia), followed by the absorption nodes (17 elements for methanol-based systems and 18 for ammonia-based systems) and then by the restoration nodes, which have the lowest number of elements (13 for both types of systems). Additionally, the adaptation nodes have a high degree of interconnection between them, while there is only one interconnection between the absorption nodes and none in the restoration nodes. This means that the events that are part of the adaptation node could tend to have a more significant effect on the system, as they could also affect other elements within the BN. This preliminary expectation, however, should be verified when applying the model and, specifically, when performing sensibility analyses that aim to find out which of the nodes tend to have the greatest influence on the state of functionality of the system. Nevertheless, this could suggest that even if it is not possible to prevent all disruptive situations from happening or affecting the system (via the absorption capacity), it is essential to have adequate response mechanisms that allow the system to sustain a high state of functionality in spite of them (i.e., the adaptation capacity).

5.4 Exclusions and possible extensions to the model

Another important point to discuss are the elements that were not included within the scope of this work, but could also be relevant in the context of alternative maritime fuel applications, should the model want to consider additional components or stages of the supply chain. Two of them are already considered within the IMO interim guidelines for the use of ammonia and methanol as alternative maritime fuels (IMO 2020, 2025b), which would allow to incorporate them more easily in the future. However, they were left out of this analysis, as they did not align with the target scope. The first are all considerations regarding the **alternative fuel propulsion systems** and the second are **additional emergency response mechanisms**.

Regarding the former, it is important to remark that the IMO interim guidelines were designed with the focus of covering ships that use methanol and ammonia as alternative maritime fuels. This means that while plenty of their elements were incorporated into the present analysis (covering all of fuel transport, transfer and storage processes), there were also others that were excluded. Some examples include the ship fuel supply systems (i.e., the systems whose task is to deliver the fuel from the storage tanks on board to the engine rooms of the ship), the fuel preparation rooms (which are in charge of converting the fuel from storage conditions to the ones needed for their utilization), the fuel consumers (i.e., the engines and propulsion systems themselves), and the ship exhaust systems (considering the specific implications of using of ammonia or methanol as fuels) (IMO 2020, 2025b).

Meanwhile, the additional emergency response mechanisms cover two main aspects. First are the fire detection, protection and firefighting systems, and second the first aid and shelter infrastructure for assisting workers exposed to fuel leakages. The first were excluded of the present analysis considering that the occurrence of a fire or explosion are disruptive events that force a complete interruption of the operations. This means that the state of functionality of the system would be null and it would not be expected to recover quickly or easily. Meanwhile, the response mechanisms to assist and protect workers after the occurrence of fuel leakages, while essential for the deployment of ammonia transport, storage and bunkering processes, also fall outside the scope of interest of the analysis, as they correspond to situations in which they are unable to return to operations.

Nevertheless, in order to provide an overview of what these components encompass, the IMO provisions for fire safety and explosion prevention include the presence of fire protection, detection and response mechanisms in all of the system components related to the storage, conditioning, transfer and use of ammonia or methanol as alternative maritime fuels (IMO 2020, 2025b). On the other hand, the safety infrastructure to respond to uncontrolled leakages and the exposure of workers to the fuels include mustering stations, life-saving equipment, decontamination showers and eyewashes, stretchers, medical first-aid equipment and breathing apparatus for respiratory protection (IMO 2020, 2025b).

Possible extensions to the model presented in this work precisely include **extending the scope of the supply chain to the use of the fuels on board** of the ships. However, it is also worth noting that the scope considered for the analysis presented here is strategic, as it is concerned with the ability to reliably supply the alternative maritime fuels to ships that want to be the final off-takers. Meanwhile, the resilience in the use of the fuels in the consumer ships themselves could have a different strategic importance. Lastly, ways in which the model could be expanded to analyze more complex dynamics will be presented in the following section.

5.5 Outlook and future work

Application of the model to case studies

Moving onto the prospects for the application and refinement of the work presented here, the initial step would be to utilize the model to analyze specific case studies of interest. As discussed before, this necessitates deriving the prior and conditional probabilities of all the elements presented as part of the model. Once this can be done, it would be highly recommended to perform various types of analysis. Some examples include causal reasoning, diagnostic reasoning and sensitivity analysis, as has been done by other authors who developed BN for quantitative resilience assessments (Wang et al. 2024b).

Casual reasoning, also referred to as forward or top-down reasoning, refers to inferring the probabilities of different outcomes based on known evidence, as well as analyzing the factors that influence these outcomes. One example of this applied to the developed model would be to estimate the probability of a fire during fuel storage processes following a methanol liquid fuel release from the tank. This would need to consider whether the water screens systems were activated to dilute and reduce the flammability of the leakage, if the incident occurred in an enclosed space or not and with or without the presence of an ignition source, for example.

Meanwhile, diagnostic reasoning, also known as reverse or bottom-up reasoning, aims to determine what the most probable causes of an event were, based on known evidence. For example, determining the cause of an ammonia liquid release from a bunkering pipeline given that it was not accidental. According to the developed model, the three possible causes could be the aging, mechanical wear down or wear down due to corrosion of its components.

Lastly, sensitivity analyses aim to determine what are the impact of changes in parameters on a target objective. For example, what would be the change on the probability to successfully generate an alert for additional ventilation to handle a vapor release during methanol storage processes given that the prior probability of a successful reading of the vapor concentration sensor drops from 99% to 95%.

Consideration of interdependencies between the supply chain stages

One very important consideration for the resilience assessment model proposed in this work is that the fault and event tree analysis assumed that the events in the transport, storage and bunkering stages of the fuel supply chain are independent to each other. However, from the perspective of supply chain resilience, it would be interesting to consider possible interdependencies between them. That is, to analyze how a disruption in one supply chain stage could affect the others. One such example could be to consider fuel supply bottlenecks in the event of a delay caused by an accident with the fuel transporting ship or due to adverse weather conditions encountered at sea.

Establishing this type of relationships, which could be done by expanding the BN model with the addition of extra nodes and connections, could allow to evaluate the resilience of the fuel supply chain as a whole.

Structuration of a Dynamic BN model (DBN) to include the learning capacity of the system

A final recommendation to expand and complement the quantitative resilience assessment is to convert the BN model from static to dynamic, as was previously suggested during the theory section. This would necessitate the inclusion of a temporal dimension, as well as the learning capacity of the system (Tong et al. 2020; Zinetullina et al. 2020). To this end, it is important to consider that the learning capacity has the potential to improve all of the absorption, adaptation and restoration capacities of the system. For this reason, and as it was evidenced when analyzing the structure of DBN models created for quantitative resilience assessment, the learning capacity would be connected to the other resilience attributes, as shown in Figure 59.

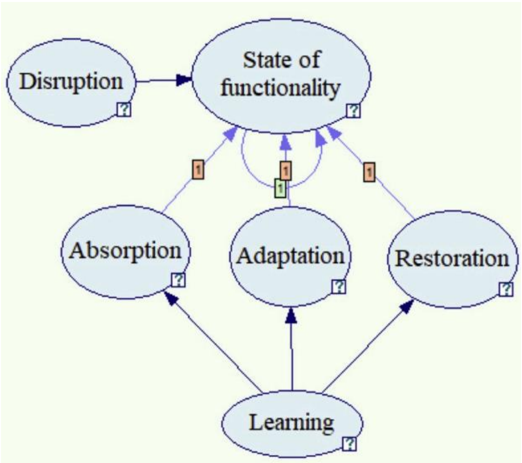

Figure 59. DBN model for quantitative resilience assessment. Source: Tong et al. (2020)

The main advantage of conducting dynamic resilience assessments compared to static ones is that it can be accounted for how much the systems change with time following the occurrence of disruptions. Additionally, incorporating the learning capacity results in a much more comprehensive resilience assessment, as it is considered that the feedback obtained from past accidents can be used to create new knowledge for responding to future disruptions more effectively. This can contribute, for example, to the correction of inappropriate technical guidelines or procedures, which would ultimately allow to improve the robustness and reliability of the systems going forward (Tong et al. 2020; Zinetullina et al. 2020).

Lastly, it is also worth considering that the inclusion of the learning capacity into the models could be further enhanced with the use of artificial intelligence (AI) tools. In particular, the application of machine learning (ML) algorithms, which could receive data of encountered disruptions and analyze their causes, as well their consequences. In this way, they could allow to characterize stressors and failures, improving the ability to learn from different scenarios and adapt to changing risks. This concept has been explored in the context of resilience assessment by Balan et al. (2025), who highlight the ability of AI tools to address issues that require contemplating multiple interconnected factors. They also emphasize how ML models are able to analyze immense quantities of data and recognize patterns and trends that may not be apparent to human observers, generating insights which can used to assist and improve decision-making.

6. CONCLUSIONS

- A methodology based on the derivation of Bayesian Network (BN) models that can be utilized to quantitively analyze the resilience of the ammonia and methanol transport, storage and bunkering stages of the supply chain for the maritime sector was developed.
- The scope of analysis included the transport of ammonia or methanol from a production site to a storage facility at a port of destination, as well as a ship-to-ship bunkering process to deliver them to final off-taker ships. The system boundaries were limited to the infrastructure and processes present in those supply chain stages.
- The models were based around a definition of resilience that considers it as the ability of a system to sustain a state of high-functionality, or recovering to a state of high-functionality from a state of low-functionality, during and after the occurrence of disruptions that affect its operations.
- The structure of the BNs was defined by considering the state of functionality as a variable dependent on the disruptions to which the system is vulnerable to, as well as its absorption, adaptation and restoration capacities. All of these are Key Performance Indicators (KPIs) that allow to assess the system's resilience.
- The elements of the BNs were derived with the development of bow-tie (BT) models, which consist on the creation of fault and event trees. Disruptions were extracted from the fault trees, while indicators for the absorption and adaptation capacities were derived from the event trees, and indicators for the restoration capacity were based on the identification of possible restoration measures.
- A method for assigning weighting factors to the parent nodes that contribute to the same child nodes was developed based on the Fuzzy Analytical Hierarchy Process (FAHP). This can be utilized as an approach to derive the conditional probabilities required for the application of the model in systems where obtaining this information from historical data is not feasible.
- A series of recommendations for improving the resilience of the target systems based on their resilience attributes were generated. In terms of the potential disruptions, focus should be given to the prevention of events that can have

multiple possible consequences in the systems. Regarding the absorption capacity, adequate and intensive crew training to prevent potentially disruptive situations is recommended, alongside the preventive monitoring of operational parameters with earlier warning signs. For the adaptation capacity, it is essential to guarantee that workers make adequate use of PPE during regular operations and emergency situations, as well as to include, inspect and regularly test all of the response mechanisms described and analyzed as part of this work. Lastly, concerning the restoration capacity, the importance of providing training to personnel on the effects of methanol or ammonia exposure and the ability to incorporate backup components and infrastructure when possible are highlighted.

- Finally, the prospects for future work include to consider possible interdependencies between the supply chain stages; to convert the BN model from static to dynamic by incorporating a temporal dimension, as well as the learning capacity of the system; and lastly, to explore the use of artificial intelligence (AI) and machine learning (ML) tools to enhance the resilience assessment of the systems.

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