Design of an Ammonia Bunker Installation for Sea-going Vessels

A Best Worst Method approach

by

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TU Delft

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Summary

Climate change remains a driving force for industries to adopt measures to reduce emissions. The shipping sector, which contributes about 3% to the CO_2 emissions of the world, is no exception. The use of petroleum products currently makes up 95% of the fuel mixture, which generates large amounts of harmful sulphur oxides, nitrogen oxides, carbon dioxide as well as particulate matter, and their use needs to be reduced drastically. It is projected that the use of ammonia as a shipping fuel can facilitate a path toward a zero-emission future, constituting 50% of the fuel mixture by 2050. However, there exist several challenges that prohibit the implementation of ammonia today. Bunkering is one of these challenges, and little research is done in this area. Challenges around the characteristics of ammonia make implementation in ports not straightforward. Insight into possible port facilities can shed light on the other challenges that remain around ammonia implementation

This thesis proposes a design for a bunker installation for ammonia. Starting with a bottom-up approach to determine system requirements for a bunker system that is suitable to handle the characteristics of ammonia.

When this group of requirements is found, research is done to translate these requirements into functions. Then, suitable solutions for these functions that ultimately adhere to the requirements are found. Industry, literature, and experts are consulted to create a complete picture of available technologies presented in an overview.

The Best Worst Method (BWM), a Multi-Criteria Decision Making (MCDM) method, is chosen above others to create system configurations. For this analysis design criteria are introduced and an ordinal analysis is performed. This provides an objective analysis, which allows room for subjective decision-making based on stakeholders. This method eliminates researcher bias, as well as provides a complete evaluation where all solutions are considered.

Stakeholder input from three terminals situated in The Port of Rotterdam provides the subjective decision-making for the analysis. The resulting configurations show many similarities due to the overall prioritisation of safety, and a sensitivity analysis indicated that the results are robust, although three out of twelve possible areas of sensitivity in the solutions were identified. Finally, after testing if all requirements are respected as well as making sure there are no infeasible combinations of components, viability is confirmed. The results are discussed and the preferred configurations of the stakeholders are unified in a final configuration.

It is concluded that the resulting configuration is applicable to more ports that The Port of Rotterdam due to the expertise of the stakeholders in areas of bunkering and handling ammonia, and the generally observed prioritisation of safety. Due to the fact that stakeholders in the same field in other ports will most likely not differ much in opinion from the surveyed stakeholders. The diversity in the survey input, and the robust results further support this conclusion. Furthermore, a flow rate lower than the current industry standard is found to bunker large ships in an exclusive action. This combined with expected reduced risk contours further support broader applicability.

Several possibilities for future research are proposed. First, it is recommended that further research is done into making the ordinal analysis quantitative to increase the quality of the BWM. Second, an increased amount of stakeholder surveys from The Port of Rotterdam and other ports can provide more insight into what a general configuration looks like, or if it exists. Third, a quantitative risk assessment or other risk analysis of the final configuration can provide more insight into the possible placement possibilities of the system. Fourth, when new technologies emerge or are missed, it can be interesting to see what their performance is in the BWM. Finally, the system can be extended into a more detailed design.

Contents

1

Introduction

Climate change is still a pressing issue in the world. Shipping contributes about 11% to the total CO_2 emissions of the transport sector, which totals around $2-3\%$ of global CO_2 emissions [1]. This contribution can mostly be attributed to the use of polluting fuels currently in use by this sector. Petroleum products such as Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), and Marine Diesel Oil (MDO), currently makeup 95% of the fuel mixture [2] These fuels produce massive amounts of sulphur oxides (SO_x), nitrogen oxides (NO_x), as well as carbon dioxide (CO_2) and particulate matter. According to the climate goals for 2050, these emissions are dangerous and need to be reduced drastically [3].

1.1. Background

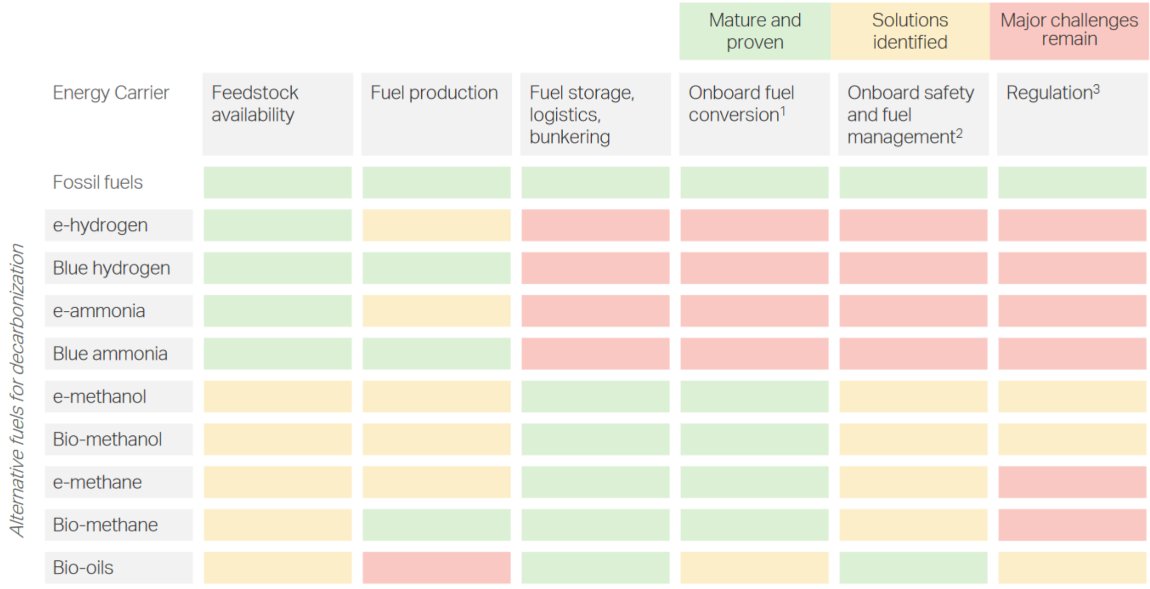
To accomplish this, much research is conducted to determine possible alternative fuels for the shipping industry [4][5][2]. Selecting the best future fuel is difficult, due to the complexity of the complete well-to-wake emission considerations, not fully mature technologies and undefined regulations [2]. DNV-GL (2019) compared eight alternative fuels on factors such as environmental considerations as well as applicability, economics and scalability in order to make this determination more clear [5]. From this study, it becomes apparent that short-term improvements in terms of sustainability are possible, but there currently is no readily implementable solution for a zero-emission shipping fuel, because of the aforementioned factors. Such a short-term improvement is already being implemented, namely the adoption of Liquefied Natural Gas (LNG). LNG as a shipping fuel already has the potential to cut on board SO_x, NO_x and particulate matter emissions by 90%, 80% and 100%, respectively, as well as reducing CO_2 emissions by around 20% [6]. Natural gas, being a fossil fuel, is not going to be a permanent solution. Furthermore, the methane slip associated with burning LNG in combustion engines is larger than expected [7]. Looking forward, there are two main candidates for a future renewable fuel for this industry: hydrogen and ammonia. Both being hydrogen-based energy carriers and thus having the potential of eliminating on board SO_x, CO_2 and particulate matter emissions completely [8][9][10]. In the case of ammonia, NO_x emissions are very manageable through either air-to-fuel mixture regulation or through the use of fuel cells [11][12]. Furthermore, because ammonia and hydrogen can both be produced through electrolysis of water, they offer the only current option for producing fuel solely through renewables such as wind, wave or solar power [2][5].

For the case of deep-sea shipping, ammonia is being put forward as a main candidate for a renewable and sustainable fuel. Hydrogen is considered infeasible for deep sea shipping due to the amount of storage space it needs, and its associated complexity [13]. Ammonia is expected to make up 50% of the fuel mixture for the shipping industry by 2050 [14], thereby contributing to the realization of the climate goals set by the International Maritime Organisation (IMO). Because several challenges remain that prevent this desired implementation of ammonia, more research into using ammonia as a shipping fuel is required.

1.2. Research Gap

Ammonia is not readily implementable as a fuel as of now. There exist significant challenges that prevent its implementation. These challenges are centred around four topics [14]:

1. Fuel storage, logistics and bunkering
2. Onboard fuel conversion
3. Onboard safety and fuel management
4. Regulation



🟩	🟨	🟥
Mature and proven	Solutions identified	Major challenges remain

Alternative fuels for decarbonization

Energy Carrier	Feedstock availability	Fuel production	Fuel storage, logistics, bunkering	Onboard fuel conversion[1]	Onboard safety and fuel management[2]	Regulation[3]
Fossil fuels	🟩	🟩	🟩	🟩	🟩	🟩
e-hydrogen	🟩	🟨	🟥	🟥	🟥	🟥
Blue hydrogen	🟩	🟩	🟥	🟥	🟥	🟥
e-ammonia	🟩	🟨	🟥	🟥	🟥	🟥
Blue ammonia	🟩	🟩	🟥	🟥	🟥	🟥
e-methanol	🟨	🟨	🟩	🟩	🟨	🟨
Bio-methanol	🟨	🟨	🟩	🟩	🟨	🟨
e-methane	🟨	🟨	🟩	🟩	🟨	🟥
Bio-methane	🟨	🟩	🟩	🟩	🟨	🟥
Bio-oils	🟨	🟥	🟩	🟨	🟩	🟨

Source: MMM Center for Zero Carbon Shipping
Note: Emissions reduction impact from direct electrification of ships and nuclear-powered vessels is not modeled in NavigaTE 1.0
1 Considers onboard fuel supply and storage, fuel conversion and emissions control systems
2 Considers fuel toxicity, flammability and explosiveness
3 Includes regulatory framework supporting onboard regulatory aspects, and market mechanisms supporting adoption

Figure 1.1: Readiness of different aspects for the implementation as a new potential shipping fuel, as of April 2022 [14]

Figure 1.1 gives a complete picture of the readiness of implementation of ammonia, as well as other sustainable fuels. The four challenges listed before need to be addressed in order for ammonia to become a viable fuel for the shipping industry. Research into several of these topics is being done. For instance, Percic et al. (2022) performed a Life-Cycle Analysis (LCA) and Life-Cycle Cost (LCCA) Analysis for ships with several conversion technologies and fuels. The implementation of blue ammonia in a Solid Oxide Fuel Cell (SOFC) leads to significant reductions in greenhouse gasses (65% - 72%) at an acceptable cost, which is 37% - 43% higher than that of a diesel power system. [15]. Cheliotis et al. (2021), reviewed the safe use of ammonia in fuel cells in the marine industry. They conclude that it is imperative to develop large-scale production infrastructures for green or blue ammonia. Furthermore, there is a clear need for the identification of the hazards and consequences of ammonia release [16]. Yadav et al. (2022) used Computational Fluid Dynamics (CFD) to look at ammonia dispersion onboard ship engine rooms to evaluate the safety of using ammonia as a marine fuel [17]. Aside from a few parties such as Duong et al. (2023) [18] who performed a safety review regarding ammonia bunkering, there is little research being done into ammonia bunkering. Research into ammonia bunker installations can also provide insight into the other remaining challenges. For instance, to provide a system which can undergo a risk analysis, on which regulatory matters can be based.

It is not straightforward to assume that every seaport can implement an ammonia bunker installation. This is due to the fact that ammonia is a substance that is associated with multiple hazards that make it more challenging to handle than, for instance, HFO. Severe acute over-exposure due to inhaling can lead to death within minutes, when exposed to skin ammonia will react with available water, for instance, sweat, and produce ammonium hydroxide which burns the skin [19]. What further complicates the use of liquid ammonia, are its corrosive nature and its storage conditions. Corrosion can lead to an increased risk of leaks, which will in turn increase the risk of exposure to nearby people and nature. Unlike HFO, ammonia needs to be stored at $-33°C$ or under pressure at $7.5\ bar$ [20]. This liquefaction is necessary to increase its volumetric energy density [21]. Liquefaction through increasing pressure creates an outward pressure gradient. This further increases exposure risk due to pressure equalisation in case of an unexpected release.

1.3. Problem Definition

Thus, it is important to find out what design for a bunker installation for ammonia is viable to be placed in a seaport. To serve as a basis to gauge port readiness, and for risk analysis that can provide input into deciding regulatory matters. This statement is formalised in the following research question and sub-questions:

Research Question:

What design for an ammonia bunker installation is most viable for ports that handle sea-going vessels?

Sub-Questions:

1. What requirements are associated with a bunker installation that is suitable for ammonia?

2. Which system functions and corresponding components can be used for an ammonia bunker installation that complies with the defined requirements?

3. Which model can be used for decision-making with respect to discovered bunker station components?

4. What design criteria can be used to evaluate bunker station components and how do the selected system components perform on the defined design criteria?

5. What design do stakeholders from a suitable port for sea-going vessels such as The Port of Rotterdam prefer, and is this configuration viable?

1.4. Scope

The scope of this research will encompass part of the ammonia bunker supply chain for ammonia-fueled vessels. More precisely: a storage volume which supplies a secondary storage volume with ammonia. This refers to the terminal storage, the pipeline under bunker options, and bunker station in Figure 1.2. This scoping is specifically chosen because it is a prerequisite for providing all four other options with their fuel. However, the intended system edges for this research that is outside of the scope are: the supply options on the left side and the ammonia-fueled ship on the right side of the system represented in Figure 1.2.

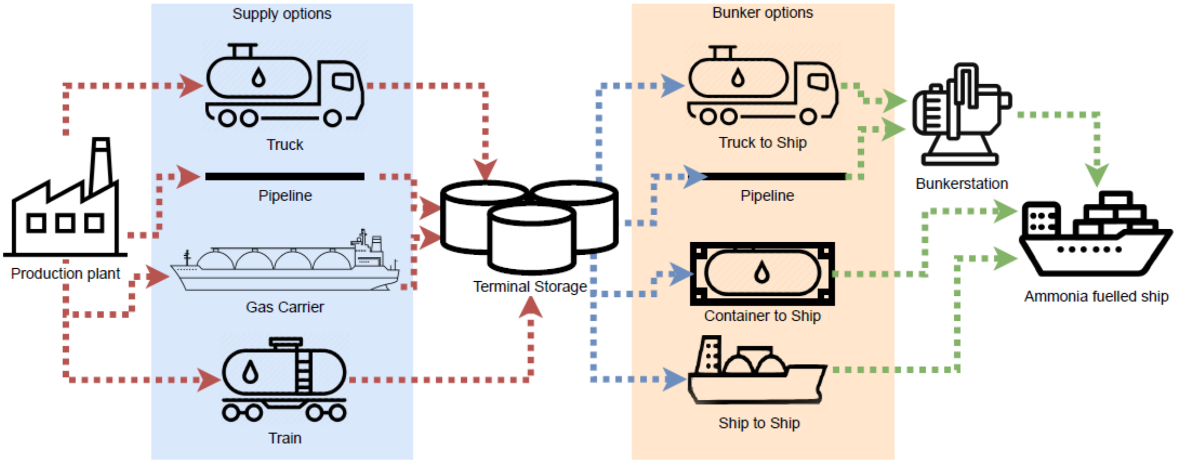


Figure 1.2: An overview of the ammonia supply chain for ammonia fueled vessels [22]

1.5. Research Approach

In order to find the answers to the research question and sub-questions, a classic system engineering process is proposed, specified for a bunker installation for ammonia. Research into other industries that handle ammonia, as well as other bunker installations that handle liquefied gases, will be done. Additionally, experts will be contacted to fill in the gaps. With this information, system requirements, system functions, and solutions adhering to those requirements are proposed. Decision-making to create configurations will be done by use of a Multi-Criteria Decision Making (MCDM) method. For this method, the solutions will be evaluated based on design criteria by means of ordinal analysis. This objective analysis will be combined with subjective expert stakeholder input from the Port of Rotterdam to solve the MCDM problem. Stakeholders are asked to evaluate the relative importance of the design criteria with the goal of allocating weights to the design criteria. The Port of Rotterdam is also where the result will be tested to see if the result adheres to all requirements.

The second chapter is concerned with defining requirements for the system. This is done by analysis of a basic bunker system, in order to find operational requirements. Subsequently, the characteristics of ammonia will be researched, and from these characteristics, ammonia safety requirements will be inferred. Thus, arriving at the total system requirements.

The third chapter will focus on translating the requirements into system functions and finding solutions that fulfil these functions while adhering to the requirements imposed by a bunker system that is suitable for ammonia. This is done through analysis of comparable systems to look for common practice solutions to the base system. Furthermore, literature research and consulting experts will constitute the rest of the information on solutions. Finally, an overview of the discovered solutions for each function is given.

In the fourth chapter, several MCDM methods are introduced and compared. Furthermore, a choice in MCDM method is made. Then, the chosen MCDM will be introduced.

In the fifth chapter, the design criteria that will be used to evaluate the discovered solutions will be introduced. Furthermore, the ordinal analysis that will serve as the objective part of the MCDM method will be performed.

In the sixth chapter, the stakeholders that are providing input for the MCDM method are introduced, followed by the execution of the MCDM method and displaying its results. Subsequently, a sensitivity analysis is performed to gain insight into the results. Lastly, the results are tested on viability, feasibility, and the results are discussed.

Finally, in the seventh chapter, the conclusion of the thesis is presented in the form of an answer to the research question, and recommendations for future research are proposed.

2

Defining Requirements

The goal of this chapter is to answer the first sub-question:

What requirements are associated with a bunker installation that is suitable for ammonia?

In order to find the answer to this sub-question, operational requirements are inferred from a basic bunker system in Section 2.1. Then, several characteristics of ammonia are explored in Section 2.2, and these characteristics are translated into concrete requirements in Section 2.3. Finally, the findings of this chapter and the answer to the sub-question can be found in Section 2.4.

2.1. Operational Requirements

The goal of a bunker installation is to supply a water-going vessel with a substance that can be used as fuel [23]. It can simply be defined as a non-permanent connection between two storage vessels, that allows controlled flow between those vessels. Usually, the flow is only in a single direction. This simplification is graphically represented in Figure 2.1. Additional requirements on, for instance, materials used, safety installations, bunker temperature, viable bunker methods other possible factors depend on what substance is being bunkered. The only bunker method excluded from this representation is Portable Tank Transfer (PTT). This method is considered to be inviable for the volumes of fuel needed for deep sea shipping and is therefore not further considered in this research [21].

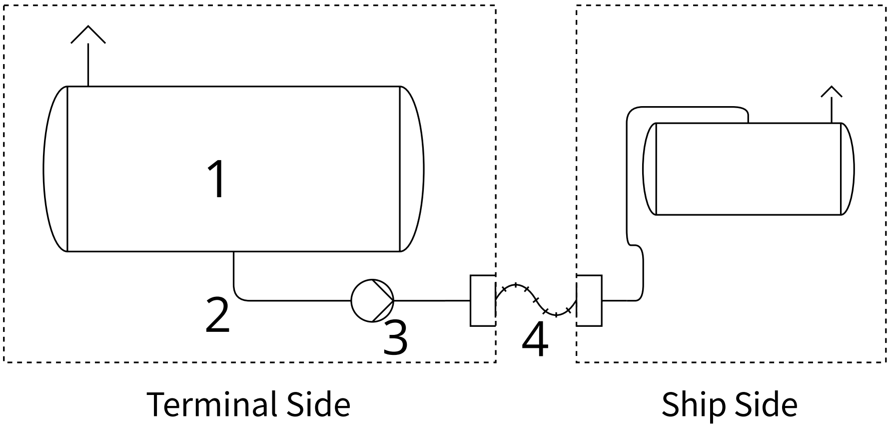


Figure 2.1: Schematic of a simplified, basic bunker installation consisting of a storage vessel on the terminal side, a pump, a non-permanent connection and another storage vessel aboard a ship

This base system gives rise to the following operational requirements:

1. The bunker system is required to be able to store a liquid medium at the terminal side
2. The bunker system is required to have piping in place to form a connection from the terminal to the ship side through which the medium can flow
3. The bunker system is required to have a pump to actuate the medium in a controlled manner from the terminal side storage to the ship side storage
4. The bunker system is required to have a detachable coupling between the terminal and ship side of the installation.

2.2. Characteristics of Ammonia

This section will give an overview of the most important characteristics of liquid ammonia. Information about health hazards, exposure limits and chemical properties will be shown.

Anhydrous ammonia, for use as a fuel, is pure NH_3. It is a colourless gas (or liquid) with a sharp, intensely irritating odour and is lighter than air. The substance has an auto-ignition temperature of $651°C$ [24] and can form explosive mixtures with air between $15 - 28\%$ [25]. The energy density of ammonia is about 50% of LNG, which in turn has about 65% of the energy density of traditional HFO [5][26]. To increase its energy density per storage volume for fuel applications, it is typically stored as a liquid at $-33°C$, though it can also be liquefied at $10 bar$ at room temperature [21]. Gaseous ammonia can expand to 850 times its liquid volume [27]. Furthermore, ammonia will corrode galvanized surfaces and copper and will attack some forms of plastics, rubbers and coatings [25].

Ammonia is classified through the Globally Harmonized System (GHS) for Hazard Communication under the European Union (EU) REGULATION (EC) No 1272/2008 as being [28]:

- H221: Flammable gas [Danger Flammable gases]
- H314: Causes severe skin burns and eye damage [Danger Skin corrosion/irritation]
- H331: Toxic if inhaled [Danger Acute toxicity, inhalation]
- H400: Very toxic to aquatic life [Warning Hazardous to the aquatic environment, acute hazard]

2.2.1. Exposure Limits

Exposure to ammonia, as seen above, is toxic when inhaled and can react with available water on the skin and eyes, causing burns. Table 2.1 classifies the danger associated with ammonia concentrations in the air with corresponding exposure times.

Table 2.1: Acute Exposure Guideline Levels (AEGL) with their corresponding effect descriptions for certain concentrations of ammonia in air along with their corresponding exposure times [25]

		Exposure Time [min]		
AEGL	**Effect**	10	30	60
1	Discomfort, non-disabling	30 ppm	30 ppm	30 ppm
2	Irreversible or other serious, long-lasting effects or impaired ability to escape	220 ppm	220 ppm	160 ppm
3	Life-threatening effects or death	2700 ppm	1600 ppm	1100 ppm

2.2.2. LSIR Contour and Focus Area

Other metrics that can classify the safety critical zones around ammonia during an operation such as bunkering are the Location Specific Individual Risk (LSIR) contour and the focus area. The LSIR contour defines the risk of a single fatality occurring around a hazardous activity, such as bunkering, involving an unprotected individual. Granted that this individual is somewhere outside and around this activity for 24 hours a day, 365 days a year. The fatality occurs because of the harmful effects of an accident scenario within the establishment under consideration [29]. For the LSIR contour, an occurrence of $10^{-6}/year$ is defined. This corresponds to a population density-independent contour where the number represents the likelihood of the aforementioned fatality. The occurrence value is chosen because, per the BEVI standard, within this contour no vulnerable objects (such as dwellings in residential areas, hospitals, schools, large offices etc.) are allowed [30].

The focus area provides insight into the potential hazards in an area and where extra protection might be necessary. The focus area itself defines the radius of an area around activities such as bunkering where, indoors, people are insufficiently protected against the consequences of accidents involving hazardous substances. The competent authority further defines where and what kind of measures are necessary to sufficiently protect people in focus areas [29].

For ammonia, the $10^{-6}/year$ LSIR contour and the focus area for a toxic cloud are defined in Table 2.2:

Table 2.2: Focus area and $10^{-6}/year$ LSIR contour radii around an ammonia bunker operation [29]

	Focus Area toxic cloud [m]	**LSIR Contour $10^{-6} year$ [m]**
Ammonia Bunker Operation	2624	427

2.3. Requirements to Handle Ammonia

In this section, the characteristics of ammonia determined in the previous section will be associated with concrete requirements. Therefore a short overview of the characteristics that need to be addressed will be given:

1. Toxicity
2. Corrosiveness
3. Explosiveness
4. Relatively lower energy density

These characteristics are determined to be the defining traits of ammonia for bunkering applications. These characteristics will impose extra functions and requirements to the basic system as described in Section 2.1.

2.3.1. Toxicity

As could be seen in Table 2.1, exposure to high enough concentrations of ammonia, can lead to death within minutes. Therefore, it is required to make sure that the risk of exposure to people and the environment is mitigated in the design of the bunker installation.

There are multiple concerns when dealing with a toxic substance. There is the risk of uncontrolled release of ammonia into the atmosphere during bunkering or passive storage that could endanger workers, bystanders and nature around the bunker installation. Therefore, the subsequent toxic cloud, as well as the liquid ammonia spill need to be contained. Furthermore, there is the risk of leakages from left-over ammonia in fuel lines that could pose an exposure risk. Therefore it is required to purge the fuel lines before they are disconnected.

The risk associated with an uncontrolled release could potentially affect the viability of bunker locations. Furthermore, the risk of an uncontrolled release while sailing could prove to be decisive in determining what ships will be ammonia powered and where they will sail. This will also impact the design of the bunker installation because ships for inland shipping and ships for deep-sea shipping often favour different aspects in a bunker installation. For instance, preferred access locations for inland and seagoing ships are different and since the tank sizes of inland ships are generally smaller, different bunker methods might be more efficient. Therefore, the first design requirements will be the determination of the upper size limit of ships that can use the bunker installation as well as requirements on the construction location of the bunker installation.

Target Ships
The toxicity of ammonia will play a role in determining the viability of the ships it can be used for. This is due to the possibility of an uncontrolled release. Whether this is due to accidents, ammonia slip in the combustion system or other challenges surrounding toxicity and the related risk, ammonia release in residential or populated areas is undesirable. This is also concluded by the European Maritime Safety Agency (EMSA) (2022) who, in their 2022 study on the potential of ammonia as a fuel, came to the same conclusion [31]. Furthermore, a fuel such as hydrogen finds its niche application as a zero-emission fuel in inland shipping and short ferry rides due to the trade-offs between its storage volume and cost being more favourable for this application [32]. This shows that the characteristics of a fuel influence the application in which it is used. In this case, it is clear that fuels such as hydrogen might be better suitable for inland and shorter-range shipping applications and ammonia is more suitable for deep-sea applications.

With the application of ammonia clear, the next step will be defining the ship class(es) that will most likely use ammonia as a fuel in the future.

Ships are mainly classified in the following categories [33]:

1. Container Ships
2. Bulk Carriers
3. Tanker Ships
4. Roll-on Roll-off (Ro-Ro) Ships
5. Passenger Ships
6. Naval Ships
7. Offshore Ships
8. Special Purpose Ships

Looking at the list of ships presented above, the ships that either operate around populated areas, contain people as part of their cargo or operate at short-sea distances would be removed from the list of target ships. This is because of the aforementioned risks of using ammonia, and it is therefore assumed that these classes are the first to adopt ammonia as a fuel. This would mean that the list reduces to the first four ship types; Container, Bulk, Tanker and Ro-Ro, in other words, cargo vessels. Between these ship classes, container ships contain the largest ships currently in service [34]. Therefore, this ship class will be used to put an approximate upper limit on the tank size that is required to be serviced.

The largest container ship currently in service is the MSC Irina, with a capacity of $24,346 TEU$ and Dead Weight Tonnage (DWT) of around $240,739$ [35]. This ship will be used as a reference to derive upper limit figures for the design of the bunker installation. In other words, it is required for the bunker installation to be able to bunker ships of this size.

Location
The second design requirement that the toxicity of ammonia will impose is the location where bunker operations can take place. This topic is difficult to precisely determine due to the existing regulatory gaps [14][31], but some base assumptions can be made.

Firstly, due to the 99% lethality footprint of $2,543 m^2$ of a simulated unintended ammonia release as described by Ming et. al [36], it can be assumed that simultaneous operations (SimOps) cannot take place. SimOps refers to the simultaneous unloading of cargo and bunkering. This method of Ship to Ship (STS) bunkering is preferred for the more mature procedure of bunkering LNG in the Port of Rotterdam, as an interview with M. Neef, the account manager LNG at the Port of Rotterdam, pointed out [37]. This is because of the possibility to fill the bunker barges at locations close to the source of the LNG storage in the Gate Terminal, and the flexibility of said barges to sail to where the target ship is offloading its cargo. The lethality footprint along with the toxic cloud focus area and LSIR contour of ammonia as described in 2.2, prohibits this solution and further significantly constrains where a bunker operation can be performed.

The location of a bunker installation is also influenced by the ships it will bunker. The size of the aforementioned ship, the MSC Irina, also defines requirements on the depth and size of the access canals to the bunker installation. For instance, it can be impossible, or highly impractical, for large ships to enter narrow canals to reach a bunker installation. In such a case, bunker barges, or a different location would be necessary.

2.3.2. Corrosiveness

Ammonia is a corrosive substance. This means that not all materials are viable to be in contact with ammonia. This will impose further design requirements by excluding certain materials from being used. Galvanised metals and copper are unable to be used, as described in Section 2.2. Furthermore, since ammonia will attack and dissolve some plastics, rubbers and coating, it is required to make sure that parts such as couplings and pumps, for example, do not contain these materials.

Since actuated flow by use of a pump will be utilized to move the ammonia through the system, there will be increased pressure throughout the system. The storage tank will also be subjected to outward pressure due to the presence of liquid ammonia. In an ammonia environment, materials under residual or applied stress are susceptible to ammonia Stress Corrosion Cracking (SCC) and characterized by sub-critical crack propagation due to the combined simultaneous interaction of mechanical stress and environmental exposure [38] [39].

The corrosion behaviour of materials differs due to the presence of water or other contaminants around anhydrous ammonia. For example, in the case of liquid ammonia stored in ASTM A517 Grade F Steel, which is steel that is designed for pressure vessel applications [40], the presence of air or water can cause ammonia SSC to occur or be inhibited, respectively [41]. Though the goal should be to only have anhydrous ammonia in the system, due to the possibility of the presence of impurities or air/water contamination, it is required to take this behaviour into account when selecting material for the system.

2.3.3. Explosiveness

It was introduced in Section 2.2 that ammonia can form explosive mixtures between $15-28\%$. Leaks in enclosed spaces or remnants of ammonia in fuel lines can therefore be at risk of forming this explosive mixture. Therefore it is required to make sure this mixture never forms. Moments when this could occur are when the coupling between the supply tank and the tank of the target vessel is disconnected. As mentioned in Section 2.3.1, leftover ammonia in the fuel lines will not only pose a toxic risk, but this will also allow ammonia to mix with air and possibly form an explosive mixture. Therefore, this also supports the requirement to purge the fuel lines before they are disconnected.

Ammonia itself is lighter than air and will rise when it is released into the air, as became clear from Section 2.2. However, it can form vapours that are heavier than air when the air is moist. Furthermore, vapours from a leak will initially hug the ground [42][43]. In these situations, it is possible for the conditions to become favourable for an explosive mixture to form. Therefore, it is required to be able to detect or mitigate released ammonia with a safety system that will ensure no explosive mixture can form in the surrounding atmosphere.

2.3.4. Energy Density

Liquid ammonia has about half of the energy density of typical hydrocarbon fuels but higher than most metal hydrides [44]. Previous research showed that the energy density of HFO is almost 3.5 times higher than that of ammonia [21]. This means that almost 3.5 times more volume of ammonia needs to be bunkered to match the amount of available onboard energy when bunkering HFO. As Subsection 2.3.1 explained, it is most likely impossible for SimOps to take place during bunkering, due to the toxicity of ammonia. Atop the required liquefaction, it will probably be required to raise flow rates for the bunker installation in order to not disturb the supply chain as it is now.

Liquefaction

As mentioned in Section 2.2, ammonia needs to be liquefied for fuel applications to increase its energy density. However, there exist three methods to accomplish this. One of the options is liquefaction by increasing pressure to about 10 bar, the second option is lowering the temperature below the freezing point of ammonia, at $-33°C$. The third option would be a combination of these two methods. This trade-off can be visualised by looking at the phase diagram of ammonia, which can be found in Figure 2.2.

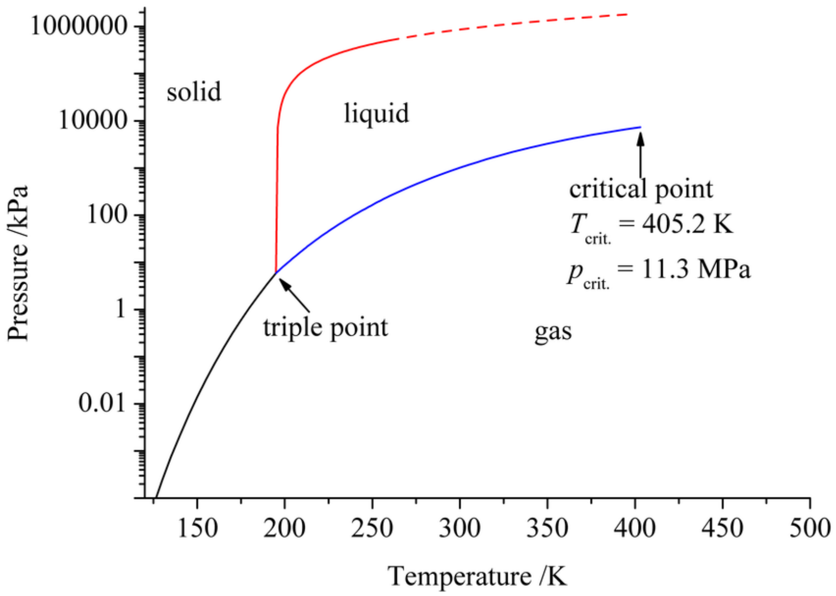


Figure 2.2: The phase diagram of ammonia, the dashed lines are extrapolated [45]

A study done by Ekinci et al. (2022) found that at higher storage temperatures, the size of the threat zone in case of an unintended release of ammonia will increase [46]. Moreover, ammonia stored under higher pressure inadvertently will lead to a high flow rate at the point of failure, because of the larger pressure difference. Because of the toxic nature of ammonia, it is in the interest of safety to make sure the amount of released gas is minimized in case of a release. Furthermore, the energy density of ammonia, liquefied through cooling, is slightly more energy dense than ammonia which has been liquefied through pressure. At $15.37\ MJ/L$ and $13.77\ MJ/L$, respectively [47]. These three arguments point to storing ammonia in its liquid form through lowering the temperature, under atmospheric pressure. This means that ammonia is required to be stored and handled in its liquid form at $-33°C$ for this design.

Boil-off Gas

Keeping ammonia in its liquid state by cooling brings forth other complications. The liquid ammonia in the system will start to behave as a boiling liquid due to the influx of heat into the system. This heat influx will cause the ammonia to boil and create Boil-off Gas (BOG). Heat will flow into a system from all places that have more energy, but six main points for heat influx can be identified [48]:

1. Depressurization of the boiling liquid (flashing)
2. Heat added by equipment like pumps
3. Tank breathing or vapor displacement
4. Environmental heat leaks through containers and pipelines

5. Carrying vessels being relatively hot while loading
6. uninsulated pipes

Heat influx into the system, and subsequent BOG generation, can significantly influence the loading rate of a jetty or bunker installation. As demonstrated by a study done on BOG by Kurle et. al, in the case of LNG bunkering [48]. The study showed that on average loading times of LNG range from 17 to 30 hours, depending on the individual case. If the receiving ship is hotter than $30°C$, loading rates can increase by 8 hours due to BOG generation and the increase in required pressure management. This effect will be of a lesser degree when considering ammonia, due to the significantly lesser storage temperature compared to LNG ($-162°C$ v.s.$-33°C$), but it is not negligible.

Ammonia will increase in volume by a factor of 850 when it transitions from liquid to gas, as could be seen in Section 2.2. Because of this, the pressure in the system will increase when BOG is generated [48][49]. This increase in pressure can result in leaks and failures at several points in the system. It is therefore required to manage the pressure-increasing effect of BOG during a bunker operation. Additionally, temperature management needs to be done when the system is not performing a bunker operation because heat influx can still pose a problem here. The storage tanks of a bunker installation are at risk of a Boiling Liquid Expanding Vapour Explosion (BLEVE) [50]. This occurs when the temperature inside a storage vessel exceeds the boiling point of the substance stored inside. Especially with a substance like ammonia, which is corrosive, the storage vessels might be more prone to generating weak points. Therefore, insulating the system is required.

Flow Rate

Because of the lower energy density of ammonia, and the fact that SimOps will most likely be impossible, it can be assumed that flow rate requirements will be higher than those of comparable bunker installations if the goal is to not disturb the current supply chain.

Increasing flow rates cannot be done indefinitely. There exists an upper limit, above which, the risk of fracturing piping or blowing off caps can occur [51]. This upper limit is defined as critical or chocked flow [52]. This is best explained by observing Figure 2.3

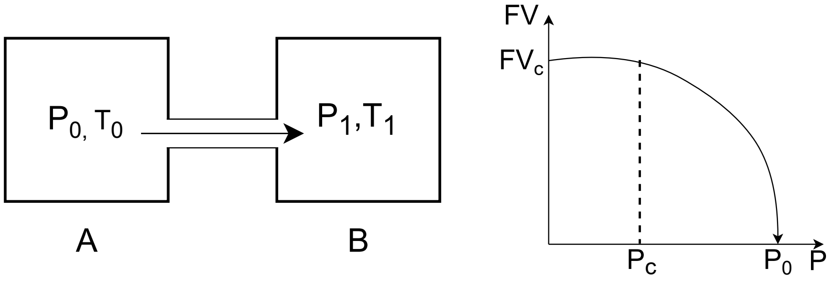


Figure 2.3: Flow between two arbitrarily large reservoirs A and B (left) and the Flow velocity as a function of pressure (right). Where P_c is the critical pressure, FV_c is the critical flow velocity and T is temperature

When P_1 is reduced relative to P_0, the flow will be promoted through the connection of arbitrary geometry between the two reservoirs. This pressure drop and subsequent flow can increase up until the point that the flow velocity at some point achieves the local sonic velocity. For liquid ammonia, this is at $1,729m/s$ at $-33\deg C$ [53]. At this location, a choked plane forms and this plane inhibits the influence of further pressure reductions downstream from having an effect. This is due to the rarefaction waves that travel at the local speed of sound that are stalled at this choke plane.

To maximize the flow rate, either the diameter of the piping can be enlarged, or the flow velocity can be increased. However, it is required that the flow velocity of the liquid ammonia in the piping of the system never exceeds $1,729m/s$.

2.4. Conclusions

The goal of this chapter was to perform a functional decomposition of a bunker system and create a set of requirements that the intended use of liquid ammonia would impose on this system. This section will give an overview of said functions and requirements.

Operational Requirements

1. The bunker system is required to be able to store a liquid medium at the terminal side.
2. The bunker system is required to have piping in place to form a connection from the terminal to the ship side through which the medium can flow.
3. The bunker system is required to have a pump to actuate the medium in a controlled manner from the terminal side storage to the ship side storage.
4. The bunker system is required to have a detachable coupling between the terminal and the ship side of the installation.

Ammonia Safety Requirements

An overview of the reasoning behind the determined requirements can be found in Figure 2.4.

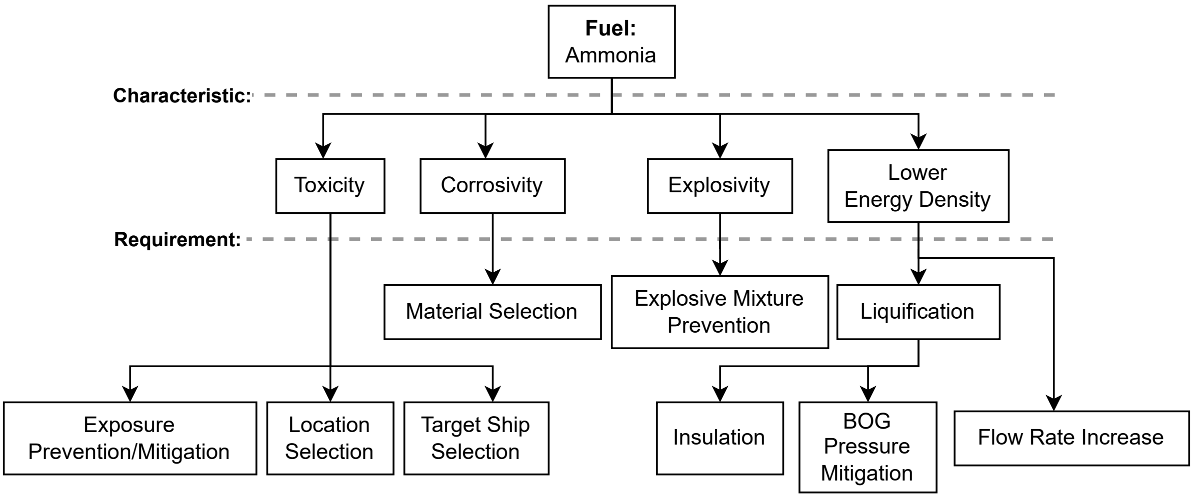


Figure 2.4: Derivation of design requirements for the intended use of ammonia in the bunker installation

Finally, a descriptive overview of the design requirements that are imposed on the base system is given below:

1. It is required to have exposure prevention and mitigation systems in place with the goal of mitigating the toxic hazard associated with ammonia, in case of an unintended release.
2. It is required to have a location that is suitable such that, in case of an unintended release, there are acceptable risks of exposure to surrounding structures, people and other vulnerable objects.
3. It is required that the design be able to bunker the largest vessels in service. The largest vessel currently in service, the MSC Irina, has a Dead Weight Tonnage (DWT) of around $240,739$.
4. It is required that the materials used in the design are able to withstand the corrosivity of ammonia.
5. It is required that there be systems and protocols in place that have the absolute goal of preventing an explosive mixture from forming.
6. It is required to have systems and protocols in place that have the absolute goal of preventing ammonia leakage into the atmosphere.

7. It is required that the design be able to minimize the heat influx at all storage and transfer media in order to keep ammonia in its liquid form.
8. It is required that BOG and its consequent pressure-increasing effect is handled in the design.
9. It is required that the flow velocity in the piping never exceeds the sonic velocity in liquid ammonia at $1,729 m/s$.

3

Functions and Alternatives

The goal of this chapter will be to translate the requirements as they are stated in Chapter 2 to functions, and to find solutions for those functions. This is done to answer the second sub-question:

Which system functions and corresponding components can be used for an ammonia bunker installation that complies with the defined requirements?

To achieve this, the following steps are executed. First, a state-of-the-art analysis is performed in Section 3.1. Then, all operational and ammonia safety requirements are translated into functions, followed by research to find solutions that adhere to the imposed requirements in Sections 3.2 and 3.3. The solutions for each function are presented in an overview in Section 3.4.

3.1. State of the Art Analysis

Analysing the current state of the art for a comparable, mature technology can give insight into common practice solutions and procedures. The DNV made a step-by-step bunker plan for a base LNG system [54]. This plan contains details about the operational procedure and placement of certain important components for a bunker system that has a boiling liquid as a medium. This system can be found in Figure 3.1.

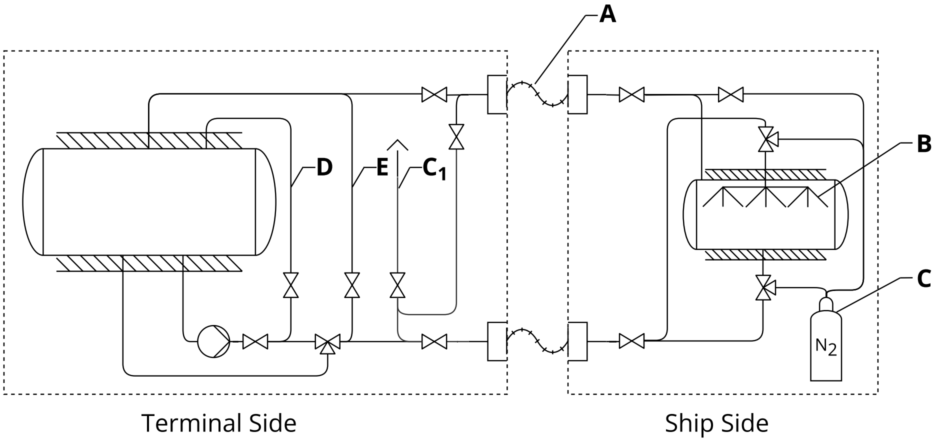


Figure 3.1: An extended functional system based on an LNG bunker system [54]. Including indicators of new components.

The base LNG system is a good candidate for adaption towards a system that is suitable for ammonia. This is because the methane that makes up LNG is preferably not released into the atmosphere due to its explosivity and being a potent greenhouse gas, even though it is still common practice to vent trace amounts of LNG to the atmosphere after the inerting sequence [55][5]. Furthermore, its cryogenic nature shares similarities in procedure with ammonia because LNG is also bunkered as a boiling liquid at subzero temperatures. This introduces the need for certain required components and protocols. Such as a purging sequence to prevent substance slip into the atmosphere and pre-cooling of both the fuel lines and pump to minimize BOG. In addition, a vapour return line to mitigate the pressure-increasing effect of BOG is commonly implemented for LNG. Even though the difference in density between the liquid state and ambient temperature state of ammonia is larger than for LNG, the temperature difference is much greater for LNG, as can be seen in Equations (3.1) and (3.2) [20]. This means that the boil-off rate of ammonia is less than LNG, due to a lesser temperature difference [56], but the potential pressure increment is higher in the case of ammonia. Therefore, BOG mitigation protocols and equipment are useful when bunkering ammonia as well.

$$\rho^{Ammonia}_{-33^\circ C} - \rho^{Ammonia}_{20^\circ C} = 696 kg/m^3 - 0.796 kg/m^3 = 695,204 kg/m^3 \tag{3.1}$$

$$\rho^{LNG}_{-162^\circ C} - \rho^{Ammonia}_{20^\circ C} = 422.6 kg/m^3 - 0.717 kg/m^3 = 421,883 kg/m^3 \tag{3.2}$$

At location A in figure 3.1 the vapour return line can be found. The vapour return line has been found to be very important in regulating pressure in the system when bunkering LNG [57]. Due to ammonia also being treated as a boiling liquid, a vapour return line is going to be important as well, in order to control the pressure-increasing effect of BOG during bunkering.

At location B in figure 3.1 the ship-side spray nozzles can be found. Spray nozzles make counteracting stratification possible. Thermal stratification is the separation of the bunker fuel layers as a result of different densities due to a non-uniform temperature profile in the receiving tank [58]. Ammonia is also susceptible to this effect due to the non-ambient temperature at which it is bunkered. When the separated layers rollover due to ship motion, the lower density that was on the bottom of the tank, rises to the top and starts to boil off quickly, leading to a sudden increase of pressure. This can have adverse effects. This stratification can be counteracted by mixing the bunker fuel in the receiving tank during bunkering by alternating top and bottom filling. This alternating filling sequence can be viewed in Figure 3.2.

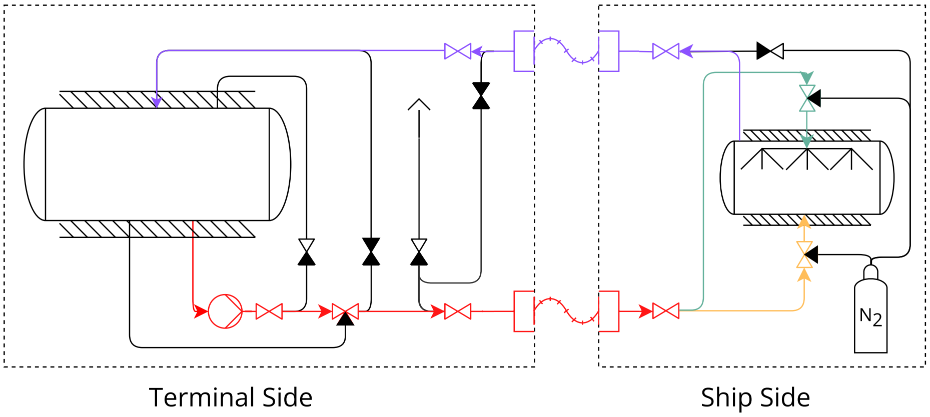


Figure 3.2: Filling Sequence. With the top filling flow consisting of the red and green lines, the bottom filling flow is represented by the red and yellow lines. Finally, the vapour return flow is represented with the purple line.

At location C in figure 3.1 the purging system can be found. Purging the fuel lines is imperative to prevent explosive mixtures from forming and from leaking residual ammonia into the atmosphere when disconnecting the fuel and vapour return lines after bunkering. Purging is commonly done with nitrogen gas due to its availability and inert nature [54]. In LNG systems, purging is completed by venting the residual methane and nitrogen mixture through the vent at location C_1. This is not possible for ammonia purposes because this would violate the exposure prevention requirement. The purging sequence can be seen in Figure 3.3.

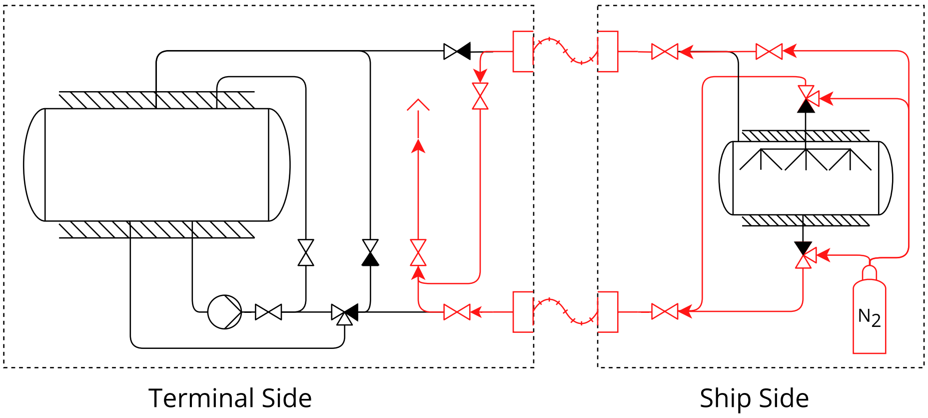


Figure 3.3: Inerting sequence

In order to minimize BOG when bunkering starts, the pump and fuel lines are pre-cooled. The loop at location D in figure 3.1 shows the pre-cooling loop for cooling the pump. This is done by circulating the cold fuel from the terminal tank through the pump and back into the terminal side tank as shown in Figure 3.4. This sequence is similar in function to the fuel line pre-cooling loop that can be found at location E in Figure 3.1. The flow of fuel through this loop can be seen in Figure 3.5.

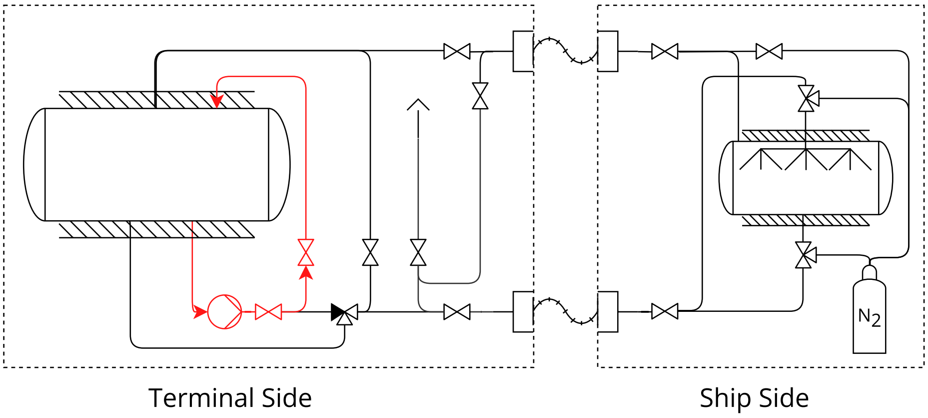


Figure 3.4: Pump cooling sequence

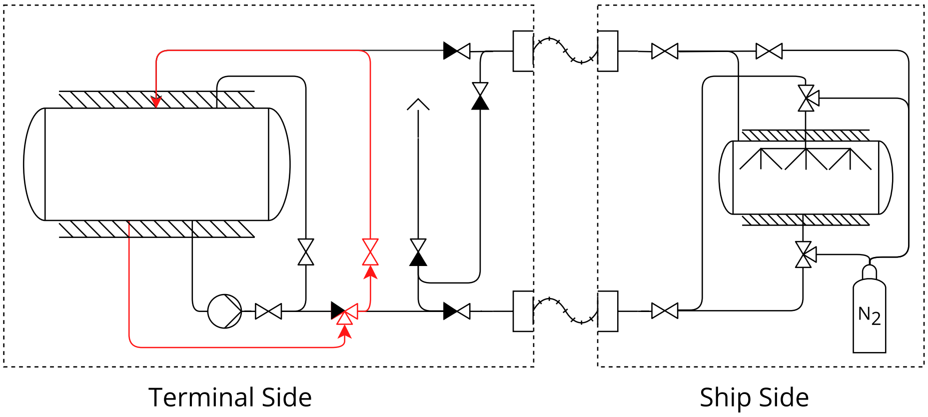


Figure 3.5: Fuel line cooling sequence

3.2. Operational Functions

The operational requirements for the system as stated in Section 2.4 make the system technically operational. These requirements are translated into the following operational functions:

1. Storing
2. Conducting
3. Actuating
4. Connecting

There exist multiple possible solutions to adhere to these functions, these possibilities will be explored in this section.

3.2.1. Storing

The first operational function of the ammonia bunker system is the ability to store liquid ammonia. This concerns the storage on the terminal side of the installation. Since the liquid ammonia is kept under atmospheric conditions ($< 0.5 barg$), it falls in the operating pressure of insulated flat bottom tanks [59]. Bullet or spherical thanks can also be used to store liquid ammonia. These storage tanks are rated for higher pressures but generally for smaller storage volumes than the flat bottom tanks can accommodate. Because of the atmospheric pressure of liquid ammonia and the higher manufacturing cost of spherical tanks [60], bullet tanks are the preferred non-flat bottom storage tanks for storing liquid ammonia.

There are three categories relevant for ammonia storage tanks: single containment, double containment and full containment [61]. The difference between these storage tanks is the ability to handle failures of the tank. Bullet and spherical tanks do not have the same definition by codes and the containment philosophies cannot be directly copied from atmospheric storage [59]. Therefore, basic containment safety requirements will be copied to the spherical and bullet tanks for comparison purposes.

For ammonia applications, the inner and outer steel tanks should be all-welded construction and fabricated from normalized carbon-manganese steel as per standard [62]. All of the flat-bottom tanks should be constructed on concrete pillars or a heating system in the foundation to prevent frost lens and possible ground heaving [61].

Single containment

Single containment offers no further containment after the primary and in this case, only, tank fails. This category of storage tank is the easiest to produce and the least costly, but there is a requirement to add some form of bund (earth dyke or concrete walls) around the perimeter of the tank to contain liquid leakages. This increases the footprint of the storage tank depending on the height of the bund. An example of a flat bottom single containment tank can be found in Figure 3.7. A single containment spherical tank, for instance, follows the same conceptual design. Where there is no secondary containment of liquid or gas in place after the primary containment fails. An example of a single containment spherical tank can be found in figure 3.6.

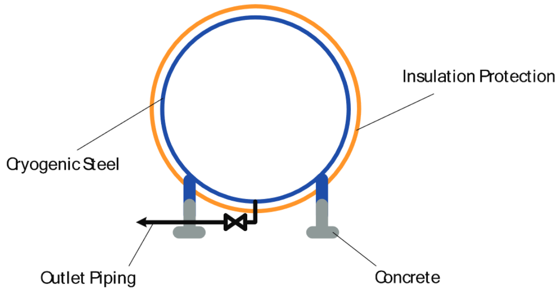


Figure 3.6: A schematic of a single containment ammonia storage spherical tank design [59]

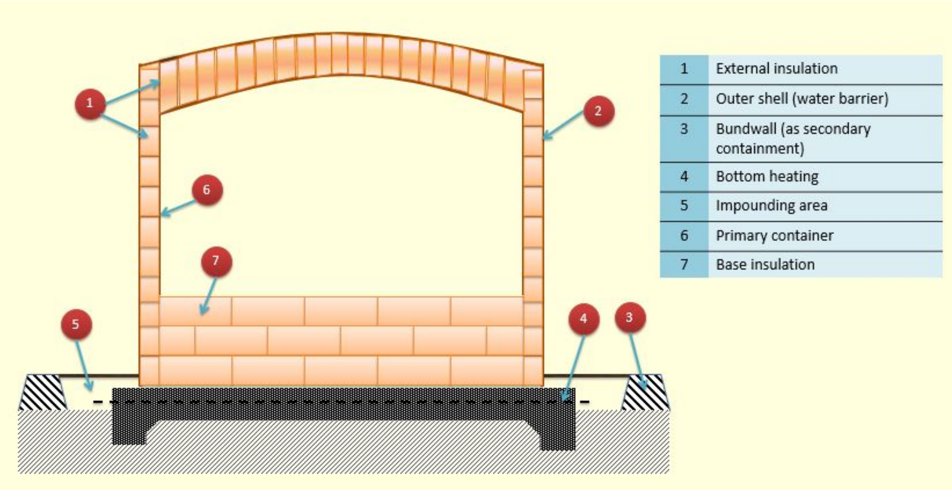


Figure 3.7: A schematic of a single containment ammonia storage flat bottom design

Double containment

Double containment offers a secondary outer containment layer that is capable of independently containing the refrigerated liquid. The secondary container is intended to contain any leakage of the refrigerated liquid from the primary tank, but not the vapour resulting from this leak. In principle, this is a concrete bund directly outside the storage tank that is high enough to contain the entirety of the liquid volume of the primary tank. This category increases cost but because the bund is incorporated in the design and directly outside the tank, the footprint is reduced compared to the single containment tank with a bund dyke. An example of a double containment flat bottom tank can be found in Figure 3.9. The equivalent bullet tank design can be seen in Figure 3.8.

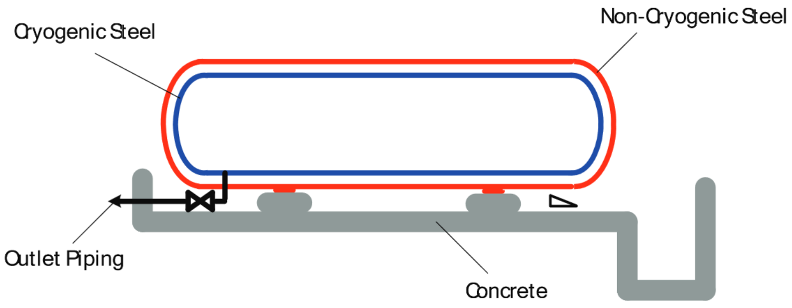


Figure 3.8: A schematic of a double containment ammonia storage bullet tank design [59]

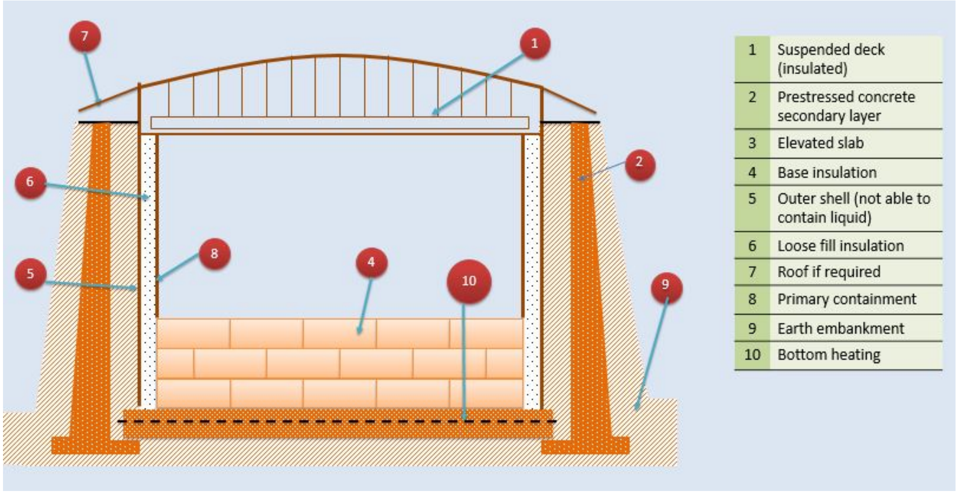


Figure 3.9: A schematic of a double containment ammonia storage flat bottom design

Full containment

Full containment is designed similarly to the double containment vessel, with the exception being that it can also vent the vapour that results from a liquid leakage after a credible event in a controlled manner. In other words, the entire second containment layer is enclosed and insulated such that operations can continue if the primary tank fails [61]. Cost with these tanks are higher but failure rates are about one-hundredth of the rate of single containment tanks [61]. An example of a full containment flat bottom tank can be found in Figure 3.11. The bullet tank design equivalent can be found in Figure 3.10.

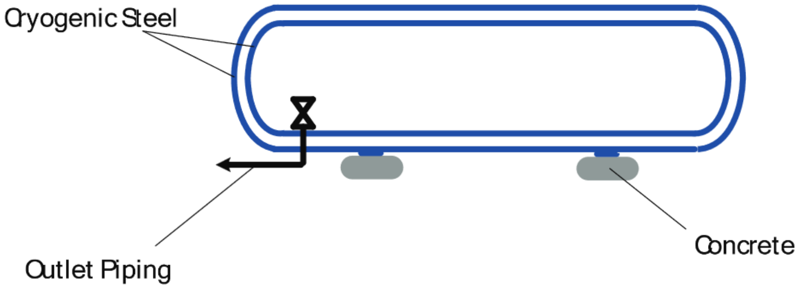


Figure 3.10: A schematic of a full containment ammonia storage bullet tank design [59]

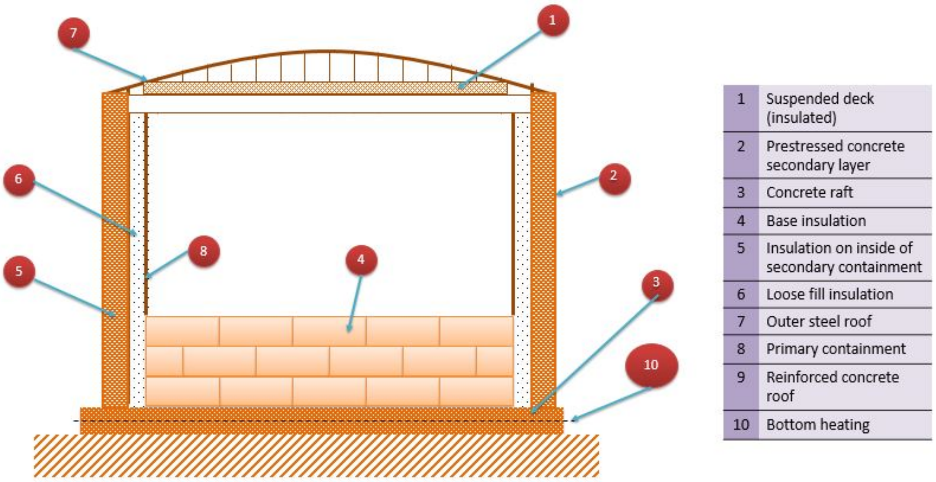


Figure 3.11: A schematic of a full containment ammonia storage flat bottom design

Considerations
There are many different sizes of storage tanks available. The biggest ones currently in service offer are LNG flat bottom tanks and offer available full containment storage of $200,000m^3$, with a base diameter of $91m$. This tank is situated in Korea [63]. Another example is the $270,000m^3$ flat bottom tank with an estimated $98m$ diameter footprint (based on available dimensions from the Korean storage tank). Repurposing these tanks would allow for larger ammonia storage to be possible than what is currently available since the largest ammonia storage tanks hold about $50,000tonnes$ or about $73,250m^3$ with a tank base diameter of about $40m$ [61][64]. The largest bullet tanks offer storage volumes of $14,000m^3$ and have a length of about $74m$ [65]. Spherical designs are difficult and more costly to manufacture but can handle more pressure, therefore bullet tanks are preferred if the operational pressure allows for their use [61].

3.2.2. Conducting

The second operational function of the ammonia bunker system is conducting the medium from the terminal storage tank to the bunker connection hose. It is important that there is as little heat loss as possible here and that the flow produced by the actuator in the system can be handled.

Possible solutions for pipes are centred around flexible or rigid piping or a floating flexible pipe. Rigid piping is preferred for on-land applications due to the restricted movement of the pipes, but a flexible floating pipe could make a floating terminal much more practical.

3.2.3. Actuating

The third operational function of the ammonia bunker system is the ability to actuate the liquid ammonia through the system. This is done by the use of a pump. There are several pumps commercially available that can handle the characteristics of ammonia, though few can provide the kind of flow rate that is desirable. Currently, the Gate terminal has a jetty that they use to provide LNG bunker barges with fuel. These barges are in turn used to bunker the largest container vessels such as the MSC Irina [37]. The jetty is able to bunker LNG at a flow rate of $1000m^3/h$ [66].

The classes of pumps that are suitable for pumping liquid ammonia at a flow rate close to current, comparable, LNG systems are mag-drive pumps, canned motor pumps, and double mechanically sealed pumps because of their hermetically sealed nature. These pumps can be submersible or non-submersible. Submersible pumps offer the advantage of not having to be primed because they remain submerged in the medium that is to be pumped. This comes at the cost of being more difficult to service the pump because of the required scaffolding, disconnecting, removing insulation etc. when having to get into the storage vessel [67].

The configuration of the three types of pumps can be seen in Figure 3.12. These pumps also come in their non-submerged configuration. To illustrate a dry installed configuration, Figure 3.13 can be observed showing a dry installed canned motor pump.

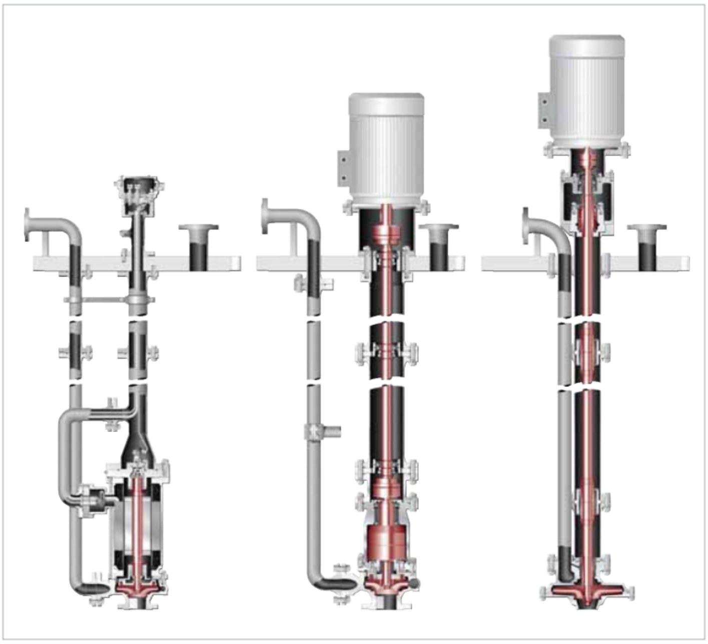


Figure 3.12: Pumps in their vertical submersible configuration. From left to right: Canned motor pump, Mag-drive pump, double mechanically sealed pump (left) [68]. Dry canned motor pump schematic (right) [69]

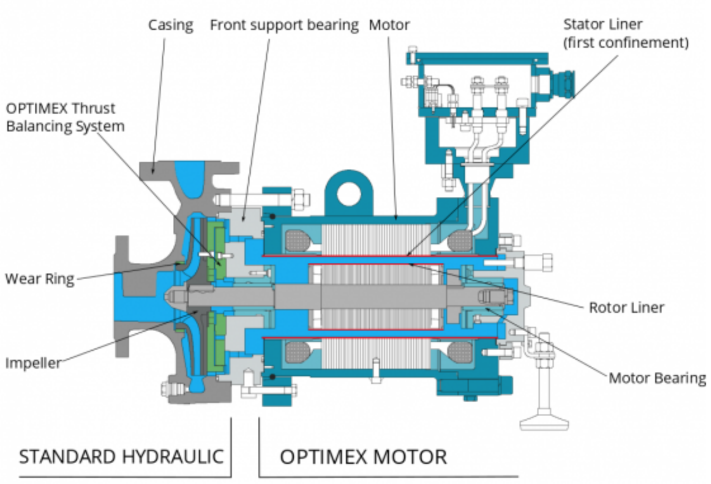


Figure 3.13: Canned motor pump schematic, non-submerged version [69]

Considerations

Between the two classes, submersible pumps are generally more expensive due to the necessity to make the full system watertight and the larger constructions required for lowering them into storage tanks. Canned motor pumps offer double containment, as opposed to mag-drive pumps which only have a single containment layer [70]. An advantage of the double mechanically sealed and mag-drive pumps is that their duty point can be altered by modifying the motor specifications, this is not possible for canned motor pumps [70][68]. When selecting pumps for this application, service life and cost of repairs are arguably more important than the initial cost. Double mechanically sealed pumps are initially less expensive than the mag drive and canned counterparts [71], but from canned motor designs to mag-drive, to mechanically sealed, the service life goes down respectively [67]. This can be seen in Figure

3.14. Although repairing a canned motor pump requires specialty care and the part often needs to be sent back to the manufacturer, mag-drive pumps can usually be repaired on-site [72]. Furthermore, because of the inaccessibility of the canned motor pump, additional downtime is possible.

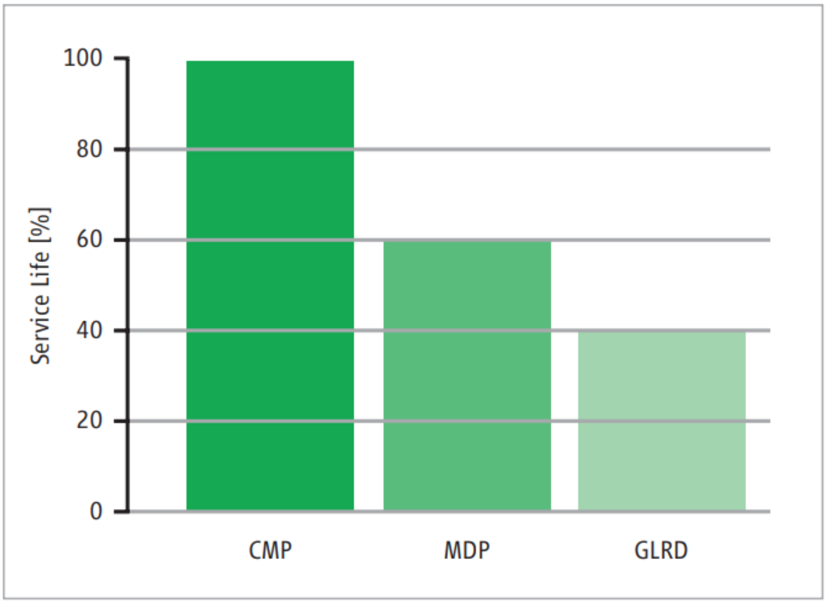


Figure 3.14: Service life of the three considered pump types. CMP: Canned Motor Pump, MDP: Magnetic Drive Pump, GLRD: Double Mechanical Seal Pump [68]

3.2.4. Connecting

The fourth operational function of the ammonia bunker system is establishing a connection between the terminal side to the ship side of the system. This part of the installation is a critical safety system because of the impermanent connection is prone to human error and wear. Furthermore, the possible relative motion between the terminal and the ship can create extra complications during a bunker operation.

The connection between the terminal and the ship consists of two components: the bunker hose and the coupling. These two parts will be discussed separately.

Bunker Hose

The bunker hose to connect the terminal to the ship side of the system plays a significant role in the determination of the bunker procedure. It is common practice to have a flexible bunker hose as a connection between the terminal and the ship side of the system. This is because the flexible hose can absorb some of the relative motion between the ship and the terminal. Furthermore, it is important that the hose is insulated to minimize heat influx. There are two options for such a flexible bunker hose, floating or suspended. Between the floating and the suspended design options, it is important to note that air is a much better insulator than water. This is an important consideration when deciding if a floating or hanging design is preferable.

Coupling

Coupling refers to connecting the bunker hose to the bunker manifold of the receiving ship. When releasing the coupling, it is imperative that there is no residual fuel in the coupling, because workers can be present close to the coupling. In the case of ammonia, that spillage could pose a serious risk. The three main systems that are employed in industry that offer a coupling that prevents residual fuel leak are: the dry disconnect coupling, the break-away coupling and the powered emergency release coupling [73].

The dry disconnect coupling features an internal system that blocks the flow of gas when a worker disconnects the coupling manually. This means that there is no open connection when the bunker hose is disconnected from the manifold, thus minimizing the possibility of releasing residual fuel into the atmosphere.

The breakaway coupling features a coupling that, aside from incorporating the same features as the dry release coupling, releases the connection in case of excess tension on the bunker hose. For instance, in the case of relative motion between bunker installation and bunker receiving ship. When the tension becomes too high, the coupling passively shuts down the flow and the coupling fails, severing the connection. This system prevents tension from building up somewhere else and possibly rupturing a bunker hose or some other part of the installation. This will lead to an uncontrolled release of the bunker medium.

The powered emergency release coupling is able to be hooked up to an Emergency Shutdown (ESD) system. It is then activated hydraulically or pneumatically. Activating the ESD system will stop the flow of the bunker medium and break the connection automatically. Additionally, the system still functions as a breakaway coupling, also passively disconnection when the tension exceeds a limit.

The difference between the manual dry disconnect coupling and the breakaway coupling can be seen in Figure 3.15.

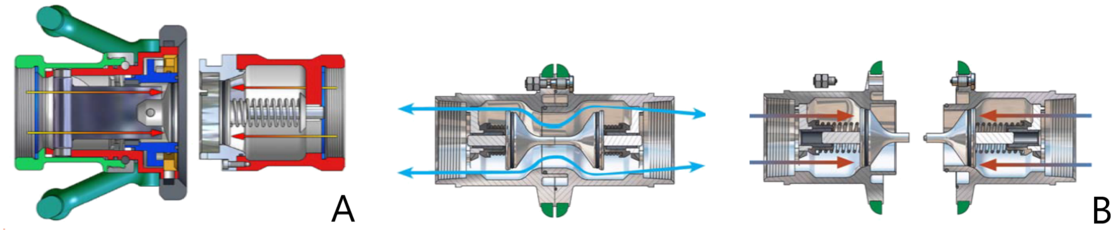


Figure 3.15: Two kinds of couplings, the dry disconnect coupling (A) and the passive break away coupling (B) [73]

3.3. Ammonia Safety Functions

Because of the hazards associated with ammonia, mitigation systems that can be used in case of an unintended release can contribute to a safer operation of the installation. Furthermore, the sub-zero temperatures of liquid ammonia impose further critical safety functions that need to be added to the system. Aside from standard practice protection such as Personal Protection Equipment (PPE), there also exist larger scale prevention and mitigation systems that require additional consideration. The mentioned safety systems will be discussed in this section. To state the ammonia safety functions in a compact form:

1. Bunker Location
2. Substance slip prevention
3. Toxic cloud mitigation
4. Spill containment
5. BOG vapour pressure equalisation
6. Insulation of the system
7. Purging of fuel lines

3.3.1. Bunker Location

Bunkering can be done in more than one standard location. This influences the configuration and viable components of the system, each location has its own distinct set of pros and cons. Therefore, it is important to take this into account. The bunker locations that will be handled in this research will be dictated by the intended end user: Ships. Specifically, where ships can sail to in order to receive the bunker fuel. Namely, at the quay, near the quay but not fully docked, or not near a quay. These are hereafter referred to as follows, respectively:

1. Onshore Bunkering
2. Nearshore Bunkering
3. Offshore Bunkering

Onshore bunkering refers to bunker configurations where the entirety of the installation resides onshore. A vessel that requires bunkering will dock at a quay and a bunker hose will be connected. An advantage of this configuration is the solid ground to build on providing more available space and stability.

Nearshore bunkering refers to bunker configurations where the storage and pumps of the bunker installation reside onshore, but the jetty with the bunker hose connection is offshore. Usually, the jetty remains close to the quay where the storage tanks are situated. A floating jetty such as IQuay from ECONNECT Energy [74] is an example of such a system. An advantage of this is the lack of relative motion between the bunker vessel and the jetty and little restriction on the orientation of the bunker object. Furthermore, a nearshore system is not bounded by the quay depth. Potentially being able to service ships with a bigger draft more easily, without the need for dredging.

Offshore bunkering refers to bunker configurations where the entire bunker installation resides offshore. Offshore drilling rigs with bunkering capabilities, or fully offshore jetties could be an example of this. An advantage of this configuration is the independence of port-side facilities and being away from port traffic. A downside would be the vulnerability to weather and expensive supply piping or supply ships that need to keep the reserves of the installation full enough for operation.

3.3.2. Substance Slip Prevention

Following the exposure prevention requirement, substance slip needs to be prevented. There are two considered strategies that can fulfil this function. The first is gas detectors that are coupled to an ESD. These gas detectors can prevent large amounts of substance slip by shutting down the installation or closing specific valves when ammonia is detected. The placement of these sensors, however, is a crucial consideration when gauging their effectiveness. Early detection and early measures prevent large amounts of ammonia from being released.

The second strategy considers a water spray system that is positioned over the bunker manifold, and possibly other locations in the system that are prone to leakage. This water spray system continuously sprays water over these leak-prone locations to reduce ammonia vapours in the air. A drainage system could be placed underneath these spray systems in order to dispose of the contaminated water. A system that measures the ammonia content of the wastewater could be implemented to detect leaks outside normal operation.

3.3.3. Toxic Cloud Mitigation

Toxic cloud mitigation systems are systems that can be placed around the installation with the goal of mitigating the hazards of a toxic cloud. Ammonia clouds can drift large distances inland and can subsequently pose health hazards there. Release distances involving ammonia can drift more than three kilometres downwind and still pose a 10% lethality risk in an area of more than $423.000m^2$ in the case of pressurized ammonia bunkering scenario [75].

Overpressurisation

It is possible for vulnerable objects in close proximity to a bunker operation to create an environment where the pressure inside an enclosed space is higher than the ambient pressure outside. This prevents the ammonia from a passing toxic cloud from entering the vulnerable object. Ksenia et al. (2021) showed that through the internal overpressurisation of the insides of a ship, sufficient protection against potential ammonia hazards could be offered [75]. The effectiveness of this safety strategy does, however, depend strictly on the percentage of persons that are within this protected area at a given time, in addition to the persons that can be moved to a protected area within the time granted by the toxic cloud migration speed.

Water Curtain
A widely studied mitigation solution for an ammonia release scenario is employing a water curtain. The operating principle of this is to generate a curtain of water around, or in the path of, the ammonia cloud in order to make use of its reactivity with water. This leads to the cloud being absorbed by the water and falling to the ground. This mitigation system has been tested in multiple researches and its effectiveness will be summarized.

It has been found that the effectiveness of cloud mitigation increases with reduced distance to the point of release, placement on a dyke around the storage is recommended [76]. Furthermore, the effectiveness enhances when ammonia is absorbed [77]. Finally, the effectiveness in reducing the toxic cloud can be as high as 90% at $10m$ behind the release location [78].

The application of this mitigation strategy will reduce the LSIR contour of the system and thus make construction closer to vulnerable objects possible. This strategy does produce ammonium hydroxide as a reagent, which poses a health hazard to nature and humans if swallowed or if it comes into contact with the skin [79]. Thus, proper handling of the reagent needs to be taken into account. A practical simulation was done by Cheng et al. (2014) to see the effectiveness of the water curtain with wind speeds up to $4.4m/s$, Figure 3.16 can be observed.

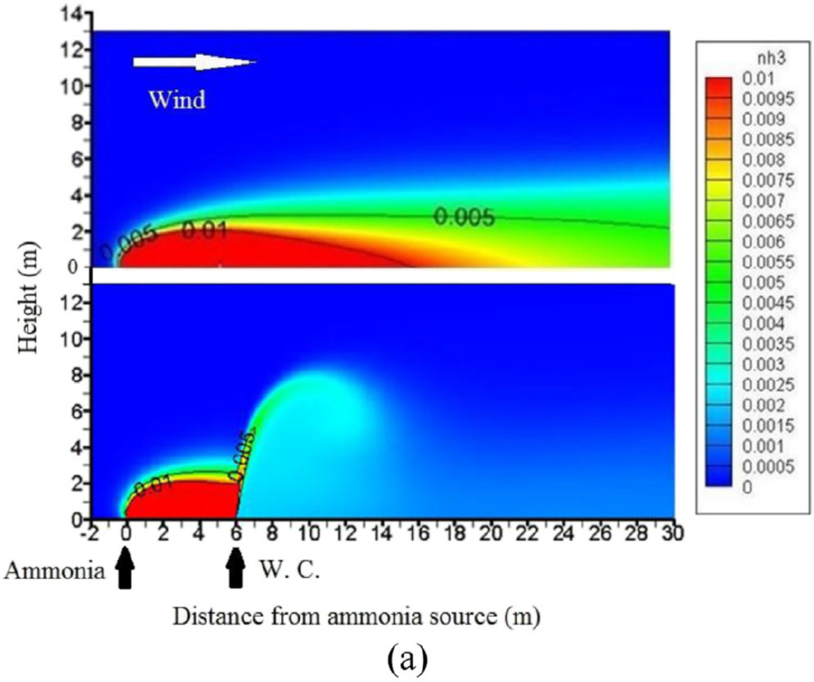


Figure 3.16: Effectiveness of a water curtain mitigation system at $6m$ with $4.4m/s$ wind [77]

Mesh Barrier
The mesh barrier is comparable to the water curtain in the sense that it also tries to create a barrier that hinders the downstream migration of a toxic ammonia cloud. The working principle is through the reduction of vortices downstream, thus increasing the concentration of ammonia on the ground surface [80].

The mesh barrier works best when placed close to the leak source and works optimally when the leak mass flow rate is around $0.4kg/s$. Because of the dynamics of this system, it is very effective at reducing the dispersion of the toxic cloud downstream, as can be seen in Figure 3.17

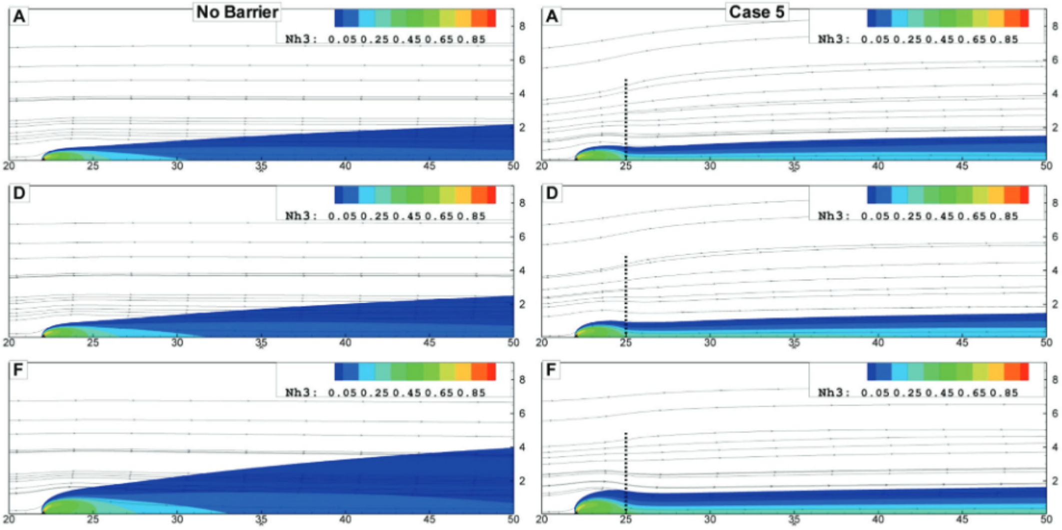


Fig. 9. Comparison of atmospheric condition on size of danger zone with/without mesh barrier with MC = 12 (case 5) ($m^{\circ} = 0.2$ Kg/s). All dimension is in meter.

Figure 3.17: Efficacy of a mesh barrier mitigation system [80]

This effectiveness in reducing the spread of the danger zone downstream could prove useful in providing an option for other mitigation systems, like dykes and additional water curtains. These systems could be more effective and compact because of this reduced dispersion. The mesh barrier does need a secondary system to completely mitigate the toxic cloud, but the decreased dispersion does help with containment. Furthermore, if the use case has a lot of natural barriers around the release locations, mesh barriers can prove useful by keeping the cloud close to the ground, thus preventing it from migrating large distances.

3.3.4. Additional Spill containment

Aside from the containment levels that are incorporated in the double and full containment storage vessels, additional spill containment is also possible. These possibilities are discussed in this section.

Bund Dyke

A bund dyke is a passive liquid ammonia spill mitigation system. It works by creating a barrier with an internal volume that is equal to or greater than the storage volume. When ammonia is spilt out of the storage vessel, it is mostly contained in its liquid state within the bund walls. The barrier between liquid and gaseous ammonia acts as an insulator which prevents rapid vaporisation of the liquid ammonia. This liquid ammonia can then be siphoned off or reclaimed before it can freely vaporise and form a large toxic cloud [61]. Though this is an effective partial containment method, there will still be ammonia vapour generation and thus a significant risk for the surrounding area will remain.

Modified Carbon Nano-particles

Modified carbon nano-particles can be used in the basins in which liquid ammonia has been released. Such as around a single containment flat bottom tank as seen in Section 3.2.1. The operating principle is to increase the adsorption of the liquid ammonia such that less of the substance can evaporate and drift downwind [81].

The addition of the modified carbon nano-particles to an ammonia pool in, for instance, the dyke area around a failed storage, can reduce the threat zone by 50% [81]. This mitigation strategy could offer additional containment in combination with other measures.

3.3.5. BOG vapour Pressure Equalisation

The pressure-increasing effect of BOG is required to be handled. This section will discuss the means that can make this possible.

BOG Return Hose

A BOG return hose, as seen in Section 3.1, is common practice for boiling liquid bunker installations, such as for LNG bunker installations. It is preferred because it forms a fully closed system. The generated ammonia gas is sent back to the terminal side storage tank, where it can compensate for the displaced volume of fuel that has been transferred to the ship side. The potential risk with this set-up is equal to the risk of the fuel line connection: because of the impermanent connection that is usually made by humans, there is a tendency for error.

Buffer Tank

A buffer tank can be used to store the generated BOG to keep the pressure in the fuel tank at nominal levels. Since the liquid ammonia has to be evaporated to be used as fuel [82]. This ship-side extra tank could double as the ammonia fuel expansion chamber. A downside to this method could be the limited available space in such a tank. Furthermore, this would require extra space on the ship to be lost to such a tank, space which could be used for cargo and other purposes.

Vent with Scrubber

It is possible to vent excess pressure into the atmosphere when the vent is equipped with a scrubber. This option allows operational pressure to be quickly equalised, without the need for extra tanks or fuel lines. However, this option does use up a scrubber medium, which could be associated with high costs.

3.3.6. Insulation

Thermal insulation is needed to reduce the influx of heat and make sure that BOG is kept at a minimum, especially around the transfer pipes. There exists the option to employ the use of a low thermal conducting material in order to minimize the heat flux (mechanical insulation), or there exists the option to employ vacuum insulation.

There are considerations with both options. Vacuum seal can generally create a better insulating layer for a smaller diameter of piping, even up to 20 times as much as fibre or foam solutions [83]. Though the vacuum insulated pipes generally perform better in their rigid pipe design [84]. Piping that has regular mechanical insulation is more easily patched up, as opposed to a segment of vacuum-sealed piping where the integrity of the entire pipe can be lost in case of a break [85]. Although this is the case, the constant draw-in of moisture and the warm and cold duty cycle of a mechanical insulation layer makes it prone to deterioration [86].

3.3.7. Purging of Fuel Lines

As could be seen in Section 2.2, even though the flammability range of ammonia is higher than that of for example LNG ($15 - 28\%$ vs $5.3 - 17\%$, respectively), ammonia is a lethal toxin at much smaller concentrations than the flammability ranges of either substances. Moreover, this lower flammability range and higher ignition energy ($8mJ$ vs $0.27mJ$, respectively) does not mean there is a negligible flammability and explosivity risk when bunkering ammonia. This leads marine fuel safety handbooks to conclude that the purging of fuel lines with inert gas is required in an ammonia bunker installation [87].

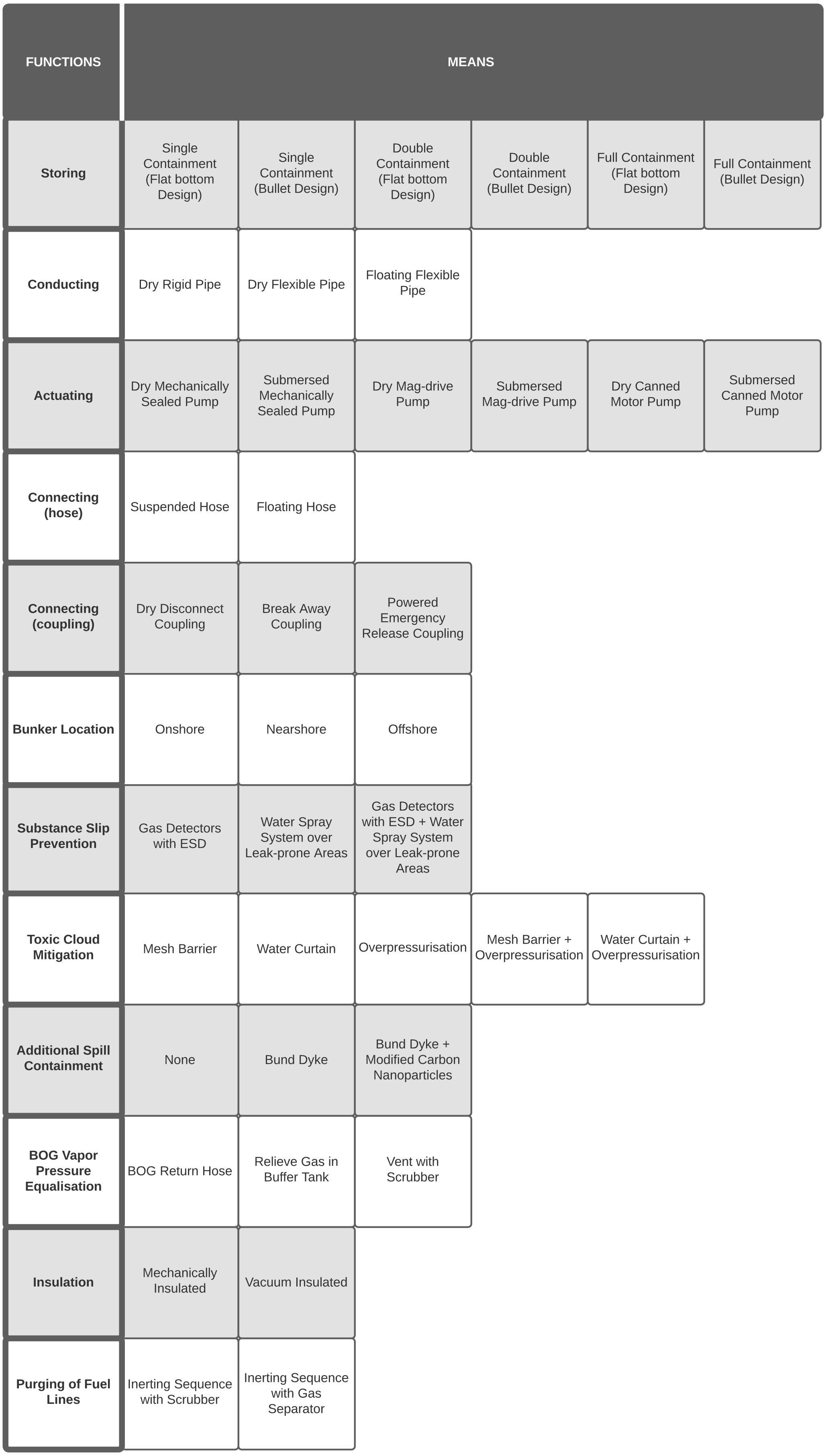
However, there exists the problem of where the gas mixture resulting from the purging sequence is supposed to be led to since direct venting into the atmosphere is considered undesirable due to the toxic nature of ammonia. Furthermore, burning the residual ammonia gas releases undesirable NO_x and N_2O, the latter being a potent greenhouse gas [87], making this an unfavorable alternative as well.

Ksenia et al. (2021) solve this problem by introducing citric acid scrubbers at the ventilation mast, in order to reduce the amount of vented ammonia [75]. These scrubbers are only around 90.12% effective [88], and the scrubbing medium is used up in the scrubbing process, about five weight units of citric acid per weight unit of removed NH_3. However, Ksenia et al. (2021) deem it effective enough to use for use around ammonia-powered passenger ships.

Another option would be to redirect the resulting gas mixture from the purging sequence, first to an external tank, or directly to a gas separation system. Such a system could make use of a fractional distillation technique to separate the nitrogen en ammonia gases from each other. This is a technique which uses the different boiling points of the two gases ($-33.34°c$ for ammonia and $-195.8°C$ for nitrogen) to separate them. Aside from fractional distillation, there exist multiple other methods to achieve the separation of the two gases. These techniques would allow for the reclamation of both gases and would completely eliminate any venting to the atmosphere. However, this installation could be costly to install and use.

3.4. Conclusions

In this section, an overview is presented. This overview shows all the derived functions for the system under ”functions”, as well as their discovered solutions under ”means”. This figure can be found in Figure 3.18.



FUNCTIONS	MEANS					
Storing	Single Containment (Flat bottom Design)	Single Containment (Bullet Design)	Double Containment (Flat bottom Design)	Double Containment (Bullet Design)	Full Containment (Flat bottom Design)	Full Containment (Bullet Design)
Conducting	Dry Rigid Pipe	Dry Flexible Pipe	Floating Flexible Pipe			
Actuating	Dry Mechanically Sealed Pump	Submersed Mechanically Sealed Pump	Dry Mag-drive Pump	Submersed Mag-drive Pump	Dry Canned Motor Pump	Submersed Canned Motor Pump
Connecting (hose)	Suspended Hose	Floating Hose				
Connecting (coupling)	Dry Disconnect Coupling	Break Away Coupling	Powered Emergency Release Coupling			
Bunker Location	Onshore	Nearshore	Offshore			
Substance Slip Prevention	Gas Detectors with ESD	Water Spray System over Leak-prone Areas	Gas Detectors with ESD + Water Spray System over Leak-prone Areas			
Toxic Cloud Mitigation	Mesh Barrier	Water Curtain	Overpressurisation	Mesh Barrier + Overpressurisation	Water Curtain + Overpressurisation	
Additional Spill Containment	None	Bund Dyke	Bund Dyke + Modified Carbon Nanoparticles			
BOG Vapor Pressure Equalisation	BOG Return Hose	Relieve Gas in Buffer Tank	Vent with Scrubber			
Insulation	Mechanically Insulated	Vacuum Insulated				
Purging of Fuel Lines	Inerting Sequence with Scrubber	Inerting Sequence with Gas Separator				

Figure 3.18: Overview that displays the derived functions under ”functions”, and discovered solutions under ”means” for a bunker installation for refrigerated liquid ammonia.

4

Evaluation Method

The previous chapter resulted in an overview which contained all derived functions for a bunker installation for ammonia, as well as the proposed solutions. This chapter will evaluate several Multi-Criteria Decision Making (MCDM) methods, and decide on a model to use. This model will serve as the main decision-making model to select configurations of solutions from Figure 3.18 and thus answer the third sub-question:

Which model can be used for decision making with respect to discovered bunker station components?

4.1. Decision Making Methods

In a classic system engineering approach, a morphological analysis can be used to generate system configurations [89]. However, this method allows for researcher bias when generating concepts, which is deemed undesirable. A MCDM method can be used to get around this bias and to make sure all solutions from the overview are considered. Because a MCDM method requires an objective analysis of the solutions with respect to design criteria, and shifts the decision-maker bias towards stakeholders, the researcher bias can be circumvented. Several MCDM methods which use subjective weighing of design criteria by experts exist, such as the analytical hierarchical process (AHP), the analytical network process (ANP), and BWM, among others [90].

There exist several factors that determine the usability of a specific use case for these methods. These are for instance: computational time, simplicity, the number of pairwise comparisons required, and the requirement for software among others. On these factors, the BWM provides the lowest amount of computational time, both the ANP and BWM are the most simple to use, the BWM requires the least number of pairwise comparisons, and the AHP and BWM do not require software to be performed. Furthermore, even though the results obtained from AHP and ANP can be said to be reliable, those of the BWN can be said to be more consistent in their comparisons. This would indicate that these results are more reliable than the AHP and ANP [90].

Because it is desired to perform decision-making through stakeholder input, a straightforward and consistent survey is required. The simplicity of the survey for the decision maker is desirable to ensure more reliable results. Because consistency can be quickly evaluated, and the number of comparisons is low with the BWM, it is possible to ensure a survey result of sufficient quality from stakeholders; if the quality is not sufficient, the survey can easily be altered by the decision maker. Additionally, the low computational time required to perform the BWM and the lack of additionally required software led to the BWM being chosen for the purposes of this research.

4.2. The Best Worst Method

The BWM, proposed by J. Rezaei (2015) [91], can solve discrete MCDM problems. A discrete MCDM problem can be generally formulated in a matrix as follows:

$$A = \begin{array}{c} \\ a_1 \\ a_2 \\ \vdots \\ a_m \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{pmatrix} \end{array} \tag{4.1}$$

where $\{a_1, a_2, \cdots, a_m\}$ is a set of feasible alternatives and $\{c_1, c_2, \cdots, c_n\}$ is a set of decision-making criteria. For each function as can be seen in Figure 3.18, the set of design alternatives would correspond to a unique vector $\vec{a}$. The values for p_{ij} correspond to the relative value for the criterion j with respect to the alternative i. Chapter 2 focused on determining the alternatives $\vec{a}$, whereas this chapter will focus on determining the criteria $\vec{c}$ and the values for p_{ij}. The values for p_{ij} are not always available. This can be the case when quantitative data is not available. In this case, the procedure of comparing alternatives to criteria can still be carried out by using ordinal values for p_{ij}. With these values, the goal of finding the best alternative, or the alternative i with the highest value V_i, for a specific function of the system can be achieved. This is done with the equation as follows:

$$V_i = \sum_{j=1}^{n} w_j p_{ij} \tag{4.2}$$

Where:

$$w_j \geq 0, \sum w_j = 1 \tag{4.3}$$

In Equations (4.2) and (4.3), the values for $w = \{w_1, w_2, \cdots, w_n\}$ correspond to the weights associated with the importance of each criterion. The determination of the optimal values for w, w^*, is done by starting with the following matrix B:

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix} \tag{4.4}$$

where b_{ij} is the relative preference of criterion i to criterion j. Suppose we have n criteria and we want to perform a pairwise comparison of these criteria using 1 to 9 scale. Thus, $a_{ij} = 1$ shows that criterion i and j are of the same importance, $a_{ij} > 1$ shows that i is more important than j, and $a_{ij} = 9$ shows that criterion i is extremely more important than j.

Instead of determining the all relative importance b_{ij}, the BWM starts by determining the best (most important) criterion and the worst (least important) criterion. Subsequently, the preference of the best criterion over all the other criteria, and the preference of the other criteria over the worst criterion is determined. These preferences are allocated a number between 1 and 9. Resulting in the Best-to-Others and Others-to-Worst vectors, respectively:

$$B_B = (b_{B1}, b_{B2}, \cdots, b_{Bn}) \tag{4.5}$$

$$B_W = (b_{1W}, b_{2W}, \cdots, b_{Wn})^T \tag{4.6}$$

where $b_{BB} = 1$, and $b_{WW} = 1$.

Finally, to calculate the optimal weights w_j^* and ξ^*, the following problem can be solved:

$$min\ \xi$$

s.t.

Table 4.1: Consistency index for different values of b_{BW} [91]

b_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

$$\begin{gathered} \left|\frac{w_B}{w_j} - b_{Bj}\right| \leq \xi,\ \forall j \\ \left|\frac{w_j}{w_W} - b_{jW}\right| \leq \xi,\ \forall j \\ \sum_j w_j = 1 \\ w \geq 0,\ \forall j \end{gathered} \tag{4.7}$$

Finally, to ensure the quality of the assessment of the weights w_j, a high consistency is desired. To determine the consistency of a BWM analysis, a Consistency Ratio (CR) is proposed [92], as follows:

$$Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index} \tag{4.8}$$

where $Consistency\ Ratio \in [0,1]$, values close to 0 are more consistent, while values close to 1 are less consistent. To calculate the consistency index the consistency ratio needs to be determined, this is found through the following equation:

$$\xi^2 - (1 + 2b_{BW})\xi + (b_{BW}^2 - b_{BW}) = 0 \tag{4.9}$$

Solving Equation (4.9) for different values for b_{BW}, the maximum value for ξ can be found. This value is used as the consistency index. Table 4.1 shows the maximum values of ξ (consistency index) for different values of b_{BW} [91].

With the solutions for (4.2) known for each function, and the solution of (4.8) as a measure of the quality of the pairwise comparison, a decision for the best alternative can be made.

4.3. Conclusions

This section will give an overview of the findings of this chapter, as well as the answer to the third sub-question.

Three MCDM methods were evaluated: the AHP, ANP and BWM. All three are suitable for decision-making with respect to the discovered bunker station components. However, the straightforward and consistent survey of the BWM that requires a small number of comparisons, combined with the reliable results associated with this method made it a better fit for this research. Furthermore, its low computational time and lack of additional required software also make it desirable above the other two methods. Therefore, the method that is chosen for decision-making is the BWM.

5
Evaluation of Alternatives

To evaluate the solutions, design criteria are introduced in Section 5.1 and an ordinal analysis is performed in Section 5.2. In this analysis, the solutions are ranked with respect to the design criteria. Both are needed to execute the BWM. These two components together will answer the fourth sub-question:

What design criteria can be used to evaluate bunker station components and how do the selected system components perform on the defined design criteria?

5.1. Design Criteria

In this section, the design criteria for the BWM will be proposed. Design criteria are used as a metric with respect to whom, alternatives can be evaluated. Correctly defining these parameters will allow the design to be optimized for desired criteria. The design criteria are based on important parameters that are involved in a bunker process that is part of a supply chain [93], and the challenges around different energy densities, safety requirements and costs associated with alternative fuels, as stated by the Port of Rotterdam [94]. This leads to an emphasis on reducing cost, preventing downtime and minimizing bunker time. Additionally, energy efficiency is important from a sustainability point of view. Finally, safety must be guaranteed and therefore must also be taken into consideration. This section will discuss the design criteria selection and show what subcategories they are composed of.

Cost

The cost of the installation is a considered design criterion. This cost does not only describe the initial cost of acquisition but also takes into account the maintenance cost and the operational cost of the installation.

- Capital Expenditure (CapEx)
- Operational Expenditure (OpEx)

Energy Efficiency

The energy efficiency of the system concerns how efficient a design option can potentially be in terms of its energy usage. Design options that use more energy will score lower on this criterion. It is also possible that the environment the design option operates in will require higher energy use. For example, a submersed pump leaking its heat into the liquid ammonia will require compensation from cooling systems, this is less energy efficient. Therefore it is important to be as effective as possible, while also minimizing energy usage from a sustainability point of view. Because of the emphasis on sustainability, this criterion is evaluated separately from the OpEx which it usually is a part of.

- Running cooling systems
- Running pumps
- Other energy usage

Safety
The safety design criterion concerns all safety parameters that a design offers. This involves systems that might be of influence on the LSIR contour, such as possible mitigation systems/strategies. Furthermore, where possible, the inherent safety of a design option and the possible threat it might pose to the environment will be taken into account.

- LSIR contour
- Inherent design safety
- Environmental Safety

Reliability
The reliability design criterion concerns the degree of resistance to calamities the design has. Offshore bunker installations, for example, are more susceptible to weather influences than onshore installations. Furthermore, some options can be more resistant to downtime, due to less complex repairs. This will also be taken into account.

- Downtime prevention
- Vulnerability to environmental hazards

Bunker Time
The final design criterion concerns the estimated bunker time of an installation. This design criterion is the cumulative indicator for the amount of time a ship would require to manoeuvre to the installation and into place, the possible complexity of the pre- and post- checks to enable safe operation, and the possible flow rate that would dictate the time of the actual filling of the ship-side storage tank.

- Pre-check and Post-check
- Manoeuvring
- Flow rate

5.2. Ordinal Analysis

In this section, an ordinal analysis will be performed to find the values for p_{ij}. Because of the unavailability of quantitative data, the value for each alternative with respect to a criterion will be ranked relatively. For example, if there exist a set of three alternatives that go up in total cost in order of appearance, then their respective $p_{i,cost}$ value will be $p_{1,cost} = 3$, $p_{2,cost} = 2$, $p_{3,cost} = 1$. Since the criterion cost is to be minimized, the best value, 3, is allocated to the first alternative and the worst value, 1, is allocated to alternative three. If there is no discernible difference between two alternatives, an equal value can also be allocated. For instance, if alternatives 1 and 2 are of the same cost, but less expensive than alternative 3, then their respective $p_{i,cost}$ value will be $p_{1,cost} = 2$, $p_{2,cost} = 2$, $p_{3,cost} = 1$. Due to the possibility of an equal ranking in the case of no discernible difference, the data needs to be normalised. This normalisation will be done following the paper by Munim et al. (2020), dividing each value under the same criterion by the highest allocated value for each function.

5.2.1. Storing

Cost
The storage cost for liquid ammonia, as per Bartels (2008), for 15 days and 182 days is $0.06\ \$/kg\ H_2$ and $0.54\ \$/kg\ H_2$, respectively [47]. This involves OpEx. There is no mention in literature that increasing the integrity of the containment between single, double, and full containment, leads to a significant change in the storage price. Therefore, this difference in OpEx is assumed to be negligible.

The CapEx cost for storage of ammonia at low temperatures is the least in the flat bottom tanks at atmospheric pressure. The bullet tanks, which are rated for higher pressures than the atmospheric flat bottom tanks, store liquid ammonia nearly 15 times less cost-efficient than atmospheric storage [47].

This is due to the much higher ratio of steel to storage volume required for pressurized storage vessels. Additionally, the cost of production for added layers of complexity with respect to containment leads to a higher CapEx.

Energy Efficiency
The heat influx for large-scale ammonia storage is 0.1% per day [47], but this increases when there is more surface area exposed to the atmosphere. In other words, the large single flat bottom tanks have more energy-efficient storage. Aside from this, there is no difference in energy usage between single or double containment concepts, as mentioned before. Full containment, however, is able to remain operational in case of a primary tank failure, as mentioned in Section 3.2.1, and therefore has less potential for needing extra energy usage associated with reclaiming and possibly reliquefying spilt ammonia.

Safety
Rath et al. (2013), studied the different risk levels between the different storage methods, and containment levels for storing LNG by use of Frequency v.s. Number of Fatality (FN) curves [59]. Spherical, bullet and flat-bottom tanks were evaluated. This risk assessment was done under the assumption of an equal storage volume, where this volume would be stored in a single flat bottom tank ($4000\ m^3$), or five bullet tanks (5 times $800\ m^3$). This research concluded that, indeed the risk reduces when the containment level is increased for all storage methods. Single containment bears the most risk, and full containment bears the least risk. The research further concluded that in the full containment category, flat-bottom tanks are the safest option, followed by bullet tanks. After this, for double containment, the flat bottom tanks are also safer than bullet tanks. Finally, for single containment tanks, the bullet tanks are safer than the flat bottom tanks in terms of risk.

Reliability
In terms of downtime prevention, it is clear that full containment concepts are best. It is the only option that allows for continued operation in case of a primary tank failure, as mentioned in Section 3.2.1. Downtime is inevitable in case of a loss of containment in a double or single containment scenario. However, in the case of multiple bullet tanks, because the stored volume is divided over multiple tanks, it can be assumed that there still are undamaged tanks that can be used to potentially continue operations.

Bunker Time
The segments that are associated with the bunker time criterion create no distinction in the means of storage. Therefore, the values for this criterion are set to one for all options.

Overview
The above-mentioned findings have been summarized in Table 5.1.

Table 5.1: p_{ij} values for the means that fulfil the function: Storing. Where SC denotes Single Containment, DC denotes Double Containment, and FC denotes Full Containment

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
SC, Flat Bottom	6	2	1	1	1
SC, Bullet Design	3	1	2	2	1
DC, Flat Bottom	5	2	4	1	1
DC, Bullet Design	2	1	3	2	1
FC, Flat Bottom	4	4	6	3	1
FC, Bullet Design	1	3	5	3	1

5.2.2. Conducting

Cost
The complexity involved with manufacturing piping that can withstand the cold temperatures of liquid

ammonia, while still retaining their flexibility is higher than straight, rigid pipes. This will inadvertently lead to a higher CapEx. Furthermore, the fatigue and wear of flexible piping might undergo will have a negative impact on service life. Therefore, their OpEx will be higher than rigid piping. These same factors apply to flexible, floating pipes. Moreover, these floating pipes will have to be made buoyant, further increasing the cost.

Energy Efficiency
Flexible hoses are more difficult to insulate with, for instance, vacuum insulation. This leads to slightly lower insulation values [84]. This effect is also present in the floating pipes, but these floating pipes are also exposed to seawater, which will increase thermal conductivity and therefore BOG, as stated in Section 5.2.4. This BOG has a negative influence on the energy efficiency of the system.

Safety
Rigid piping can is safer due to it being fixed in place. Sudden changes in pressure will not cause the movement of the pipe. The lower susceptibility of rigid piping to wear will also contribute to conserving structural integrity. This same argumentation is also true for floating piping, but this piping is generally more vulnerable to external hazards due to being more exposed to external influences.

Reliability
Because flexible piping is more susceptible to wear, it is also required to be inspected and replaced more often. This will lead to increased downtime. Floating pipes are more exposed in seawater, where they are also more susceptible to environmental hazards and thus will need to be inspected and replaced even more often. Furthermore, the low visibility of the floating pipes risks them being damaged by passing ships.

Bunker Time
Flexible piping can be assumed to be not perfectly straight everywhere. Increasing bend angle in piping increases friction factor [95]. With an increased friction factor, the flow will decelerate and therefore flow rate will reduce. Furthermore, the relative motion of water in floating pipes will make these bends periodically more extreme and irregular. This can further negatively impact the flow rate.

Overview
The above-mentioned findings have been summarized in Table 5.2.

Table 5.2: p_{ij} values for the means that fulfil the function: Conducting

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Dry Rigid Pipe	3	3	3	3	3
Dry Flexible Pipe	2	2	2	2	2
Floating Flexible Pipe	1	1	1	1	1

5.2.3. Actuating

Cost
When looking at the CapEx for the pumps that will actuate the liquid ammonia, the cost of a canned motor and a mag-drive pump are higher than that of a double mechanically sealed pump, as could be seen in Section 3.2.3. But the more important factor here is service life, which is part of the OpEx: because of the sealless nature of canned and mag-drive pumps, they require little to no maintenance [96]. Canned motor pumps are designed as a one-piece assembly. This means that, in case of motor failure, the entire assembly has to be replaced. Magnetic drive pumps do not have this issue, as their motor is separate from the rest of the assembly. Moreover, this creates the possibility to repair magnetic drive pumps on-site [72], and as such, they are considered to be the most cost-efficient option.

Finally, as stated in Section 3.2.3, the cost of submersible pumps is inherently higher than dry-installed pumps due to the better maintenance accessibility for the latter, and the cost involved with making a pump suitable for submersion.

Energy Efficiency
Generally, canned motor pumps are considered to be more efficient in terms of power transmission to the impeller than magnetic drive pumps. This is due to magnetic losses present in the magnetic coupling of this pump, caused by the gap between the internal and external magnet [72]. There are newer magnetic drive pumps available, with patents pending, that are able to reduce the aforementioned magnetic losses by 75%. On the other hand, canned motor pumps dissipate more heat into the medium due to their rotor winding being immersed in the medium in case of pump submersion, which has to be compensated for. Heat influx into the system leads to increased BOG which in turn increases bunker time due to the necessity of pressure management. Running systems for longer periods of time, and using external systems to compensate for the heat influx reduces energy efficiency. Because of the external installation of the motor in the case of magnetic drive and mechanically sealed pumps, this heat influx is not a problem. Submerged pumps have the advantage of the head pressure of the medium weighing down on the suction end, helping them operate. This is, however, achievable through clever placement of the dry-installed pump as well [97].

Finally, according to ZB pumps (2019), in terms of operating efficiency, the mechanically sealed pump is about $15/20\%$ more efficient than canned motor pumps of the same parameters. Magnetic drive pumps are in turn 5 times less efficient than mechanically sealed pumps, with an efficiency of around $92-95\%$ [98].

Safety
In terms of containment, mechanically sealed pumps have the worst performance. Their dynamic seals are prone to wear and therefore leakage. Magnetic drive pumps offer a hermetically sealed pump chamber due to the magnetic coupling between the motor and impeller and therefore offer a sealless, leak-free option. A canned motor pump offers the same hermetic seal, but these pumps offer an additional containment layer [70]. Because the rotor of the canned motor is immersed in the medium, with the stator outside of the medium, separated by a stator liner, a first containment barrier is formed. Outside of this, the motor casing, which forms the second containment layer, can be found. This means that in case of stator liner rupture, the fluid will stay contained within the motor housing.

When considering the difference between submersed and dry-installed pumps, there exists the problem of cavitation in dry-installed pumps. Cavitation can lead to the degradation of the impeller and therefore lead to imbalance and vibrations. This is a potential safety hazard, as metal particles can not only contaminate the medium but also damage other parts of the installation. Potentially leading to loss of containment. Cavitation, however, can be easily avoided by providing adequate inlet pressure by placing the dry-installed pump lower than the supply tank, for instance.

Reliability
Considering a single pump, submersed canned motor pumps are advertised to have a maintenance-free service life of 8-10 years [68]. Mechanical seals need to be replaced every two to three years as per Standard API 682 [99] and as could be seen in Figure 3.14, magnetic drive pumps have a service life that is somewhere in the middle of those two values, as per 3.14. This means that overall mechanically sealed pumps would cause the most downtime due to service. It is more difficult to access submersed pumps, but this is negligible in comparison to the difference in service life, and thus the frequency that service is needed, of the three considered pump types. It is worth noting that small maintenance to motors and pumps is more easily done on the magnetic drive and mechanically sealed pumps, due to the separation of the motor from the assembly. Finally, it is true that submersed pumps are more reliable than dry-installed pumps because they do not need to be primed, which eliminates the risk of running the pump dry and thus damaging it. Moreover, the head pressure at the suction side significantly reduces the risk of cavitation in submersed pumps, which reduces wear.

Bunker Time
All of the three considered pumps have commercially available models that can operate in excess of $1500\,m^3/h$ [68][100], but much virtually any flow rate is possible. This flow rate value is already higher than the $1000\,m^3/h$ that is currently used for bunkering LNG at the Gate Terminal [66], which would

mean that theoretically very short bunker times are possible. What sets the different pump designs apart, is their flexibility within the available flow rates. Every pump has its own duty point, moving too far from this point negatively affects efficiency. Canned motor pumps, for instance, would have to have their complete assembly replaced if different flow rates were required. In the case of the magnetic drive and mechanically sealed pumps, more is possible by changing the motor.

A way to solve the flexibility problem is to install more pumps. This is no problem for dry-installed pumps. However, submersible pumps use significant space in their entire assembly in a supply tank, requiring significant structures to support piping, manifolds, and valving [101]. Therefore, it is not always possible to install multiple pumps to accommodate many different flow rates. However, this is very dependent on the size of the installation and its specific use case.

Finally, the priming that is involved with dry-installed pumps can possibly increase bunker time. However, if this priming is done before ship mooring, it does not have to negatively impact bunker times. The required pump cooling sequence, as seen in Figure 3.4, will already perform pump priming.

Overview

The above-mentioned findings have been summarized in Table 5.3.

Table 5.3: p_{ij} values for the means that fulfil the function: Actuating

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Dry Mechanically Sealed Pump	4	1	1	1	4
Submersed Mechanically Sealed Pump	1	2	2	2	3
Dry Mag-drive Pump	6	3	3	3	4
Submersed Mag-drive Pump	3	5	4	4	3
Dry Canned Motor Pump	5	4	5	5	2
Submersed Canned Motor Pump	2	6	6	6	1

5.2.4. Connecting (Hose)

Cost

Given that the composition of the construction of floating and suspended bunker hoses is essentially identical, with the only difference being the inclusion of buoyancy features in the former, it follows that the CapEx of floating hoses is higher. Furthermore, because of the corrosive properties of seawater [102], the exposure of floating hoses to seawater and air leads to greater corrosive effects. The long-term implications of this exposure include increased instances of corrosion on the floating hose, which ultimately manifests in higher OpEx.

Energy Efficiency

The connecting hoses of the installation do not use power. The only distinction that can be made is that the medium surrounding the floating hose is water, in contrast to the air surrounding the suspended hose. The temperature of the seawater is often lower than the air above it, and the thermal conductivity of seawater is higher than that of air ($0.056\ W/mK$ v.s $0.025\ W/mK$ at $0 \deg C$[103][104]). This can potentially cause more heat influx into the system, thus increasing BOG, which has to be compensated for. This is possible through liquefaction which uses more energy, or it can lead to increased bunker times, as was discussed in Section 2.3.4, leading to longer run-time of the involved systems.

Safety

Because both bunker hoses are designed to conform to strict safety standards and their functional design is equal, safety concerns inherent to their design offer little distinction. Therefore, external influences specific to the use case will be considered. The use cases are that the floating hose will be surrounded by seawater and air, and the suspended hose is suspended in the air. Considering this, Floating hoses are generally longer than suspended hoses that are connected to a jetty and moored vessel [105]. Therefore, floating hoses have exposed areas that could be susceptible to outside influences or entanglement, thus putting them at greater risk.

Reliability

Because of the generally longer length of the hose, in combination with this length being more exposed than a suspended hose that is directly connected from a jetty to a ship, floating hoses are more vulnerable to environmental hazards. For instance, large waves can impede the functionality of floating hoses. Therefore, these hoses are considered to be less reliable.

Bunker Time

The hose connection procedure of suspended hoses is less complex than the connection procedure of a floating hose [66][105]. The suspended hose connection is made by extending a loading arm that positions the hose close to the manifold of the ship, where it can be lowered down to the appropriate height. It is very likely that the movement of the hose to the ship and the upward movement of the hose takes more time than the described procedure for a suspended hose.

Overview

The above-mentioned findings have been summarized in Table 5.4.

Table 5.4: p_{ij} values for the means that fulfil the function: Connecting (hose)

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Suspended Hose	2	2	2	2	2
Floating Hose	1	1	1	1	1

5.2.5. Connecting (coupling)

Cost

Since the dry disconnect coupling is a simpler version of the breakaway coupling, which in turn is a simpler version of the PERC, CapEx also goes down with increasing simplicity. CapEx is assumed to be the dominant cost factor due to the similarity of the use case, and thus requirements for maintenance. However, there is a distinction when comparing break-away couplings and PERCs to dry disconnect couplings. This distinction is that there is no protocol in place for the dry disconnect coupling in case of excessive motion. This means that damage to the installation will follow such a scenario. In the case of the other two options, there is only a connector bolt replacement required.

Energy Efficiency

The dry disconnect coupling, as well as the breakaway coupling, do not use any energy. The PERC, however, does use energy to force the coupling to disconnect in case of an emergency.

Safety

The safety of the couplings increases with increased complexity. All three alternatives are designed to be leak free when the coupling is disconnected. Only the breakaway coupling and PERC are designed to release in case of excessive tensile stress on the hose. Finally, only the PERC is designed to disconnect in case of an ESD button being pressed, and can therefore be considered to be safer than the breakaway coupling.

Reliability

The fact that a dry disconnect coupling can potentially damage the installation in case of excessive tensile stress on the hose, means it can cause serious calamity to the terminal. Because the PERC is in connection to the ESD and manual override systems, it will always disconnect in case of an emergency. This can potentially cause downtime in case of a human error or false alarm. Resetting this coupling can cause extra unwanted downtime, a passive breakaway coupling does not have this problem.

Bunker Time

There is no discernible distinction in the complexity, possible flow or procedure when comparing these three couplings.

Overview
The above-mentioned findings have been summarized in Table 5.5.

Table 5.5: p_{ij} values for the means that fulfil the function: Connecting (coupling)

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Dry Disconnect Coupling	3	2	1	1	1
Break Away Coupling	2	2	2	3	1
PERC	1	1	3	2	1

5.2.6. Bunker Location

Cost
The cost of making any part of a system such as this being able to float is always going to be higher than constructing on dry land. Therefore, when more of the critical systems need to be made floating, the higher the cost is going to be. Therefore, it can be assumed that the OPEX and CAPEX costs are going to increase respectively over on-, near-, and offshore systems.

Energy Efficiency
The energy efficiency of a bunker location can be dependent on several factors. This could include whether or not one decides to transport gaseous ammonia to an offshore location where it can be reliquefied, or if the pipes are cooled and it is piped in its liquid form. Furthermore, tanker vessels could directly deliver their cargo to the offshore installation, but this would require large amounts of storage offshore to be viable. Nearshore and onshore bunker locations can store a lot of liquid ammonia more easily in their land-based storage tanks where their supply routes are much less complex and therefore less frequent, and thus more energy efficient. When making a distinction between the near and onshore systems, it can be informative to look at the lesser insulating value of water versus that of air when considering transfer pipes. Either this has to be compensated with extra insulation, or this has to be compensated by reliquefaction systems, which costs energy. Therefore, it can be concluded that the energy efficiency of bunker locations increases respectively over off-, near- and onshore systems.

Safety
The safety of the bunker location is a complicated factor. This is because increasing the distance between the bunker operation and the port inherently increases safety because the metrics for this, LSIR contours and focus areas, are distance-based. Therefore it follows that offshore systems are safer than nearshore systems, are safer than onshore systems when considering possible vulnerable people within said LSIR contour. The caveat here, however, is that the off- and nearshore systems do not allow for many toxic cloud mitigation systems. A water curtain will, when activated, convert ammonia to ammonia hydroxide, which will then contaminate the water and harm the flora and fauna around the installation. Even though this still occurs to a lesser degree in case of a release, the effect is much greater when a water curtain is applied. Additionally, the release over open water is associated with longer dispersion distances, due to the lesser amount of obstruction [75], which would require an offshore installation to be placed further away from land to respect that in the 10^{-6} LSIR contour there are no vulnerable objects, for example.

The possibility to implement mitigation strategies with less adverse effects to the surroundings, near the point of release, offers greater control over the risk. Offshore systems that have less control over a toxic cloud are more dependent on the weather situation and wind direction for example. Since the toxic cloud offers the greatest contribution to the risk [75], it is safe to assume that more control over this risk offers more safety.

The optimal distance for all of the toxic cloud mitigation strategies that offer this control is close to the point of release [77][80]. Combining this with a current nearshore system for bunkering LNG from a floating jetty where the distance between the shore and floating jetty is often more than $5m - 10m$

[74], mitigation systems lose effectiveness. Additionally, the connection to the bunker receiving vessel can contribute between 26.6% and 45% of the leak frequency [75], thus there is a point of failure for the nearshore systems that are out of the optimal control range of the considered mitigation systems. Therefore, it is concluded that onshore systems offer the safest bunker location, followed by nearshore and finally offshore systems.

Reliability

It is possible for a port to offer more controlled conditions due to implemented protection from the wave conditions of the open sea. Waves are reduced due to shore banks, and an increase in obstacles provides natural protection from wind. This means that there is a higher probability for safe working conditions in port, than in offshore conditions. Nearshore systems are able to follow the movements of the bunker receiving vessel, whether this is riding waves or pivoting due to changing wind. Less relative motion between the jetty and the vessel creates more robustness to weather influences, preventing calamity and thus downtime. Onshore systems, however, offer a stable quay to prevent pivoting motion, but travel from and to this quay is often restricted in high wind conditions.

The Beaufort wind scale offers insight into the correlation between wind and waves. For the LNG Gate Terminal, travel from and to the jetties is no longer allowed with winds reaching 6 on the Beaufort scale [66], this correlates to a wave height of $3m - 4m$ at sea [106]. Typical nearshore systems are able to operate in waves with a significant wave height of $2.5m$ and maximum wave heights of $5m$ [105]. Thus, since travel is restricted for vessels before the safe working conditions are exceeded for nearshore systems, it is concluded that the reliability for bunker locations is best for nearshore systems, followed by onshore systems and finally for offshore systems.

Bunker Time

Bunker time for onshore systems is dependent on the time it takes a ship to navigate to the quay, this is assumed to be the dominating factor for bunkering onshore. When considering the manoeuvring of vessels, the nearshore systems have the advantage of being able to dock to a ship, regardless of orientation. This is not the case with on- and offshore systems. Systems such as the IQuay are pushed into position by use of tugs [74], which also takes time. However, this positioning can also be done by the jetty itself, by use of electronic motors. Furthermore, between two and eight mooring lines are needed to secure the vessel, depending on weather conditions. Nearshore systems remove the need for mooring teams and therefore mooring is possible in under a minute [74]. Transfer rates are not necessarily dependent on bunker location, since all locations could accommodate multiple pumps to reach arbitrary transfer rates. The above-mentioned arguments lead to the conclusion that bunker time is best for nearshore systems, followed by offshore systems and finally onshore systems.

Overview

The above-mentioned findings have been summarized in Table 5.6.

Table 5.6: p_{ij} values for the means that fulfil the function: Bunker Location. A score of 3 indicates the best score, and a score of 1 indicates the worst score

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Onshore	3	3	3	2	1
Nearshore	2	2	2	3	3
Offshore	1	1	1	1	2

5.2.7. Substance Slip Prevention

Cost

The cost associated with a low-tech spray nozzle over several places in the installation is considered to be lower than more complex gas detection units. Even when considering water pumps that might be necessary, the low-pressure pumps required to spray water at the required locations will not exceed the cost of gas detectors, which can be found commercially available exceeding $€2,000$.

Energy Efficiency
From an energy efficiency point of view, there exists a larger energy usage with the water spray systems than with a gas detection system, which only requires energy to power its electronic systems. The water pumps that are required to be run for the water spray system to operate will require more energy, even though they are only active when a bunker operation is being performed. Furthermore, the water will probably be recycled from a sustainability point of view and thus needs to be decontaminated. This process will also cost energy.

Safety
Gas detectors in combination with an ESD system will only pick up the leaking gas once it has reached the sensor of the detector. The following ESD signal will shut down the system. In the case of an open path gas detector system, which uses two cameras over the transfer pipes for immediate detection, potentially unnoticed gas buildup due to a leak can be prevented through quick detection.

The water spray system over the manifold and other leak-prone objects creates a passive mitigating effect, rather than only shutting down the system to prevent more gas from escaping. However, it is impractical to cover all systems with a permanent water blanket. This is due to increased slipping hazards, for instance. Therefore, the combination of these two systems offers a complimentary coverage of passive mitigation of leak-prone objects as well as detection of other less common leakages.

Even though a passive water spray system might be able to detect excessive amounts of ammonia in its wastewater, and thus be able to detect leaks, it does not offer the overall coverage of gas detectors.

Reliability
Gas detection systems will be able to detect ammonia leakages and shut off valves or the entire system, this will ensure a calamity for the system. Even when small leakages build up enough to trigger gas detection systems, a calamity will occur. On the other hand, a passive water spray system will be able to mitigate small leaks over leak-prone objects. When excessive amounts of ammonia are detected in the wastewater, a targeted inspection can be executed. The difference is that this can be done after the bunker operation, thus averting a calamity. A combination of the two systems is still equal to the performance of the water spray with respect to this criterion.

Bunker Time
There is no discernible difference in bunker time, considering the implementation of either or both of the systems.

Overview
The above-mentioned findings have been summarized in Table 5.7.

Table 5.7: p_{ij} values for the means that fulfil the function: Substance Slip Prevention

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Gas Detectors with ESD	2	2	2	1	1
Water Spray System over Leak-prone Areas	3	1	1	2	1
Combination of the two systems	1	1	3	2	1

5.2.8. Toxic Cloud Mitigation

Cost
A mesh barrier is a passive mitigation strategy for toxic cloud mitigation. The barrier material can be

made from any cheap material and requires no maintenance or power, therefore making it a very cost-effective mitigation strategy if its working principle fits the end user.

A water curtain is an active system. Even though the spray medium, water, is abundant, there exists non-negligible CapEx with regards to installing pumps, trigger systems and electronics. Furthermore, because this is an active system, testing will have to occur. This testing and the included maintenance will increase OpEx. Even though these costs exist, due to the low complexity of the system and commercial availability of the parts, literature refers to this mitigation strategy as ”low cost” [78].

For a mitigation strategy that uses overpressurisation of volumes in which vulnerable persons could be present, there exist multiple cost-increasing features. For instance, this system is in need of constant pressure regulation. Pumps would have to be running constantly in order to maintain positive pressure with respect to the atmosphere. Furthermore, it needs to be ensured that windows and doors are sealed appropriately in order to minimize pressure loss. Since this is a building-wide system, which has to be active on all workdays, this is considered the most costly system. Furthermore, cost scales with the number of buildings that need to be protected.

The combination of a mesh barrier with the overpressurisation strategy would not differ much in overall cost with respect to only using the overpressurisation strategy, due to the low cost of the mesh barrier. The combination of the water curtain with the overpressurisation strategy would impose the most cost considering all other alternatives.

Energy Efficiency
Due to the passive nature of the mesh barrier, it is considered the most energy-efficient solution. Followed by the water curtain, which is only active when testing or when a toxic cloud is present. Finally, the constant maintenance of the positive pressure that allows overpressurisation to work, causes it to have a relatively low energy efficiency.

Combining the mesh barrier with the overpressurisation mitigation strategy equals the energy usage of only the overpressurisation mitigation strategy, due to the passive nature of the mesh barrier. However, when a mesh barrier is used and thus the toxic cloud is kept from freely dispersing, it is possible that fewer buildings need to be pressurised to reach the same reduction in exposure risk. Less active systems reduce the amount of energy needed. The combination of a water curtain with the overpressurisation strategy would create the least energy-efficient solution.

Safety
The working principle of mesh barriers is to keep the ammonia cloud from rising vertically. If there is elevated terrain surrounding the release site, or some other natural or artificial barrier, the mesh barrier keeps the ammonia cloud low to the ground such that those barriers can impede inland migration of the cloud. This strategy, however, is very susceptible to strong winds, for instance. If there is no further action to remove the toxic cloud, the influence of wind could potentially still allow the cloud to migrate inland.

A water curtain is an adequate mitigation strategy for ammonia toxic clouds. Being able to dilute these clouds, and mitigate their spread. The effectiveness in reducing the toxic cloud can be up to 90% up to $10m$ behind the water curtain [78]. This would have a large impact on reducing the size of the risk contours surrounding a bunker installation where this system would be present.

Overpressurisation of vulnerable objects surrounding a bunker installation can prevent the toxic cloud from affecting the people inside. However, animals and persons outside of these safe zones are still at risk. Since the toxic cloud can potentially drift several kilometres inland [81], there can potentially be a lot of buildings that need this system installed. With an increasing number of people, the chances of them not being indoors increases. This is still the case if there is some kind of alarm in place. Therefore significant risk remains if this strategy is used by itself.

Combining the overpressurisation strategy with a mesh barrier can potentially impede the inland migration of the toxic cloud. Because of the mesh barrier, fewer buildings within the originally affected area would have to be protected. However, this combination does not affect the drawbacks of either of the mitigation strategies, therefore combining them still leaves significant risk.

Finally, the combination of a water curtain with the overpressurisation strategy can enhance total risk reduction. As stated before, the effectiveness of a water curtain is not 100%. Though significant reduction is possible, there exists the possibility of a percentage of the toxic cloud reaching vulnerable objects. Overpressurising these objects, or creating pressurised safety zones in combination with an alarm, could amount to a minimized risk scenario.

Reliability
The mesh barrier, due to its passive nature, can be considered to be very reliable. There are no moving parts that can potentially halt the operation of the mitigation system. Since the water curtain only needs to be activated in case of a loss of containment, with proper testing, it has little risk of failure and can therefore be considered to be reliable. The overpressurisation strategy is considered to be less reliable than the other two separate systems. Because it is a system under continuous operation, any downtime affects the effectiveness of the mitigation strategy.

The combination of implementing a mesh barrier with over-pressurising buildings in close proximity can potentially improve the reliability of the system by reducing the number of buildings that need to be pressurised, thus reducing points of failure. The combination of a water curtain with the overpressurisation strategy can potentially further reduce the number of buildings that need to be pressurised.

Bunker Time
There is no discernible difference that the choice of toxic cloud mitigation strategy might have on the bunker time associated with the installation. Since these strategies do not interfere with regular bunker procedures and are only activated in case of an unintended release.

Overview
The above-mentioned findings have been summarized in Table 5.8.

Table 5.8: p_{ij} values for the means that fulfil the function: Toxic Cloud Mitigation

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Mesh Barrier	5	5	1	5	1
Water Curtain	4	4	4	4	1
Overpressurisation	3	2	2	1	1
Mesh Barrier + Overpressurisation	2	3	3	2	1
Water Curtain + Overpressurisation	1	1	5	3	1

5.2.9. Additional Spill Containment

Cost
The cost of the additional spill containment goes up with the addition of more spill mitigation technologies. The passive bund dyke has little to no OpEx. The modified carbon nano-particles will have to be replaced after a spill, leading to more OpEx.

Energy Efficiency
There is little to no discernible difference in energy efficiency concerning the considered additional spill containment strategies because all three options are passive. Only the carbon nano-particles could need processing after use, but this is not considered in this analysis.

Safety
Additional containment layers will intuitively increase safety. However, only the single and double con-

tainment vessels will have non-negligible risk reduction through the application of these additional spill containment strategies. This is due to the fact that a full containment option already has secondary containment built into the design.

Reliability
A bund dyke will increase the reliability of the installation by allowing the contained liquid to be pumped away, allowing for quicker restarting of the installation. The addition of carbon nano-particles can increase the speed of this containment process, while also preventing more off-gassing. Thus decreasing the time before the installation can restart.

Bunker Time
There is no discernible difference that the choice of additional spill containment might have on the bunker time associated with the installation. Since these strategies do not interfere with regular bunker procedures and are only activated in case of an ammonia spill.

Overview
The above-mentioned findings have been summarized in Table 5.9.

Table 5.9: p_{ij} values for the means that fulfil the function: Additional Spill Containment

	Cost	**Energy Efficiency**	**Safety**	**Reliability**	**Bunker Time**
None	3	1	1	1	1
Bund Dyke	2	1	2	2	1
Bund Dyke + Carbon Nano-particles	1	1	3	3	1

5.2.10. BOG Vapor Pressure Equalisation

Cost
The CapEx that is associated with a BOG return system, consists of extra plumbing and a secondary connection hose. The OpEx would revolve around the maintenance of this system, but due to the low complexity and impact, it is assumed to be of low cost.

Relieving gas into an external tank, whether that tank is placed at the terminal side or the ship side of the installation, will increase CapEx more than using existing storage. Although it can be assumed that ship-side instalment will be the most costly, due to the limited and expensive space it will occupy there. The OpEx associated with maintenance and further installations necessary here will also be higher, due to the fact that more storage tanks and associated systems need to be maintained.

Finally, relieving excess pressure into the atmosphere through a vent equipped with a scrubber will be the least cost-efficient solution. As mentioned in Section 5.2.7, the cost of a scrubber citric acid scrubber is $€3.43$ per gram removed nitrogen. Furthermore, there is a cost associated with the placement of the scrubber system and the lost, or to-be-reclaimed ammonia.

Energy Efficiency
The BOG return hose and corresponding plumbing will form a connection from the receiving tank, back to the storage. The pressure-increasing effect of the BOG at the receiving tank side, and the pressure decrease at the supply tank due to lower levels of fuel will create passively actuated flow through the BOG return hose. This removes the need for active pressure equalisation, thus creating an energy-efficient system.

For some fuel applications, the liquid ammonia first has to be evaporated back to its gaseous state [31]. If a buffer tank that is used in the bunkering process to relieve pressure build-up due to BOG is installed on the ship side, then this fuel would be ready to use for as and therefore could provide an energy-efficient solution. However, since liquid ammonia takes up 850 times less space than gaseous ammonia, as seen in Section 2.2, this ship-side buffer tank will potentially have to be very large. On the other hand, if the buffer tank is to be installed on the terminal side, the situation is different. There might exist a need to pump away or reliquefy the ammonia gas so it can be used for a subsequent bunker action, which will cost energy. Therefore, making this option less energy efficient.

A vent with a scrubber is a passive solution that can equalize pressure if the pressure in the receiving tank becomes too high. There might be additional energy requirements associated with reclaiming the ammonia from the scrubbing medium, thus making this a moderately energy-efficient solution.

Safety
The BOG return line does form a closed system with the fuel supply system and therefore can be concluded to be a safe option. However, the impermanent connection does allow for an extra point of human error.

The buffer tank also forms a closed system with the fuel supply system. However, if the buffer tank is installed on the ship side of the installation, there might not be enough volume to handle all the BOG, leading to overpressure. This makes this option less safe than the BOG return hose.

A vent with a scrubber will not be able to scrub a 100% of the ammonia from the vent exhaust. Especially when less of the scrubbing medium becomes available due to operation, there will be a decrease in performance [107]. The possibility of ammonia being vented to the atmosphere so regularly due to this option being employed as a pressure regulating measure impacts safety very negatively.

Reliability
Since the BOG return hose is a passive system, there are not a lot of points of failure. Regular inspection of the plumbing and connecting hose will prevent major downtime. Furthermore, since there is no complex or relatively expensive technology, spare parts can be kept on-site to keep downtime to a minimum.

The buffer tanks failing can cause severe downtime. This is due to the larger amounts of ammonia that are stored here, and the inability to easily replace these tanks. There exists technology, such as full containment vessels, that can continue operation in the case of primary tank failure and thus this is still a reliable option.

A vent with a scrubber is not a reliable way of equalizing the BOG pressure-increasing effect. The scrubbing medium will have to be replaced regularly, which will inhibit operation and thus cause downtime.

Bunker Time
The BOG return hose will positively impact bunker times. This has been demonstrated in practice with LNG bunker processes as mentioned in Section 2.3.4.

The buffer tank might have a similar positive effect on bunker times as the BOG return hose. Due to the pressure relieving effect, which allows higher flow rates into the receiving tank. However, the buffer tank is limited by its size, and therefore might only have a limited effect.

A vent with a scrubber can potentially have a positive effect on the bunker time as it will be able to relieve all excess pressure into the atmosphere. However, there might also be additional time associated with checking the integrity of the scrubbing medium.

Overview
The above-mentioned findings have been summarized in Table 5.10.

Table 5.10: p_{ij} values for the means that fulfil the function: BOG Pressure Equalisation

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
BOG Return Hose	3	3	3	3	3
Relieve Gas in Buffer Tank	2	1	2	2	1
Vent with Scrubber	1	2	1	1	2

5.2.11. Insulation

Cost
The cost comparison of vacuum insulation versus mechanical insulation is complex. Mechanical insulation has a lower OpEx than the more complex vacuum technology [86]. However, mechanical insulation will start to draw in moisture when cooled. This moisture will freeze and deteriorate the material, forcing regular maintenance of the insulation. There are many different types of vacuum insulation, such as with aerogel in the annular space or static/dynamic vacuums, which create different cost profiles. For example, the vacuum in dynamic vacuum insulation will have to be maintained, which will increase OpEx due to running vacuum pumps. Aerogel vacuum insulation still allows significant heat to reach the medium and static vacuum tubes are very expensive to produce, but they will offer a superior insulation value. Curtis (2007) implies that piping with a length of over $200m$ can start to become a viable economical candidate for vacuum insulation [86] in the case of handling LNG.

It can be determined that vacuum-insulated pipe has a higher CapEx than mechanical insulation [108]. The typical advertised use case for vacuum insulation is for handling LNG. The large temperature gradient of LNG with the atmosphere makes insulation very important, and this greater gradient will cause mechanical insulation to deteriorate fast. Furthermore, it will cause significant costs in compensating for the lesser insulation value due to BOG and reliquefaction. In the case of liquid ammonia, the temperature gradient is much smaller. This means less moisture will be pulled into the mechanical insulation, which will decrease degradation speed. Furthermore, following Equation (5.1) which denotes the heat influx into a pipe, the heat influx is lower because of the lower temperature gradient.

$$Q = k \cdot A_2 \cdot \frac{(T_1 - T_2)}{r_2 \cdot ln(\frac{r_2}{r_1})} \tag{5.1}$$

Where, Q denotes the heat gain in W, k is the thermal conductivity in W/mK, A_2 is the outer surface of a pipe in m^2, and r_1 and r_2 are the inner and outer radii of the pipe in m, respectively.

The thermal conductivity of high-performance mechanical insulators, such as polyisocyanurate, around pipes, has a value for k between 0.022 and 0.035 W/mK [109], whereas vacuum insulated pipe can reach k values of 0.008 W/mK [110]. Therefore, the insulating value of vacuum insulation is $8 \cdot 10^1$ % better than that of mechanical insulation. In spite of this superior insulation value, the lower temperature difference with the atmosphere in the case of liquid ammonia will increase the economically viable pipe length beyond the previous minimum of $200m$. In the case of the LNG jetty in the Gate Terminal, distances from tank to jetty do not exceed $40m$ [66]. Therefore it is concluded that mechanical insulation is the more cost-effective choice.

Energy Efficiency
In terms of energy efficiency, the superior insulating properties of vacuum insulation make it the more energy-efficient choice. This way of insulating will keep the most amount of energy from entering the system.

Safety
There is no hermetic seal created by the mechanical insulation, and due to impurities and/or degradation, it could create a way for ammonia to escape in case of pipe failure. In the case of vacuum insulation, a double containment layer is present[111][86]. Therefore it can be seen as safer than mechanically insulated pipes.

Reliability
Due to the constant degradation of the mechanical insulation in regular operation, it will require regular checks and maintenance. Vacuum insulation is advertised as having $25+$ years of maintenance-free operation, as well as an anticipated design life of over 40 years [83]. This makes vacuum insulation the superior choice in terms of reliability.

Bunker Time
There are similar pipe diameters available for both pipes with mechanical and vacuum insulation. Therefore, there is no apparent distinction in flow rates possible. Because the integrity of the mechanically insulated pipe might have to be checked in a pre-check procedure, this can affect bunker time.

Overview
The above-mentioned findings have been summarized in Table 5.11.

Table 5.11: p_{ij} values for the means that fulfil the function: Insulation

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Mechanical Insulation	2	1	1	1	1
Vacuum Insulation	1	2	2	2	2

5.2.12. Purging of Fuel Lines

Cost
In terms of cost, the difference between the two systems lies in the way the gas is handled at the end of the system. The CapEx of a fractional distillation unit can quickly exceed $€350,000$ [112]. Acid scrubbers are commercially available at much lower prices, less than a thousand [113]. Furthermore, the OpEx associated with heating is considered to be higher than with pumping and spraying. Even though the citric acid costs $€3.96$ per gram removed nitrogen [107], this is negligible considering the difference in CapEx.

Energy Efficiency
Between the two systems, the required energy to boil the gas mixture for separation is much higher than the systems that are used to pump the citric acid through the scrubber. Therefore, the citric acid scrubber is found to be the most energy-efficient solution.

Safety
The fractional distillation column is part of a fully closed system. The citric acid scrubber is only about 90% effective. There exists a bigger risk of exposure to ammonia in the case of the citric acid scrubber.

Reliability
The fact that the scrubber can run out of scrubbing medium, as well as its 90% efficiency, creates a risk for calamity. However, because both systems could potentially work more efficiently from a buffer tank, there is no real discernible difference in downtime prevention on the total system.

Bunker Times
The choice of fuel line purging system can increase bunker time, as it needs to be completed before the fuel lines can be disconnected. However, since the distinction here is focused on the handling of the gas mixture at the end of the system, there is no discernible difference in bunker time between the two options.

Overview
The above-mentioned findings have been summarized in Table 5.12.

Table 5.12: p_{ij} values for the means that fulfil the function: Purging of Fuel Lines

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Inerting Sequence with Scrubber	2	2	1	1	1
Inerting Sequence with Gas Separator	1	1	2	1	1

5.3. Conclusions

This section will give an overview of the findings of this chapter, as well as the answer to the fourth sub-question.

The BWM requires an objective analysis as input, with subjective decision-making based on stakeholder input. The objective part of this analysis is done by evaluating the discovered solutions based on design criteria. These design criteria are: cost, energy efficiency, safety, reliability and bunker time. These criteria were based on important parameters in a bunker process that is part of a supply chain and challenges associated with alternative fuels. An overview of the results of the ordinal analysis based on the aforementioned design criteria is given in Table 5.13.

Table 5.13: Overview of the results of the ordinal analysis.

		Cost	**Energy Efficiency**	**Safety**	**Reliability**	**Bunker Time**
Conducting	Dry Rigid Pipe	3	3	3	3	3
	Dry Flexible Pipe	2	2	2	2	2
	Floating Flexible Pipe	1	1	1	1	1
Actuating	Dry Mechanically Sealed Pump	4	1	1	1	4
	Submersed Mechanically Sealed Pump	1	2	2	2	3
	Dry Mag-drive Pump	6	3	3	3	4
	Submersed Mag-drive Pump	3	5	4	4	3
	Dry Canned Motor Pump	5	4	5	5	2
	Submersed Canned Motor Pump	2	6	6	6	1
Connecting (hose)	Suspended Hose	2	2	2	2	2
	Floating Hose	1	1	1	1	1
Connecting (coupling)	Dry Disconnect Coupling	3	2	1	1	1
	Beak Away Coupling	2	2	2	3	1
	PERC	1	1	3	2	1
Bunker Location	Onshore	3	3	3	2	1
	Nearshore	2	2	2	3	3
	Offshore	1	1	1	1	2
Storing	SC Flat bottom	6	2	1	1	1
	SC Bullet	3	1	2	2	1
	DC Flat Bottom	5	2	4	1	1
	DC Bullet	2	1	3	2	1
	FC Flat Bottom	4	4	6	3	1
	FC Bullet	1	3	5	3	1
Substance Slip Prevention	Gas Detectors with ESD	2	2	2	1	1
	Water Spray System over Leak-prone Objects	3	1	1	2	1
	Combination of the Two Systems	1	1	3	2	1
Toxic Cloud Mitigation	Mesh Barrier	5	5	1	5	1
	Water Curtain	4	4	4	4	1
	Overpressurisation	3	2	2	1	1
	Mesh Barrier + Overpressurisation	2	3	3	2	1
	Water Curtain + Overpressurisation	1	1	5	3	1
Additional Spill Containment	None	3	0	1	1	1
	Bund Dyke	2	0	2	2	1
	Bund Dyke + Carbon Nano-particles	1	0	3	3	1
Insulation	Mechanical Insulation	2	1	1	1	1
	Vacuum Insulation	1	2	2	2	2
BOG Vapor Pressure Equalisation	BOG Return Hose	3	3	3	3	3
	Relieve Gas in Buffer Tank	2	1	2	2	1
	Vent with Scrubber	1	2	1	1	2
Purging of Fuel Lines	Inerting Sequence with Scrubber	2	2	1	0	1
	Inerting Sequence with Gas Separator	1	1	2	1	1

6

Case Study Results

This chapter will perform the subjective part of the BWM analysis. Input from stakeholders is needed to finish the BWM analysis, these stakeholders will be introduced in section 6.1 and the results of the BWM analysis are presented in Section 6.2. A sensitivity analysis to gain insight into the robustness of the results is performed in Section 6.3 and finally the viability of the result is tested by checking if all design requirements are met in Section 6.4. This information will lead to the answer to the fifth sub-question:

What design do stakeholders from a suitable port for sea-going vessels such as The Port of Rotterdam prefer, and is this configuration viable?

6.1. Stakeholder Survey

To create a configuration that is suitable for The Port of Rotterdam, stakeholders from this port need to be surveyed. The survey that is used is based on J. Rezaei (2015) [91], and can be found in Appendix B. For this, three terminals within the Port of Rotterdam have been asked to take part in the survey. These terminals are:

1. The Gate Terminal
2. The ACE Terminal
3. OCI N.V.

The Gate Terminal is the LNG hub of Europe. A professional access gateway for LNG that is supplied from across the world. Because of its international connections, it is a representative candidate for evaluating the design criteria. LNG bunkering shares some similarities to ammonia bunkering and since this terminal is already familiar with building bunkering infrastructure in the Port of Rotterdam, it is an interesting candidate for creating a representative overview of the values of said port.

The ACE terminal is a terminal situated on the Maasvlakte in the Port of Rotterdam, which aims to store hydrogen in the form of ammonia. In their planned location, they aim to offer cracking facilities to convert the ammonia back to hydrogen to be used for their customers. This terminal will be receiving and storing ammonia and could therefore be indicative of the considered concerns associated with handling and storing ammonia. Thus, this terminal is interesting to survey for this research.

Finally, OCI N.V. is going to expand to The Port of Rotterdam by creating an ammonia import terminal. This terminal will be involved with facilitating ocean-going vessels with ammonia as well as being an ammonia hub for imported hydrogen in the form of ammonia. Furthermore, they aim to create scalable ammonia jetty infrastructure that is very similar to the goal of this study, making them an interesting candidate.

Based on the survey that has been filled out by the aforementioned stakeholders of the port of Rotterdam, calculations for finalizing the BWM can be carried out. Each of the stakeholders provided a Best-to-Others vector, and a Others-to-Worst vector, corresponding to Equations (4.5) and (4.6), respectively. These can be found in Appendix C. The weights and consistency ratio are calculated through the solver based on the linear model provided by Rezaei (2016) [92]. This solver is based on Equations (4.7), (4.8) and (4.9). The results can be found in Table 6.1.

Table 6.1: Optimal weights based on survey results of each respondent

Resp.	**Cost**	**Energy Efficiency**	**Safety**	**Reliability**	**Bunker Time**	**CR**	**CR Acceptable (y/n)**
Gate Terminal	0.182	0.0909	0.409	0.273	0.0455	0.232	y
Ace Terminal	0.228	0.152	0.400	0.0690	0.152	0.200	y
OCI Terminal	0.0520	0.141	0.587	0.141	0.0784	0.222	y

Finally, by filling out Equation (4.2) with the results from Section 5.2 and Table 6.1, the final scores of the alternatives can be calculated. These final scores will determine the final configuration of alternatives per stakeholder. These results will be compared and discussed.

6.2. Results

In this section, the resulting configurations from the BWM will be shown and discussed. This will result in a configuration that most accurately represents the values of three large terminal operator stakeholders situated in the Port of Rotterdam. The separate resulting configurations of each stakeholder can be found in Table 6.2. The full calculation results can be found in Appendix D.

Table 6.2: Bunker installation configurations resulting from the Best Worst Method based on the weights generated by three stakeholders in The Port of Rotterdam.

Functions	Gate Terminal	ACE Terminal	OCI
Storing	FC Flat Bottom	FC Flat Bottom	FC Flat Bottom
Conducting	Dry Rigid Pipe	Dry Rigid Pipe	Dry Rigid Pipe
Actuating	Submersed Canned Motor Pump	Dry Canned Motor Pump	Submersed Canned Motor Pump
Connecting (hose)	Suspended Hose	Suspended Hose	Suspended Hose
Connecting (coupling)	Beak Away Coupling	Beak Away Coupling	PERC
Bunker Location	Onshore	Onshore	Onshore
Substance Slip Prevention	Gas Detectors with ESD + Water Spray System over Leak-prone Objects	Gas Detectors with ESD + Water Spray System over Leak-prone Objects	Gas Detectors with ESD + Water Spray System over Leak-prone Objects
Toxic Cloud Mitigation	Water Curtain	Water Curtain	Water Curtain
Additional Spill Containment	Bund Dyke + Carbon Nano-particles	Bund Dyke + Carbon Nano-particles	Bund Dyke + Carbon Nano-particles
BOG Vapor Pressure Equalisation	BOG Return Hose	BOG Return Hose	BOG Return Hose
Insulation	Vacuum Insulation	Vacuum Insulation	Vacuum Insulation
Purging of Fuel Lines	Inerting Sequence with Gas Separator	Inerting Sequence with Gas Separator	Inerting Sequence with Gas Separator

It becomes clear from Table 6.2 that there are many similarities between the configurations of stakeholders. All three stakeholders selected safety as their most important criterion, and all three chose different least important criteria. Bunker time, reliability and cost, respectively. These factors, alongside the different weights and the results from the ordinal analysis, resulted in final configurations that differed only in a submerged or dry-installed version of the canned motor pump for the actuation function, and the breakaway coupling or the PERC for the connecting (coupling) function. Where, both the Gate and ACE terminals opted for a breakaway coupling, as opposed to the PERC for OCI. Additionally, both the Gate Terminal and OCI opted for a submersed canned motor pump, whereas the ACE terminal opted for a dry canned motor pump.

6.3. Sensitivity Analysis

Due to the complex relationships that result in the final scores of the alternatives, it is difficult to say if a small difference in the final score indicates that it actually was a close choice. In other words, if a close final score actually meant a small difference in the Best-to-Others and Others-to-Worst vectors from Vectors (4.5) and (4.6), respectively. Based on Muzarek et. al (2021), by looking at the influence of small variations in the aforementioned vectors, insight into the robustness of the final configuration can be found [114]. Here, attention is also paid if an order violation occurs, meaning a different alternative becomes the best alternative. For this research, the occurrence of an order violation following a small change in Vectors (4.5) and (4.6) is interpreted as the new best alternative lying close to the interests of the stakeholder.

The results of this analysis can be found in Appendix C. From these results, it becomes clear that there are only a small amount of order violations following the analysis. When a change in the Vectors (4.5) and (4.6) caused the CR to become unacceptable, the result is not taken into account. The remaining instances are listed below:

Gate Terminal

1. Decreasing the cost criterion value in Vector (4.5) (Best to Others) causes the configuration to change to include a dry-installed canned motor pump.

ACE Terminal

1. Increasing the cost criterion value in Vector (4.5) (Best to Others) causes the configuration to change to include a submersed canned motor pump.
2. Decreasing the safety criterion value in Vector (4.6) (Others to Worst) causes the configuration to change to include an inerting sequence with a scrubber.

OCI NV

- There were no changes in the configuration after changing the values in either vector.

The results from this analysis point to an overall robust choice of alternatives except for the functions: actuating, and purging of fuel lines. Here, a perturbation causes the actuating function to switch from dry installed to submerged canned motor pumps and vice versa, depending on which of two is the starting result. This indicates that for a general configuration, choosing either option will still represent the overall interests of the stakeholders closely. Furthermore, even though the inerting sequence with a gas separator is considered to represent the interests of the stakeholders best, the results from at least one stakeholder are sensitive to the choice for this function, due to the order violation occurring.

6.4. Testing

To ensure the feasibility of the resulting configuration, infeasible combinations must be removed if they are present. To test the viability of the resulting configuration, it must be checked if none of the requirements are violated. These two tests will be executed in this section.

6.4.1. Requirements

The requirements that were stated in Section 2.4 will be repeated here:

1. It is required to have exposure prevention and mitigation systems in place with the goal of mitigating the toxic hazard associated with ammonia, in case of an unintended release
2. It is required to have a location that is suitable such that, in case of an unintended release, there are acceptable risks of exposure to surrounding structures, people and other vulnerable objects
3. It is required that the design be able to bunker the largest vessels in service. The largest vessel currently in service, the MSC Irina, has a Dead Weight Tonnage (DWT) of around $240,739$
4. It is required that the materials used in the design are able to withstand the corrosivity of ammonia
5. It is required that there be systems and protocols in place that have the absolute goal of preventing an explosive mixture from forming
6. It is required to have systems and protocols in place that have the absolute goal of preventing ammonia leakage into the atmosphere
7. It is required that the design be able to minimize the heat influx at all storage and transfer media in order to keep ammonia in its liquid form
8. It is required that BOG and its consequent pressure-increasing effect is handled in the design
9. It is required that the flow velocity in the piping never exceeds the sonic velocity in liquid ammonia at $1,729 m/s$

There are several requirements that are inherently adhered to, because of the selection of components. These requirements are $1, 4, 5, 6, 7, 8$.

Requirements 2 and 3 are location-specific requirements that will require further investigation. To answer this question, a map of The Port of Rotterdam is shown in Figure 6.1

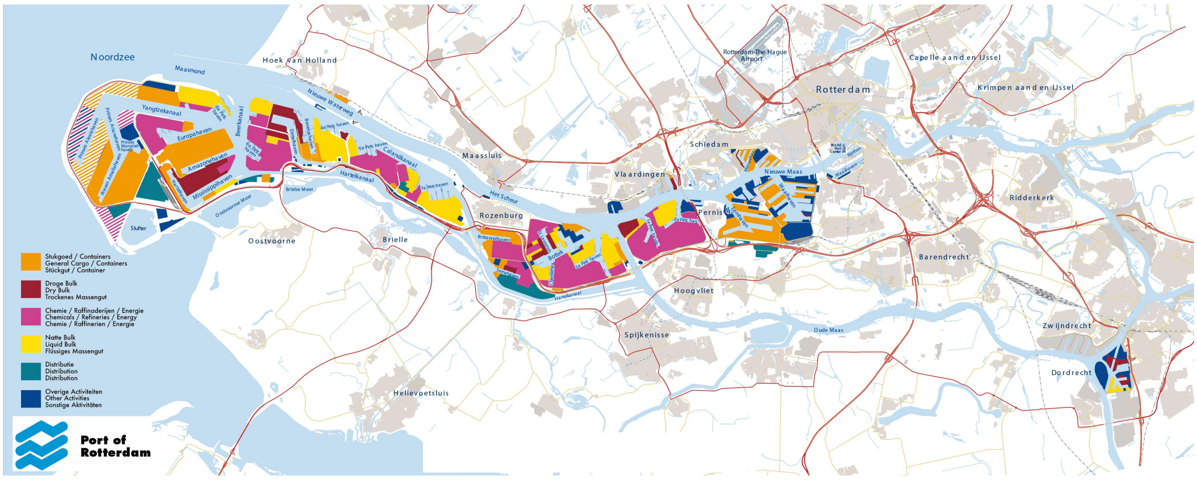


Figure 6.1: A map of the Port of Rotterdam, including different designated areas [115]

Both the Gate Terminal and the ACE Terminal, are located on the Maasvlakte. This location encompasses the leftmost edge of the coloured Port of Rotterdam area. The Maasvlakte II, which is still partially under construction, will offer more surface area for the development of extra port facilities, such as future ammonia terminals. This location offers a large distance from neighbouring cities and dwellings and direct access to the North Sea. It is desirable to have as much distance as possible between vulnerable objects, in order to satisfy LSIR contours. Furthermore, the direct access to the North Sea means that larger ships can bunker directly at the proposed bunker installation, thus not restricting the use of the installation to just bunker barges.

The depth of the fairways into the Maasvlakte is between $23m$ NAP to $24m$ NAP [116], this can also be seen in Figure 6.2. This means that classes of ships that have a Dead Weight Tonnage (DWT) of $300,000$ can safely pass into the port since their average draught is around 20m [117]. Since the DWT of the MSC Irina is around $240,739$ [118], it should be able to reach the proposed installation. If this is undesirable due to other influences, it can still be serviced by bunker barges. Thus satisfying requirement 3.

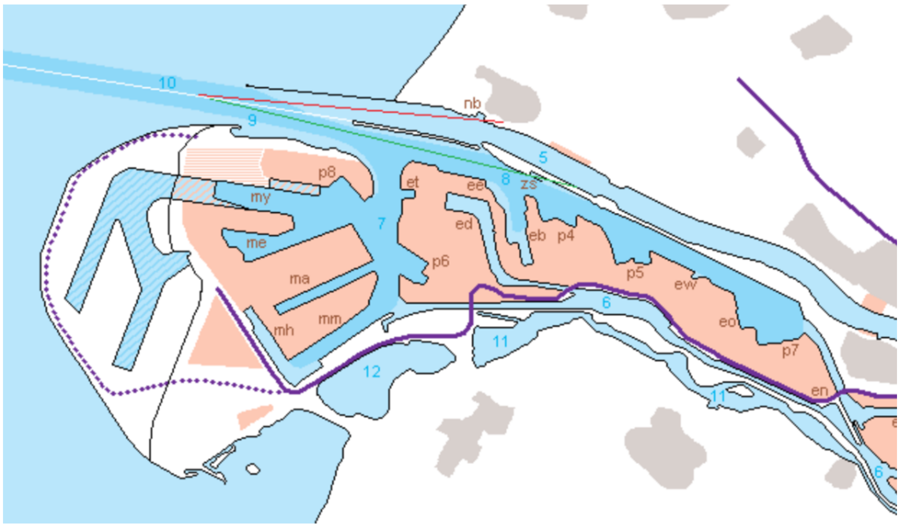


Figure 6.2: Water depth surrounding the sea-adjacent area of The Port of Rotterdam. (Source: Wikipedia)

The closest cities to the Maasvlakte II, are Hoek van Holland and Oostvoorne. These two cities are 4.32km and 6.25km, respectively, measured from the area that will become the Maasvlakte II. The Port of Amsterdam (2021) in their study, defined a $10^{-}6$ LSIR contour around a bunker operation concerning refrigerated ammonia to be 427 meters [29]. In this contour, there can be no vulnerable objects such as dwellings and residential areas. Furthermore, the focus area as defined by this same study, provides an area with a radius of $2624m$ in which people are insufficiently protected indoors against the consequences of accidents involving hazardous substances, without additional measures. The focus area is not restrictive on development, but indicative for relevant authorities to state what measures are sufficient to protect persons. Since both of these distances are smaller than the closest populated area, the Maasvlakte II is deemed as being sufficient for requirement 2.

Requirement 9, the requirement not to exceed the sonic velocity of ammonia in the piping, depends on a balance between pipe diameter and pump flow rate. From this research, it became clear that the flow rate of pumps is trivial. This is due to the fact that a set of multiple pumps, or a single large pump can produce virtually any flow rate. Certainly exceeding current $1000m^3/h$ LNG flow rates in the Gate Terminal that are used to fill bunker barges. Therefore this requirement remains a design specification of the system to be kept in mind when moving to a more detailed design.

Thus, it can be concluded that the design as it is generated for stakeholders from The Port of Rotterdam is able to adhere to all stated requirements.

6.4.2. Infeasible Combinations

There are several solutions that are infeasible to combine. These combinations need to be identified. These combinations will be used to evaluate the final configuration on feasibility, and if needed, adapted to become feasible. To do this, the component overview in Figure 3.18 will be analysed.

The selection of a flat-bottom tank, for instance, does not combine with an offshore design. Due to the size and weight of the storage technology, it is highly impractical to install this on any offshore installation. Therefore, in an offshore design, bullet tanks will be used instead of flat-bottom tanks.

Secondly, the selection of an onshore design will restrict the usage of floating pipes. It could still be possible for the connecting pipes from the terminal side to the ship side to be floating pipes, but it is not possible for the conducting pipes of a land-based installation to be floating.

Thirdly, the selection of an inerting sequence with a gas separator is considered infeasible for an offshore bunker installation due to its size.

These combinations do not occur in any of the stakeholder configurations.

6.5. Discussion

From the case study, it can be seen that there is a clear preferred combination of components. This can be seen in Table 6.2 Due to the overall consensus that safety is going to be very important if not the most important criterion when working with ammonia. This generally equal prioritisation between stakeholders creates less diversity in the final configurations, which presents itself as a robust result. It is possible that other ports that handle sea-going vessels have different secondary priorities which will most likely result in differences in the four categories that showed a more sensitive result: actuating, coupling, and purging of fuel lines. The only actual difference in the final result is seen as the difference between a submerged or dry-installed canned motor pump, and a break-away coupling or a PERC.

With regards to the pump, the results switch between the dry-installed and submersed versions of the canned motor pump as a result of small perturbations in the survey input for two of the stakeholders, indicating that both options represent the stakeholder interest very well. Since the final configuration of two out of three stakeholders chooses the submersed version, and the fact that a small perturbation in the input vector of the third stakeholder also results in the submersed version, it is concluded that this version represents stakeholder interests best.

With regards to the choice for a break-away coupling or a PERC for the final general configuration, the choice still falls to a break-away coupling. Since two out of three stakeholders included the break-away coupling in their final configuration. After this option, the PERC represents the interest of the stakeholders best.

The final configuration can be found in Table 6.3. A graphical representation of what such a configuration might look like in a terminal can be seen in Figure 6.3.

Table 6.3: Final configuration for the most viable bunker installation for ammonia for ports that handle sea-going vessels

Functions	Final Configuration
Storing	FC Flat Bottom
Conducting	Dry Rigid Pipe
Actuating	Submersed Canned Motor Pump
Connecting (hose)	Suspended Hose
Connecting (coupling)	Beak Away Coupling
Bunker Location	Onshore
Substance Slip Prevention	Gas Detectors with ESD + Water Spray System over Leak-prone Objects
Toxic Cloud Mitigation	Water Curtain
Additional Spill Containment	Bund Dyke + Carbon Nano-particles
BOG Vapor Pressure Equalisation	BOG Return Hose
Insulation	Vacuum Insulation
Purging of Fuel Lines	Inerting Sequence with Gas Separator

Figure 6.3: Real life terminal [119], with locations of components from Table 6.3 indicated

6.5.1. Desired Flow Rate Estimation

Since the bunker installation will be part of a supply chain, it can be informative to estimate the maximum required flow rate of the system. Since SimOps is probably not possible when bunkering ammonia, the current waiting times in The Port of Rotterdam can provide an estimation of the available extra time for such an exclusive bunker operation, whilst not disturbing the supply chain. Combining this data with the tank size of the MSC Irina, a minimal flow rate can be estimated. The Port of Rotterdam published data about the waiting times for container vessels [120]. In Figure 6.4 data is presented about the number of ships that are waiting at a specific time for the five considered ports. In Figures 6.5 and 6.6 data is presented about the total days that all waiting ships combined have been waiting at a specific time about the longest waiting vessel at a given time, respectively.

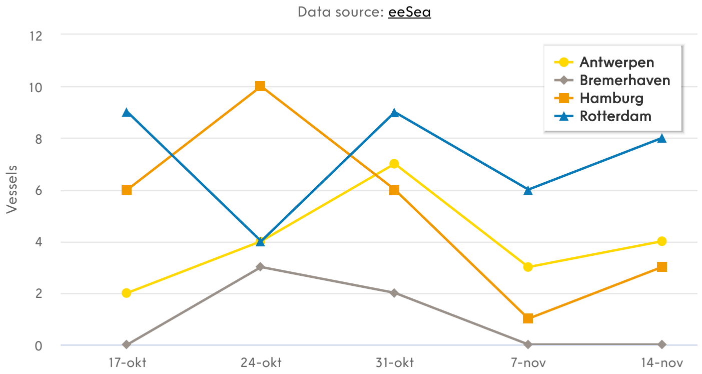


Figure 6.4: Port Performance Data for five ports. Number of ships waiting at a specific time [120]

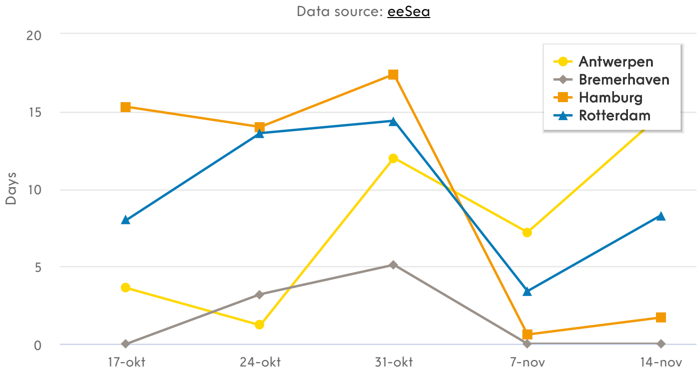


Figure 6.5: Port Performance Data for five ports. Total number of days waiting for all waiting ships combined at a specific time [120]

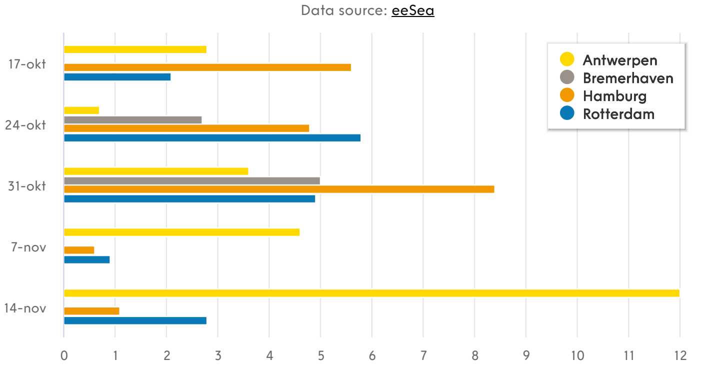


Figure 6.6: Port Performance Data for five ports. Longest waiting vessel at a specific time [120]

By combining data from Figures 6.4 and 6.5 an estimation can be made about how much a single ship is waiting at any given data point, i.e give insight into the average queue time for the considered ports. This queue time can then be used as an indication of the time a vessel would have to bunker fuel as an exclusive operation since this time would already be spent waiting. This data can optionally be corrected by subtracting the longest waiting ship to correct the average due to an outlier in the data. This should give a realistic estimation of waiting times over several Western European ports. The uncorrected and corrected data can be found in Figure 6.7 on the left and Figure 6.7 on the right, respectively.

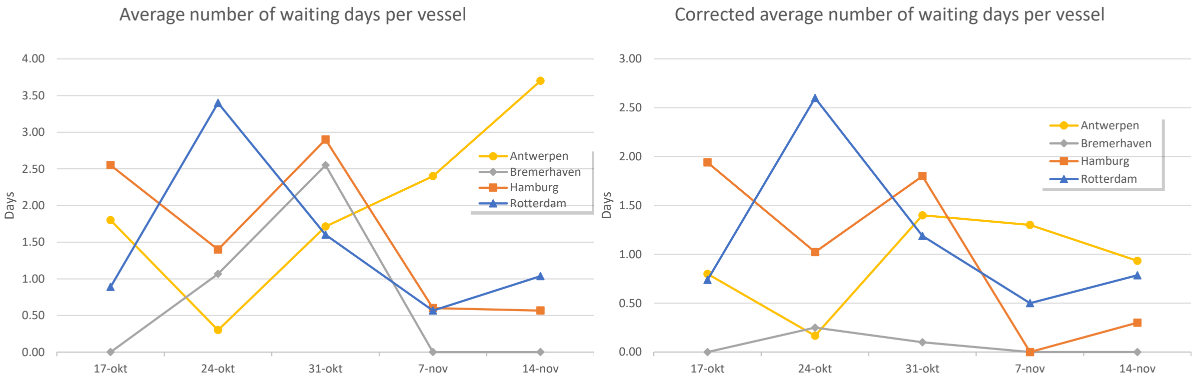


Figure 6.7: Days a container vessel spends waiting on average in the considered ports at a given time for all data (left) and corrected by removing the longest waiting ship (right)

If the average of the data per port from Figure 6.7 is taken, an average waiting time can be estimated for these ports. By taking the average of all four considered ports, a representative average of West-European ports can be found. This is done in Table 6.4.

Table 6.4: Number of days waiting per port averaged over all days and averaged over all ports. Both the uncorrected data and the data corrected by removing the longest waiting vessel

	Average waiting time	**Corrected waiting time**
Antwerpen	1.98	0.92
Bremerhaven	0.72	0.07
Hamburg	1.60	1.01
Rotterdam	1.50	1.16
Combined Average	1.45	0.79

The combined average from Table 6.4 gives an indication of the average available unallocated time a ship has in port due to queue times. This time is therefore available to be utilized for other purposes, such as performing an exclusive operation like bunkering ammonia. Therefore. this value sets a requirement for the maximum bunker time for the design. The flow rate of the system is required to be sufficient enough for the ship to bunker within a bunker time of 1.45 days, maximum. However, in the ideal case, the bunker time will not surpass 0.79 days.

Because of the unavailability of data about the exact tank size of the MSC Irina, an estimation is made with data from the CMA CGM Benjamin Franklin. This ship, which has 74% of the $24,346$ TEU capacity of the MSC Irina, carries 3.5 million gallons, or approximately $13,249\ m^3$ of fuel oil [121]. For this calculation, it is assumed that ships will not have space available to accommodate the extra volume required for an equal amount of energy when using ammonia. Thus, only correcting for the lesser carrying capacity of the CMA CGM Benjamin Franklin with respect to the MSC Irina, a tank size of approximately $16,700\ m^3$ is found.

Thus, the submersed canned motor pumps of the proposed configuration would need a flow rate of $480\ m^3/h$ to adhere to the uncorrected average waiting time, or $881\ m^3/h$ to adhere to the corrected average waiting time. These flow rates are also suitable for The Port of Rotterdam, due to both waiting times being longer for this port. As could be seen in Section 3.2.3, these flow rates are within the capacity of these pumps. Furthermore, the Gate Terminal currently bunkers LNG at $1000\ m^3/h$, further indicating that these flow rates are well within current possibilities.

6.5.2. Port Applicability

Even though the results are representative of terminals in the Port of Rotterdam, the expertise from the stakeholders does extrapolate to ports that handle sea-going vessels in general. There are several arguments that would support this conclusion. First, the fact that a stakeholder such as the Gate Terminal would come to a very similar result as two stakeholders that are specialised in ammonia, can indicate that a broader group of experts in bunkering will come to a similar result. Due to the noticeable difference in input vectors, and the subsequent similarity in results, in combination with the overall prioritisation of safety, it can be concluded that stakeholders in other ports will most likely not have vastly different configurations. This is further supported by the robustness of the results.

A separate argument for broader system viability, at least for ports situated in Western Europe, is given by the reasonable flow rates required to service the largest ships without disturbing the supply chain. The current average waiting times can be used to allow for exclusive ammonia bunkering at very manageable flow rates. This would mean that switching to ammonia is not likely to disturb current supply chain dependencies, which enables easier implementation of this new fuel.

Finally, there are specific requirements that can only be checked in a practical placement scenario, such as is done in the case study in Section 6. It is difficult to say if a configuration is generally viable for ports that handle sea-going vessels, without checking all ports individually and without performing a quantitative risk assessment. However, because of the effectiveness of mitigation strategies and the safety assurances of the technologies that are available, the LSIR contour will shrink substantially. Therefore, the final configuration, and its associated risk, are expected to be viable for most ports that handle sea-going vessels.

6.6. Conclusions

This section will provide an overview of the findings of this chapter, as well as the answer to the fourth sub-question as stated at the beginning of this chapter.

Stakeholder input from three terminals located in The Port of Rotterdam was collected. The considered terminals were:

1. The Gate Terminal
2. The ACE Terminal
3. OCI N.V.

The input from these stakeholders generated three configurations of solutions which can be found in Figure 6.2. A sensitivity analysis was performed to gain insight into the robustness of the result. The result was found to be robust. Still, a small number of sensitive areas were identified around: bunker location, actuating, and purging of fuel lines.

Testing of the configurations was done to see if they adhere to the requirements and to see if there were no infeasible combinations. Both of these conditions were met, therefore it is concluded that the configurations are viable.

Finally, the results were discussed. This lead to the final configuration that can be found in Figure 6.3. The difference in configurations between stakeholders around a dry-installed or submersed canned motor pump was resolved in favour of the submersed version. Due to the sensitivity analysis resulting in the dry-installed canned motor pump choice of the ACE Terminal changing to the submersed version. Thus arguing that this option also represents their interests well. Furthermore, to come to unify configurations, it is opted to include the breakaway coupling in the final configuration. This is done because the general stakeholder interests are respected best with this configuration.

A maximum flow rate estimation was made to see what flow rates are required to serve the largest vessels that might use the bunker installation, while not disturbing the supply chain that the system is a part of. In order to utilize extra unallocated waiting time due to port delays, a maximum flow rate of $881\ m^3/h$ is required. This is well within the possibilities of the desired actuating technology, and even below the current industry standard.

The broader applicability of the system is suggested due to several factors. The different areas of expertise of the stakeholders yield similar results. Other stakeholders will most likely prioritise safety as well, which means final configurations will not be vastly different. Finally, due to the effectiveness of mitigation strategies, LSIR contours will shrink substantially. Therefore, the final configuration, and its associated risk, are expected to be viable for most ports that handle sea-going vessels. Thus, an ammonia bunker installation that is viable for ports that handle sea-going vessels is configured.

7

Conclusion and Recommendations

In this chapter, first, the conclusion to the research is made by answering the research question in Section 7.1. Secondly, recommendations for future research are given in Section 7.2

7.1. Conclusion

This research is done to create a design for an ammonia bunker installation that is viable for ports that handle sea-going vessels. Because of the need for less polluting fuels for the shipping industry in order to adhere to the 2050 climate goals set by the IMO, ammonia is being put forward as a promising candidate for a zero-emission fuel. Ammonia is projected to make up 50% of the fuel mixture by 2050 as a possible path to adhere to these goals. However, there exist challenges that currently hinder the adoption of ammonia as a shipping fuel, bunkering ammonia is one of these challenges. It is determined that research into an ammonia bunker installation for ports that handle sea-going vessels can provide a good basis for gauging port readiness for the adoption of ammonia as a fuel, as well as provide a basis for further research into other existing challenges around the adoption of ammonia as a fuel. To design such an ammonia bunker installation, system functions and requirements are proposed, and solutions that fulfil these functions while adhering to the requirements are found. Subsequently. these solutions undergo objective analysis, followed by a subjective decision for three final configurations based on input from stakeholders from The Port of Rotterdam. After this configuration is tested and viability is proven, a single final, viable, configuration is proposed. With this, the sub-questions, and finally the research question can be answered.

1. ***What functions and requirements are associated with a bunker installation that is suitable for ammonia?***

A bunker installation that is suitable for ammonia has the following operational functions: storing, conducting, actuating, and coupling. Furthermore, there are functions that are specific to the intended usage of ammonia, namely: Substance slip prevention, toxic cloud mitigation, spill containment, BOG vapour pressure equalisation, insulation of the system, and purging of fuel lines. Upon these functions, nine design requirements are imposed that were based on the intended use of ammonia and its characteristics. These requirements can be found in Section 2.4.

2 ***Which system functions and corresponding components can be used for an ammonia bunker installation that complies with the defined requirements?***

By analysing the state of the art surrounding a mature technology, such as bunkering LNG, several standard practice solutions were found. Furthermore, by consulting literature, as well as experts, remaining suitable components to fulfil system functions were found. The system components that are found that comply with the defined requirements can be found in Figure 3.18.

3 ***Which model can be used for decision-making with respect to discovered bunker station components?***

Several methods that are suitable to evaluate the bunker station components are found, such as morphological analysis and several MCDM methods. It is opted to use a MCDM method. This is done because a MCDM method circumvents researcher bias. The BWM is specifically chosen because it requires a small number of comparisons because it produces reliable results. Furthermore, its low computational time and lack of additional required software also make it desirable above the other MCDM methods.

4 ***What design criteria can be used to evaluate bunker station components and how do the selected system components perform on the defined design criteria?***

The design criteria used to evaluate the bunker installation components are: cost, energy efficiency, safety, reliability, and bunker time. These criteria are chosen based on systems that are part of a supply chain, and common challenges around implementation of future fuels, as per The Port of Rotterdam. Finally, the resulting performance of the alternatives can be found in Table 5.13.

5 ***What design do stakeholders from a suitable port for sea-going vessels such as The Port of Rotterdam prefer, and is this configuration viable?***

The results of the BWM analysis provided three individual configurations which are tested to be viable. This testing is done by checking for infeasible configurations, and by testing if requirements are respected. Finally, a general configuration is proposed. A sensitivity analysis showed confidence in the result and was further used to provide an argument to unify stakeholder configurations. The resulting final configuration can be found in Figure 6.3.

What design for an ammonia bunker installation is most viable for ports that handle sea-going vessels?

The answer to the research question is found by combining the answers to all sub-questions. A generally robust resulting configuration is found, with only two of twelve functions displaying sensitive results due to an order violation occurring. There are some differences between the stakeholders in the functions for actuating and coupling, but there is general consensus over most of the system components. The onshore situated final configuration can be found in Table 6.3.

Even though the results are representative of terminals in the Port of Rotterdam, the expertise from the stakeholders does extrapolate to ports that handle sea-going vessels in general. There are several arguments that would support this conclusion. First, the fact that stakeholders with different expertise come to a very similar result. This can indicate that a broader group of experts in bunkering will come to a similar result. Other experts can be expected to prioritise safety, but have different secondary priorities. This research pointed out that this does not produce vastly different configurations.

A separate argument for broader system viability for ports situated in Western Europe is given by the reasonable flow rates required to service the largest ships without disturbing the supply chain. It was pointed out that at sub $1000\ m^3/h$ flow rates, bunkering of ammonia for the largest vessels can be done with current technologies within existing waiting times at port.

Finally, because of the effectiveness of mitigation strategies and the safety assurances of the technologies that are available, the LSIR contour is expected to be well manageable. Therefore, the final configuration, and its associated risk, are expected to be viable for most ports that handle sea-going vessels.

7.2. Recommendations

In this section, recommendations for future research will be discussed.

The first recommendation is to improve the ordinal analysis to a quantitative analysis. The ordinal analysis lacks nuance between the rankings. For example, if option A is better than option B with respect to a certain criterion, there is no information about how much option A is better than option B.

This remains a difficult problem due to the complexity and variability of the criterion score. For example, the CapEx of several components, such as pumps, will differ in model and maker. Furthermore, OpEx for components can depend on the current electricity price or on the cost to replace citric acid for scrubbers, for instance. However, performing a more detailed analysis of criteria to be able to include some form of nuance between the rankings will increase the quality of the outcome of the BWM analysis.

The second recommendation is to increase the amount of stakeholders in The Port of Rotterdam that are surveyed, this can increase the quality and robustness of the final result. Furthermore, the survey can be expanded to survey multiple ports. Even though the Port of Rotterdam is considered a representative port that handles sea-going vessels for this research, the inclusion of multiple ports could create more insight into the possibility of a generally viable design or indicate that the difference in interests between ports is too big to come to a general design. It can also be interesting to

As stated in the conclusion, it is believed that the configuration is a widely applicable one for ports that handle sea-going vessels. However, it is also stated that this will depend on the risk contours and the proximity to vulnerable objects in a specific port that handles sea-going vessels. Therefore, a quantitative risk assessment of the final configuration could offer more insight into this. If the specific LSIR contour of the configuration is known, definite conclusions on its viability for an arbitrary port that handles sea-going vessels can be drawn. Furthermore, a Hazard and Operability Study (HAZOP) and Hazard Identification (HAZID) can provide insight into abnormalities in the work environment and pinpoint their root causes, and provide management with information on any threats and hazards on the job site, respectively.

It is possible for new technologies to be able to be included in the model that is used for the BWM analysis. The p_{ij} matrix can be extended with new technology for a certain function. After analysis with respect to the criteria it can be included and considered as a possible outcome for the final configuration.

This research focused on a system design, not a detailed design. This is reflected in the inability to definitively answer requirement 9, as could be seen when testing the configuration in Section 6.4. Furthermore, several additional details such as: supply tank size, number of pumps, number of jetties and jetty geometry, can only be determined in such a detailed design. The final recommendation, therefore, is to create a detailed design to determine these characteristics, incorporating the proposed system components. Determining these characteristics could be based on a desired throughput requirement. This throughput could be based off of a projected number of future ammonia-powered ships at a certain port, for instance.

A

Paper

Design of an Ammonia Bunker Installation for Sea-going Vessels - A Best Worst Method Approach

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ABSTRACT

The use of petroleum-based fuels in the shipping sector creates harmful emissions that need to be reduced to reach climate goals. Ammonia is being considered as a possible fuel to reduce emissions, but there exist several challenges that prevent its implementation. Research into these several of these challenges is being done, but there is little research into the bunkering process of ammonia. Therefore, the purpose of this research is to identify an installation to bunker ammonia that is suitable for ports that handle sea-going vessels. In order to do this, requirements, functions and alternatives are proposed for this system. Subsequently, these alternatives are evaluated through an ordinal analysis and a decision is made on a configuration through the Best Worst Method (BWM). To do this, Stakeholders from the port of Rotterdam are surveyed and used as input for the BWM. A viable configuration is found that adheres to all requirements. Finally, it is concluded that the configuration is applicable to multiple ports due to the general prioritization of safety, robustness of the result and similar results between stakeholders with different secondary priorities. Furthermore, the effectiveness of mitigation strategies implies sufficiently small risk contours, to allow ports that are in close proximity to vulnerable objects to be able to build an ammonia bunker installation as well.

1. Introduction

Shipping contributes about 11% to the total CO_2 emissions of the transport sector, which totals around $2-3\%$ of global CO_2 emissions [38]. This contribution can mostly be attributed to the use of polluting fuels currently in use by this sector. Petroleum-based fuels, currently make up 95% of the fuel mixture [20] These fuels produce massive amounts of sulphur oxides (SO_x), nitrogen oxides (NO_x), as well as carbon dioxide (CO_2) and particulate matter. According to the climate goals for 2050, these emissions are dangerous and need to be reduced drastically [26].

To accomplish this reduction in emissions, several future fuels are under consideration by the marine industry. It becomes clear that a quick-win is possible through the implementation of LNG, having the potential to cut on board SO_x, NO_x and particulate matter emissions by 90%, 80% and 100%, respectively, as well as reducing CO_2 emissions by around 20% [7]. However, due to LNG still being a fossil fuel, it is not viable in the long run. Furthermore, the fourth Greenhouse Gas (GHG) study of the International Maritime Organisation (IMO) pointed out that the methane slip in combustion engines is larger than expected. Since methane is a strong GHG, the decrease in anthropogenic emissions is minimal [25]. Instead, hydrogen and ammonia are carbon-free hydrogen carriers that can potentially almost eliminate onboard emissions [50, 1, 3, 47, 53]. Furthermore, they can be produced through electrolysis, powered by renewables [36, 14]. Between these two future fuels, hydrogen is deemed infeasible for deep-sea shipping due to storage size and cost [8, 31]. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (2022) expects ammonia to make up 50% of the fuel mixture for the shipping industry by 2050 [36], thereby contributing to the realization of the 2050 climate goals.

Ammonia is not readily implementable as a fuel as of now. There exist significant challenges that prevent its implementation. These challenges are centred around four topics [36]:

1. Fuel storage, logistics and bunkering
2. Onboard fuel conversion
3. Onboard safety and fuel management
4. Regulations

The four challenges listed before need to be addressed for ammonia to become a viable fuel for the shipping industry. Research into several of these topics is being done. For instance, Percic et al. (2022) performed a Life-Cycle Analysis (LCA) and Life-Cycle Cost (LCCA) Analysis for ships with several conversion technologies and fuels. The implementation of blue ammonia in a Solid Oxide Fuel Cell (SOFC) leads to significant reductions in greenhouse gasses (65% - 72%) at an acceptable cost, which is 37% - 43% higher than that of a diesel power system. [40]. Cheliotis et al. (2021), reviewed the safe use of ammonia in fuel cells in the marine industry. They conclude that it is imperative to develop large-scale production infrastructures for green or blue ammonia. Furthermore, there is a clear need for the identification of the hazards and consequences of ammonia release [10]. Yadav et al. (2022) used Computational Fluid Dynamics (CFD) to look at ammonia dispersion onboard ship engine rooms to evaluate the safety of using ammonia as a marine fuel [54]. Aside from a few parties such as Duong et al. (2023) [15] who performed a safety review

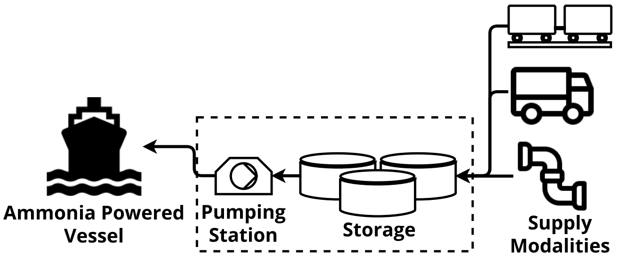

Figure 1: Bunker Supply Chain, with the scope of this research in the dashed box

regarding ammonia bunkering, there is little research being done into ammonia bunkering.

The purpose of this research is to identify an installation to bunker ammonia that is viable for ports that handle sea-going vessels. The scope of this research encompasses part of the ammonia bunker supply chain for ammonia-fueled vessels. More precisely: the connection between a storage vessel which supplies an ammonia-powered ship with its fuel. This refers to the area in the dashed box in Figure 1.

In order to fulfil the purpose of this research, the following structure is proposed. First, a system description is given in Section 2. Then, an decision-making model is proposed in Section 3. The results of the research are proposed in Section 4, and will subsequently be discussed in Section 5. Finally, the conclusions of the research are proposed in Section 6.

2. System Description

This section explains what requirements and functions a bunkering system needs to fulfil, and of which possible components a bunkering station consists. In order to describe the system, requirements are proposed. These requirements can then be translated into functions of the bunkering system. Every function can be satisfied by different system components, which are called alternatives. To define the requirements, a basic bunker installation is analysed in Section 2.1. Subsequently, the operational requirements are translated into system functions and corresponding alternatives are proposed in Section 2.2. The same is done for the safety requirements in Section 2.3.

2.1. Requirements

A distinction between requirements is made: operational requirements and safety requirements. Operational requirements make the system technically operational, whereas safety requirements are imposed by the intended use of ammonia and its associated characteristics.

2.1.1. Operational Requirements

Figure 2 shows a schematic version of a basic bunkering system. Bunkering can be done in multiple ways, Ship to Ship (STS), Port to Ship (PTS) and Truck to Ship (TTS). These methods can be generally described as a storage vessel connected to another storage vessel via an impermanent connection. This is graphically represented in Figure 2 The ship side of the system is not part of the scope of this research. Furthermore, the only bunker method excluded from this representation is Portable Tank Transfer (PTT). This method is considered to be inviable for the volumes of fuel needed for deep sea shipping and is therefore not further considered in this research [24]. From this figure, operational requirements are derived:

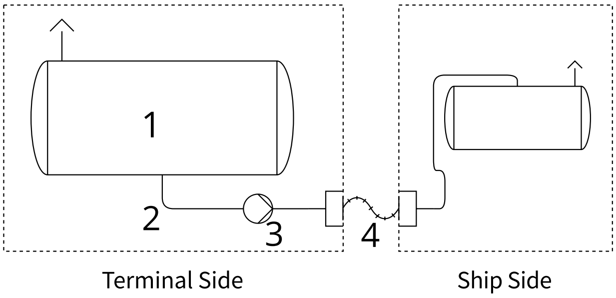

Figure 2: Basic Bunker System. The location of each operational function is labeled with its corresponding number

1. The system is required to be able to store a medium at the terminal side
2. The system is required to have piping in place to form a connection from the terminal to the ship side through which the medium can flow
3. The system is required to have a pump to actuate the medium in a controlled manner from the terminal side storage to the ship side storage
4. The system is required to have a detachable coupling between the terminal and ship side of the installation.

2.1.2. Safety Requirements

Ammonia is toxic and thus life-threatening in concentrations above 2700 *ppm* when exposed for 10 minutes or more [9], can form explosive mixtures with air between $15-28\%$ [9], and is corrosive [9]. Furthermore, The energy density of ammonia is about 50% of LNG, which in turn has about 65% of the energy density of traditional Heavy Fuel Oil (HFO) [14, 2]. Therefore, it needs to be liquefied. This is done by lowering the temperature to $-33°C$ instead of liquefaction through pressure because of better safety and higher energy density [4, 16]. Furthermore, this difference in temperature means liquid ammonia will start to boil, and thus evaporate, under the influence of heat that enters the system. This Boil Off Gas (BOG) increases pressure in the system because gaseous ammonia expands to 850 times its liquid volume [13]. This effect needs to be handled in the installation. Because of the aforementioned intended deep-sea application of ammonia, large vessels need to be able to use the bunker installation. Thus, the largest vessel currently in use, the MSC Irina with a Dead Weight Tonnage (DWT) of around $240,739$ [34] needs to be able to use the installation. These characteristics associated with ammonia and

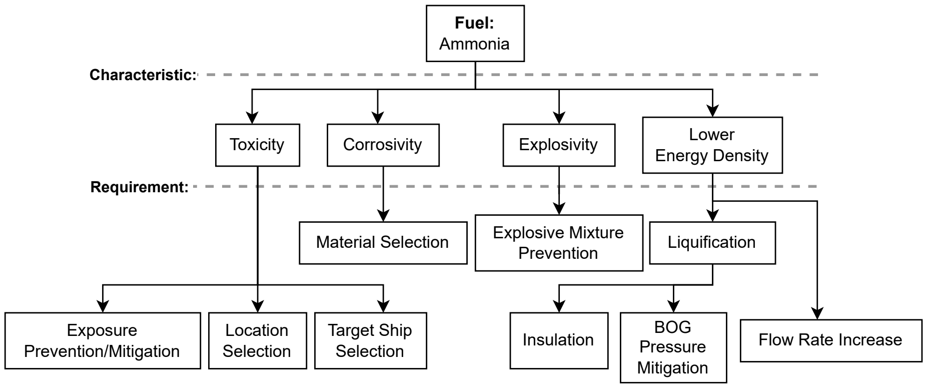

Figure 3: Ammonia Safety Requirements

the resulting derivation of requirements are graphically represented in Figure 3. The ammonia safety requirements are defined as follows:

1. It is required to have exposure prevention and mitigation systems in place with the goal of mitigating the toxic hazard associated with ammonia, in case of an unintended release.
2. It is required to have a location that is suitable such that, in case of an unintended release, there are acceptable risks of exposure to surrounding structures, people and other vulnerable objects.
3. It is required that the bunker system is able to bunker the largest vessels in service. The largest vessel currently in service, the MSC Irina, has a Dead Weight Tonnage (DWT) of around $240,739$.
4. It is required that the materials used in the bunker system are able to withstand the corrosivity of ammonia.
5. It is required that there be systems and protocols in place that have the absolute goal of preventing an explosive mixture from forming.
6. It is required to have systems and protocols in place that have the absolute goal of preventing ammonia leakage into the atmosphere.
7. It is required that the bunker system is able to minimize the heat influx at all storage and transfer media in order to keep ammonia in its liquid form.
8. It is required that BOG and its consequent pressure-increasing effect is handled in the bunker system.
9. It is required that the flow velocity in the piping never exceeds the sonic velocity in liquid ammonia at $1,729 m/s$.

2.2. Operational Functions

The operational requirements from Section 2.1.1 are translated into four operational functions, their corresponding locations can be found in Figure 2. These operational functions are:

1. Storing
2. Conducting
3. Actuating
4. Connecting

The solutions that fulfil these functions, while complying with the requirements are described in the following sections.

2.2.1. Storage

There are three categories relevant for ammonia storage tanks: single containment, double containment and full containment [52]. The difference between these storage tanks is the ability to handle failures of the primary tank. For this research, pressure-ready bullet tanks and atmospheric flat-bottom tanks are considered. Bullet tanks do not have the same definition by codes, and the containment philosophies cannot be directly copied from atmospheric storage [49]. Therefore, basic containment safety requirements are copied to the bullet tanks for comparison purposes. Single containment offers no further containment than the primary tank, double containment offers liquid spillage containment without considering released ammonia gas, and full containment is able to store liquid and gas in case of a primary tank failure. Thus being able to remain operational [52]l.

2.2.2. Conducting

The medium needs to be conducted within the system through pipes. Possible solutions for pipes are flexible or rigid piping. Furthermore, floating flexible piping can be used. Rigid piping is preferred for on-land applications due to the restricted movement of the pipes, but a flexible floating pipe could make a floating terminal much more practical.

2.2.3. Actuating

There are several pumps commercially available that can handle the characteristics of ammonia, as well as offer high enough flow rates. High enough is considered to be 1000 m^3/u, which is the LNG bunker flow rate at the Gate Terminal [18]. Three pump types that are suitable for ammonia are: mag-drive pumps, canned motor pumps, and double mechanically sealed pumps, due to their hermetically sealed nature. These pumps can be dry-installed or submersed in the medium [30]. Canned motor pumps offer double containment, as opposed to mag-drive pumps which only have a single containment layer [22]. Double mechanically sealed pumps are initially less expensive than the mag drive and canned counterparts [43], but from canned motor designs to mag-drive, to mechanically sealed, the service life goes down respectively [17].

2.2.4. Connecting

Establishing a connection between the terminal side to the ship side of the system is a critical safety system because the impermanent connection is prone to human error and wear. This function consists of two parts, the connecting hose, and the coupling. Two options for the connecting hose are possible, a floating hose or a suspended hose. Concerning the coupling, three options are considered: the dry disconnect coupling, the break-away coupling and the Powered Emergency Release Coupling (PERC) [33]. These couplings all feature a system that prevents the ammonia from leaking when the coupling is released. The latter two feature systems that automatically disconnect in case of excess tensile stress, and the PERC is able to disconnect when an Emergency Shut-Down (ESD) button is pressed.

2.3. Safety Functions

The safety requirements from Section 2.1.2 are translated into the following seven safety functions:

1. Bunker location
2. Substance slip prevention
3. Toxic cloud mitigation
4. Spill containment
5. BOG vapour pressure equalisation
6. Insulation
7. Purging of fuel lines

The solutions that fulfil these functions, while complying with the requirements are described in the following sections. An overview of the discovered solutions can be found in Figure 5 in the appendix.

2.3.1. Bunker location

The bunker locations that are handled in this research are dictated by the intended end user: Ships. Specifically, where ships can sail in order to receive the bunker fuel. Namely, at the quay, near the quay but not fully docked, or not near a quay. Hereafter referred to as onshore-, nearshore-, and offshore bunkering. Onshore bunkering offers solid ground to build on providing more available space and stability. Nearshore bunkering prevents relative motion between the bunker vessel and the jetty and offers little restriction on the orientation of the bunker vessel. Furthermore, a nearshore system is not bounded by the quay depth. Offshore bunkering is independent of port-side facilities and away from port traffic. This comes at the cost of vulnerability to weather and increased supply complexity.

2.3.2. Substance slip prevention

Substance slip can be prevented by the use of gas detectors coupled to an ESD, or a passive water spray system over the bunker manifold and other leak-prone objects. The gas detectors can prevent large amounts of substance slip by shutting down the installation or closing specific valves when ammonia is detected. A water spray system can leverage the solubility of ammonia in water to prevent vapours in the air around leak-prone objects. Furthermore, leaks could be detected by monitoring wastewater from this system.

2.3.3. Toxic cloud mitigation

Mitigating toxic clouds in case of an unintended release is very important to ensure safety. Three strategies are proposed: overpressurisation, a mesh barrier and a water curtain. Ksenia et al. (2021) showed that through the internal overpressurisation of the insides of a ship, sufficient protection against potential ammonia hazards could be offered [29], and this could be leveraged to protect buildings near an ammonia bunker installation. The working principle of a mesh barrier is through the reduction of vortices downstream, thus increasing the concentration of ammonia on the ground surface [5], thus preventing long-distance migration of a toxic cloud. The operating principle of a water curtain is to leverage the reactivity of ammonia with water. This leads to the cloud being absorbed by the water and falling to the ground. This system is reported to have a possible reduction percentage as high as 90% at $10m$ behind the release location [12].

2.3.4. Spill containment

Spill containment is incorporated in double- and full containment levels inside storage tanks. Though, it is possible to have additional spill containment. This comes in the form of a bund dyke that is able to contain the storage tank volume. The addition of modified carbon nano-particles to an ammonia pool in, the dyke area around compromised storage, can reduce the threat zone by 50% [37].

2.3.5. BOG vapour pressure equalisation

BOG pressure can be handled by the use of three systems: the BOG return hose, a vent with a scrubber to relieve excess pressure, or pressure can be relieved by rerouting it to a buffer tank. A BOG return hose is able to form a closed system, where excess pressure is relieved without the need for pumps back to the storage. The vent with a scrubber can relieve pressure without the need to add storage tanks or extra connections. Since ammonia needs to be gaseous to be used as a fuel [19], the buffer tank can serve as an expansion tank, as well as a pressure relief system.

2.3.6. Insulation

Two considered options to insulate the system are mechanical and vacuum insulation. Vacuum seals can generally create a better insulating layer for a smaller diameter of piping, even up to 20 times as much as fibre or foam solutions [51], but are generally much more expensive than mechanical insulation. However, mechanical insulation is prone to degradation [11].

2.3.7. Purging of fuel lines

To prevent explosive mixtures, as well as preventing ammonia from spilling from fuel lines, a purging sequence is required for ammonia bunker installations [21]. A solution is needed that handles the vented gases because they cannot be vented into the atmosphere. This can be done with a scrubber on the vent, or by redirecting the gas mixture to a buffer tank that is connected to a gas separator. These scrubbers are only around 90.12% effective [28], and require refilling of the medium. Gas separation units can be costly to install and use.

3. Methodology

In the previous section, research into bunker installations that handle liquefied gases is done. With this information, system requirements, system functions, and solutions adhering to those requirements are proposed. In this section, these solutions are evaluated based on design criteria, which are proposed in Section 3.2, by means of an ordinal analysis, in Section 3.3. This analysis is combined with stakeholder input from the Port of Rotterdam, discussed in Section 3.4, to perform a Best Worst Method (BWM) analysis. In this analysis, stakeholders are asked to evaluate the relative importance of the design criteria. Subsequently, the results undergo a sensitivity analysis, are checked for infeasible combinations, and testing of the requirements is done. When this is done, the results are unified in a final configuration.

3.1. Model Description

Several Multi-Criteria Decision Making (MCDM) methods exist that use subjective weighing of design criteria by experts, such as the analytical hierarchical process (AHP), and the analytical network process (ANP) [48]. This use of subjective weighing is preferred because it circumvents researcher bias. Because it is desired to perform decision-making through stakeholder input, a straightforward and consistent survey is required. The simplicity of the survey for the decision maker is desirable to ensure more reliable results. With BWM it is possible to ensure survey results of sufficient quality with a low number of comparisons. Moreover, the consistency of the stakeholder input can be quickly evaluated. Additionally, the low computational time required to perform the BWM and the lack of additionally required software led to the BWM being chosen for the purposes of this research.

3.1.1. The Best Worst Method

The BWM, proposed by J. Rezaei (2015) [44], can solve discrete MCDM problems, which can be generally formulated as follows:

$$A = \begin{array}{c c} & \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{array}{c} a_1 \\ a_2 \\ \vdots \\ a_m \end{array} & \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{pmatrix} \end{array} \tag{1}$$

where $\{a_1, a_2, \cdots, a_m\}$ is a set of feasible alternatives and $\{c_1, c_2, \cdots, c_n\}$ is a set of decision-making criteria. The values for p_{ij} correspond to the relative value for the criterion j with respect to the alternative i. These are the values which are later determined by means of an ordinal analysis. With these values, the best alternative i with the highest value V_i for a specific function can be found. This is done with Equation (2)

$$V_i = \sum_{j=1}^{n} w_j p_{ij} \tag{2}$$

Where:

$$w_j \geq 0, \sum w_j = 1 \tag{3}$$

In Equations (2) and (3), the values for $w = \{w_1, w_2, \cdots, w_n\}$ correspond to the weights associated with the importance of each criterion.

Instead of determining all relative values of all criteria, the BWM starts by determining the best (most important) criterion and the worst (least important) criterion. Subsequently, the preference of the best criterion over all the other criteria, and the preference of the other criteria over the worst criterion is determined. These preferences are allocated a number between 1 and 9. Resulting in the Best-to-Others and Others-to-Worst vectors, respectively:

$$B_B = (b_{B1}, b_{B2}, \cdots, b_{Bn}) \tag{4}$$

$$B_W = (b_{1W}, b_{2W}, \cdots, b_{Wn})^T \tag{5}$$

where $b_{BB} = 1$, and $b_{WW} = 1$.

Finally, to calculate the optimal weights w_j^* and ξ^*, with '*' denoting the optimal value, the following problem can be solved:

$$min\ \xi$$

s.t.

$$\left|\frac{w_B}{w_j} - b_{Bj}\right| \leq \xi,\ \forall j$$
$$\left|\frac{w_j}{w_W} - b_{jW}\right| \leq \xi,\ \forall j \tag{6}$$
$$\sum_j w_j = 1$$
$$w \geq 0,\ \forall j$$

Finally, to ensure the quality of the assessment of the weights w_j, a high consistency is desired. To determine the consistency of a BWM analysis, a Consistency Ratio (CR) is proposed, as follows:

$$Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index} \tag{7}$$

where $Consistency\ Ratio \in [0,1]$, values close to 0 are more consistent, while values close to 1 are less consistent. To calculate the consistency index the the consistency ratio needs to be determined, this is found through the following equation:

$$\xi^2 - (1 + 2b_{BW})\xi + (b_{BW}^2 - b_{BW}) = 0 \tag{8}$$

Solving Equation (8) for different values for b_{BW}, the maximum value for ξ can be found. This value is used as the consistency index. With the solutions for (2) known for each function, and the solution of (7) as a measure of the quality of the pairwise comparison, a decision for the best alternative can be made.

3.2. Design Criteria

Design criteria are based on important parameters that are involved in a bunker process that is part of a supply chain and implementation of a new fuel [27, 41]. This leads to an emphasis on reducing cost, having a reliable installation and minimizing bunker time. Additionally, energy efficiency is important from a sustainability point of view. Finally, safety must be guaranteed. Thus, the design criteria are:

- Cost
- Energy Efficiency
- Safety
- Reliability
- Bunker Time

3.3. Ordinal Analysis

In order to find the values for p_{ij} in Equation (1), an ordinal analysis of the alternatives is performed. For each function, the alternatives are evaluated for each of the design criteria, and a ranking with respect to these design criteria is allocated. Below, as an example, the analysis for the function connecting (coupling) is shown. The same analysis is done for all functions and alternatives. The full analysis derivation can be found in Hofste (2023) [39]. The full results of the analysis can be found in the appendix in Table 4.

Connecting (coupling)

Cost

Since the dry disconnect coupling is a simpler version of the breakaway coupling, which in turn is a simpler version of the PERC, Capital Expenditure (CapEx) also goes down with increasing simplicity. CapEx, as opposed to Operational Expenditure (OpEx), is assumed to be the dominant cost factor due to the similarity of the use case, and thus requirements for maintenance. However, there is a distinction when comparing breakaway couplings and PERCs to dry disconnect couplings. This distinction is that there is no protocol in place for the dry disconnect coupling in case of excessive motion. This means that damage to the installation will follow such a scenario. In the case of the other two options, there is only a connector bolt replacement required.

Energy Efficiency

The dry disconnect coupling, as well as the breakaway coupling, do not use any energy. The PERC, however, does use energy to force the coupling to disconnect in the case of an emergency.

Safety

The safety of the couplings increases with increased complexity. All three alternatives are designed to be leak free when the coupling is disconnected. Only the breakaway coupling and PERC are designed to release in case of excessive tensile stress on the hose. Finally, only the PERC is designed to disconnect in case of an ESD button being pressed, and can therefore be considered to be safer than the breakaway coupling.

Reliability

The fact that a dry disconnect coupling can potentially damage the installation in case of excessive tensile stress on the hose means it can cause serious calamity to the terminal. Because the PERC is in connection to the ESD and manual override systems, it will always disconnect in case of an emergency. This can potentially cause downtime in case of a human error or false alarm. Resetting this coupling can cause extra unwanted downtime, a passive breakaway coupling does not have this problem.

Bunker Time

There is no discernible distinction in the complexity, possible flow or procedure when comparing these three couplings.

Overview

The above-mentioned findings have been summarized in Table 1.

3.4. Stakeholder Survey

Input from three stakeholders in the Port of Rotterdam is used to create the final input to execute the BWM. Input from these stakeholders is used to generate weights which can be used in Equation (2), to generate alternative scores. The

Table 1
p_{ij} values for the means that fulfil the function: Connecting (coupling). EE denotes Energy Efficiency, BT denotes Bunker Time

	Cost	EE	Safety	Reliability	BT
Dry Disconnect	3	2	1	1	1
breakaway	2	2	2	3	1
PERC	1	1	3	2	1

Table 2
Optimal weights based on the survey results of each respondent. EE denotes Energy Effieciency, BT denotes Bunker Time, CR denotes Consistency Ratio

Resp.	Cost	EE	Safety	Reliability	BT	CR	Accept (y/n)
Gate Terminal	0.182	0.0909	0.409	0.273	0.0455	0.232	y
ACE Terminal	0.228	0.152	0.400	0.0690	0.152	0.200	y
OCI NV	0.0520	0.141	0.587	0.141	0.0784	0.222	y

considered stakeholders are: The Gate Terminal, the ACE Terminal and OCI N.V. These stakeholders are chosen due to their expertise in bunkering or their expertise considering the handling of ammonia. The survey that is used is based on J. Rezaei (2015) [44]. The final derivation of the weights is done through the linear model provided by J. Rezaei (2016) [45] and its results can be found in Table 2.

4. Results

From the analysis, it became clear that there are many similarities between the configurations of stakeholders. All three stakeholders selected safety as their most important criterion, and all three chose different least important criteria. Bunker time, reliability and cost, respectively. These factors, alongside the different weights and the results from the ordinal analysis, resulted in final configurations that differed only in a submerged or dry-installed version of the canned motor pump for the actuation function, and the breakaway coupling or the PERC for the connecting (coupling) function. Where, both the Gate and ACE terminals opted for a breakaway coupling, as opposed to the PERC for OCI. Additionally, both the Gate Terminal and OCI opted for a submersed canned motor pump, whereas the ACE terminal opted for a dry canned motor pump.

Due to the complex relationships that result in the final scores of the alternatives, it is difficult to say if a small difference in the final score indicates that it is a close choice. In other words, if a close final score meant a small difference in the Best-to-Others and Others-to-Worst vectors from Vectors (4) and (5), respectively. Based on Muzarek et. al (2021), by looking at the influence of small variations in the aforementioned vectors, insight into the robustness of the final configuration can be found [35]. Here, attention is also paid if an order violation occurs, meaning a different alternative becomes the best alternative. For this research, the occurrence of an order violation following a small change in Vectors (4) and (5) is interpreted as the new best alternative lying close to the interests of the stakeholder.

Table 3
The final configuration for the most viable bunker installation for ammonia.

Functions	Final Configuration
Storing	FC flat-bottom
Conducting	Dry Rigid Pipe
Actuating	Submersed Canned Motor Pump
Connecting (hose)	Suspended Hose
Connecting (coupling)	Beak Away Coupling
Bunker Location	Onshore
Substance Slip Prevention	Gas Detectors with ESD + Water Spray System over Leak-prone Objects
Toxic Cloud Mitigation	Water Curtain
Additional Spill Containment	Bund Dyke + Carbon Nano-particles
BOG Vapor Pressure Equalisation	BOG Return Hose
Insulation	Vacuum Insulation
Purging of Fuel Lines	Inerting Sequence with Gas Separator

The results of the sensitivity analysis led to the possibility to unify the results into the final configuration as seen in Table 3. Due to the closeness in stakeholder interest for the submersed canned motor pump and the majority of stakeholders preferring the breakaway coupling, these two components were included.

5. Discussion

To ensure the feasibility of the resulting configuration, infeasible combinations must be removed if they are present. To test the viability of the resulting configuration, it must be checked if none of the requirements are violated. These two tests are executed in this section. Finally, the results are further interpreted.

5.1. Infeasible Combinations

There are several solutions that are infeasible to combine. These combinations need to be identified. These combinations are used to evaluate the final configuration on feasibility, and if needed, adapted to become feasible. To do this, the component overview in Figure 5 is analysed.

The selection of a flat-bottom tank, for instance, does not combine with an offshore design. Due to the size and weight of the storage technology, it is highly impractical to install this on any offshore installation. Therefore, in an offshore design, bullet tanks are used instead of flat-bottom tanks. Secondly, the selection of an onshore design will restrict the usage of floating pipes. It could still be possible for the connecting pipes from the terminal side to the ship side to be floating pipes, but it is not possible for the conducting pipes of a land-based installation to be floating. Thirdly, the selection of an inerting sequence with a gas separator is considered infeasible for an offshore bunker installation due to its size. These combinations do not occur in any of the stakeholder configurations.

5.2. Requirement Testing

There are several requirements that are inherently adhered to because the selected components fulfil these requirements. These requirements are 1, 4, 5, 6, 7, and 8. Requirements 2 and 3 are location-specific requirements that will require further investigation.

Both the Gate Terminal and the ACE Terminal, are located on the Maasvlakte. The Maasvlakte II, which is still partially under construction, will offer more surface area for the development of extra port facilities, such as future ammonia terminals. This location offers a large distance from neighbouring cities and dwellings and direct access to the North Sea. It is desirable to have as much distance as possible between vulnerable objects, in order to satisfy Location Specific Individual Risk (LSIR) contours. Furthermore, the direct access to the North Sea means that larger ships can bunker directly at the proposed bunker installation, thus not restricting the use of the installation to just bunker barges.

The closest cities to the Maasvlakte II, are Hoek van Holland and Oostvoorne. Both can be seen in Figure 4. These two cities are 4.32km and 6.25km, respectively, measured from the area that will become the Maasvlakte II. The Port of Amsterdam (2021) in their study, defined a $10^{-}6$ LSIR contour around a bunker operation concerning refrigerated ammonia to be 427 meters [23]. In this contour, there can be no vulnerable objects such as dwellings and residential areas. Furthermore, the focus area as defined by this same study, provides an area with a radius of $2624m$ in which people are insufficiently protected indoors against the consequences of accidents involving hazardous substances, without additional measures. The focus area is not restrictive on development, but indicative for relevant authorities to state what measures are sufficient to protect persons. Since both of these distances are smaller than the closest populated area, the Maasvlakte II is deemed as being sufficient for requirement 2.

The depth of the fairways to the Maasvlakte II from the Noordzee, as can be seen in Figure 4, is between $23m$ NAP to $24m$ NAP [42]. This means that classes of ships that have a Dead Weight Tonnage (DWT) of $300,000$ can safely pass into the port since their average draught is around 20m [6]. Since the DWT of the MSC Irina is around $240,739$ [32], it should be able to reach the proposed installation. If this is undesirable due to other influences, it can still be serviced by bunker barges. Thus satisfying requirement 3.

Requirement 9, the requirement not to exceed the sonic velocity of ammonia in the piping, depends on a balance between pipe diameter and pump flow rate. From this research, it became clear that the flow rate of pumps is trivial. This is due to the fact that a set of multiple pumps, or a single large pump can produce virtually any flow rate. Certainly exceeding current $1000m^3/h$ LNG flow rates in the Gate Terminal that are used to fill bunker barges. Therefore this requirement remains a design specification of the system to be kept in mind when moving to a more detailed design.

Even though the results represent a configuration that is based on stakeholders from The Port of Rotterdam, broader applicability is suggested due to several conclusions. First, the fact that a stakeholder such as the Gate Terminal would come to a very similar result as two stakeholders that are specialised in ammonia, can indicate that a broader group of experts in bunkering will come to a similar result. Due to the noticeable difference in input vectors, and the subsequent similarity in results, in combination with the overall prioritisation of safety, it can be concluded that stakeholders in other ports will most likely not have vastly different configurations. This is further supported by the robustness of the results. It is difficult to say if a configuration is generally viable for ports that handle sea-going vessels, without checking all ports individually and without performing a quantitative risk assessment. However, because of the effectiveness of mitigation strategies and the safety assurances of the technologies that are available, the LSIR contour will shrink substantially. Therefore, the final configuration, and its associated risk, are expected to be viable for most ports that handle sea-going vessels.

6. Conclusion

Ammonia as a shipping fuel is not readily implementable as of now, and several challenges remain. Little research has been published on the bunkering of ammonia. Challenges around handling the toxic and explosive characteristics of ammonia are identified. Furthermore, the lower energy density of ammonia when compared to other hydrocarbon fuels imposes challenges around liquefaction and flow rate. Therefore, the purpose of this research is to identify an installation to bunker ammonia that is suitable for ports that handle sea-going vessels.

To accomplish this, requirements, functions, and alternatives for such a system are proposed. Next, a BWM analysis is performed to decide on a final configuration. The BWM uses an ordinal analysis of the alternatives with respect to design criteria, as well as stakeholder input from the Port of Rotterdam. This leads to a resulting configura-

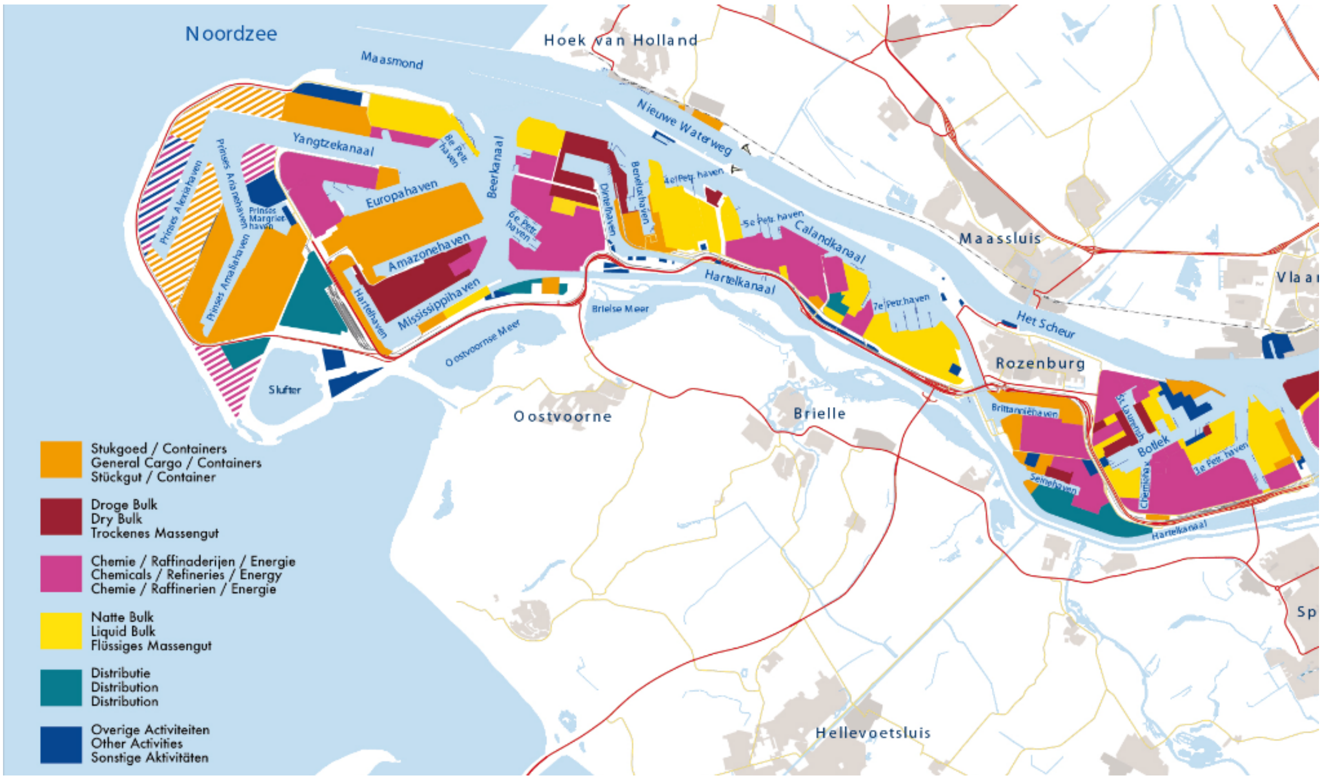

Figure 4: A map of the Port of Rotterdam, including different designated areas. The striped areas on the left side denote the unfinished Maasvlakte II [46]

tion that is similar between stakeholders. The remaining differences are unified into a final configuration which is deemed viable. Viability is ensured through testing of the requirements.

A viable configuration for an ammonia bunker installation for ports that handle seagoing vessels is found, see Table 3. This configuration is based on stakeholders from The Port of Rotterdam. However, broader applicability is suggested due to several factors. The different areas of expertise of the stakeholders yield similar results. Other stakeholders will most likely prioritise safety as well, which means final configurations will not be vastly different. Finally, due to the effectiveness of mitigation strategies, LSIR contours will shrink substantially. Therefore, the final configuration, and its associated risk, are expected to be viable for most ports that handle sea-going vessels. Thus, an ammonia bunker installation that is viable for ports that handle sea-going vessels is configured.

Appendix

The following section shows the complete overview of all discovered solutions to the proposed functions in Figure 5, as well as the complete results of the ordinal analysis in Table 4.

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FUNCTIONS	MEANS					
Storing	Single Containment (Flat bottom Design)	Single Containment (Bullet Design)	Double Containment (Flat bottom Design)	Double Containment (Bullet Design)	Full Containment (Flat bottom Design)	Full Containment (Bullet Design)
Conducting	Dry Rigid Pipe	Dry Flexible Pipe	Floating Flexible Pipe			
Actuating	Dry Mechanically Sealed Pump	Submersed Mechanically Sealed Pump	Dry Mag-drive Pump	Submersed Mag-drive Pump	Dry Canned Motor Pump	Submersed Canned Motor Pump
Connecting (hose)	Suspended Hose	Floating Hose				
Connecting (coupling)	Dry Disconnect Coupling	Break Away Coupling	Powered Emergency Release Coupling			
Bunker Location	Onshore	Nearshore	Offshore			
Substance Slip Prevention	Gas Detectors with ESD	Water Spray System over Leak-prone Areas	Gas Detectors with ESD + Water Spray System over Leak-prone Areas			
Toxic Cloud Mitigation	Mesh Barrier	Water Curtain	Overpressurisation	Mesh Barrier + Overpressurisation	Water Curtain + Overpressurisation	
Additional Spill Containment	None	Bund Dyke	Bund Dyke + Modified Carbon Nanoparticles			
BOG Vapor Pressure Equalisation	BOG Return Hose	Relieve Gas in Buffer Tank	Vent with Scrubber			
Insulation	Mechanically Insulated	Vacuum Insulated				
Purging of Fuel Lines	Inerting Sequence with Scrubber	Inerting Sequence with Gas Separator				

Figure 5: Overview that displays the derived functions under "functions", and discovered solutions under "means" for a bunker installation for refrigerated liquid ammonia.

Table 4
Overview of the results of the ordinal analysis.

		Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Conducting	Dry Rigid Pipe	3	3	3	3	3
	Dry Flexible Pipe	2	2	2	2	2
	Floating Flexible Pipe	1	1	1	1	1
Actuating	Dry Mechanically Sealed Pump	4	1	1	1	4
	Submersed Mechanically Sealed Pump	1	2	2	2	3
	Dry Mag-drive Pump	6	3	3	3	4
	Submersed Mag-drive Pump	3	5	4	4	3
	Dry Canned Motor Pump	5	4	5	5	2
	Submersed Canned Motor Pump	2	6	6	6	1
Connecting (hose)	Suspended Hose	2	2	2	2	2
	Floating Hose	1	1	1	1	1
Connecting (coupling)	Dry Disconnect Coupling	3	2	1	1	1
	Beak Away Coupling	2	2	2	3	1
	PERC	1	1	3	2	1
Bunker Location	Onshore	3	3	3	2	1
	Nearshore	2	2	2	3	3
	Offshore	1	1	1	1	2
Storing	SC Flat bottom	6	2	1	1	1
	SC Bullet	3	1	2	2	1
	DC Flat Bottom	5	2	4	1	1
	DC Bullet	2	1	3	2	1
	FC Flat Bottom	4	4	6	3	1
	FC Bullet	1	3	5	3	1
Substance Slip Prevention	Gas Detectors with ESD	2	2	2	1	1
	Water Spray System over Leak-prone Objects	3	1	1	2	1
	Combination of the Two Systems	1	1	3	2	1
Toxic Cloud Mitigation	Mesh Barrier	5	5	1	5	1
	Water Curtain	4	4	4	4	1
	Overpressurisation	3	2	2	1	1
	Mesh Barrier + Overpressurisation	2	3	3	2	1
	Water Curtain + Overpressurisation	1	1	5	3	1
Additional Spill Containment	None	3	0	1	1	1
	Bund Dyke	2	0	2	2	1
	Bund Dyke + Carbon Nano-particles	1	0	3	3	1
Insulation	Mechanical Insulation	2	1	1	1	1
	Vacuum Insulation	1	2	2	2	2
BOG Vapor Pressure Equalisation	BOG Retrun Hose	3	3	3	3	3
	Relieve Gas in Buffer Tank	2	1	2	2	1
	Vent with Scrubber	1	2	1	1	2
Purging of Fuel Lines	Inerting Sequence with Scrubber	2	2	1	0	1
	Inerting Sequence with Gas Separator	1	1	2	1	1

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B

Survey

Dear sir/madam,

First of all, thank you for taking the time to fill out this survey, it is crucial to my research.
I will firstly introduce the topic, followed by instructions on filling out the survey.

Topic:

I am doing research into designing a bunker installation for ammonia, specifically for seaports. I am interested in validating my decision model for The Port of Rotterdam. The model, the Best Worst Method, is a Multi Criteria Decision Model which requires input on the design criteria from agents associated with the party the design is relevant for.

In this case, I want to know what ranking certain stakeholders (you) associated with The Port of Rotterdam would allocate to my selected design criteria. This will, in turn, generate a design configuration of components that would make up an ammonia bunker installation. These criteria, and their composition, can be found on the next page.

Following the instructions on page three, I would like to ask you to rank these criteria on importance. Starting with selecting the best (most important) criterion, followed by the worst (the least important) criterion. Subsequently, a pairwise ranking of the importance of the best criteria to others and others to the worst criteria needs to be filled out. Finally, I would like to leave some room for suggesting criteria that I might have missed, with a short motivation (optional).

The survey will not take more than five minutes. Once again many thanks for your time.

Best regards,

Pim Hofste

Student at Delft University of Technology
Master Mechanical Engineering, track: Multi-Machine Engineering

The design criteria are:

Cost

The cost of the installation is a considered design criteria. This does cost does not only describe the initial cost of acquisition, but also takes into account the maintenance cost and the operational cost of the installation.

- Capital Expenditure (CapEx)
- Operational Expenditure (OpEx)

Energy Efficiency

The energy efficiency of the system concerns how efficient a design option can potentially be in terms of its energy usage. Certain design options will necessitate a higher energy usage than others, certain environments or means will be less efficient with the energy that is put into the system. Therefore it is important to be as effective as possible, while also minimizing energy usage from a sustainability point of view.

- Running cooling systems
- Running pumps
- Other energy usage

Safety

The safety design criteria concerns all safety parameters that a design offers. This involves systems that might be of influence on the risk areas, such as possible mitigation systems/strategies. Furthermore, where possible, the inherent safety of a design option and the possible threat it might pose to the environment will be taken into account.

- Risk area
- Inherent design safety
- Environmental Safety

Reliability

The reliability design criteria concerns the degree of resistance to calamities the design has. Offshore bunker installations, for example, are more susceptible to weather influences than onshore installations. Furthermore, some options can be more resistant to downtime, due to less complex repairs for instance. This will also be taken into account.

- Downtime prevention
- Vulnerability to environmental hazards

Bunker Time

The final design criteria concerns the estimated bunker time of an installation. This design criteria is the cumulative indicator for the amount of time a ship would require to manoeuvre to the installation and into place, the complexity of the pre- and post-checks to enable safe operation, and the possible flow rate that would dictate the time of the actual filling of the ship-side storage tank.

- Pre-check and Post-check
- Manoeuvring
- Flow rate

Survey:

Out of the design criteria:

- Cost
- Energy Efficiency
- Safety
- Reliability
- Bunker Time

Considering the goal (designing a bunker installation for ammonia for seaports), select the **MOST IMPORTANT** criterion from the five criteria (first line), and insert it in the most left-hand side (green) cell of the second row.

Now use a number between 1 and 9 to show the preference of your **MOST IMPORTANT** criterion over the other criteria. A value of 9 will indicate extreme importance of the most important criterion over another criterion, a value of 1 indicates equal importance. For instance, a criterion compared with itself will have a value of 1. Insert these values in the corresponding grey cells.

The MOST IMPORTANT criterion	Cost	Energy Efficiency	Safety	Reliability	Bunker Time

Considering the goal (designing a bunker installation for ammonia for seaports), select the **LEAST IMPORTANT** criterion from the five criteria (first column), and insert it in the top (green) cell of the second column.

Now use a number between 1 and 9 to show the preference of the criteria (first column) over the **LEAST IMPORTANT** criterion. A value of 9 will indicate extreme importance of a criterion over the least important criterion, a value of 1 indicates equal importance. For instance, a criterion compared with itself will have a value of 1. Insert these values in the corresponding grey cells.

The LEAST IMPORTANT criterion	
Cost	
Energy Efficiency	
Safety	
Reliability	
Bunker Time	

Other criteria that are of importance to you:

C

Results Survey & Sensitivity Analysis

GATE TERMINAL

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Best to others	3	6	1	2	8

Lower all Criteria			Increase all Criteria		
	Consistent (Y/N)	Change?		Consistent (Y/N)	Change?
Cost	Y	Now Dry canned motor	**Cost**	N	
Energy Efficiency	Y		**Energy Efficiency**	Y	
Safety	🟥	🟥	**Safety**	🟥	🟥
Reliability	Y		**Reliability**	Y	
Bunker Time	N		**Bunker Time**	Y	

ACE TERIMNAL

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Best to others	2	3	1	5	3

Lower all Criteria			Increase all Criteria		
	Consistent (Y/N)	Change?		Consistent (Y/N)	Change?
Cost	Y		**Cost**	Y	Now Submersed canned motor
Energy Efficiency	Y		**Energy Efficiency**	y	
Safety	🟥	🟥	**Safety**	🟥	🟥
Reliability	N	Now Scrubber	**Reliability**	Y	
Bunker Time	Y		**Bunker Time**	N	

OCI NV

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Best to others	9	5	1	5	9

Lower all Criteria			Increase all Criteria		
	Consistent (Y/N)	Change?		Consistent (Y/N)	Change?
Cost	Y		**Cost**	Y	
Energy Efficiency	Y		**Energy Efficiency**	Y	
Safety	🟥	🟥	**Safety**	🟥	🟥
Reliability	Y		**Reliability**	Y	
Bunker Time	Y		**Bunker Time**	Y	

Figure C.1: Results of the sensitivity analysis for the Best To Others vectors of the stakeholders. The red line indicates the most important criterion of the stakeholder

GATE TERMINAL

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Others to worst	7	2	6	8	1

Lower all Criteria	Consistent (Y/N)	Change?	Increase all Criteria	Consistent (Y/N)	Change?
Cost	Y		Cost	Y	
Energy Efficiency	Y		Energy Efficiency	Y	
Safety	Y		Safety	Y	
Reliability	Y		Reliability	Y	
Bunker Time	🟥	🟥	Bunker Time	🟥	🟥

ACE TERIMNAL

	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Others to worst	3	2	5	1	3

Lower all Criteria	Consistent (Y/N)	Change?	Increase all Criteria	Consistent (Y/N)	Change?
Cost	Y		Cost	Y	
Energy Efficiency	Y		Energy Efficiency	Y	
Safety	Y	Now Scrubber	Safety	Y	
Reliability	🟥	🟥	Reliability	🟥	🟥
Bunker Time	Y		Bunker Time	N	Now Scrubber

OCI NV

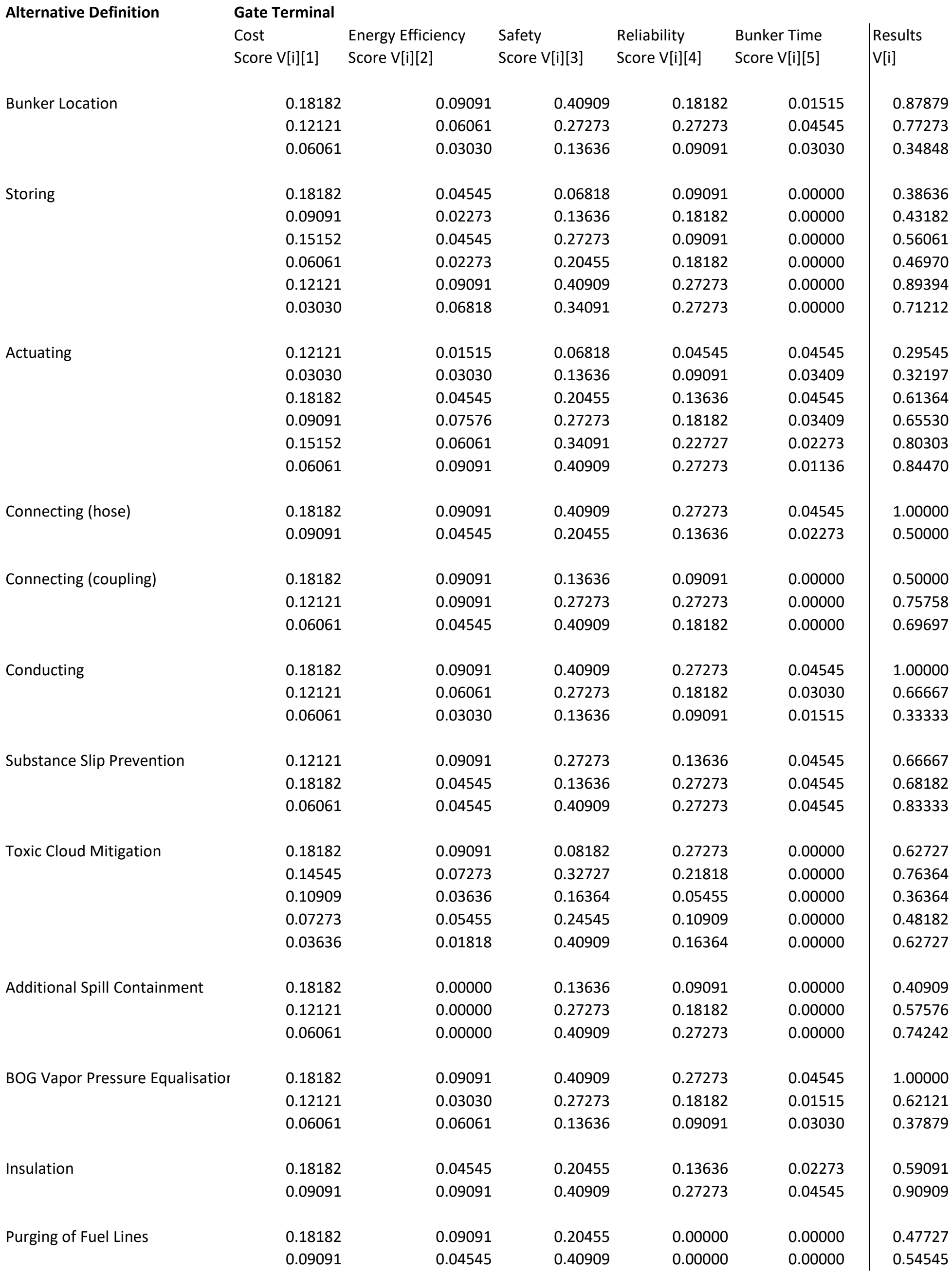
	Cost	Energy Efficiency	Safety	Reliability	Bunker Time
Others to worst	1	5	9	5	1

Lower all Criteria	Consistent (Y/N)	Change?	Increase all Criteria	Consistent (Y/N)	Change?
Cost	🟥	🟥	Cost	🟥	🟥
Energy Efficiency	Y		Energy Efficiency	Y	
Safety	Y		Safety	Y	
Reliability	Y		Reliability	Y	
Bunker Time	Y		Bunker Time	Y	

Figure C.2: Results of the sensitivity analysis for the Best To Others vectors of the stakeholders. The red line indicates the least important criterion of the stakeholder

D

Results BW Analysis



Alternative Definition	Gate Terminal					
	Cost Score V[i][1]	Energy Efficiency Score V[i][2]	Safety Score V[i][3]	Reliability Score V[i][4]	Bunker Time Score V[i][5]	Results V[i]
Bunker Location	0.18182	0.09091	0.40909	0.18182	0.01515	0.87879
	0.12121	0.06061	0.27273	0.27273	0.04545	0.77273
	0.06061	0.03030	0.13636	0.09091	0.03030	0.34848
Storing	0.18182	0.04545	0.06818	0.09091	0.00000	0.38636
	0.09091	0.02273	0.13636	0.18182	0.00000	0.43182
	0.15152	0.04545	0.27273	0.09091	0.00000	0.56061
	0.06061	0.02273	0.20455	0.18182	0.00000	0.46970
	0.12121	0.09091	0.40909	0.27273	0.00000	0.89394
	0.03030	0.06818	0.34091	0.27273	0.00000	0.71212
Actuating	0.12121	0.01515	0.06818	0.04545	0.04545	0.29545
	0.03030	0.03030	0.13636	0.09091	0.03409	0.32197
	0.18182	0.04545	0.20455	0.13636	0.04545	0.61364
	0.09091	0.07576	0.27273	0.18182	0.03409	0.65530
	0.15152	0.06061	0.34091	0.22727	0.02273	0.80303
	0.06061	0.09091	0.40909	0.27273	0.01136	0.84470
Connecting (hose)	0.18182	0.09091	0.40909	0.27273	0.04545	1.00000
	0.09091	0.04545	0.20455	0.13636	0.02273	0.50000
Connecting (coupling)	0.18182	0.09091	0.13636	0.09091	0.00000	0.50000
	0.12121	0.09091	0.27273	0.27273	0.00000	0.75758
	0.06061	0.04545	0.40909	0.18182	0.00000	0.69697
Conducting	0.18182	0.09091	0.40909	0.27273	0.04545	1.00000
	0.12121	0.06061	0.27273	0.18182	0.03030	0.66667
	0.06061	0.03030	0.13636	0.09091	0.01515	0.33333
Substance Slip Prevention	0.12121	0.09091	0.27273	0.13636	0.04545	0.66667
	0.18182	0.04545	0.13636	0.27273	0.04545	0.68182
	0.06061	0.04545	0.40909	0.27273	0.04545	0.83333
Toxic Cloud Mitigation	0.18182	0.09091	0.08182	0.27273	0.00000	0.62727
	0.14545	0.07273	0.32727	0.21818	0.00000	0.76364
	0.10909	0.03636	0.16364	0.05455	0.00000	0.36364
	0.07273	0.05455	0.24545	0.10909	0.00000	0.48182
	0.03636	0.01818	0.40909	0.16364	0.00000	0.62727
Additional Spill Containment	0.18182	0.00000	0.13636	0.09091	0.00000	0.40909
	0.12121	0.00000	0.27273	0.18182	0.00000	0.57576
	0.06061	0.00000	0.40909	0.27273	0.00000	0.74242
BOG Vapor Pressure Equalisatior	0.18182	0.09091	0.40909	0.27273	0.04545	1.00000
	0.12121	0.03030	0.27273	0.18182	0.01515	0.62121
	0.06061	0.06061	0.13636	0.09091	0.03030	0.37879
Insulation	0.18182	0.04545	0.20455	0.13636	0.02273	0.59091
	0.09091	0.09091	0.40909	0.27273	0.04545	0.90909
Purging of Fuel Lines	0.18182	0.09091	0.20455	0.00000	0.00000	0.47727
	0.09091	0.04545	0.40909	0.00000	0.00000	0.54545

Figure D.1: Results of the BW analysis for the Gate Terminal

Alternative Definition	**ACE Terminal**					
	Cost Score V[i][1]	Energy Efficiency Score V[i][2]	Safety Score V[i][3]	Reliability Score V[i][4]	Bunker Time Score V[i][5]	Results V[i]
Bunker Location	0.22759	0.15172	0.40000	0.04598	0.05057	0.87586
	0.15172	0.10115	0.26667	0.06897	0.15172	0.74023
	0.07586	0.05057	0.13333	0.02299	0.10115	0.38391
Storing	0.22759	0.07586	0.06667	0.02299	0.00000	0.39310
	0.11379	0.03793	0.13333	0.04598	0.00000	0.33103
	0.18966	0.07586	0.26667	0.02299	0.00000	0.55517
	0.07586	0.03793	0.20000	0.04598	0.00000	0.35977
	0.15172	0.15172	0.40000	0.06897	0.00000	0.77241
	0.03793	0.11379	0.33333	0.06897	0.00000	0.55402
Actuating	0.15172	0.02529	0.06667	0.01149	0.15172	0.40690
	0.03793	0.05057	0.13333	0.02299	0.11379	0.35862
	0.22759	0.07586	0.20000	0.03448	0.15172	0.68966
	0.11379	0.12644	0.26667	0.04598	0.11379	0.66667
	0.18966	0.10115	0.33333	0.05747	0.07586	0.75747
	0.07586	0.15172	0.40000	0.06897	0.03793	0.73448
Connecting (hose)	0.22759	0.15172	0.40000	0.06897	0.15172	1.00000
	0.11379	0.07586	0.20000	0.03448	0.07586	0.50000
Connecting (coupling)	0.22759	0.15172	0.13333	0.02299	0.00000	0.53563
	0.15172	0.15172	0.26667	0.06897	0.00000	0.63908
	0.07586	0.07586	0.40000	0.04598	0.00000	0.59770
Conducting	0.22759	0.15172	0.40000	0.06897	0.15172	1.00000
	0.15172	0.10115	0.26667	0.04598	0.10115	0.66667
	0.07586	0.05057	0.13333	0.02299	0.05057	0.33333
Substance Slip Prevention	0.15172	0.15172	0.26667	0.03448	0.15172	0.75632
	0.22759	0.07586	0.13333	0.06897	0.15172	0.65747
	0.07586	0.07586	0.40000	0.06897	0.15172	0.77241
Toxic Cloud Mitigation	0.22759	0.15172	0.08000	0.06897	0.00000	0.52828
	0.18207	0.12138	0.32000	0.05517	0.00000	0.67862
	0.13655	0.06069	0.16000	0.01379	0.00000	0.37103
	0.09103	0.09103	0.24000	0.02759	0.00000	0.44966
	0.04552	0.03034	0.40000	0.04138	0.00000	0.51724
Additional Spill Containment	0.22759	0.00000	0.13333	0.02299	0.00000	0.38391
	0.15172	0.00000	0.26667	0.04598	0.00000	0.46437
	0.07586	0.00000	0.40000	0.06897	0.00000	0.54483
BOG Vapor Pressure Equalisation	0.22759	0.15172	0.40000	0.06897	0.15172	1.00000
	0.15172	0.05057	0.26667	0.04598	0.05057	0.56552
	0.07586	0.10115	0.13333	0.02299	0.10115	0.43448
Insulation	0.22759	0.07586	0.20000	0.03448	0.07586	0.61379
	0.11379	0.15172	0.40000	0.06897	0.15172	0.88621
Purging of Fuel Lines	0.22759	0.15172	0.20000	0.00000	0.00000	0.57931
	0.11379	0.07586	0.40000	0.00000	0.00000	0.58966

Figure D.2: Results of the BW analysis for the ACE Terminal

Alternative Definition	**OCI NV**					
	Cost Score V[i][1]	Energy Efficiency Score V[i][2]	Safety Score V[i][3]	Reliability Score V[i][4]	Bunker Time Score V[i][5]	Results V[i]
Bunker Location	0.05202	0.14121	0.58712	0.09414	0.02615	0.90063
	0.03468	0.09414	0.39141	0.14121	0.07845	0.73988
	0.01734	0.04707	0.19571	0.04707	0.05230	0.35948
Storing	0.05202	0.07060	0.09785	0.04707	0.00000	0.26755
	0.02601	0.03530	0.19571	0.09414	0.00000	0.35116
	0.04335	0.07060	0.39141	0.04707	0.00000	0.55244
	0.01734	0.03530	0.29356	0.09414	0.00000	0.44034
	0.03468	0.14121	0.58712	0.14121	0.00000	0.90421
	0.00867	0.10590	0.48927	0.14121	0.00000	0.74505
Actuating	0.03468	0.02353	0.09785	0.02353	0.07845	0.25805
	0.00867	0.04707	0.19571	0.04707	0.05884	0.35735
	0.05202	0.07060	0.29356	0.07060	0.07845	0.56524
	0.02601	0.11767	0.39141	0.09414	0.05884	0.68807
	0.04335	0.09414	0.48927	0.11767	0.03922	0.78365
	0.01734	0.14121	0.58712	0.14121	0.01961	0.90648
Connecting (hose)	0.05202	0.14121	0.58712	0.14121	0.07845	1.00000
	0.02601	0.07060	0.29356	0.07060	0.03922	0.50000
Connecting (coupling)	0.05202	0.14121	0.19571	0.04707	0.00000	0.43600
	0.03468	0.14121	0.39141	0.14121	0.00000	0.70851
	0.01734	0.07060	0.58712	0.09414	0.00000	0.76920
Conducting	0.05202	0.14121	0.58712	0.14121	0.07845	1.00000
	0.03468	0.09414	0.39141	0.09414	0.05230	0.66667
	0.01734	0.04707	0.19571	0.04707	0.02615	0.33333
Substance Slip Prevention	0.03468	0.14121	0.39141	0.07060	0.07845	0.71635
	0.05202	0.07060	0.19571	0.14121	0.07845	0.53799
	0.01734	0.07060	0.58712	0.14121	0.07845	0.89472
Toxic Cloud Mitigation	0.05202	0.14121	0.11742	0.14121	0.00000	0.45186
	0.04162	0.11296	0.46969	0.11296	0.00000	0.73724
	0.03121	0.05648	0.23485	0.02824	0.00000	0.35078
	0.02081	0.08472	0.35227	0.05648	0.00000	0.51429
	0.01040	0.02824	0.58712	0.08472	0.00000	0.71049
Additional Spill Containment	0.05202	0.00000	0.19571	0.04707	0.00000	0.29480
	0.03468	0.00000	0.39141	0.09414	0.00000	0.52023
	0.01734	0.00000	0.58712	0.14121	0.00000	0.74566
BOG Vapor Pressure Equalisation	0.05202	0.14121	0.58712	0.14121	0.07845	1.00000
	0.03468	0.04707	0.39141	0.09414	0.02615	0.59345
	0.01734	0.09414	0.19571	0.04707	0.05230	0.40655
Insulation	0.05202	0.07060	0.29356	0.07060	0.03922	0.52601
	0.02601	0.14121	0.58712	0.14121	0.07845	0.97399
Purging of Fuel Lines	0.05202	0.14121	0.29356	0.00000	0.00000	0.48679
	0.02601	0.07060	0.58712	0.00000	0.00000	0.68373

Figure D.3: Results of the BW analysis for OCI NV

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