Ammonia bunkering and storage for the maritime industry during a global ammonia transition

By

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Summary

The worlds awareness of our emissions and the effect it has on our surroundings is increasing. This influences efforts to put new agreements into place to reduce emissions and the effects on global warming. Along with the Paris agreements, the International Maritime Organisation also came with measures to achieve these needed reductions of emissions for the maritime industry. The set goal for 2050 is a reduction of 50% of greenhouse gas emissions. To achieve this new fuels need to be used and research need to be done on these fuels.

In this thesis the workings of a liquid bulk terminal are analysed, with the use of ammonia as fuel for ships in the maritime industry. The current liquid bulk terminals need to change with the future increase in demand and use of ammonia. This thesis focusses on how this can take place. The transport and bunkering methods of ammonia need to be researched and used to formulate a model to investigate the various options.

It is opted to develop a Discrete Event Simulation model of a liquid bulk terminal. The bunkering operations and supply of ammonia within a terminal are modelled. Various bunkering and supply methods are modelled for different sizes of terminal and at various levels of supply and demand.

The model is implemented using python and a Discrete Event Simulation package Salabim. With the models simulations it is investigated how bunker and supply methods at the terminal perform at different levels of scale. This is to gain insights for the future transition to the less polluting bunker fuel ammonia. The model is verified and validated with the use of data from literature on similar terminals using LNG.

The simulation results show that using pipeline bunkering and supply options are the most suitable. This option gives the shortest time that a ship has to spend on average at the terminal. The use of pipeline bunkering is therefore more efficient and this increases with the increasing scale of size, supply and demand of ammonia at a liquid bulk terminal.

The costs of all the facilities needed for the different sizes of terminal and the various scenarios of methods are analysed. The costs show that for smaller scales, bunker vessels and train supply, are more cost efficient. For large scale supply, demand and terminal size, using pipeline supply and bunkering is the most cost efficient.

Recommendations for future research includes the use of hybrid terminals using multiple bunkering methods at the same time. Investigating the safety risks for each method of bunkering and supply. And to use the proposed model for a case study at a location to investigate the suitability of the bunkering and supply methods for such locations.

Contents

List of Figures

List of Tables

1 Introduction

In 2018 the International Maritime Organisation (IMO) started to adopt mandatory measures to reduce green house emissions in the maritime industry. These measures led to the goal to reduce 50% of the green house emissions by 2050 in comparison to 2018 [1, 2]. This mandatory measures force the industry to change and adopt new more efficient ways to transport to reduce emissions. One of the options to consider is changing the fuel that are used by ships [3]. This starts an industry wide transition to green fuel alternatives. The transition brings challenges in ports on how to bunker the new alternative fuels to these ships and what methods to use. While managing the expected increase of the future demand. This gives logistical challenges that need to be investigated.

1.1 Background

In this section the background behind this research is elaborated on. The use of a liquid bulk terminal is explained and the different potential alternative fuels for the maritime industry are discussed.

1.1.1 Liquid bulk terminal

A terminal is a location at a seaport where the loading and unloading of goods takes place. This study focusses on a liquid bulk terminal. An example of a liquid bulk terminal can be seen in Figure 1. This type of terminal handles free-flowing liquids that are unpackaged also known as bulk [5]. Therefore these liquids are stored in large tank spaces. Liquid bulk is mostly transported by using ships but are also transported by truck, train or pipeline. Most liquid-gas terminals have a few different components that together form the terminal. These components are storage tanks, berthing locations, access canals and access points to the hinterland. The storage tanks are used to store the different liquid bulk. The berthing locations are places at a dock where a ship is tied down to be able to load and unload goods. The access canals and access points are used by ships, trains and trucks to access the terminal and to eventually load and unload goods to and from the storage tanks.

Figure 1: Liquid bulk terminal [4]

A terminal tries to fulfil three functions in the maritime industry using the previous described components. These functions are the storage of goods, the transport of goods and value added logistics [6, 7]. The value added logistics includes that a liquid bulk terminal also handles the process of bunkering. Bunkering is supplying ships with fuel to their onboard tanks for later use to transport the goods.

The processes on a terminal can best be described using Figure 2. This figure shows the different functions and processes that occur at a terminal. When a ship arrives at a terminal it berths at a berth or jetty. When a ship is secured different loading and unloading processes can take place. The bulk is transferred from or to the ship and storage tanks. The terminal then handles it via different transport methods like trains, trucks, pipelines or again a different ship to an other location. These steps fulfil the three functions of a terminal.

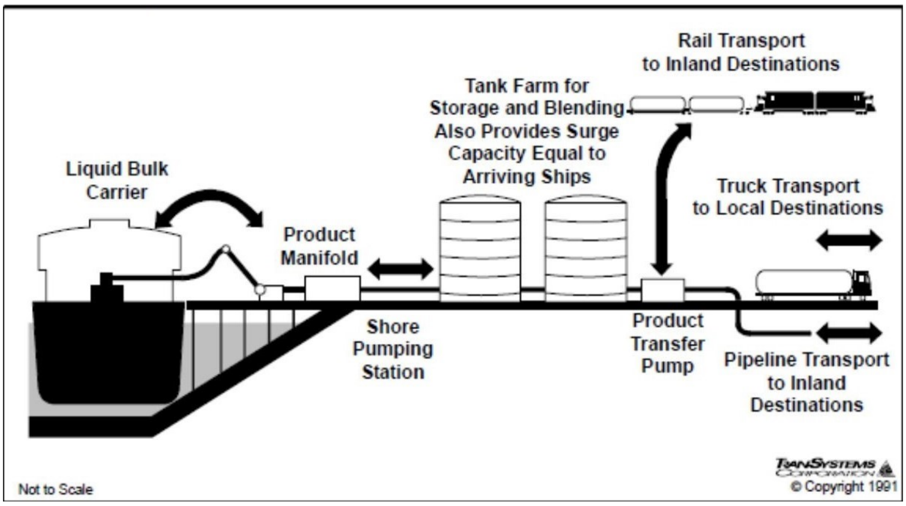


Figure 2: Operations at a liquid bulk terminal [8]

Research has been conducted on the operations of a liquid bulk terminal. These researches are focused different parts or processes of the liquid bulk terminal. The authors Verheul [6], Tam [9] and Madueke [8] investigate the performance of a liquid bulk terminal. Verheul [6] investigates different key performance indicators to effectively measure the performance of the terminal. He analyses the subsystems of the terminal and proposes methods to measure the performance of each subsystem. Tam [9] investigates different loading and unloading methods and their compatibility. These methods determine the overall performance of a terminal. Madueke [8] measures the efficiency and productivity at a liquid bulk terminal.
The authors Dohmen [7], Park and Park [10] and Bugaric et al. [11] research the different facilities within a liquid bulk terminal. Park and Park [10] analyses the processes within the terminal and tries to optimise different components by using simulation models. Bugaric et al. [11] simulates a bulk terminal to analyse different combinations of facilities. This is done to find the optimal utilisation of a bulk terminal. Dohmen [7] models the scheduling of ships arriving at the terminal. This helps optimising the performance and all the facilities at a liquid bulk terminal.

1.1.2 Possible alternative fuels

In the maritime industry the current fuel that is mostly used is Heavy Fuel Oil (HFO) [12]. This fuel and their cleaner alternatives, Marine Fuel Oil (MFO) and Light Fuel Oil (LFO), release apart from carbon dioxide (CO_2) also different extra pollutants [13]. HFO contains concentrations of sulphur that is released when when burned. These additional emissions are harmful. This emphasises that new alternative fuels are needed in the maritime industry to reduce the current emissions to reach the Paris climate agreements and the goal of IMO.

Alternative fuels or energy sources for ships have been studied extensively. The different options includes battery's, Liquid Natural Gas (LNG), Hydrogen, different hydrogen carriers like ammonia and methanol. Most studies consider battery's to be too heavy and expensive to use [14]. However the other options required more research. Ampah et al. [3] researched the research trend on fuel alternatives in the maritime industry due to the climate goals of the IMO. Ampah et al. concluded that LNG is the most researched upon alternative shipping fuel. However there is a change in trend that researchers are turning their attention to different fuels like methanol, ammonia and hydrogen [3]. The focus changed to to mainly the potential of different alternative fuels as replacement of the conventional marine fuels.

LNG
LNG has grown significantly more as a maritime fuel in the recent years. As a liquefied gas, natural gas occupies 1/600 less volume than in a gaseous state. This makes it a space efficient fuel as a bunker [3]. It is currently used as a more environmentally fuel option instead of HFO as the sulphuric emissions are lower. However LNG does require specialised engines to burn and cryogenic double-walled fuel tanks to store.

Methanol
Methanol is comparable as a shipping fuel to LNG. The main differences are that methanol is liquid at ambient temperatures and normal pressure. This makes Methanol easier to handle. The emissions from the use of

methanol powered vessels are reported to be less than with the use of LNG powered vessels [15]. It is important to note that these emissions are only lower when methanol is produced from renewable energy sources instead of natural gas. The future use would greatly depend on the precise amount of emissions from the use of methanol as bunker in maritime vessels.

Hydrogen
Hydrogen has a very efficient energy to weight ratio comparing to other fuels. Furthermore hydrogen can be used as alternative fuel in internal combustion engines or fuel cells. It also has the advantage that is does not produce any carbon or sulphur emissions. The only harmful emissions are NO_x [3]. However to use hydrogen as an alternative fuel, significant additional infrastructure is needed. Despite the high energy to weight ratio, hydrogen has a low volumetric energy density. Hydrogen therefore needs high pressures (250 bar to 750 bar) to store or very low temperatures ($-253\,^{\circ}C$) to be stored as liquid.

Ammonia
The most promising alternative is to use ammonia as fuel [16]. Furthermore it is considered that it could play a key role in IMO's decarbonisation plans [3]. The use of ammonia as alternative fuel does not produce any carbon or sulphur emissions. This is if ammonia is produced with renewable energy sources. The International Energy Agency forecasts that ammonia will account for 45% of the energy demand for shipping in 2050 to achieve net-zero emissions [17]. Ammonia is stored as a liquid at easier temperatures ($-33.6\,^{\circ}C$) and pressures (8.6 bar). Furthermore ammonia is already commonly transported by ships and trains and has storage systems. This gives ammonia a well-established infrastructure.

1.1.3 Ammonia as bunker

From the different alternative fuels ammonia is selected to study in this research as it is seen as the best option. Ammonia (NH_3) is a compound of nitrogen and hydrogen and is also considered as a hydrogen carrier. Ammonia is a gas that is colourless and has a recognisable pungent smell. It dissolves easily in water and has corrosive properties [18]. When ammonia is used as fuel it does not produce greenhouse gasses. The production of ammonia however can produce greenhouse gasses. The so called grey ammonia uses fossil fuels when produced. The current production of grey ammonia uses a Haber-Bosch synthesis process. This process converts natural gas (CH_4) to hydrogen (H_2) combined with nitrogen (N_2) into ammonia (NH_3). The Haber-Bosch process is very energy intensive which releases carbon dioxide (CO_2). This is therefore not feasible as a green alternative. Blue ammonia is produced in a similar way as grey ammonia. However this process is carbon dioxide neutral. The carbon dioxide is captured within the process instead of released. The capture of carbon dioxide within the process does bring extra costs.
Eventually the use of green ammonia is desired. Green ammonia is produced using renewable energy sources and does not produce carbon dioxide within the whole synthesis process [19]. The green synthesis of ammonia can still use the Haber-Bosch process by providing the hydrogen from the electrolysis of water instead of using natural gas. The nitrogen is obtained by using an air separation unit that compresses and cools the air. Other ammonia synthesis methods are thermochemical ammonia synthesis or solid state ammonia synthesis. These methods are however currently less common but are growing in use and development.

On multiple topics within ammonia different research has been done. De Herder [14], Seo and Han [16], Erdemir and Dincer [18], Kommers [19], Zincir [20], ABS [21, 22], DNV [23], Yadav and Jeong [24] and Alfa Laval et al. [25] all researched whether ammonia could be an alternative fuel for the maritime industry. These studies focused on different aspects of the use of ammonia as a maritime fuel.

Feasibility
De Herder [14], Erdemir and Dincer [18], Zincir [20] and Kommers [19] researched the feasibility of using ammonia as a marine fuel to reduce emissions and so reach the goals of the IMO for 2050. They concluded that ammonia is an attractive choice to use as an alternative fuel. However these authors did note that there are barriers to overcome. There is still a lack of availability of an engine that uses ammonia as fuel and there is no legislation implemented yet that complies for these engines. Additionally the production and availability is not on a level yet to be used in the maritime industry. Furthermore due to the lower energy density of ammonia, fuel tanks need to be larger resulting in less space for cargo or extra bunkering stops are required.

Previous researches occasionally took an economic evaluation into account. To evaluate whether it is economically feasible to use ammonia as a marine fuel. Seo and Han [16] made a full economic evaluation on ammonia fuelled carriers. Seo and Han concluded that carriers using an additional independent fuel tanks were better of in terms of economics. This study balanced the payoff of less cargo or extra stops needed to bunker.

ABS [21, 22], DNV [23], Yadav and Jeong [24] and Alfa Laval et al. [25] researched the safety requirements and therefore feasibility of ammonia when handling and storing. The most important safety aspects like toxicity, fire safety and corrosion are discussed in detail in subsubsection 2.3.1. Also the handling requirements of ammonia concerning storage and bunkering solutions are discussed in sections 2 and 3.

1.2 Problem statement

Due to the transition to ammonia in the maritime industry liquid bulk terminals need to adapt to the increasing use of ammonia to bunker ships. However there is no clear view of how such a terminal operates within these changes. There are different aspects of a liquid bulk terminal that need to be considered. The way an ammonia terminal scales to the increasing demand and the factors that are important with the scale of a terminal. The different configurations that can be used need to be identified. These configurations include the setup of what methods and steps are done to transfer ammonia from the storage of a terminal to the bunkered ship. To investigate the feasibility of these configurations a simulation model needs to be developed. With a simulation model the different configurations in relation to different demands and sizes can be investigated this shows the most suitable configuration for different scales. Eventually the influence of each component can be researched upon.

The literature does not research the use of ammonia as a fuel for ships within a terminal. And the preferred methods for different steps in relation to the scale of a terminal is not yet researched upon. This provides a literature gap. Therefore the goal of this research is to find these preferred solutions for a terminal to bunker ammonia to ships and to investigate the bunkering logistics of ammonia to ships at a terminal. The research tries to find strategic solutions for a terminal to handle the bunkering and storage of ammonia throughout the increasing use of ammonia in the maritime industry.

1.3 Research questions

For this research the following main research question will be answered:
What are the possible bunkering configurations for ships at a terminal using ammonia, and which solutions are the most suitable at different scales of ammonia demand to use in a terminal during an ammonia transition?

Furthermore the following sub-research questions will be answered:

1. How does a liquid bulk terminal function and what influences the scale of a terminal?
2. What are the possible ways to bunker ammonia to ships and supply ammonia to a terminal?
3. How can the ammonia supply and bunkering within a terminal be modelled?
4. What are the most suitable configurations to bunker and supply ammonia for each scale of a terminal?

1.4 Scope

The scope for this research is defined to investigate the use of ammonia within a Liquid Bulk Terminal. This thus includes the handling and storage of ammonia in the terminal and with ships. The supply of ammonia within the terminal is included to investigate the full operation of a liquid bulk terminal. This excludes the production of ammonia.

1.5 Structure of study

This study is organised as follows. Each sub-research question will be answered individually. In section 2 the first sub-research question will be answered. This question is answered by conducting a literature review. First the function of a terminal is analysed, including the storage and transport of ammonia. Additionally influences on the scale of a terminal is analysed. The second sub-research question is answered in section 3. The possible ammonia bunkering options are identified and the second sub-research question is answered. Section 4 answers the third research question by formulation a conceptual model of the handling of ammonia within a terminal to bunker ships. This includes the scope and requirements for the model. Additionally the classes of the conceptual model are explained. Section 5 shows the implementation of the conceptual model including the verification, validation and the experimental plan of the model. The results of the simulations are analysed. An estimate of the costs for facilities at the terminal are made and are combined with the simulation results to answer the last sub-research question.

2 Liquid Bulk Terminal

In this section the first sub-research question is answered. This sub-research question is: ***How does a liquid bulk terminal function and what influences the scale of a terminal?*** To answer the first sub-research question the concept of a terminal needs to be analysed.

In the previous subsubsection 1.1.1 the functions of a liquid bulk terminal are discussed. These different functions and components are elaborated on in this section. Thereafter the important factors that influence the scale of a terminal are analysed.

2.1 Storage

At atmospheric pressure ammonia is a gas. To handle and store ammonia easier, ammonia is transformed to liquid. Ammonia storage is usually pressurised below 2000 tonne of ammonia [26, 27]. Larger storage units use cooling to liquefy ammonia with a re-liquefaction plant [23]. With these large scale industrial purposes ammonia is cooled to a temperature below $-33.6\,^{\circ}\mathrm{C}$ and stored [28, 29]. This is more cost efficient than storage under pressure [21]. As at ambient temperatures ammonia should be pressurised at 8.6 bar or more for transport and storage as liquid ammonia. Ammonia can therefore be stored as a liquid in cooled tank terminals or as liquid under pressure.

2.1.1 Pressurised ammonia storage

When storing ammonia under pressure, the pressure tanks are commonly operated at a pressure of 17 bar [30]. This is done to always keep the ammonia liquid when the outside temperatures may vary. The pressures used are minor and therefore carbon steel can be used for the tank. The size of these pressure tanks is practically limited to 270 t, due to the tank needing too much steel [30]. A pressure tank for ammonia storage can be seen in Figure 3a. These quantities are suitable for small fuelling terminals. Larger tanks are needed to handle the output of large ammonia production facilities. These facilities can produce over a thousand tonnes of ammonia a day.

2.1.2 Refrigerated ammonia storage

When cooled low temperature storage is used for ammonia, a large insulated tank with refrigeration system is used [31]. An example of such a cooled ammonia tank can be seen in Figure 3b. With this the fuel stored and the new fuel that is added is kept or turned liquid for storage [30]. Due to that the tank only needs to retain static pressure, the material requirements for the tank are greatly reduced compared to pressure storage. The downside of low temperature cooling is that the storage uses fuel to keep the ammonia stored. There is constant boil off, evaporation of the liquid, within the tank and therefore the boil off needs to be re-liquefied or the fuel would be lost [32]. Ammonia low temperature storage tanks are produced in the range of sizes. These range from 4500 t to 60 000 t. Most tanks store between 15 000 t and 60 000 t [19, 30, 32, 33]. Due to the fact that less steel is needed for the construction of the tank cooled storage is 15 times more efficient than pressure storage. [30]. This reduces the capital costs needed and therefore cooled storage is more likely to be used for large scale ammonia storage.

(a) Pressure storage ammonia [34]   (b) Cooled storage ammonia [35]

Figure 3: Different ammonia storage tanks

2.2 Transport

The current transport for ammonia uses ships, pipelines, trucks and trains [35, 36, 37]. The transport of ammonia is carried out in two different conditions, liquid cooled transport or transport as liquid under pressure, equivalent as with the storage seen in subsection 2.1. Cooled transport is possible for higher volumes but requires constant energy usage to keep the ammonia cooled and to re-liquefy the boil off. However it requires relatively less weight. Pressure transport does not require continuous additional energy, although the tanks containing pressurised ammonia are heavier to be able to withstand the pressures.

2.2.1 Ship

Ships can use either pressure or cooled transport for ammonia. Low temperature is more suitable as it is lighter and therefore it is possible to transport more ammonia at the same time. Ships can transport 50 000 t of ammonia [30]. Most ammonia is currently shipped using Medium Gas Carriers (MGC) and Large Gas Carriers (LGC), depending on the distance to travel. These carriers have a capacity of 23 000 t and 40 200 t for MGC and LGC respectively [37].

2.2.2 Pipeline

Transport by pipeline of liquid is considered safe, low risk and cost effective when installed [30, 37]. Pipeline transport consists of pump stations between destinations. These pump stations boost the flow of the liquid inside due to the losses from friction [37]. Pipelines can transport ammonia under high pressures at a ambient temperature or low pressures at a low temperature [37]. Pipelines are mostly used for long transport [30].

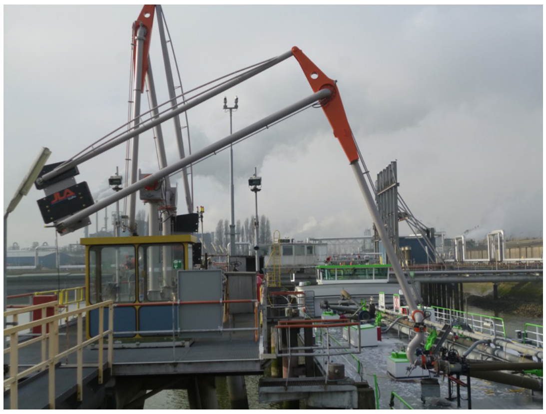
2.2.3 Road and Rail

Ammonia transportation by road or rail is mostly done using pressure storage. The road truck transport capacity is 43 530 L operating at a pressure of 20.7 bar [30]. Equivalent to 26.6 t of ammonia per truck. Nayak-Luke et al. even suggest up to 36 t of ammonia per truck. For rail transport the pressure tank contains 126 810 L at 15.5 bar equivalent to 77.5 t of ammonia [30, 35]. Nayak-Luke et al. states that even 110 t of ammonia can be transport per tank. A freight train can consist of 50 to 150 tanks. This adds up to 11 000 t per train [37].

2.3 Loading and unloading of ammonia

To transport the ammonia from a storage location into a mode of transport like ships, trains or trucks a loading and unloading arm or hoses are used [9, 35, 38]. Different type connections using arms or hoses are seen in Figure 4. The connections are connected using specific safety procedures. It consists of an arm or hose for the gaseous phase and one for the liquid phase. A pump is used to pump ammonia from one connection to the other. These loading and unloading stations also maintain a proper earthing of both storage containers as bad earthing could lead to fire hazards [35]. Additionally an emergency release coupling is used if something goes wrong within the process to prevent additional problems. There is a big variety of loading and unloading systems however they are not yet used with large scale terminal loading and unloading of ammonia. However Liquefied Petrol Gas (LPG) is very similar to ammonia as a liquid and LPG is already widely used at terminals [21].

(a) An example of a loading and unloading arm for ammonia with a train [35]



(b) An example of a loading and unloading arm for ammonia with a ship [39]

(c) An example of a loading and unloading connection for ammonia with ship to ship loading [9]

Figure 4: Ammonia transport between storage and transport modalities

2.3.1 Safety

Ammonia is at normal pressures and temperatures a colourless gas with a pungent smell. At higher pressures or lower temperatures it turns into liquid. This is mostly done for the transport and storage of ammonia [21]. The dangers that ammonia can cause are explained.

Toxicity
Ammonia can be found in nature but is toxic in higher concentrations [21]. It is classified as a harmful substance and therefore requires regulations. People can smell ammonia at very low concentrations, within the range of 0.037-1 ppm [21]. These concentrations are below levels that form health risks, however higher concentrations, 25 ppm, can be toxic to people [40]. Therefore where ammonia is stored or used the space needs to be well ventilated [19].

Fire Safety
Ammonia is a flammable gas with a narrow flammability. Ammonia is less likely to auto ignite due to the high auto-ignite temperature of 651 °C [21]. This makes ammonia relatively less risky as a fire hazard as fuels like hydrocarbons. Ammonia can react with halogens and oxidisers potentially causing reactions are explosions. To safely handle ammonia it should be stored in a well ventilated area away for sources of ignition. If it does ignite care needs to be taken for environmental damage that can be caused by the toxic ammonia.

Corrosion
Ammonia can be highly corrosive to certain materials. Therefore handling equipment should be designed to withstand these corrosive aspects. Ammonia corrodes copper, brass, zinc and other alloys [21]. Materials should therefore be selected carefully. To prevent leaks or other issues different regulations are in effect, these include requirements, inspections and procedures [29, 41].

2.4 Scale

For the scale of the terminal size, a few factors are the most important. The biggest aspect is the throughput in and out of the terminal. The throughput depends on a few different factors like how much cargo is transported, vessel calls and terminal capacity [42]. How much cargo is transported is of less importance for this study as it focusses on bunkering ammonia. However is does has an effect on the size of ships entering the terminal, bigger ships require more ammonia. Vessel calls are the number of ships entering the terminal in a period of time. This has an effect on the frequency of ships entering the terminal. The terminal capacity is linked to the size of storage a terminal has and the number of available facilities. These include the number of bunkering stations, trucks and bunker vessels but also loading locations for bunkering trucks and vessels.

2.5 Performance

The performance of a liquid bulk terminal is measured using performance indicators. In literature Verheul [6], Dohmen [7], Madueke [8], Iannone et al. [43] and Umang et al. [44] describe performance indicators of a terminal. The described performance indicators are:

- Berth Occupancy
- Tank occupancy
- Vessel turnaround time
- Turnover factor
- Throughput per berth/quay
- Realized loading capacity
- Berth efficiency
- Number of vessels
- Average waiting time
- Revenue per vessel
- Revenue per m^3 tank volume

These performance indicators are used to evaluate the performance of the terminal and to determine whether there are certain components need to be improved or are not functioning as intended.

2.6 Conclusion

This section investigated the function of a potential ammonia terminal and the influences on the scale of a shipping terminal. To answer the sub-research question: ***How does a liquid bulk terminal function and what influences the scale of a terminal***

An ammonia liquid bulk terminal has three important tasks to fulfil. These tasks are the storage, transport and (un)loading of ammonia. The storage of ammonia is done as a liquid under pressure or cooled. Ammonia is transported using ships, trucks, trains and pipelines. Loading and unloading is done using loading and unloading stations using pipe connections or loading arms. The biggest influence on the scale of a terminal is the throughput, this depends on how much cargo is transported, vessel calls and terminal capacity.

3 Bunkering and supply options

This section answers the second sub-research question: ***What are the possible ways to bunker ammonia to ships and supply ammonia to a terminal?***. To answer the second research question a literature study is used to analyse the bunkering and supply process at a liquid bulk terminal.

Bunkering is defined as the supply of fuel to the vessel for propulsion or other energy uses. To supply ammonia to ships within the maritime sector infrastructure and facilities are needed. There are already 120 ammonia terminals [19]. It can be assumed that these terminals have the necessary equipment and storage. The literature of bunkering ammonia is not extensive however the process of bunkering for LPG and LNG are well documented. LPG has similar characteristics to ammonia and can therefore be compared with for future solutions [21, 23, 37]. LNG have mostly similar characteristics to ammonia. The biggest differences for storage is that LNG is stored at much lower temperatures than is needed for ammonia. Therefore it can be assumed that the facilities used for LNG are similar or can also be applied to ammonia.

Within the literature four methods of bunkering are described. These four methods can be divided as bunkering form shore to ship or bunkering from ship to ship [45, 46, 47, 48]. The different methods are elaborated on in the next subsections.

3.1 Ship to Ship

Ship to Ship (STS) bunkering uses a bunkering vessel to bunker the fuel to a ship. The ammonia fuel can be bunkered while it is fully, semi or non-refrigerated (pressurised). However the receiving ship (bunkering vessel and to be bunkered ship) should be able to handle such temperatures and or pressures. Future concepts of ships with engines using ammonia suggest the use of refrigerated storage [49]. It is likely that the ships in the future will thus also use refrigerated storage tanks. Furthermore for higher volumes of storages and therefore larger ships pressurised storage is not or less feasible. Therefore most ships in the future should have equipment for the re-liquefaction of ammonia to store refrigerated ammonia and to handle boil off gasses. It can be assumed that ships will therefore likely bunker refrigerated liquid ammonia [21, 23].
STS bunkering provides flexibility with the the volume and transfer rate of bunkering. Furthermore STS bunkering provides flexibility in locations to bunker at. STS bunkering can be done at sea or at the port. While STS bunkering at the port when the ship is docked, it is possible that the ship could have other logistical activities simultaneously. This includes loading and unloading of other cargo [46, 50]. It is considered as the least disruptive to the ship and dockside operations [47].
However STS bunkering exposes the vessels to external influences like wind, currents, waves and the risk of collisions between the ships. Furthermore additional infrastructure is required to refill the bunkering vessels.

3.2 Truck to Ship

For Truck to Ship (TTS) handling the ammonia fuel is supplied to the ship at the dock using trucks. From the dock the ship is attached to a gas liquid system that pumps ammonia from the truck to the ship. The trucks can only carry non-refrigerated ammonia, thus under pressure as the truck cannot be equipped with the cooling systems. TTS bunkering gives great flexibility in locations as these tanks are easily transported to a location [50]. TTS bunkering is mainly suitable for small volumes fuel tanks. The tank size of the truck is limited by transport legislation [47]. Therefore it can be used as a start-up method for bunkering ammonia [46]. TTS Bunkering is less suitable for larger volumes as the number of trucks and the transfer rate limits it.

3.3 Pipe to Ship

When a Pipe to Ship (PTS) method is used the ship is bunkered using a pipeline connection from the shore storage of the terminal directly to the vessel while docked at the dock. This likely to be pressurised, however this method can be done at different temperatures. PTS bunkering is similar to TTS bunkering as mostly the same facilities can be used. However the supply to this bunkering station is by pipeline from the storage instead of a truck. PTS bunkering is able to supply bigger volumes at a much higher supply rate [46, 47, 48, 50]. PTS is therefore flexible with loading different volumes and transfer rates, however this method is not flexible with its location. The facilities used are fixed and can thus not be moved.

3.4 Container to Ship

Container bunkering (CTS) uses a special way of loading. Instead of directly bunkering, the fuel tanks are removed and replaced with new full fuel tanks. These container fuel tanks are non refrigerated and remove the need of complicated bunkering systems. The pressurised cylindrical tank is build into a typical container [45]. This uniform form factor is standard and helps for easy handling with the current infrastructure and cranes. These tanks containers are in two sizes 20 or 40 foot containers [46, 47, 50]. Trucks can supply this tanks to the terminal to be loaded onboard. On the ship the tanks are connected to the fuel system. CTS bunkering has the same flexibility as TTS bunkering, as the fuel can easily be transported to the ship, however this type of bunkering does require the ship is compatible for this way of bunkering [46]. The handling and refilling of container tanks does bring additional risks. The tanks require more connections to be made and unmade and the physical transfer of the tanks exposes them to a bigger probability of leaks and external impacts.

3.5 Supply options

For the supply of ammonia to the liquid bulk terminal four main methods can be identified. Most of these methods are similar to the previous mentioned bunkering options. A terminal can be supplied by gas carriers, pipeline connection, trains and by trucks. These transport methods are also discussed in subsection 2.2.

3.5.1 Gas carrier

A gas carrier is a large vessel that transports big volumes of gas. These vessels can be used to supply ammonia to a terminal. The produced ammonia is produced elsewhere and transported to the terminal by vessel and stored at the terminal. This option is flexible as the terminal only needs to be able to offload ammonia from such a ship [48]. Additionally this method is flexible for different volumes of demand for the terminal. As the terminal is able to bunker small and larger ships.

3.5.2 Pipeline supply

This option depends on the possibility of a relative nearby ammonia production location. The produced ammonia is transported by pipeline into the terminal storage [48]. This method can supply large and small amounts of ammonia to the terminal. Furthermore it provides a steady supply of ammonia to the terminal.

3.5.3 Train supply

The supply of ammonia by trains is also possible. For this method a sufficient connection to a rail road network is needed. This method gives the possibility to provide large volumes of ammonia to the terminal and to be stored. However infrastructure is needed to unload the train wagons with ammonia.

3.5.4 Truck supply

This option to supply the terminal is likely only feasible for a small scale. As the volume each truck can carry is very limited compared to other options. Furthermore a large number of trucks are needed to be able to supply a bigger volume of ammonia. This method is however flexible in its supply as very little additional infrastructure is needed at the terminal.

3.6 Option comparison

To create an overview of all the different options, Figure 5 can be seen. The four supply and four bunkering options are illustrated. The discussed bunkering options show that certain methods are more suitable in certain situations. STS bunkering is considered as a flexible option to use and can be used for a wide range of volumes. TTS bunkering is suitable to be used for smaller fuel tank capacities and possible when less infrastructure is available. PTS bunkering is likely to be used for larger volumes of bunkering [46]. CTS bunkering is still new and uncertain how it will develop.

Literature already shows that there are a few preferences for certain methods. The authors Park and Park state that from these methods Ship to Ship and Truck to Ship bunkering are considered as the two proper ways to reduce travel time and waiting times [10]. Additionally Park and Park foresee problems of using pipelines to bunker ships. Due to that pipelines could be exposed to port unloading and loading causing accidents. Furthermore the DNV states that for deep sea shipping Ship to Ship bunkering will likely be the preferred solution [23].

For the supply to the terminal gas carriers or a pipeline connection would be the most likely options. This is due to the larger possible volumes it can transfer.

Important to consider is the temperature that is used to load the bunker vessels and to bunker the ships. The tanks used to store the ammonia on the vessels should be designed to hold the ammonia at the same temperature type. When transferring refrigerated ammonia to a pressurized tank the ammonia should be heated using a heating system and compressed to the correct temperature and pressure to store according to the tank design specifications. In the reverse scenario from pressurised to cooled a cooling system is required. Furthermore a vapour collection system is required when handling a different temperatures to convert the boil off gasses back into liquid [23].

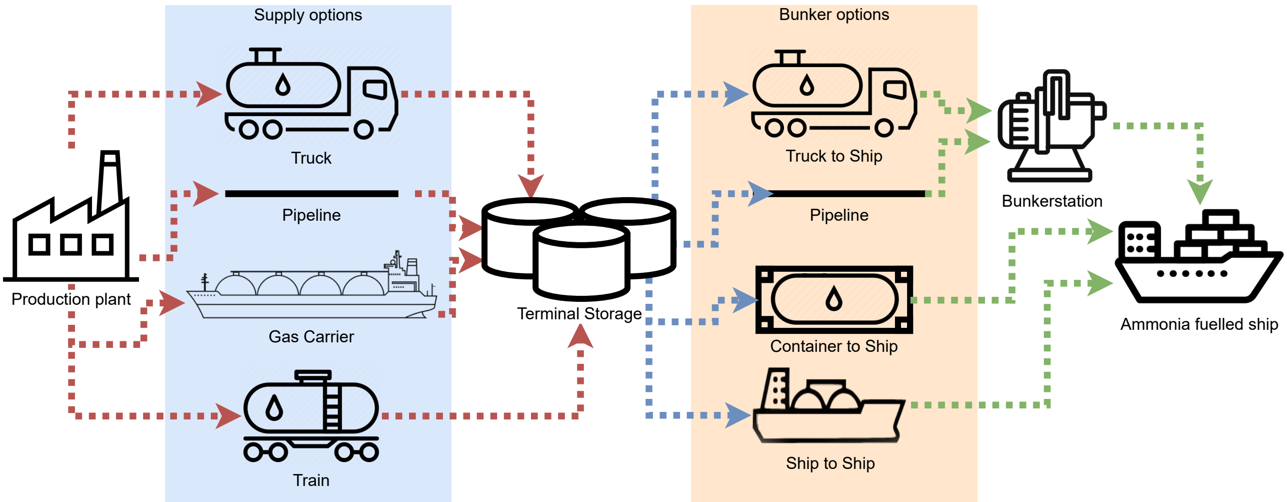


Figure 5: An overview of the different supply and bunker methods

3.7 Conclusion

In this section the second sub-research question is answered. The second sub-research question: ***What are the possible ways to bunker ammonia to ships and supply ammonia to a terminal?***.
To answer this sub-question literature research has been done. The possible bunkering options found are Ship to Ship, Truck to Ship, Pipe to Ship and Container to Ship bunkering. However literature shows that is it more likely to use Ship to Ship or Pipe to Ship bunkering. For the supply of ammonia to the terminal it is most likely that Gas carriers or a pipeline connection will be used. Furthermore the temperature or pressure of ammonia from and to the storage and from and to the transport method is important to consider as the ship or storage may not be able to store and/or handle it.

4 Model Development

This section answers the third sub-research question: ***How can the ammonia supply and bunkering within a terminal be modelled?***. Therefore a conceptual model is created to model the terminal. In the following sub-sections the goal, requirements, the conceptual model itself and other specifics for the model are discussed.

4.1 Goal and Scope

The goal for this model is to find the best configurations for a terminal to bunker ammonia to ships with the changing scale, supply and demand of ammonia within a terminal. And to gain insights into the bunkering logistics of ammonia to ships in a terminal.

The scope of this model is determined such that it includes the storage of ammonia at the terminal, the handling of ammonia within a terminal (using different methods) and the demand of ships that need bunkering. This scope also includes the supply of ammonia, using different methods, to the storage of the terminal but does not specify the production of ammonia itself. Thus the method of supply to the storage can vary. The scale of the supply determines the supply rate to the terminal ammonia storage(s). The scale of the ships determines the size of the ships and consequently the demand for ammonia. The scale of the terminal determines the size of the terminal which influences the size of the storage and number of bunkering facilities. Figure 6 shows how the scope of this research is defined. Furthermore it illustrates the steps involved to be modelled and researched.

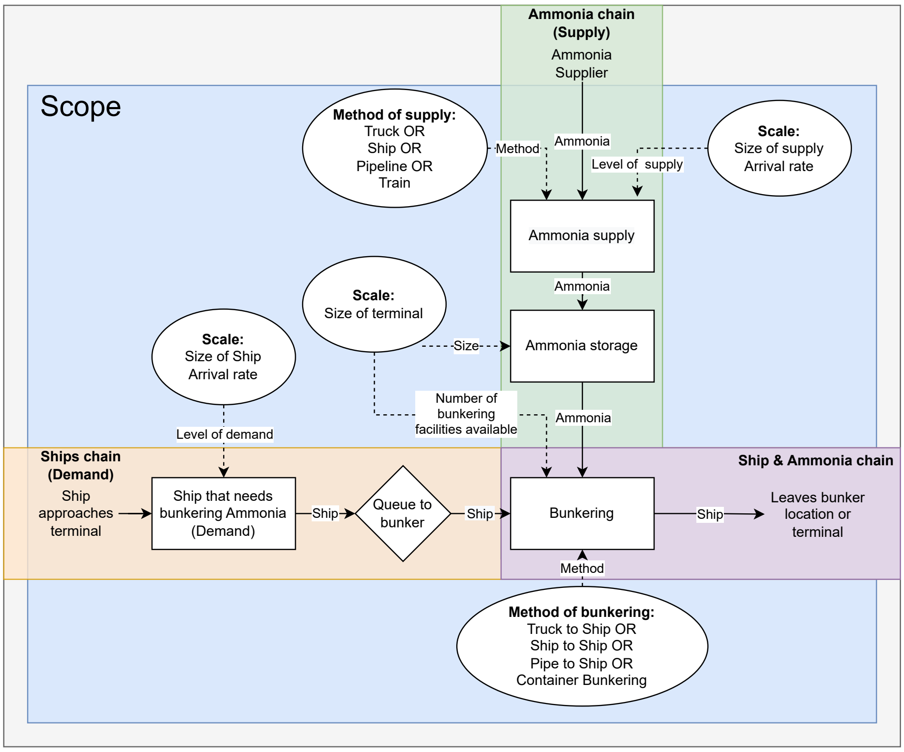


Figure 6: The defined scope of the model

4.2 Requirements

Requirements for this model are formulated. These requirements are necessary to develop the right model for this research and to reach the intended goal of this research. The following requirements are formulated:

- This model is required to keep track of the processes that are needed to load and unload ammonia in a successful way simultaneously with other processes.
- The model needs to keep track of the storage. This includes the current storage of different ships, but also the storage used in the terminal storage tanks. With this the model can model the correct volumes transferred from and to the terminal and or other ships.
- The handled ships need to have a demand for ammonia and an arrival time interval which is simulated by a distribution. This is to create random differences between ships.

- The model needs to be able to handle queues of different ships and components within the terminal. The queues involve waiting for a location to bunker but also trucks that wait to bunker ships etc.
- The model should be able to use different parameters of bunkering to calculate the performance indicators for the selected parameters. The performance indicators will be elaborated on in subsection 4.5. These are needed to be able to answer the different research questions.

4.3 Assumptions

Model assumptions need to be made to make the modelling process more simple or possible. The first assumption is that all to be bunkered ships require refrigerated ammonia. From literature it is found that this is the most likely the standard to be used for ships especially for larger ships [21, 49].
The second assumption is that ships can only leave the terminal when loading is complete. This forces a ship in the model to wait until it is eventually bunkered at the terminal. The ship can therefore not bunker elsewhere when the queue is long etc. However for the supply to the terminal, the supply ships/train/truck can leave the terminal earlier. When the supply modality completely fills the terminal storage it will leave the terminal and thus not stay until the full transfer is completed. This assumption is made to clearly evaluate the time that is needed for a ship to complete the full cycle of arriving and receiving bunker at the terminal. If a ship can leave earlier these "losses" that the terminal has are not recorded. This would give the impression that the terminal can cope with the demand but actually it cannot. The supply can leave however, if it could not leave before being completely unloaded this queue of supply would eventually create an extra storage to the terminal waiting to be unloaded. This effect would be unrealistic and undesirable.
Furthermore it is assumed that there is always enough personnel to complete all the bunkering processes within the terminal. The personnel needed is not included within the scope of this research therefore is assumed to be always available.
All the ammonia that enters or leaves the terminal goes through the storage of the terminal first. It is not possible to directly bunker a ship from a supply vessel or truck. This assumption is needed as it would be easier at the terminal. In this way the pressures and temperatures would be regulated better. Furthermore this would also prevent extra infrastructure that would be needed for this to happen.
While loading a constant transfer rate is assumed. As in a normal loading process the start and end have a lower transfer rate as pumps are starting up and need to be slowed down to prevent overfilling. To mitigate these differences constant lower transfer rates are used.
The boil off within the storage tanks is assumed to be re-liquefied by the storage systems onboard the bunkering vessel or in the terminal. And it is assumed that these systems can handle all the boil off so no emergency venting is needed. This can be assumed because the boil off of ammonia in comparison to LNG is relatively small as the storage temperature of ammonia is not as low as for LNG with -33 °C instead of -161°C [16]. Furthermore for ammonia and LPG carriers the generated boil off gas is re-liquefied [16]. The boil off can be considered to be less than 0.1% per day of the total volume in the tank and therefore be assumed to able to be handled by the refrigeration system [23, 30, 37, 50, 51, 52]. Furthermore it can be assumed that there is no ammonia lost in the re-liquefying process and thus the volumes in the storages are not effected [37].
Furthermore any effect of maintenance or breakdown of the facilities at the terminal are not taken into account. These effects are not part of the scope of this research.
Any effect that the weather or tide has on the terminal is not taken into account. The terminal is considered to operate continuously, therefore day, night and weekend effects are neglected.

4.4 Parameters and Input specifications

In this subsection the different parameters and inputs that can be used within the model are explained. To research a terminal that bunkers ammonia, different parameters can be changed to evaluate various terminal configurations and scenarios at the terminal. The five parameters to change are the bunkering method, the method of ammonia supply to the terminal, and three scale parameters, size of the liquid bulk terminal, the size of the ships needing ammonia to bunker and the size (rate) of supply of ammonia to the terminal. The bunker method and terminal size together form the configuration of the terminal, and ammonia supply method and size, with the ship size (demand) together provide for different scenarios in this research.

The different bunkering and supply options described in section 3 can be used in this model. The selected methods for this study are Ship to Ship, Truck to Ship and Pipe to Ship. However it is opted to not include container bunkering. Container bunkering is currently barely used and there is limited literature on it. The available literature shows that this method is still partly conceptual, that the ships need to be adapted to be able to receive these tanks and the additional connections needed give additional risk. This makes container bunkering not mature enough to be used in this model of a liquid bulk terminal.

The methods for the supply of ammonia to a terminal are discussed in subsection 3.5. These methods are the supply by ship, a pipeline, trucks or by using trains.

The third parameter influence the scale of the terminal. The size of the terminal defines the size and number of facilities available at the terminal. Like the number of bunker locations and the size of the ammonia storage.

The fourth and fifth parameter is the size of the ships that arrive at the terminal and the supply that enters the terminal. The size of the ships influence the average demand for ammonia that each ship has when it enters the terminal. The supply and demand both influence the rate of arrival/frequency of ships and the supply of ammonia to the terminal and its storage. The size and frequency together create the rate of ammonia demand and supply. Defined as the ship size and supply size parameters.

4.5 Key Performance Indicators and outputs

To measure the results of the model different performance indicators are measured. The described performance indicators in subsection 2.5 can be used to evaluate the performance of the modelled terminal. Not all of these indicators are useful to evaluate the performance of the terminal for this research. The found indicators that are useful according to the requirements and assumptions are:

- Berth occupancy
- Storage tank occupancy
- Number of ships handled
- Total terminal ammonia throughput
- Average ammonia throughput per handled ship
- Average time spent at the terminal
- Average time spent in the bunkering process
- Delay for a bunkering position
- Delay at bunkering station
- Total delay at the terminal
- The average length of queue to enter the terminal

The occupancy of a berth or storage tank shows on average how much they are used or filled. For the berth it shows, of all the locations, how much of the total time it is occupied. for this research the term bunker occupancy is used instead of berth occupancy. This is done to include the occupancy of bunkering vessels. The storage occupancy is the average level of how much the storage tanks are filled. The number of ships handled show how many ships have completed the whole process of bunkering and left the terminal. This gives a measure on the effectiveness of a method compared to a different method at the same scale of operation. The throughput of a terminal or ship show the volume that has been bunkered to ships within the terminal. This gives a measure on how effective a method is in comparison to another method. The average time spent shows how long a component or the whole process took to complete. The delay shows how much time a ship has spent extra at a certain process. It identifies the different processes that are a bottle neck for the whole system. And if or which resources limit the smooth operation of the liquid bulk terminal.

For this research key performance indicators are selected to determine whether a terminal configuration is effective or not. The four key performance indicators are the number of ships handled, the average time a ship spends at the terminal, consisting of the time spend on average and the average total delay of a ship at the terminal; the bunker occupancy and the storage occupancy. The average time at the terminal spent is important as ships want to stay at a terminal for the shortest amount of time as that is financial beneficial. The delay of the terminal shows whether the system is stable and if the terminal can keep up with the arriving ships needing bunker. The bunker occupancy show busy a bunker method is compared to another method. The storage occupancy gives insights in how effective a supply method is. With these four key performance indicators it can be seen how many ships, how fast and how efficient a configuration is and helps to answer the research questions.

4.6 Model Formulation

To formulate a conceptual model that fulfils the previously mentioned goal, requirements, assumptions and previous literature on this topic is researched. There are two methods of modelling that are widely used for research of a terminal. These methods are mathematical models or discrete event simulation models. Mathematical models are mostly used in research for vehicle routing problems, queue theory and berth allocation problems [44, 53, 54, 55]. This mostly involves in optimisation of current situations. Discrete Element Simulation (DES) models are more useful when considering the feasibility of systems and methods. The use of DES fits the goal, requirements and assumptions better than mathematical models. This can also be seen in the literature. Iannone et al. [43], Cartenì and Luca [56], Triska and Frazzon [57] and Legato and Mazza [58] used models to describe different shipping terminals with different goals. These researchers use Discrete Event Simulations to model the terminal. DES models a sequence of events. Every event occurs at a time and changes the state of the system. The system is assumed to be constant between events so only the events need to be simulated. DES is used in their studies because it helps to overcome mathematical limitations of optimisation approaches, support computer generated strategies and support decision processes through a "what if" approach [56]. The what if approach helps to understand the response and consequences of different scenarios within the terminal. Furthermore DES is a common approach for modelling the operations of a system as a discrete sequence of events over time [43].

The main components of a DES simulation are entities, queues and events. Entities are dynamic objects which interact with other entities following their processes and set attributes. Queues are the lines in which entities wait until it is possible to perform an activity. Events happen at a specific instant of time during the simulation and can change the entities attribute and variables. This type of model and the steps taken follow the goal and requirements for this study. Therefore for this study also a discrete event simulation approach is used.

The model consists of different classes, which form entities, that together form the terminal. Depending on the different methods of supply and bunkering other sets of classes are used. To give a better understanding of how all the components are connected and how the flow of ammonia travels Figure 7 and Figure 8 can be seen.
In Figure 7, a flow chart is given to illustrate a simplified representation of the processes that are involved in the terminal. The model can be divided into three processes; a bunkering process, a reloading process and a supply process. These three processes operate simultaneously and depend on each other. The bunkering process needs the reloading and supply process to operate. The reloading process provides the trucks and vessels needed to bunker. The supply process the ammonia to refill bunkering vehicles or the bunker ships.
Figure 8 shows how classes of the model are linked and the flow of ammonia through the terminal. The sharp boxes indicate classes, dashed lines show influence and continuous lines show the flow of ammonia.

The model consists of two generators. One generator creates according to the ship size parameter ships with an ammonia demand. The other generator creates supply vehicles according to the supply method parameter. The time between each generated vehicle or ship that needs bunkering is dependant on the size of the ships that need bunkering or size of supply to the terminal. Thus having more frequent and larger supplies for larger ships or supply and less for smaller ships and supply. Depending on which method of supply or bunkering is selected a selection of the classes are used. It is not possible to have multiple supply or bunkering methods at the same time. There are fifteen classes that handle ammonia and have interactions with other classes and their processes.

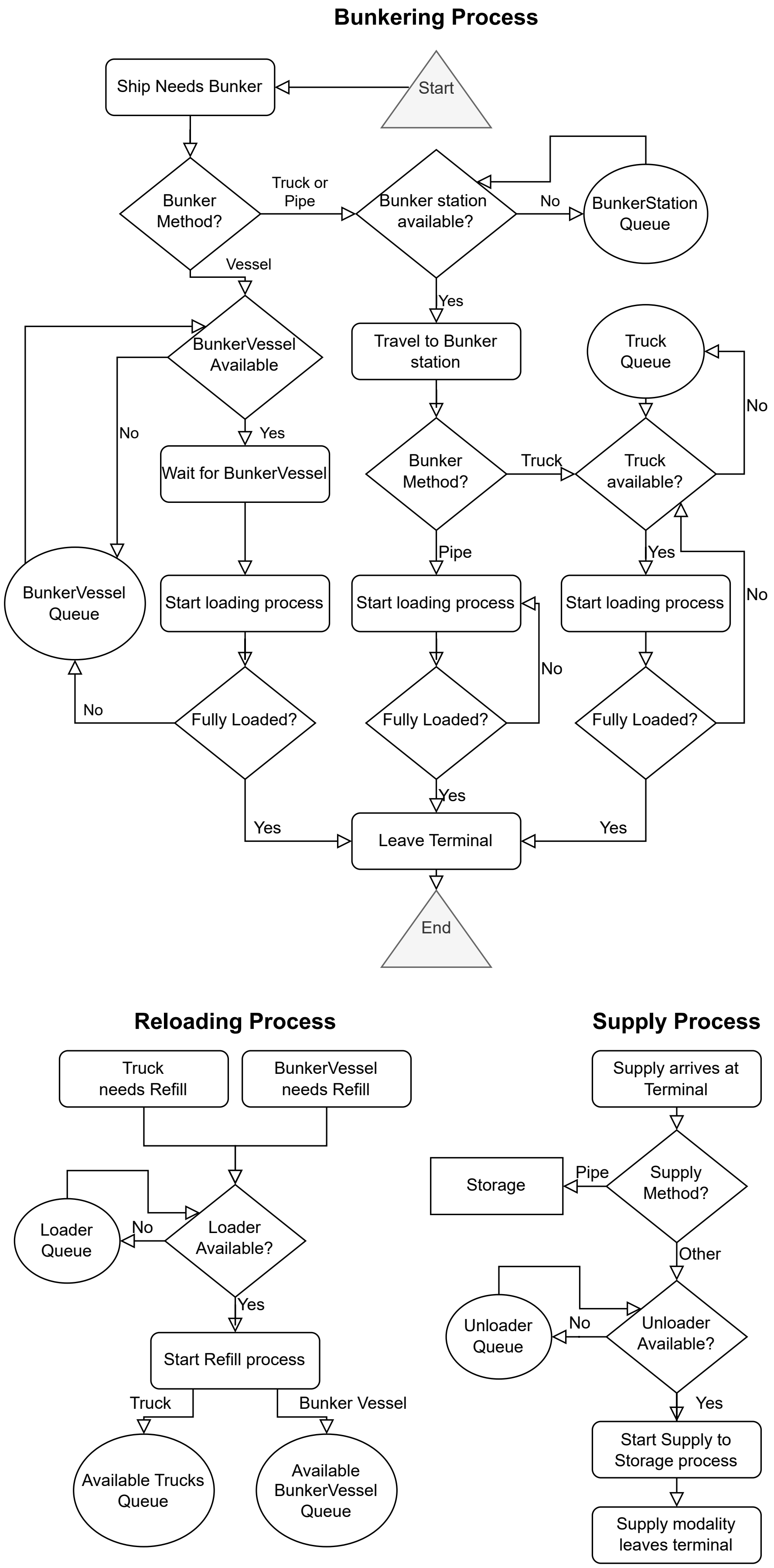


Figure 7: Flow diagram of the simplified processes within the terminal

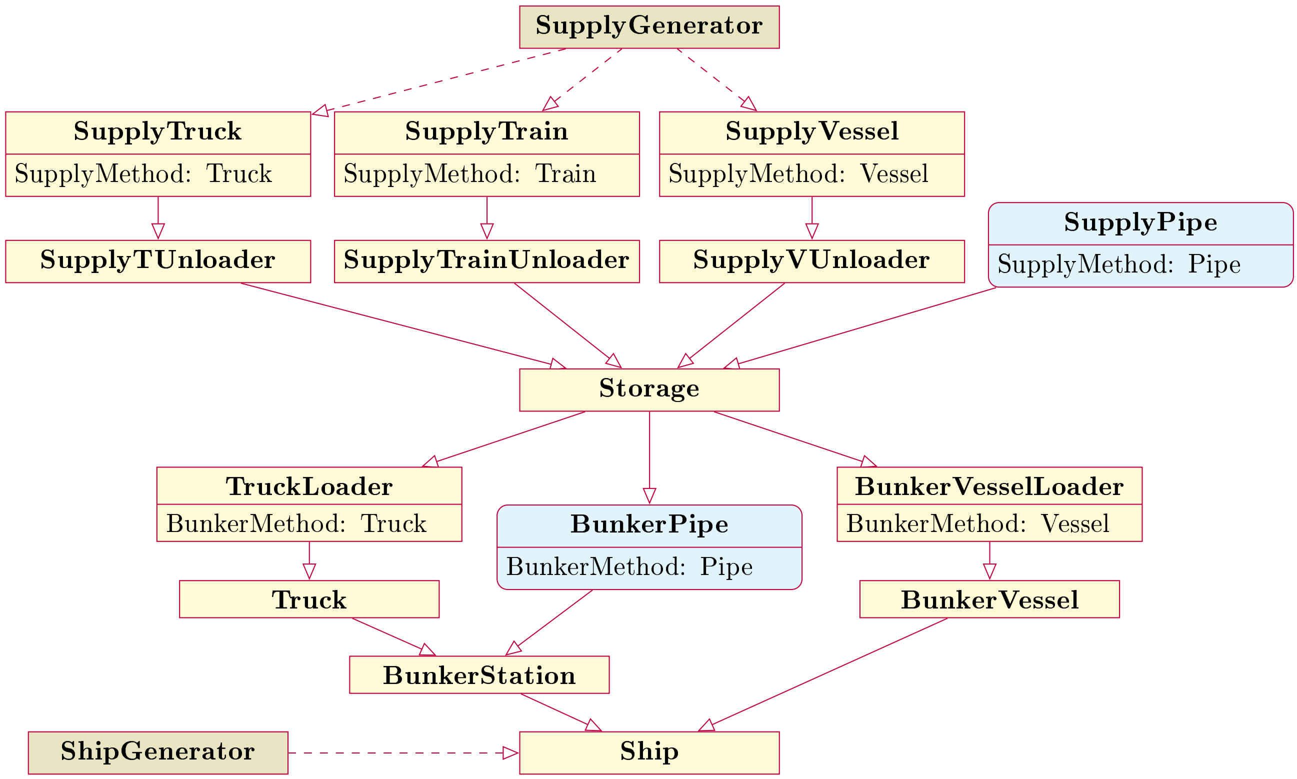


Figure 8: The flow of ammonia between classes and the relation between them

In Figures 9 to 11 on the following pages show the formulation of the different classes in this model. For each class the attributes and processes are given. Some classes also have sub-processes. Most processes are repeated many times until a condition is met. The attribute "Load Time Factor" is used to calculate the time that the model has to wait for the loading or unloading to complete. This factor is the transfer rate that is used to transfer ammonia.

Class: Ship

Attributes:
Ammonia Demand

Process:
Enter the queue for ships needing bunkering
While the Bunkering method is trucks or pipe:
-Wait for an available Bunker Station
-Hold Travel time to Bunker Station
-Wait until fully loaded
While the Bunkering
method is Bunkering Vessel:
-Wait for an available Bunkering Vessel
-Wait until loaded
-Repeat until fully loaded
Leave terminal

Class: BunkerStation

Attributes:
Setup Time
Decoupling Time
Load Time Factor

Process:
Enter queue for bunkerstations available for ships
Wait for an avaiable Ship
Sub-process: Truck loading
While bunkering method is truck:
-Enter queue for bunkerstations needing trucks
-Wait for available Truck
-Wait for Truck and Ship
-Hold Setup Time
-Calculate and hold loading time
-Update Ship demand
-Hold Decoupling Time
-Repeat until Ship demand is fulfilled
End of sub process Truck loading
Sub-process: Pipe loading
While bunkering method is pipe:
-Wait for Ship
-Hold Setup Time
-Calculate and hold loading time
-Update Demand Ship
-Hold Decoupling Time
End of sub process Pipe loading
Activate Ship

Class: ShipGenerator

Attributes:
Distribution Ship inter-arrival time
Distribution ammonia demand for Ship

Process:
Generate Ships with their inter-arrival time
and attributes

Class: Truck

Attributes:
Travel time
Storage

Process:
Sub-process: Bunkering
While the storage of the truck is full:
Enter the queue for trucks available for bunkering
-Wait for an available Bunker Station
-Hold Travel time to Bunker Station
-Wait until unloaded
End of sub process Bunkering
Sub-process: Refill
While the storage of the truck is not full:
-Enter the queue for trucks needing refilling
-Wait for an available Truck Loading Station
-Hold Travel time to Truck Loading Station
-Wait until loaded
End of sub process Refill

Class: TruckLoader

Attributes:
Setup Time
Decoupling Time
Load Time Factor

Process:
While the terminal storage is not empty:
-Enter queue for truckloaders available for trucks
-Wait for available Truck
-Wait for Truck to arrive
-Hold Setup Time
-Calculate and hold loading time
-Update Truck and terminal storage
-Hold Decoupling Time

Figure 9: Conceptual model part 1

Class: BunkerVessel

Attributes:
Setup Time
Decoupling Time
Load Time Factor
Travel time
Storage
Loading threshold

Process:
Sub-process: Bunkering
While the storage of the Bunker Vessel is higher than loading threshold:
-Enter queue for bunkervessels available for ships
-Wait for available Ship
-Hold travel time to ship
-Hold Setup Time
-Calculate and hold loading time
-Update BunkerVessel storage and Ship demand
-Hold Decoupling Time
End of sub process Bunkering
Sub-process: Refill
While the storage of the Bunker Vessel is lower than loading threshold:
-Enter the queue for bunker vessels needing refilling
-Wait for an available Bunker Vessel Loading Station
-Hold Travel time to Bunker Vessel Loading Station
-Wait until loaded
End of sub process Refill

Class: SupplyGenerator

Attributes:
Distribution supply inter-arrival time

Process:
While the supply method is truck:
-Generate supply trucks with their inter-arrival time and attributes
While the supply method is vessel:
-Generate supply vessels with their inter-arrival time and attributes

Class: SupplyVessel

Attributes:
Travel time
Storage
Load time factor

Process:
Enter the queue for supply ships available to supply
Hold Travel time to storage
Wait until done unloading
Leave terminal

Class: BunkerVesselLoader

Attributes:
Setup Time
Decoupling Time
Load Time Factor

Process:
While the terminal storage is not empty:
-Enter queue for bunker vessel loaders available for a bunker vessel
-Wait for available Bunker Vessel
-Wait for Bunker Vessel to arrive
-Hold Setup Time
-Calculate and hold loading time
-Update Bunker Vessel and terminal storage
-Hold Decoupling Time

Class: Storage

Attributes:
Terminal storage
Maximum terminal storage
Supply rate
Supply rate time

Process: Pipe loading
While bunkering method is pipe and terminal storage is not over maximum:
-Hold supply rate time
-Update terminal storage with supply rate
-Repeat

Class: SupplyTruck

Attributes:
Travel time
Storage
Load time factor

Process:
Enter the queue for supply trucks available to supply
Hold Travel time to storage
Wait until done unloading
Leave terminal

Class: SupplyTrain

Attributes:
Travel time
Storage
Load time factor
Number of Carriages

Process:
Enter the queue for supply trains available to supply
Hold Travel time to storage
Wait until done unloading
Leave terminal

Figure 10: Conceptual model part 2

Class: SupplyTUnloader
Attributes: Setup Time Decoupling Time
Process: While supply method is truck: *-Enter queue for Storage needing supply* *-Wait for available Supply Truck* *-Wait for Supply Truck to arrive* *-Hold Setup Time* *-Calculate and hold loading time* *-Update terminal storage and supply truck storage* *-Hold Decoupling Time*

Class: SupplyVUnloader
Attributes: Setup Time Decoupling Time
Process: While supply method is vessel: *-Enter queue for Storage needing supply* *-Wait for available Supply vessel* *-Wait for Supply vessel to arrive* *-Hold Setup Time* *-Calculate and hold loading time* *-Update terminal storage* *and supply vessel storage* *-Hold Decoupling Time*

Class: SupplyTrainUnloader
Attributes: Setup Time Decoupling Time Number of carriage unloaders
Process: While supply method is train: *-Enter queue for Storage needing supply* *-Wait for available Supply Train* *-Wait for Supply Train to arrive* For every carriage: *-Hold Setup Time* *-Calculate and hold loading time* *-Update terminal storage and supply train storage* *-Hold Decoupling Time*

Figure 11: Conceptual model part 3

4.7 Conclusion

In this section a conceptual model is developed and answers the sub-research question: ***How can the ammonia supply and bunkering within a terminal be modelled?***.
By formulation a discrete event simulation model different components within the terminal are modelled. The model handles queues, components of the terminal and their storages. The model consists of 15 classes that together form a liquid bulk terminal. By using a selection of the classes various configurations of a terminal can be modelled. Each class has attributes and different processes. In the model ships are modelled that enter the liquid bulk terminal. The ships can be bunkered by using different bunkering methods. Furthermore the supply of ammonia to the terminal is modelled. This ammonia supply to the terminal can be done using different methods.

5 Model implementation and experimental plan

By implementing the conceptual model, the most suitable configurations at different scales, of ammonia terminal size, supply and demand, are investigated. With these results the last sub-research question can be answered. In the following subsections implementation of the model, experimental plan and results of the model will be elaborated on. Furthermore the costs for the facilities at the terminal are estimated.

5.1 Implementation

For the implementation of this discrete event model the programming language Python is used. In combination with python the package Salabim is used. Salabim is a package for discrete event simulation, queue handling, resources, statistical sampling and monitoring [59, 60]. With Salabim the model can take into account the storage at a terminal, processes and limitations that are needed or required. Salabim is therefore able to simulate the logistics within a terminal to bunker a ship. These specifications fit the conceptual model and its requirements. It is therefore used for the implementation of the conceptual model discussed in section 4.

5.2 Verification

Verification is the process of making sure that the designed concept model is implemented with sufficient accuracy [61]. To state it more simple: Is the model built right? This implemented model is also verified for this purpose. The verification is done by using different parameters and comparing the expectation with the results of the KPI of the simulation. As the expected results are known outcomes. Additionally extreme situations are tested to see whether the model behaves accordingly. The behaviour and quantities of the ships and their storage is verified. Also the different bunkering and supply methods are verified by changing the number of facilities and storages. The precise results of this verification can be seen in Appendix B.
Additionally the the model outputs a trace which includes all the steps it takes and at which moment and under what conditions. By analysing the trace of this model it can be verified that the model does in fact operates in a logical order and manner. Therefore the implementation behaves as the defined conceptual model from section 4.

5.3 Validation

The validation of a model is the process of ensuring that the model is accurate enough for the intended purpose, in other words asking the question if the right model is build [61]. For this model checking whether the model is right and simulates a realistic liquid bulk terminal is difficult. The model models a terminal that uses ammonia to bunker ships, this is not yet implemented in the real world yet. This makes it hard to compare the model to data or the real world to determine its accuracy. The different configurations within the model are validated by using three methods, the first method is using data validation, the second method is process validation and the third is performance validation.

5.3.1 Data Validation

To validate parts of this model the parameters of the terminal configurations are chosen such that it can be assumed that the model represents a real world situation. One of the biggest factors within the model are the transfer rates used for bunkering process and the transfer of ammonia. By comparing values from different literature, assumptions for the transfer rates can be made. With this method the transfer rates of ammonia within the liquid bulk terminal can be estimated for the different bunkering methods. In table 1 an overview of different estimates for ammonia or LNG bunkering can be found using different bunkering and supply methods. The found values in the literature are converted to the same unit that can be used as a parameter value in the implemented model. Some research uses different assumptions and different temperatures or pressures. However when comparing the values a realistic value for the different transfer rates can be assumed for this model.

Bunker method	Converted value	Unit	Value in literature	Unit	Remarks	Source
Truck to Ship	0.576	$m^3\,min^{-1}$	14	$t\,h^{-1}$	Storage to Truck LNG	Park and Park [10]
	0.576	$m^3\,min^{-1}$	14	$t\,h^{-1}$	Truck to Ship LNG	Park and Park [10]
	0.631	$m^3\,min^{-1}$	10000	gal h^{-1}	Lowest transfer rate LNG	Holden [46]
	0.833	$m^3\,min^{-1}$	50	$m^3\,h^{-1}$	Expert knowledge LNG	Holden [46]
	0.667	$m^3\,min^{-1}$	40	$m^3\,h^{-1}$	Low transfer rate LNG	EMSA [50]
	1.000	$m^3\,min^{-1}$	60	$m^3\,h^{-1}$	High transfer rate LNG	EMSA [50]
Ship to Ship	16.667	$m^3\,min^{-1}$	1000	$m^3\,h^{-1}$	Storage to vessel LNG	Park and Park [10]
	16.667	$m^3\,min^{-1}$	1000	$m^3\,h^{-1}$	Storage to gas carrier LNG	Gate Terminal [62]
	50.000	$m^3\,min^{-1}$	3000	$m^3\,h^{-1}$	Storage to gas carrier LNG	Gate Terminal [62]
	10.000	$m^3\,min^{-1}$	600	$m^3\,h^{-1}$	Bunkervessel to Ship LNG	Park and Park [10]
	8.333	$m^3\,min^{-1}$	500	$m^3\,h^{-1}$	Ammonia bunkering	Fan et al. [63]
	1.117	$m^3\,min^{-1}$	67	$m^3\,h^{-1}$	Low transfer rate low T LNG	Holden [46]
	10.000	$m^3\,min^{-1}$	600	$m^3\,h^{-1}$	High transfer rate low T LNG	Holden [46]
	8.333	$m^3\,min^{-1}$	500	$m^3\,h^{-1}$	Low transfer rate LNG	EMSA [50]
	16.667	$m^3\,min^{-1}$	1000	$m^3\,h^{-1}$	High transfer rate LNG	EMSA [50]
Pipe to Ship	0.833	$m^3\,min^{-1}$	50	$m^3\,h^{-1}$	Low transfer rate low T LNG	Holden [46]
	10.000	$m^3\,min^{-1}$	600	$m^3\,h^{-1}$	High transfer rate low T LNG	Holden [46]
	16.667	$m^3\,min^{-1}$	1000	$m^3\,h^{-1}$	Low transfer rate LNG	EMSA [50]
	33.333	$m^3\,min^{-1}$	2000	$m^3\,h^{-1}$	High transfer rate LNG	EMSA [50]

Table 1: Overview within the literature of ammonia transfer rates of different bunker methods

Table 1 is used to assume transfer rates of ammonia for the various processes within the terminal. By using the data from literature a way of validation can be done. This is to assure that the model is as accurate as needed for the simulations. The selected values for each process are for three different sizes of terminal. The selection of sizes of the terminal is later elaborated on in subsubsection 5.4.1. The selected transfer rates can be seen in Table 2.

Transfer rate	Process	Value for terminal size S	M	L	Unit
Bunkering	Truck to Ship	0.85	0.85	0.85	$m^3\,min^{-1}$
	Bunkervessel to Ship	8.00	12.00	16.00	$m^3\,min^{-1}$
	Pipe to Ship	8.00	12.00	20.00	$m^3\,min^{-1}$
Loaders	Storage ↔ Truck	0.85	0.85	0.85	$m^3\,min^{-1}$
	Storage ↔ Vessel	15.00	30.00	50.00	$m^3\,min^{-1}$
Supply	Truck to Storage	0.85	0.85	0.85	$m^3\,min^{-1}$
	Gas Carrier to Storage	15.00	30.00	50.00	$m^3\,min^{-1}$
	Train to Storage	3.00	3.00	3.00	$m^3\,min^{-1}$

Table 2: Selected values of the transfer rates of ammonia in the model

For the time needed to setup a bunkering process and the time needed to stop the bunkering process literature is consulted. Unfortunately only Park and Park [10] and Sundaram and Karimi [64] discusses the additional times needed within the bunkering process. These values are used for the model and can be seen in Table 3.

Bunker method	Value in literature (min)	Remarks	Source
Truck to Ship and Pipe to Ship	5 5	Setup time Decoupling time	Park and Park [10]
Ship to Ship	60 60	Setup time, incl. berthing storage to vessel Decoupling time, incl. berthing storage to vessel	Park and Park [10]
	40 35	Setup time, incl. berthing vessel to ship Decoupling time, incl. berthing vessel to ship	Park and Park [10]
Undefined	15 37	Setup time, incl. pre-inerting and purging Decoupling time, incl. draining and post-inerting	Sundaram and Karimi [64]

Table 3: Overview of additional time needed for bunkering

5.3.2 Process Validation

For the process validation an expert on the topic of bunkering and terminals was asked to review the model and all the steps it takes. The whole model was discussed and different situations were considered. The expert van Veldhuizen [65] stated that the processes within the model followed the correct steps under the made assumptions for this model.

5.3.3 Performance Validation

For the performance validation of this model it is not possible to use an ammonia terminal. As of now they are not yet in use for large scale operations. However as done with the data validation, LNG terminals can be used to validate the performance of the model. This is due to that the parameters and situations of LNG bunkering are very similar to ammonia bunkering.
The EMSA [50] and Park and Park [10] describe typical bunkering times for different sizes of ships. The values they present do differ quite a bit however. The model is used to calculate the loading durations for all these sizes of ships. The values of Park and Park [10], EMSA [50] and the computed validation values can be found in Table 4.
It should however be noted that for this model the transfer rates are determined by the size of the terminal. This is chosen as such under the assumption that bigger terminals have better and bigger pumps to achieve these rates. This results however that for large terminals and small ships the transfer rate would exceed normal found values. Therefore this model can only be validated for scenarios where the ships are the same scale as the terminal. If it was chosen that the transfer rates were dependant on ship size, small terminals could handle big ships at such a rate that would not be feasible for the size of the terminal. In Table 4 it can seen that for the smaller ships and smaller terminal sizes the loading durations are correct. This can also be seen for larger ships at larger terminals. However the values are less acceptable for the largest sizes of ship and terminal. But when comparing to value of Park and Park it could be considered acceptable. Therefore the model can be considered less accurate for the largest bunker quantities as the validation values are also widely spread.

Vessel Type	Bunker Quantity (m^3)	Load Duration Literature (h)	Load Duration Model (h)			Source
			Terminal size			
			S	M	L	
Large Ro-Ro	800	2	1.7	1.2	0.7	EMSA [50]
Small cargo, container and freight	2000	2	4.3	2.8	1.7	EMSA [50]
Small cargo, container and freight	3000	3	6.5	4.3	2.6	EMSA [50]
Large freight	4000	4	8.7	5.8	3.5	EMSA [50]
Undefined Ship	5000	8	10.8	7.2	4.3	Park and Park [10]
Large tankers and bulk carriers	10000	4	21.7	14.4	8.3	EMSA [50]

Table 4: Performance validation from LNG bunkering from literature

5.4 Experimental plan

To conduct this experiment the implemented model is setup as follows. There are five main variables that can be changed. Two of these variables change the configuration of the terminal. These are the bunkering method and the terminal size which influences the scale. The scale of the terminal depends on the number of facilities and storage size. The other three main variables change the scenarios that the terminal operates in. This is the size of the ships that require ammonia, the supply of ammonia to the terminal and the method of ammonia supply to the terminal. The size of ships corresponds with the ammonia demand at the terminal and the supply size with the supply of the terminal. The scenarios used in this research are elaborated on in subsubsection 5.4.2. The different terminal configurations are explained in subsubsection 5.4.1. By changing the variables different configurations and scenarios can be simulated. This combined should give all the significant situations needed for this research. For this research all the scenarios are simulated as such that the supply and demand are equal. This is done because otherwise the effect on the bunker methods cannot be measured correctly.

The bunkering methods and supply methods are previously elaborated on in section 3 and modelled in section 4. Therefore these methods are not discussed again separately but combined with the terminal configurations and scenarios.

5.4.1 Terminal configurations

As stated before the experiment has different terminal configurations. These terminal configurations are defined in this subsection.

Terminal size and Bunkering methods
For the implementation of this model it is chosen to use three sizes of terminal. The size of the terminal determines the number of facilities for each bunker method. Combined it creates different configurations. Each scenario influences these configurations, these influences are used within this research. The possible bunkering options that are modelled are discussed in subsection 4.6. Table 5 shows the different values for the used attributes in this model. As the terminal size influences the bunkering methods they are combined within one table. A larger terminal has more or larger facilities. The different configurations are selected in such a way that they have the same amount of facilities between the methods. This is done to have a better comparison between the methods in which is more effective than the other.

Component/Method	Attributes	Terminal Size S	M	L
Terminal	No. Unloader locations	1	2	4
	No. Carriage Unloaders	2	5	10
Storage	Storage (m^3)	10000	50000	180000
Bunkering Truck & Pipe	No. Bunker Stations	1	3	6
Bunkering Truck	No. Trucks	3	7	10
	No. Truck Loader	1	3	6
Bunkering Vessel	No. Vessels	1	3	6
	No. Vessel Loader	1	2	3
	Bunker Vessel Storage (m^3)	3000	10000	25000

Table 5: Parameters used in the model for different terminal configurations

5.4.2 Scenarios

As stated before different scenarios at the terminal are researched.

Ship size
For this research three sizes of ships are selected. The ships are mostly selected from the study of De Herder [14]. The three sizes are Nordic Grace, CMA CGM Louga and Ore China. Nordic grace (S) is a tanker ship, CMA CGM Louga (M) is a container vessel and Ore China (L) is an ore carrier [14]. These three ships are selected to have realistic values for the amount of bunker, in this case ammonia, a ship can take and may take in the future. The demand of ship size S is lowered to create a more even spread of demand between the available ships. The values used in the simulation model for these three sizes of ships can be seen in Table 6. In the model it is assumed that a ship would require between 75% and the maximum amount of demand to bunker.

This is done to mimic a more realistic demand. Combined with the inter arrival times of the ships the demand for ammonia at the terminal is created.

Attributes	Ship Size		
	S	M	L
Maximum Demand (m^3)	1500	3850	8616
Inter Arrival Time (min)	750	330	180

Table 6: Three sizes of ships used in the model for requesting bunkering.

Supply Methods and Supply Size

The different supply methods of the model: truck, vessel, pipe and train; that are used for this experiment is elaborated on in subsection 4.6. The supply size has an influence on the selected method. Therefore the different possible supply sizes and methods used for this research with their corresponding values are shown together in table 7.

To keep the supply sizes comparable, the values are selected as such that each size supplies the same amount of ammonia over time as the same size category of ship demands in ammonia. This gives the equal amounts of supply and demand for the terminal. The supply rate of the different methods is determined by the total storage transferred divided by the inter arrival time. This is however not possible for the supply trucks for all the sizes of terminal. For the larger sizes the interval time would be unrealistic to achieve.

Component/Method	Attributes	Supply Size		
		S	M	L
Supply Truck	Storage (m^3)	30	30	30
	Inter Arrival Time (min)	60	30	15
Supply Vessel	Storage (m^3)	5000	10000	20000
	Inter Arrival Time (min)	2600	790	445
Supply Pipe	Supply rate ($m^3\,min^{-1}$)	2.9	16.5	53
Supply Train	Storage per carriage (m^3)	150	150	150
	No. Carriages	40	100	130
	Inter Arrival Time (min)	3150	1180	435

Table 7: Parameters used in the model for different supply sizes

5.4.3 Inter Arrival Times

To assure a realistic as possible inter arrival times for the ships that need bunkering in the model, literature is used. Within the literature an Erlang distribution is stated as the best to simulate inter arrival times at a terminal or port. The Erlang distribution is generalisation of the exponential distribution [66]. The Erlang random variable describes the time interval between any event and the k-th following event. Therefore the Erlang distribution is referred to as Erlang-k distribution. UNCTAD [67], Aytaç et al. [68] and Robinson [69] suggest that the use of an Erlang-2 distribution gives the best results. While Kuo et al. [70] suggest the use of Erlang-1. For this model a Erlang-2 distribution is selected as it is used the most and is assumed to be the most suitable for specialised terminals [67].

5.4.4 Simulations

With the different methods of bunkering and supply; the different sizes in terminal, ships and supply the simulations are run. These methods and sizes give a lot of configurations of the terminal and scenarios. With these configurations only one method for bunkering, one method for supply, one size of ship, one size of supply and one size of terminal can be selected. All these possibilities are simulated.
Most configurations of the terminal have a simulation time of under 10 seconds when the terminal is simulated for 365 days. To get accurate results the performance indicators are analysed to see if the terminal is operating at a steady state. This is done to get results of the terminal when it is operating in a logical manner and that startup effects of the terminal can be neglected. These startup effects or the warm up period is determined to be two weeks. This period is determined by looking at the storage levels and delays. These values were stable after about two weeks. From that point the recorded statistics were reset and the terminal was simulated for 365 days.

The formulated performance indicators for the modelled terminal discussed in subsection 4.5 are used as results to evaluate the different terminal configurations with various scenarios. These results can be seen in subsection 5.5

Replications

To investigate the results of the model, multiple replications of the model using different seeds are done. This is done to evaluate the results when they are less dependant of the stochastic effects of the Erlang distribution used in the demand. It is chosen to use 10 different seeds. This causes the average and the standard deviation to be stable. Otherwise a single simulation could have great effect on the overall results. The delay was selected as measure of stability as it has relatively the highest standard deviation. The changes in mean and standard deviation over the number of simulations can be seen in Figure 12. The complete overview of all the results can be seen in subsection 5.5.

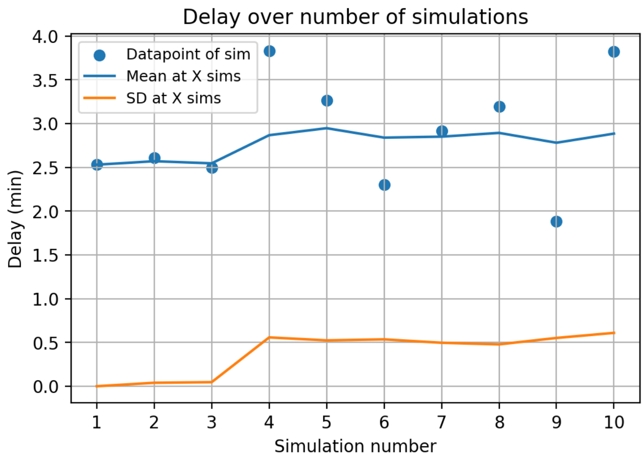


Figure 12: The mean and standard deviation of the delay over the number simulations for size L ships, supply and terminal

5.5 Simulation results

All the configurations and scenarios give 108 simulation results. These results are too much to be shown in a comprehensive manner, but can be seen in Appendix C. First the feasibility of the different methods is researched. This can be done by investigating the first KPI, number of ships handled. This can be seen in Figure 13. To give the best overview a selection of the simulations are shown. It is opted to select the same category of the terminal, ship and supply size. When the size of ships and supply are equal, the supply and demand is equal too. This gives more realistic situations to compare the bunkering and supply options. For the terminal size the same category is selected. For example a small supply and demand is researched for a small terminal.

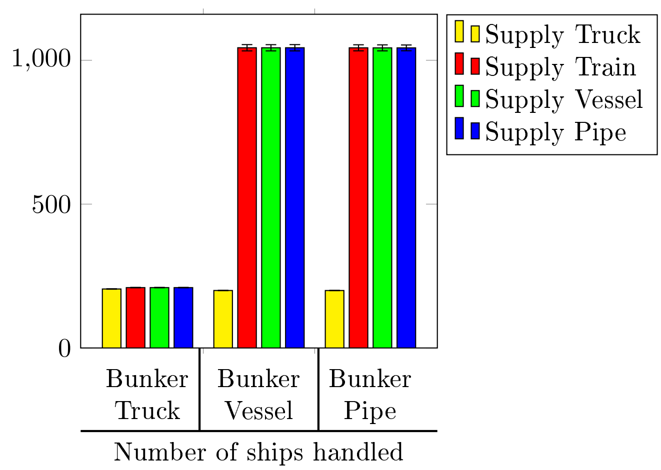


Figure 13: Number of ships handled for a Small terminal with Small ships, showing all bunkering and supply methods

Bunker Method	Supply Method	No. Ships Handled Mean	SD
truck	truck	205.0	0.77
truck	train	209.8	0.75
truck	vessel	209.8	0.75
truck	pipe	209.8	0.75
vessel	truck	199.8	0.75
vessel	train	1043.6	10.93
vessel	vessel	1043.5	10.79
vessel	pipe	1043.6	10.93
pipe	truck	199.7	0.64
pipe	train	1043.4	10.52
pipe	vessel	1043.2	10.42
pipe	pipe	1043.2	10.03

Table 8: Values of the key performance indicator seen in Figure 13 for a terminal size S and ships size S

In Figure 13 it can be seen that when a bunkering truck is used the least ships are handled. The use of a bunkering vessel and bunkering pipe seem to give comparable number of ships handled. For the supply methods it can be seen that when truck supply is used for the terminal less ships are handled in comparison to the other three supply methods. Therefore it can be concluded that the use of bunkering trucks and supply trucks is not feasible to use in a terminal. This is because truck bunkering and truck supply are not keeping up. This is likely that the trucks can not keep up with the required demand and supply. The number of ships handled is five times lower, this makes the truck bunkering and supply options not suitable to be used. For the terminal and ship sizes M and L the results are comparable and can be seen in Appendix D in combination with the time spent at the terminal and delay at the terminal. Due to that the trucks are not feasible, bunker truck and supply truck methods are omitted for the next subsections. In Figures 14 to 16 three key performance indices can be seen for the three sizes. Their corresponding Tables 8, 10 and 11, provide the values that are shown in these figures.

5.5.1 Small Terminal, Supply and Demand

Figure 14 shows the difference in average time spent at the terminal, the storage occupancy and bunker occupancy. The time spent is build up from two components. The dark colours shows the time bunkering at the terminal and the transparent colours show the average delay at the terminal. These combined form the average total time that a ships spends at the terminal. The average time spent at the terminal KPI shows that the use of a bunkering vessel gives longer times. Using a bunker vessels takes around 14 hours and using a bunker pipe takes between 6 and 7 hours. There is especially a big difference with the delay. The delay with bunker vessels is up to 10 hours, while for a bunker pipe 1-2 hours. For the supply methods the differences are small. However there seems to be a bit longer delay and time spent at the terminal for the use of supply vessels.

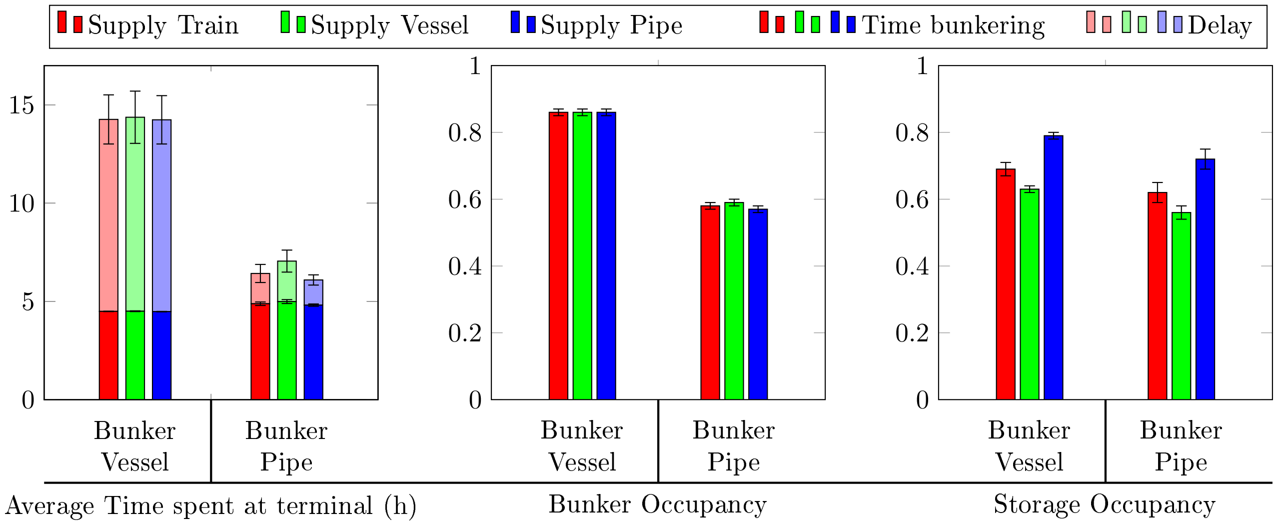


Figure 14: Three KPI shown for a Small terminal, with Small ships and with Small supply

Bunker Method	Supply Method	Average time at terminal (h)		Time in bunkering process (h)		Delay at terminal (h)		Bunkering Occupancy		Storage Occupancy	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
vessel	train	14.3	1.26	4.5	0.01	9.8	1.25	0.86	0.01	0.69	0.02
vessel	vessel	14.4	1.34	4.5	0.02	9.9	1.33	0.86	0.01	0.63	0.01
vessel	pipe	14.2	1.24	4.5	0.01	9.8	1.23	0.86	0.01	0.79	0.01
pipe	train	6.4	0.56	4.9	0.09	1.5	0.46	0.58	0.01	0.62	0.03
pipe	vessel	7.0	0.65	5.0	0.10	2.1	0.56	0.59	0.01	0.56	0.02
pipe	pipe	6.1	0.31	4.8	0.06	1.3	0.26	0.57	0.01	0.72	0.03

Table 9: Values of the key performance indicators seen in Figure 14 for a terminal size S, ships size S and supply size S

To analyse and explain the differences observed from the first performance indicator, other performance indicators can be used. When looking at the time in bunkering process, darker part of time spent, it can be seen that the bunkering itself for a bunker vessel is slightly shorter than for pipe bunkering. There is only a difference of half an hour. However there is a large difference in the delay part of the total time spent at the terminal. This difference can be explained that pipe bunkering is more efficient in the handling of ships. This can be seen from the bunker occupancy, this is a measure of how much of the total time the bunkering facilities were in use. Therefore the higher occupancy, the more busy or occupied the facilities have been. When looking at Figure 14, the bunker occupancy is higher for bunker vessels than pipe bunkering. This results in that the queues for the terminal are longer and thus longer delays and thus the average time spent at the terminal is longer. The higher occupancy can be explained by that bunker vessels have time that they are not available to bunker. This is due to that the vessel has to return to a loader to be refilled to be ready to bunker the next ships. This refilling is not needed for pipeline bunkering.

When looking at the storage occupancy in Figure 14, differences in supply can be seen. Using a pipeline to resupply the storage occupancy is higher than the other supply methods. This is due to that a pipeline has a more consistent flow into the terminal while the other two methods have a periodic supply and therefore the storage occupancy fluctuates more which gives a lower average. This however does not make one of the methods better than the other, because each method keeps the storage of the terminal mostly high enough to keep consistent operation of the terminal. For the use of train supply the storage occupancy is higher than for vessel supply. This could suggest that this method is better for this scale. It should be noted that between the three supply methods the use of supply vessel seems the worst however it is the most flexible method to be used. As a terminal always has access to water or sea, while train and pipe supply need railroads, pipes and other infrastructure to even be possible to be used.

5.5.2 Medium Terminal, Supply and Demand

When observing the differences for a M sized ships, terminal and supply in Figure 15, roughly the same differences can be seen as with the S size terminal, ships and supply. For the time spent at the terminal the use of pipe bunkering gives a lower time of around 7 hours in comparison to 11 for bunker vessels. In total the time spent is much shorter for this larger terminal in comparison to the terminal size S for vessels. This difference is mostly due to the differences in delay. The delay shows a difference of more than ten times for pipe bunkering. For the use of bunker vessels there is more than 4 hours delay in comparison to the less than half an hour for bunkering with a pipeline connection. These differences are more extreme than before observed with size S.

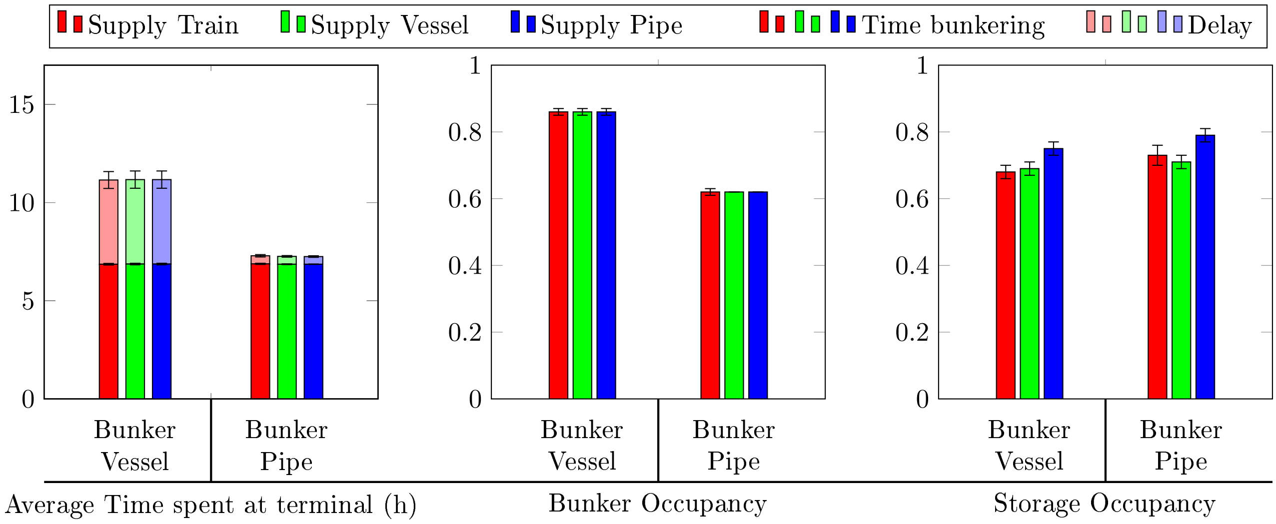


Figure 15: Three KPI shown for a Medium terminal, with Medium ships and Medium supply

Bunker Method	Supply Method	Average time at terminal (h)		Time in bunkering process (h)		Delay at terminal (h)		Bunkering Occupancy		Storage Occupancy	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
vessel	train	10.9	0.44	6.9	0.04	4.3	0.43	0.86	0.01	0.68	0.02
vessel	vessel	10.9	0.45	6.9	0.04	4.3	0.44	0.86	0.01	0.69	0.02
vessel	pipe	10.9	0.45	6.9	0.04	4.3	0.44	0.86	0.01	0.75	0.02
pipe	train	7.3	0.09	6.9	0.03	0.4	0.06	0.62	0.01	0.73	0.03
pipe	vessel	7.3	0.05	6.9	0.02	0.4	0.04	0.62	0.00	0.71	0.02
pipe	pipe	7.3	0.04	6.9	0.01	0.4	0.04	0.62	0.00	0.79	0.02

Table 10: Values of performance indicators seen in Figure 15

When looking at the other performance indicators seen in Figure 15 the same conclusions can be drawn as in subsubsection 5.5.1. Bunkering using pipelines gives the lowest time spent at the terminal. However there is a change in average time in the bunker process. For the small scenario bunker vessels resulted in lower average time in the bunkering process than pipe bunkering. For the medium size the time bunkering is the same. Furthermore it can be seen from the storage occupancy that supply via pipelines is more consistent than the other supply methods.

5.5.3 Large Terminal, Supply and Demand

When investigating the results for the terminal, ship and supply size L shown in Figure 16, it can be seen that they are similar as shown in Sections 5.5.1 and 5.5.2. The use of bunker vessels gives 12 hours spent and bunkering pipe 8 hours. Using pipe bunkering is more effective. However the standard deviation does increase with the increase in size, especially for the delay.

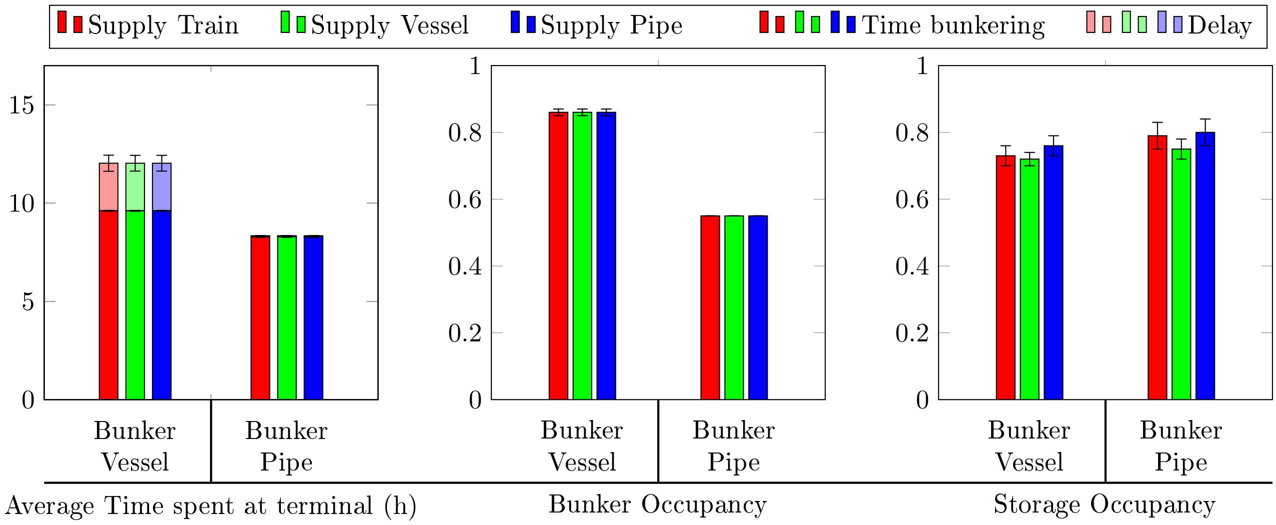


Figure 16: Three KPI shown for a Large terminal, with Large ships and Large supply

Bunker Method	Supply Method	Average time at terminal (h)		Time in bunkering process (h)		Delay at terminal (h)		Bunkering Occupancy		Storage Occupancy	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
vessel	train	12.0	0.42	9.6	0.02	2.4	0.41	0.86	0.01	0.73	0.03
vessel	vessel	12.0	0.41	9.6	0.02	2.4	0.40	0.86	0.01	0.72	0.02
vessel	pipe	12.0	0.41	9.6	0.02	2.4	0.40	0.86	0.01	0.76	0.03
pipe	train	8.3	0.03	8.3	0.03	0.0	0.01	0.55	0.00	0.79	0.04
pipe	vessel	8.3	0.04	8.3	0.03	0.0	0.01	0.55	0.00	0.75	0.03
pipe	pipe	8.3	0.05	8.3	0.04	0.0	0.01	0.55	0.00	0.80	0.04

Table 11: Values of performance indicators seen in Figure 16

When looking at the storage occupancy in Figure 16, the differences between supply methods is less visible as before. Furthermore the use of supply trains seem to be more effective than before. For the average time in the bunkering process, shown as part of the average time spent at the terminal, there is a difference. This is due that for the use of pipe bunkering the transfer rates can be higher than for vessel ship to ship bunkering. This results in a lower time in the bunker process. This shows that for a larger scale pipe bunkering becomes more effective than vessel bunkering. However pipe bunkering always had the lowest time spent at the terminal when looking at the previous scenarios.

5.5.4 Scenario size comparison

When comparing the previous sizes of terminal, the delay plays a large influence on the average time spent at the terminal. In Figure 17 the average time spent for the three sizes of terminal, supply and demand combined can be seen. The biggest difference between the sizes is seen with the delay. With the increase of size the delay seems to decrease. Especially the ratio of delay between the bunkering methods decreases. This can have multiple causes. The increase in number of facilities helps the terminal to process large spikes of demand of bunkering over time. This causes the average delay to be lower. Another explanation can be that a certain scenario could push the terminal further to its maximum limits. The selected supply and demand can be closer to the maximum that the terminal can handle. This can be different for each scenario seen in Figure 17 and thus has a large influence on the delay at the terminal. Therefore there is the possibility that the comparison between these scenarios is affected. However it still illustrates which method can handle the pressure better and is thus more efficient.

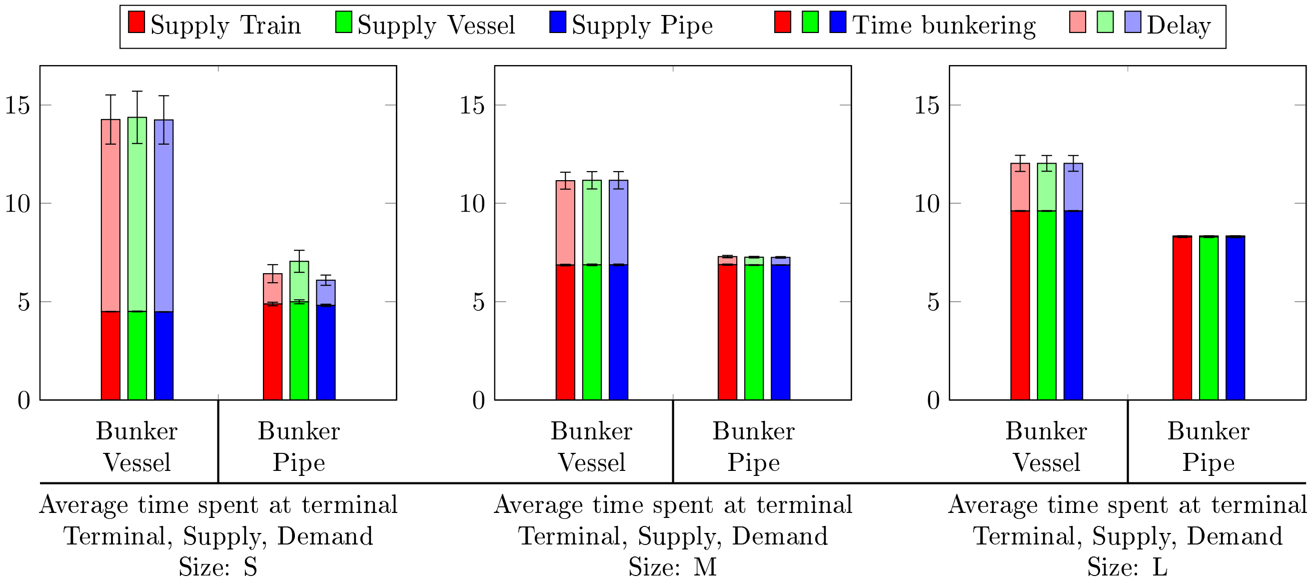


Figure 17: The average time spent at the terminal compared with different size scenarios

5.5.5 Effect demand on same terminal size

The previous results all considered scenarios and configurations of which the sizes of supply, demand and terminal are balanced. To investigate the effect of changes in supply and demand with respect to a stable terminal size, Figure 18 is created. In this figure the largest terminal is selected and the three demand and supply sizes are used. There is opted to use the largest terminal size as otherwise the average time at the terminal would be very high for the larger supply and demand scenarios. In Figure 18 can be seen that for the higher demand the time needed to bunker increases. This is likely due to that higher volumes need to be transferred to the ships and thus take longer. Furthermore it can be seen that with the increase of supply and demand, that the use of a bunker pipe results in less time spent at the terminal when compared to the bunker vessel bunkering method. In Appendix E, with Figure 28, can be seen that with the increase of demand the bunker occupancy also increases as expected.

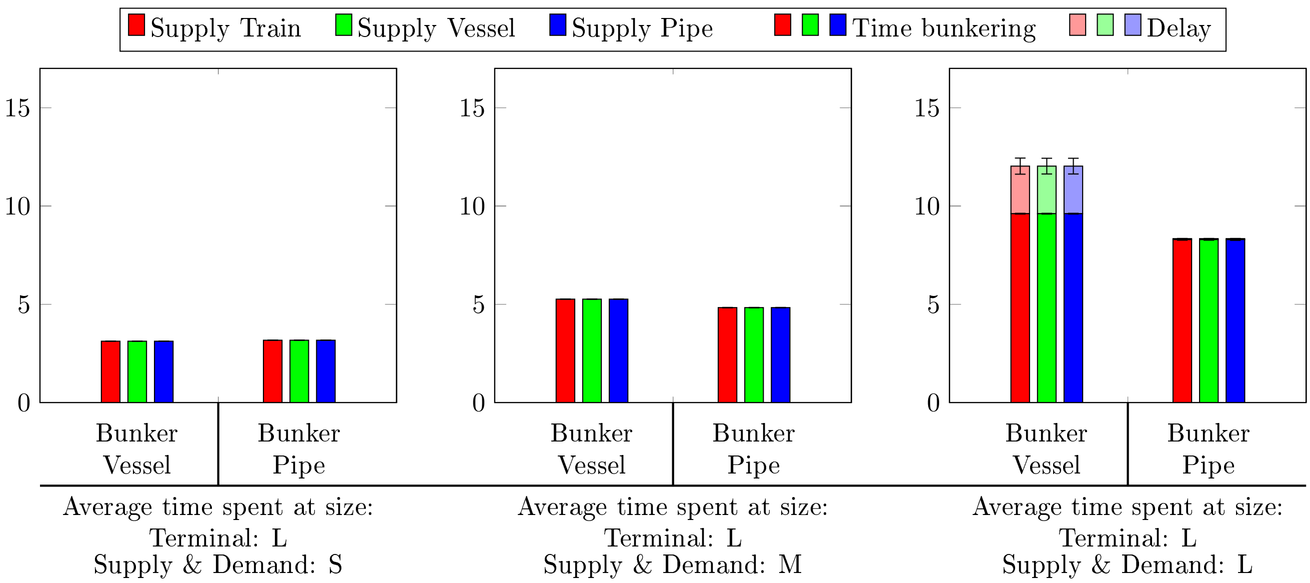


Figure 18: The average time spent of ships for different levels of supply and demand at a large terminal

5.5.6 Effect terminal size with same demand

In Figure 19, the demand is selected to be constant and the terminal size changes. With this the effect of the terminal size can be investigated on the time spend at the terminal. In the figure can be seen that with the increase in size the delay disappears and that the time needed to bunker lowers slightly. This is likely due to that at a larger terminal the transfer rates can be higher. Furthermore there are more facilities to bunker the incoming ships. However this effect is limited as extra facilities are only useful when there is a shortage of facilities. When the demand can be satisfied with the current facilities extra have no effect. This effect can be seen in Appendix E, with Figure 29. With the increase in terminal size can be seen that the bunker occupancy decreases as expected.

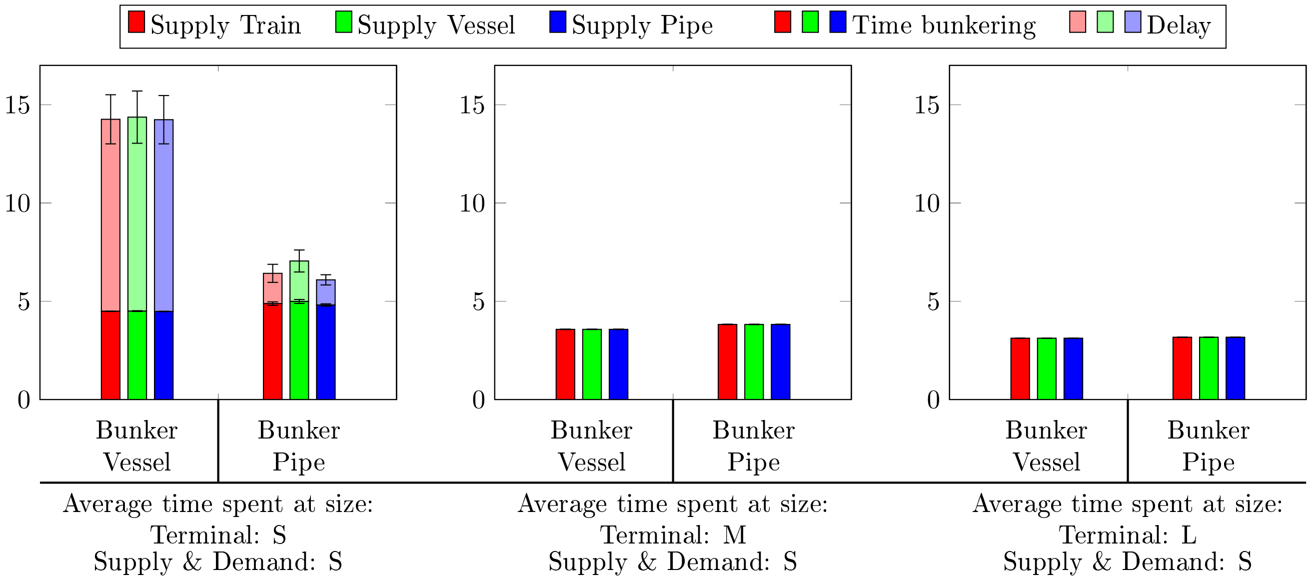


Figure 19: The average time spent of ships for different levels of terminal size at a constant supply and demand

5.5.7 Discussion

The simulation results suggests that pipe bunkering is the best and most efficient method to use. However the use of vessel bunkering could be more efficient, when the bunkering simultaneously takes place with other processes, like the loading and unloading of goods. These simultaneous operations (SIMOPS) can greatly reduce the time that a ship has to spend at a terminal. Therefore this time can be used more useful in operations and therefore saves costs.
For bunkering a ship using a pipeline connection SIMOPS is not possible as the quay would be occupied with the facilities to bunker the ship. Additionally it would bring extra safety risks. It is not desirable to lift or transport goods close to lines that are used for bunkering ammonia. In the case of a failure and a bunker line is damaged due to the loading or unloading process, spills can occur. This brings great safety and environmental risks, due to the toxicity of ammonia.
The extra time needed for bunkering with a bunker vessel can be mitigated with SIMOPS. And therefore potentially make the use of a bunker vessel when bunkering ships more effective. As mentioned before in section 3, bunker vessels give more flexibility than bunkering with a pipe connection.
The use of pipe bunkering is however more likely to be the best option for the largest sizes of ships in the future. This is due to that a bunker station can achieve higher transfer rates than bunker vessels. This is only the case when very large volumes need to be transferred to the ship. And thus creating an advantage over a bunker vessel.

The selected scenarios used in this research are great to investigate differences at certain scales in size of terminal or supply and demand. However the selected bounds directly also set the bounds of the research. For example the smallest sizes of terminal and supply and demand can be set smaller and therefore investigate a smaller scale. This could for example have as effect that truck bunkering is a feasible option. However this is only for a very small scale. The goal of the research is to investigate future possible scenarios and thus it was opted to focus on larger future demands and supply for a terminal.
Furthermore the selected scenarios can give a biased view of the changes between scales of supply, demand and terminal size. As in one scenario the selected supply and demand for a size terminal can be much more taxing to cope than for an other size, these effects can also be seen in subsubsection 5.5.4. This also partly explains the higher times spent for size S in comparison to size M. It would be expected that smaller ships would require less time spent at the terminal. But when in this case for example the terminal is relatively more busy than the other, these times could increase. Therefore the selection of scenarios can have a great impact on the results

when comparing them.

The supply for this model is set to come at a constant rate over time, for pipeline supply. Or arrive in a constant interval for vessels, trucks and trains at the same volume over time. This is done as it is assumed that a terminal would operate under a planning for its supply. Thus the supply would not "randomly" arrive as is possible for the demand. Furthermore for the scenarios in this research the supply and demand are calibrated to be equal. However this is hard to achieve. This has multiple reasons. Firstly, the demand for ammonia at the terminal arrives under an Erlang distribution, this can create situations that the demand can be high at a moment and low at a later moment. Over time the supply and demand would average out to an equal amount. But there are moments that can occur that the storage would be depleted or fully filled. In the situation of depletion of the storage, the waiting times would increase drastic. In situations of fully filled storages the supply would leave the terminal partly unloaded. When this happens the intended supply for the terminal never reaches the storage. This makes it impossible to create equal supply and demand as some supply never reaches the terminal. This can therefore create a shortage of ammonia at a later time.

As already mentioned in subsubsection 5.3.3, the transfer rate for ammonia are dependant on the terminal size. This is done under the assumption that larger terminals have better facilities and mostly larger ships to bunker. However when comparing smaller ships at larger terminals such as in subsubsection 5.5.5, the results get less realistic. It would be better to have the transfer rates dependant on the size of the terminal and on the size of the ships that need bunkering. This would prevent these effects and is something to be potentially considered in future research.

5.6 Costs of terminal facilities

For the different terminal sizes and bunkering and supply methods, facilities are needed. Certain methods require other facilities and a larger terminal requires more facilities. With the number of facilities discussed in subsubsection 5.4.1, with Table 5 and literature, the cost for the liquid bulk terminal can be estimated. With these capital costs (CAPEX) and operational costs (OPEX) the total costs for the methods and terminal sizes can be compared. In Appendix F, the assumptions for the costs of different facilities can be found for the three modelled terminal sizes. From Park and Park [10], Baresic et al. [48], Muljadi [53], Mohammed [71], Faber et al. [72], DMA [73], capital and operational costs for the terminal facilities were found. The authors analysed terminal costs for LNG terminals. The values used are assumed to be similar for an ammonia terminal. For these calculations only the capital and operational costs of the facilities at the terminal are used. The costs of transport of the supply to the terminal are not taken into account as these costs are very dependant on the distance travelled. However the costs for the facilities needed for the supply are included. The total costs of the different components and methods are computed for to the modelled terminal sizes and can be seen in Table 12. The costs are in million Euro of CAPEX and a year of OPEX combined. The OPEX of some facilities are assumed to be 9% of the CAPEX per year [30, 71].

Method	Terminal size		
	S	M	L
Truck supply	0,99	1,99	3,97
Train supply	0,87	4,36	17,44
Vessel supply	4,95	9,89	19,78
Pipeline supply (20 km)	13,08	13,08	13,08
Storage	32,70	87,20	316,10
Truck bunkering	38,06	113,71	226,46
Vessel bunkering	35,35	142,49	530,84
Pipeline bunkering	36,90	110,70	221,40

Table 12: Total costs of bunkering and supply methods for three terminal sizes in million Euro per year

Tables 13 to 15 provide a total cost matrix of the combinations of supply and bunker methods. These values include all the facilities needed at the terminal for the storage and handling of ammonia. In these tables the lowest and highest costs are highlighted in green and red. For sizes M and L the second lowest option that does not use trucks is coloured orange. In subsection 5.5 is shown that the use of trucks is not feasible therefore these cost results are less significant thus the next best cost option is used. When analysing the differences in cost over the sizes of terminal the preferred low cost configuration changes. For size S terminal, the use of a bunkering vessel in combination with train supply gives the lowest costs of nearly 69 million Euro. For size M terminal, the lowest feasible cost option is bunkering via a pipeline and supplying by train for 202 million Euro. For the L terminal size the option of bunkering and supplying ammonia via pipeline gives the lowest costs at 550 million Euro.

Supply method	Bunker method Truck	Vessel	Pipeline
Truck	71,8	69,0	70,6
Train	71,6	68,9	70,5
Vessel	75,7	73,0	74,5
Pipeline	83,8	81,1	82,7

Table 13: Total costs matrix table of bunker and supply method combinations for a S size terminal in million Euro per year

Supply method	Bunker method Truck	Vessel	Pipeline
Truck	202,9	231,7	199,9
Train	205,3	234,1	202,3
Vessel	210,8	239,6	207,8
Pipeline	214,0	242,8	211,0

Table 14: Total costs matrix table of bunker and supply method combinations for a M size terminal in million Euro per year

Supply method	Bunker method Truck	Vessel	Pipeline
Truck	546,5	850,9	541,5
Train	560,0	864,4	554,9
Vessel	562,3	866,7	557,3
Pipeline	555,6	860,0	550,6

Table 15: Total costs matrix table of bunker and supply method combinations for a L size terminal in million Euro per year

To compare the terminal sizes, the throughput of the terminal is taken from the model. With this the increase in the ratio of throughput between the sizes is calculated. From this same ratio, the increase in costs are calculated from minimum and maximum costs, of the feasible options in Tables 13 to 15. These values can be seen in Table 16. From this table could be concluded when it is more cost effective to build a larger terminal instead of two smaller terminals for example. For most scenarios the larger variant is more cost effective than an extra of the same size. Except for a large terminal in a scenario of the highest costs. Building and operating a terminal size L is less cost effective than two medium terminals, as the ratio of extra throughput is lower than the cost increase.

Terminal size	Terminal throughput (m^3)	Throughput ratio increase	Cost ratio increase Min	Max
S	1369050	-	-	-
M	8011389	5,85	2,93	2,94
L	26335957	3,29	2,72	3,57

Table 16: Costs between terminal sizes in relation to terminal throughput

5.6.1 Discussion

The estimated costs for the facilities at a liquid bulk terminal using ammonia are based on assumptions and certain factors are neglected. Most costs for a terminal are dependant on location based factors. If an ammonia supply is nearby the transport costs are much lower and especially if that enables the option for a short pipeline supply. It is opted to assume a 20 km pipeline distance but this can be very different for each location.
For the costs of the facilities the cost of land and labour are also very dependant on the location and not taken into account for this cost calculation. A train supply seems to be cost effective but requires quite some land to handle all the trains.
With the costs it is assumed that the storage facilities include systems to handle all the boil off gasses but are also able to handle pressurised supplies and can cool it for refrigerated storage. As all the values are taken van LNG studies and LNG is stored at much cooler temperatures it can be assumed that these more expensive facilities can handle the higher temperatures of ammonia.

5.7 Conclusion

In this section the the proposed conceptual model from section 4 is implemented. The implemented model has had different verification checks. Additionally the parameters and performance of the model are validated using data from different studies using LNG for bunkering. This is done as ammonia bunkering data is scarcely available. Furthermore the processes are checked and validated by an expert. By using simulations, the model is used to simulate different configurations and scenarios at terminal. These include different methods of bunkering and supply but also sizes of ships, supply and terminal. By making a selection of the combination of the same size for the ships, terminal and supply, the different bunkering and supply methods could be compared. The simulation results show that pipe bunkering is more efficient to use in comparison to truck and bunker vessel bunkering. For the supply, the use of a pipeline is preferred. If that could be realised for that location.
Furthermore of the selected scenarios a cost estimate is made. With this estimate the financial feasibility can also be evaluated and preferred economical solutions could be found. For a small terminal using a bunker vessel is the cheapest solution with the use of a supply by train. For a medium terminal the use of pipeline for bunker is preferred and the supply by train. For the largest terminal size L the fully use of a pipeline for bunkering and supply gives the lowest cost.

The last sub-research question that is investigated in this section is: ***What are the most suitable configurations to bunker and supply ammonia for each scale of a terminal?***
From the results of the simulations and the costs can be concluded that for most levels of scale of terminal with corresponding supply and demand that the method of bunkering ships using a pipeline connection is the most suitable. However for a smaller scale bunkering with a bunker vessel should be considered as it has lower cost and is very flexible in use. Depending on the scale of operation the time spent was 3 to 8 hours less for pipe bunkering instead of vessel bunkering. The delay increased from 5 times as much to 100 times more when using vessel bunkering instead of pipe bunkering. Therefore bunkering with a pipeline from the storage via a bunkering station gives the lowest time spent at the terminal and less delay than other options.
For the supply at the terminal pipeline supply resulted in the highest storage occupancy for the simulations can be seen as a reliable method. When examining the costs for the supply options the use of trains for supply are interesting as they are cheaper than pipeline supply. Therefore the supply for at small and medium sized terminals, trains are the most suitable. For large supply, demand and terminals pipeline supply is more effective due to the large volumes.

6 Conclusion

This research was done to investigate the use of ammonia as an alternative fuel in the maritime industry. The need for alternative fuels originates from the need to reduce the global green house gas emissions. The International Maritime Organisation therefore has to goal to reduce the green house gas emissions by 50% by 2050. As a result, from the possible fuel alternatives ammonia is investigated as it can possibly achieve this reduction in emissions. To investigate this potential change in fuel, the whole system of supply and demand to bunker a ship within a terminal is analysed. This includes that the workings of a liquid bulk terminal, its components and methods is researched. Additionally the bunkering and supply options using ammonia were researched. With this a conceptual model is formulated to analyse the different methods that were found. Then the model was implemented to measure the performances of the different methods of bunkering at the terminal. With this the sub-research questions are answered and ultimately the main research question will be answered.

1. How does a liquid bulk terminal function and what influences the scale of a terminal?

An ammonia terminal has three important tasks to fulfil. These tasks are the storage, transport and (un)loading of ammonia. The storage of ammonia is done under pressure or cooled as a liquid. Ammonia is transported using ships, trucks, trains and pipelines. Loading and unloading is done using loading and unloading stations using pipe connections or loading arms. This is done from the shore or other vessel. The biggest influence on the scale of a terminal is the throughput, this depends on how much cargo is transported, vessel calls and terminal capacity.

2. What are the possible ways to bunker ammonia to ships and supply ammonia to a terminal?

The possible bunkering options found are Ship to Ship, Truck to Ship, Pipe to Ship and Container to Ship bunkering. However literature shows that is it more likely to use Ship to Ship or Pipe to Ship bunkering. For the supply of ammonia to the terminal it is most likely that gas carriers or a pipeline connection will be used. Furthermore the temperature or pressure of ammonia from and to the storage and from and to the transport method is important to consider as the ship or storage may not be able to store and handle it.

3. How can the ammonia supply and bunkering within a terminal be modelled?

With the use of Discrete Event Simulation different components within the terminal are modelled. The model handles queues, components of the terminal and their storages. The model consists of 15 classes that together form a liquid bulk terminal. By using a selection of the classes various configurations of a terminal and scenarios can be modelled. Each class has attributes and different processes. In the model ships are modelled that enter the liquid bulk terminal. The ships can be bunkered by using different bunkering methods. Furthermore the supply of ammonia to the terminal is modelled. This ammonia supply to the terminal can also be done using different methods.

4. What are the most suitable configurations to bunker and supply ammonia for each scale of a terminal?

From the simulation results can be concluded that, for each scale of terminal, with corresponding supply and demand, that the method of bunkering ships using a pipeline connection is the most suitable. Depending on the scale of operation the time spent was 3 to 8 hours less for pipe bunkering instead of vessel bunkering. The delay increased from 5 times as much to 100 times more when using vessel bunkering instead of pipe bunkering. Therefore bunkering with a pipeline from the storage via a bunkering station gives the lowest time spent at the terminal and less delay than other options. For the supply at the terminal pipeline supply resulted in the highest storage occupancy for the simulations, can be seen as a reliable method. When examining the costs for the supply options, the use of trains for supply are interesting as they are cheaper than pipeline supply. Therefore the supply for at small and medium sized terminals trains are the most suitable. For large supply, demand and terminals, pipeline supply is more effective due to the large volumes.

What are the possible bunkering configurations for ships at a terminal using ammonia, and which solutions are the most suitable at different scales of ammonia demand to use in a terminal during an ammonia transition?

To answer this main research question the previous research and answers are combined. The possible bunkering configurations to bunker ammonia are truck, vessel ship to ship and pipe bunkering. However only vessel and pipe bunkering are suitable for larger scales of ammonia to use. Truck bunkering is not efficient enough for larger volumes. The use of vessel ship to ship bunkering and pipe bunkering at a bunker station is suitable. The use of pipe bunkering as bunker method is found to be the most efficient and lowest cost method to use. With this method ships spend less time at the terminal on average and therefore have less delay in doing so.

6.1 Recommendations

For future research various recommendations can be made. First off, it would be interesting to investigate hybrid systems for bunkering and potentially supply. For this research this was not investigated. However there could be found a balance to when a certain method should be used instead of the other. Additionally it could be interesting to have ships enter the terminal that vary greatly in size. For this study the demand would vary slight but larger differences could give a more full realistic view of the terminal and how it handles different ships.

For the supply to the terminal in this study it was opted to use a constant distribution. This was done under the assumption that the supply to the terminal would not have stochastic influences as it would operate under a planning and needs of the terminal. Therefore for future research it would be better that the supply follows a certain planning or that it would react to an increase in demand to create equal supply and demand. This way would be more realistic instead of a set constant interval.

For the simulations is assumed that all the boil off gasses and changes in temperature are handled by the systems, however the simulations do not take into account the time and complexity that may be required to do so. Especially when the ammonia is supplied under pressurised circumstances by train of truck for example. This pressurised liquid ammonia needs to be cooled and released from pressure to be stored in the cooled storage tanks of the terminal. This transformation can take some time but also may require quite some energy and additional costs. These additional costs and time are complicated to predict as they are very dependant on other factors, therefore they are neglected. For future studies it would be interesting to include these complications while handling ammonia from different sources.

In this study the safety requirements are taken into account for the whole terminal. However the safety specifics for each method of supply and bunkering is not. It is likely that one method has much higher risks than other methods. For example the use of a pipeline connection requires only one coupling of hoses to complete the transfer of ammonia from the storage to the ship. For the use of a bunker vessel, first coupling to the vessels is needed and later a new coupling to the to be bunkered ship. These extra steps can bring extra safety concerns, like spills and fires. For future research it would interesting to investigate the differences between these methods and whether which method could be more suitable from a safety point of view.

The proposed model uses generalised assumptions on whether it could be suitable. For future research the model could be used for a case study at a specific location. With this the geographical location could be used to determine the suitability for certain methods. For example if the supply by train or pipeline is possible. But also the space that a method of bunkering or supply could require. Furthermore the costs for such a situation could be estimated at a much more certain level. This would create a more complete study and use of the proposed model for the suitability of ammonia bunkering and its steps in the future of larger demand and operations.

A Research Paper

Ammonia bunkering and storage for the maritime industry during a global ammonia transition

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ABSTRACT

In this paper a Discrete Event Simulation model of a liquid bulk terminal is presented. The bunkering operations and supply of ammonia within a terminal are modelled. Various bunkering and supply methods are simulated for different sizes of terminal and at various levels of supply and demand. The model presents how methods perform at different levels of scale. This is to gain insights for the future transition to less polluting bunker fuel ammonia. The model is verified and validated with the use of data from literature on similar terminals using LNG. The model presents that the use of bunkering as well as supply, with a pipe to be more efficient with the increasing scale of size, supply and demand of ammonia at a liquid bulk terminal.

1. Introduction

In 2018 the International Maritime Organisation (IMO) started to adopt mandatory measures to reduce green house emissions in the maritime industry. These measures led to the goal to reduce 50% of the green house emissions by 2050 in comparison to 2018 [20, 18]. This mandatory measure forces the industry to change and adopt new more efficient ways of transport to reduce emissions. One of the options to consider is changing the fuel that is used by ships [4]. This starts an industry wide transition to green fuel alternatives. The transition brings challenges in ports on how to bunker the new alternative fuels to these ships and what methods to use. While managing the expected increase of the future demand. This gives logistical challenges that need to be investigated.

1.1. Ammonia as bunker

From different alternative fuels, ammonia is considered to be a good option as new bunker fuel [9, 35, 13, 21]. Bunkering is supplying ships with fuel to their onboard tanks for later use to transport the goods. Ammonia (NH_3) is a compound of nitrogen and hydrogen and is also considered as a hydrogen carrier. Ammonia is a gas that is colourless and has a recognisable pungent smell. It dissolves easily in water and has corrosive properties [13]. When ammonia is used as fuel it does not produce greenhouse gasses. The production of ammonia however can produce greenhouse gasses. The so called grey ammonia uses fossil fuels when produced. The current production of grey ammonia uses a Haber-Bosch synthesis process. This process converts natural gas (CH_4) to hydrogen (H_2) combined with nitrogen (N_2) into ammonia (NH_3). The Haber-Bosch process is very energy intensive which releases carbon dioxide (CO_2). This is therefore not feasible as a green alternative.
Blue ammonia is produced in a similar way as grey ammonia. However this process is carbon dioxide neutral. The carbon dioxide is captured within the process instead of released. The capture of carbon dioxide within the process does bring extra costs.
Eventually the use of green ammonia is desired. Green ammonia is produced using renewable energy sources and does not produce carbon dioxide within the whole synthesis process [21]. The green synthesis of ammonia can still use the Haber-Bosch process by providing the hydrogen from the electrolysis of water instead of using natural gas. The nitrogen is obtained by using an air separation unit that compresses and cools the air. Other ammonia synthesis methods are thermochemical ammonia synthesis or solid state ammonia synthesis. These methods are however currently less common but are growing in use and development.

On multiple topics within ammonia different research has been done. De Herder [9], Zincir [35], Kommers [21], ABS [1, 2], DNV [10], Yadav and Jeong [34], Seo and Han [27], Erdemir and Dincer [13] and Alfa Laval et al. [3] all researched whether ammonia could be an alternative fuel for the maritime industry. These studies focused on different aspects of the use of ammonia as a maritime fuel.
De Herder [9], Zincir [35], Erdemir and Dincer [13] and Kommers [21] researched the feasibility of using ammonia as a marine fuel to reduce emissions and so reach the goals of the IMO for 2050. They concluded that ammonia is an attractive choice to use as an alternative fuel. However these authors did note that there are barriers to overcome. There is still a lack of availability of an engine that uses ammonia as fuel and there is no legislation implemented yet that complies for these engines. Additionally the production and availability is not on a level yet to be used in the maritime industry. Furthermore due to the lower energy density of ammonia, fuel tanks need to be larger resulting in less space for cargo or extra bunkering stops are required.
Other researches occasionally took an economic evaluation into account. To evaluate whether it is economically feasible to use ammonia as a marine fuel. Seo and Han [27] made a full economic evaluation on ammonia fuelled carriers. Seo and Han concluded that carriers using an additional independent fuel tanks were better of in terms of economics. This study balanced the payoff of less cargo or extra stops

needed to bunker.
ABS [1, 2], Yadav and Jeong [34], DNV [10] and Alfa Laval et al. [3] researched the safety requirements and therefore feasibility of ammonia when handling and storing. The most important safety aspects are toxicity, fire safety and corrosion.

1.2. Liquid bulk terminal

To bunker ammonia a liquid bulk terminal is needed. A terminal is a location at a seaport where the loading and unloading of goods takes place. This study focusses on a liquid bulk terminal. This type of terminal handles free-flowing liquids that are unpackaged also known as bulk [7]. Therefore these liquids are stored in large tank spaces. Liquid bulk is mostly transported by using ships but are also transported by truck, train or pipeline. Most liquid-gas terminals have a few different components that together form the terminal. These components are storage tanks, berthing locations, access canals and access points to the hinterland. The storage tanks are used to store the different liquid bulk. The berthing locations are places at a dock where a ship is tied down to be able to load and unload goods. The access canals and access points are used by ships, trains and trucks to access the terminal and to eventually load and unload goods to and from the storage tanks.
A terminal tries to fulfil three functions in the maritime industry using the previous described components. These functions are the storage of goods, the transport of goods and value added logistics [31, 11]. The value added logistics includes that a liquid bulk terminal also handles the process of bunkering.

The processes on a terminal can best be described using Figure 1. This figure shows the different functions and processes that occur at a terminal. When a ship arrives at a terminal it berths at a berth or jetty. When a ship is secured different loading and unloading processes can take place. The bulk is transferred from or to the ship and storage tanks. The terminal then handles it via different transport methods like trains, trucks, pipelines or again a different ship to an other location. These steps fulfil the thee functions of a terminal.

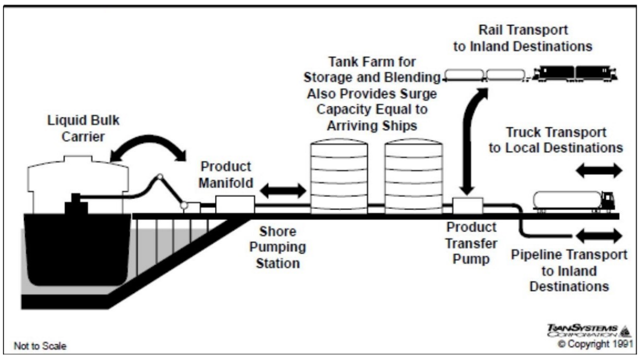

Figure 1: Operations at a liquid bulk terminal [23]

Research has been conducted on the operations of a liquid bulk terminal. These researches are focused different parts or processes of the liquid bulk terminal. The authors Verheul [31], Tam [28] and Madueke [23] investigate the performance of a liquid bulk terminal. Verheul [31] investigates different key performance indicators to effectively measure the performance of the terminal. He analyses the subsystems of the terminal and proposes methods to measure the performance of each subsystem. Tam [28] investigates different loading and unloading methods and their compatibility. These methods determine the overall performance of a terminal. Madueke [23] measures the efficiency and productivity at a liquid bulk terminal.
The authors Dohmen [11], Park and Park [25] and Bugaric et al. [6] research the different facilities within a liquid bulk terminal. Park and Park [25] analyses the processes within the terminal and tries to optimise different components by using simulation models. Bugaric et al. [6] simulates a bulk terminal to analyse different combinations of facilities. This is done to find the optimal utilisation of a bulk terminal. Dohmen [11] models the scheduling of ships arriving at the terminal. This helps optimising the performance and all the facilities at a liquid bulk terminal.

Bunkering is defined as the supply of fuel to the vessel for propulsion or other energy uses. To supply ammonia to ships within the maritime sector infrastructure and facilities are needed. There are already 120 ammonia terminals [21]. It can be assumed that these terminals have the necessary equipment and storage. The literature of bunkering ammonia is not extensive however the process of bunkering for LPG and LNG are well documented. LPG has similar characteristics to ammonia and can therefore be compared with for future solutions [10, 24, 1]. LNG have mostly similar characteristics to ammonia. The biggest differences for storage is that LNG is stored at much lower temperatures than is needed for ammonia. Therefore it can be assumed that the facilities used for LNG are similar or can also be applied to ammonia.

1.3. Bunker options

To bunker ammonia at a liquid bulk terminal there are various options. Within the literature four methods of bunkering are described. These four methods can be divided as bunkering form shore to ship or bunkering from ship to ship [14, 17, 33, 5]. The different methods are elaborated on in the next subsections.

1.3.1. Ship to Ship

Ship to Ship (STS) bunkering uses a bunkering vessel to bunker the fuel to a ship. The ammonia fuel can be bunkered while it is fully, semi or non-refrigerated (pressurised). However the receiving ship (bunkering vessel and to be bunkered ship) should be able to handle such temperatures and or pressures. Future concepts of ships with engines using ammonia suggest the use of refrigerated storage [32]. It is likely that the ships in the future will thus also use refrigerated storage tanks. Furthermore for higher volumes of storages and therefore larger ships pressurised storage is not or less feasible. Therefore most ships in the future should have equipment for the re-liquefaction of ammonia to store refrigerated ammonia and to handle boil off gasses. It can be assumed that ships will therefore likely bunker refrigerated liquid ammonia [1, 10].

STS bunkering provides flexibility with the the volume and transfer rate of bunkering. Furthermore STS bunkering provides flexibility in locations to bunker at. STS bunkering can be done at sea or at the port. While STS bunkering at the port when the ship is docked, it is possible that the ship could have other logistical activities simultaneously. This includes loading and unloading of other cargo [17, 12]. It is considered as the least disruptive to the ship and dockside operations [33].

However STS bunkering exposes the vessels to external influences like wind, currents, waves and the risk of collisions between the ships. Furthermore additional infrastructure is required to refill the bunkering vessels.

1.3.2. Truck to Ship

For Truck to Ship (TTS) handling the ammonia fuel is supplied to the ship at the dock using trucks. From the dock the ship is attached to a gas liquid system that pumps ammonia from the truck to the ship. The trucks can only carry non-refrigerated ammonia, thus under pressure as the truck cannot be equipped with the cooling systems. TTS bunkering gives great flexibility in locations as these tanks are easily transported to a location [12]. TTS bunkering is mainly suitable for small volumes fuel tanks. The tank size of the truck is limited by transport legislation [33]. Therefore it can be used as a start-up method for bunkering ammonia [17]. TTS Bunkering is less suitable for larger volumes as the number of trucks and the transfer rate limits it.

1.3.3. Pipe to Ship

When a Pipe to Ship (PTS) method is used the ship is bunkered using a pipeline connection from the shore storage of the terminal directly to the vessel while docked at the dock. This likely to be pressurised, however this method can be done at different temperatures. PTS bunkering is similar to TTS bunkering as mostly the same facilities can be used. However the supply to this bunkering station is by pipeline from the storage instead of a truck. PTS bunkering is able to supply bigger volumes at a much higher supply rate [17, 33, 5, 12]. PTS is therefore flexible with loading different volumes and transfer rates, however this method is not flexible with its location. The facilities used are fixed and can thus not be moved.

1.4. Supply options

For the supply of ammonia to the liquid bulk terminal four main methods can be identified. Most of these methods are similar to the previous mentioned bunkering options. A terminal can be supplied by gas carriers, pipeline connection and by trains. and by trucks.

A gas carrier is a large vessel that transports big volumes of gas. These vessels can be used to supply ammonia to a terminal. The produced ammonia is produced elsewhere and transported to the terminal by vessel and stored at the terminal. This option is flexible as the terminal only needs to be able to offload ammonia from such a ship [5]. Additionally this method is flexible for different volumes of demand for the terminal. As the terminal is able to bunker small and larger ships.

Pipeline supply depends on the possibility of a relative nearby ammonia production location. The produced ammonia is transported by pipeline into the terminal storage [5]. This method can supply large and small amounts of ammonia to the terminal. Furthermore it provides a steady supply of ammonia to the terminal.

The supply of ammonia by trains is also possible. For this method a sufficient connection to a rail road network is needed. This method gives the possibility to provide large volumes of ammonia to the terminal and to be stored. However infrastructure is needed to unload the train wagons with ammonia.

The supply of ammonia by truck is possible but likely not feasible, due to that the volumes possible to transport by truck are small. Therefore truck supply is not considered as an option in this study.

1.5. Problem statement

Due to the transition to ammonia in the maritime industry liquid bulk terminals need to adapt to the increasing use of ammonia to bunker ships. However there is no clear view of how such a terminal operates within these changes. There are different aspects of a liquid bulk terminal that need to be considered. The way an ammonia terminal scales to the increasing demand and the factors that are important with the scale of a terminal. The different configurations that can be used need to be identified. These configurations include the setup of what methods and steps are done to transfer ammonia from the storage of a terminal to the bunkered ship. To investigate the feasibility of these configurations a simulation model needs to be developed. With a simulation model the different configurations in relation to different demands and sizes can be investigated this shows the most suitable configuration for different scales. Eventually the influence of each component can be researched upon.

The literature does not research the use of ammonia as a fuel for ships within a terminal. And the preferred methods for different steps in relation to the scale of a terminal is not yet researched upon. This provides a literature gap. Therefore the goal of this research is to find these preferred solutions for a terminal to bunker ammonia to ships and to investigate the bunkering logistics of ammonia to ships at a terminal. The research tries to find strategic solutions for a terminal to handle the bunkering and storage of ammonia throughout the increasing use of ammonia in the maritime industry.

In this paper a simulation model is proposed that simulates a liquid bulk terminal to bunker ammonia with different options for bunkering and supply. The paper is divided into six sections. The methodology is provided in Section 2; the results are provided in Section 3 and discussed in Section 4. The main conclusions are drawn in Section 5.

2. Methodology

For this research a model is formulated. Discrete Event Simulation (DES) is widely used for research involving processes within a terminal. Iannone et al. [19], Cartenì and Luca [8], Triska and Frazzon [29] and Legato and Mazza [22] use Discrete Event Simulations to model the terminal. DES models a sequence of events. Every event occurs at a time and changes the state of the system. The system is assumed to be constant between events so only the events need to be simulated. DES is used in their studies because it helps to overcome mathematical limitations of optimisation approaches, support computer generated strategies and support decision processes through a "what if" approach [8].

2.1. Model description

The model consists of different classes, which form entities, that together create the terminal. Depending on the different methods of supply and bunkering other sets of classes are used. The proposed model uses two generator classes to create the ships with ammonia demand and supply modalities, supply vessel and trains. The other entities that are created are trucks, bunker stations, loaders, unloaders, bunker vessels and storages. A selection of the entities is used depending on the bunkering and supply methods. To give a better understanding of how all the components are connected and how the flow of ammonia travels Figure 2 can be seen. Sharp boxes indicate classes, round light blue boxes are not classes but used to illustrate the process, dashed lines show what it creates and continuous lines show the flow of ammonia.

The scope of the evaluated model is determined such that it includes the storage of ammonia at the terminal, the handling of ammonia within a terminal (using different methods) and the demand of ships that need bunkering. This scope also includes the supply of ammonia, using different methods, to the storage of the terminal but does not specify the production of ammonia itself.

2.2. Simulation Experiments

To conduct this experiment the implemented model is setup as follows. There are five main variables that can be changed. Two of these variables change the configuration of the terminal. These are the bunkering method and the terminal size which influences the scale. The scale of the terminal depends on the number of facilities and storage size. The other three main variables change the scenarios that the terminal operates in. This is the size of the ships that require ammonia, the size of the supply of ammonia to the terminal and the method of ammonia supply to the terminal. The size of ships corresponds with the ammonia demand at the terminal and the supply size with the supply of the terminal. By changing the variables different configurations

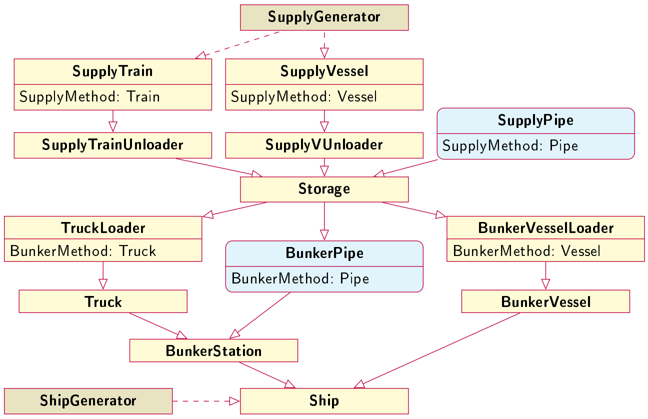

Figure 2: The flow of ammonia between classes and the relation between them

and scenarios can be simulated. For this research all the scenarios are simulated as such that the supply and demand are equal.

For the implementation of the proposed model the programming language Python is used in combination with the package Salabim. Salabim is a package for discrete event simulation, queue handling, resources, statistical sampling and monitoring [15, 16].

To measure the results of the model different performance indicators are measured. Four performance indicators are mainly used in this study. These are the number of ships handled, the average time a ship spends at the terminal which consists of the time spent bunkering and the average delay of a ship at the terminal; the bunker occupancy and storage occupancy. The bunker occupancy show the ratio of the time that the bunker facilities are occupied.

2.3. Verification and validation

Verification is the process of making sure that the designed concept model is implemented with sufficient accuracy [26]. To state it more simple: Is the model built right? This implemented model is also verified for this purpose. The verification is done by using different parameters and comparing the expectation with the results of the KPI of the simulation. As the expected results are known outcomes. Additionally extreme situations are tested to see whether the model behaves accordingly. The behaviour and quantities of the ships and their storage is verified. Also the different bunkering and supply methods are verified by changing the number of facilities and storages.

Additionally the the model outputs a trace which includes all the steps it takes and at which moment and under what conditions. By analysing the trace of this model it can be verified that the model does in fact operates in a logical order and manner.

The validation of a model is the process of ensuring that the model is accurate enough for the intended purpose, in other words asking the question if the right model is build [26]. For this model checking whether the model is right and simulates a realistic liquid bulk terminal is difficult. The model models a terminal that uses ammonia to bunker ships, this is not yet implemented in the real world yet. This makes it hard to compare the model to data or the real world, to determine its accuracy. The different configurations within the model are validated by using three methods, the first method is using data validation, the second method is process validation and the third is performance validation.

2.3.1. Data Validation

To validate parts of this model the parameters of the terminal configurations are chosen such that it can be assumed that the model represents a real world situation. One of the biggest factors within the model are the transfer rates used for the bunkering process and the transfer of ammonia. By comparing values from different literature on Ammonia, LNG and LPG, assumptions for the transfer rates can be made. With this method the transfer rates of ammonia within the liquid bulk terminal can be estimated for the different bunkering methods.

2.3.2. Process Validation

For the process validation an expert on the topic of bunkering and terminals was asked to review the model and all the steps it takes. The whole model was discussed and different situations were considered. The expert van Veldhuizen [30] stated that the processes within the model followed the correct steps for this model.

2.3.3. Performance Validation

For the performance validation of this model it is not possible to use an ammonia terminal. As of now they are not yet in use for large scale operations. However as done with the data validation, LNG terminals can be used to validate the performance of the model. This is due to that the parameters and situations of LNG bunkering are very similar to ammonia bunkering.
The EMSA [12] and Park and Park [25] describe typical bunkering times for different sizes of ships. The values they present do differ quite a bit however. The model is used to calculate the loading durations for all these sizes of ships. The model provides similar durations and is thus validated.

3. Results

In Figure 3 it can be seen that when a bunkering truck is used the least ships are handled. The use of a bunkering vessel and bunkering pipe seem to give similar number of ships handled. Therefore it can be assumed that the use of bunkering trucks is not feasible to use in a terminal. Furthermore the use of bunker trucks give very high values for the time spent at the terminal and are thus omitted to keep the results clear.
In Figures 4 to 6 three key performance indices can be seen for the three sizes.

3.1. Small Terminal, Ships and Supply

Figure 4 shows the difference in average time spent at the terminal, consisting of time bunkering and delay. For the average time spent at the terminal the use of a bunkering vessel gives longer times. Using a bunker vessels takes around 14 hours and using a bunker pipe takes between 6 and 7 hours. There is especially a big difference with the delay. The delay with bunker vessels is up to 10 hours, while for a bunker pipe 1-2 hours. For the supply methods the differences are small. However there seems to be a bit longer delay and time spent at the terminal for the use of supply vessels. When looking at the bunker occupancy the use of bunker vessels give a higher occupancy. When looking at the storage occupancy, differences in supply can be seen. Using a pipeline to resupply the storage occupancy is higher than the other supply methods.

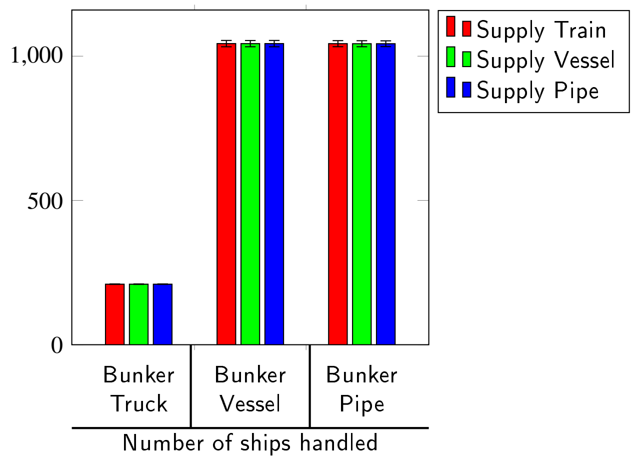

Figure 3: Number of ships handled for a Small terminal with Small ships, showing all bunkering and supply methods

3.2. Medium Terminal, Ships and Supply

When observing the differences for a M sized ships, terminal and supply in Figure 5, roughly the same differences can be seen as with the S size terminal, ships and supply. For the time spent at the terminal, the use of pipe bunkering gives a lower time of around 7 hours in comparison to 11 for bunker vessels. In total the time spent is much shorter for this larger terminal in comparison to the terminal size S for vessels. The delay shows a difference of more than ten times for pipe bunkering. For the use of bunker vessels there is more than 4 hours delay in comparison to the less than half an hour for bunkering with a pipeline connection. These differences are more extreme than before observed with size S. Furthermore there can be seen that supply via pipelines is more consistent than the other supply methods.

3.3. Large Terminal, Ships and Supply

When investigating the results for the terminal, ship and supply size L shown in Figure 6. It can be seen that they are similar as shown for the two smaller sizes. The use of bunker vessels gives 12 hours spent and bunkering pipe 8 hours. Using pipe bunkering is more effective. However the standard deviation does increase with the increase in size, especially for the delay. When looking at the storage occupancy in Figure 6, the differences between supply methods

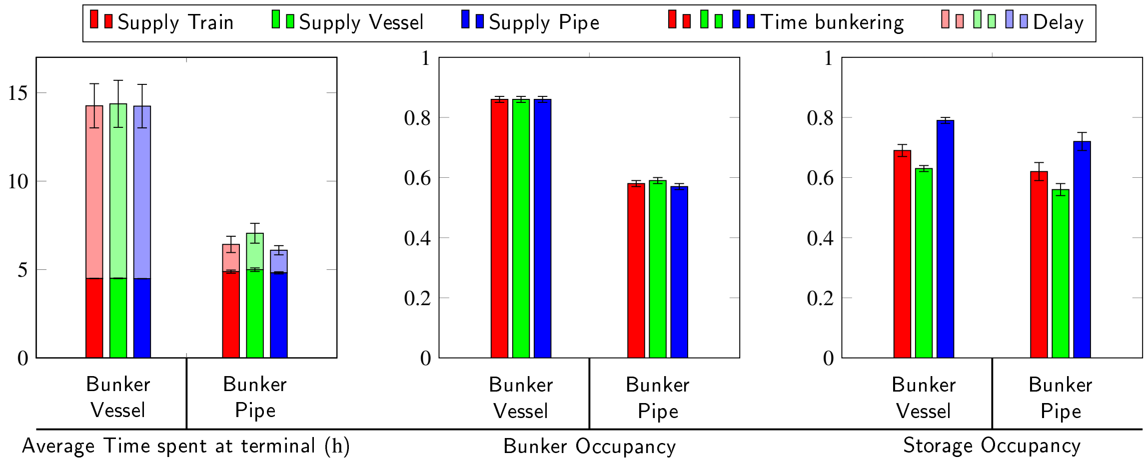

Figure 4: Three KPI shown for a Small terminal, with Small ships and with Small supply

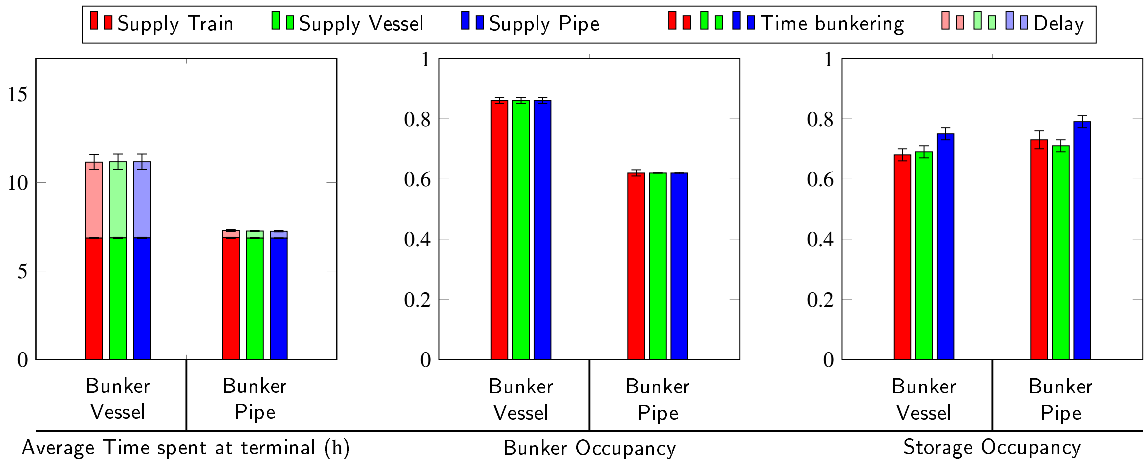

Figure 5: Three KPI shown for a Medium terminal with Medium ships

is less visible as before. Furthermore the use of supply trains seem to have less of a difference then before.

4. Discussion

From Figure 3 it can be concluded that the use of bunkering trucks is not feasible to use in a terminal. This is because truck bunkering is not keeping up. This is likely that the trucks can not keep up with the required demand. The number of ships handled is five times lower, this makes the truck bunkering not suitable to be used.

There is a large difference in the total time spent at the terminal. This difference can be explained that pipe bunkering is more efficient in the handling of ships. This can be seen from the bunker occupancy. The higher occupancy for bunker vessels show that bunker vessels are more occupied for the same amount of time and number of facilities. Thus they are less efficient. However a bunker vessel cannot be available all the time. This is due to that the bunker vessel has to return to a loader to be refilled to be ready to bunker the next ships. This results in longer waiting times at the terminal and thus a longer delay.

The simulation results suggests that pipe bunkering is the best and most efficient method to use. However the use of vessel bunkering could be more efficient when the bunkering simultaneously takes place with other processes like the loading and unloading of goods. These simultaneous operations (SIMOPS) can greatly reduce the time that a ship has to spend at a terminal. Therefore this time can be used more useful in operations and therefore saves costs.
For bunkering a ship using a pipeline connection SIMOPS is not possible as the quay would be occupied with the facilities to bunker the ship. Additionally it would bring extra safety risks. It is not desirable to lift or transport goods close to lines that are used for bunkering ammonia. In the case that something fails and a bunker line is damaged due to the loading or unloading process, spills can occur. This brings great safety and environmental risks, due to the toxicity of ammonia.
The extra time needed for bunkering with a bunker vessel can be mitigated with SIMOPS. And therefore potentially make the use of a bunker vessel when bunkering ships more

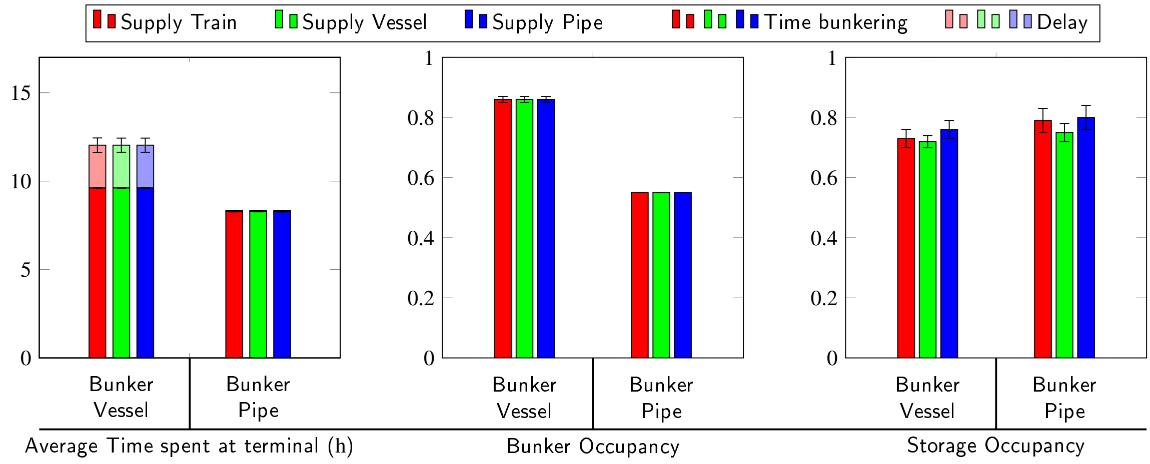

Figure 6: Three KPI shown for a Large terminal, with Large ships and Large supply

effective.
The use of of pipe bunkering is however more likely to be the best option for the largest sizes of ships in the future. This is due to that a bunker station can achieve higher transfer rates than bunker vessels. This is only the case when very large volumes need to be transferred to the ship. And thus creating an advantage over a bunker vessel.

The selected scenarios used in this research are great to investigate differences at certain scales in size of terminal or supply and demand. However the selected bounds directly also set the bounds of the research. For example the smallest sizes of terminal and supply and demand can be set smaller and therefore investigate a smaller scale. This could for example have as effect that truck bunkering is a feasible option. However this is only for a very small scale. The goal of the research is to investigate future possible scenarios and thus it was opted to focus on larger future demands and supply for a terminal.
Furthermore the selected scenarios can give a biased view of the changes between scales of supply, demand and terminal size. As in one scenario the selected supply and demand for a size terminal can be much more taxing to cope than for an other size. This also partly explains the higher times spent for size S in comparison to size M. It would be expected that smaller ships would require less time time. But when in this case for example the terminal is relatively more busy than the other these times could increase. Therefore the selection of scenarios can have a great impact on the results when comparing them.

5. Conclusion

This research was done to investigate the use of ammonia as an alternative fuel in the maritime industry. The need for alternative fuels originates from the need to reduce the global green house gas emissions. The International Maritime Organisation therefore has to goal to reduce the green house gas emissions by 50% by 2050. As a result, from the possible fuel alternatives ammonia is investigated as it can possibly achieve this reduction in emissions. To investigate this potential change in fuel, the whole system of supply and demand to bunker a ship within a terminal is analysed. This includes that the workings of a liquid bulk terminal, its components and methods is researched. Additionally the bunkering and supply options using ammonia were researched. With this a conceptual model is formulated to analyse the different methods that were found. Then the model was implemented to measure the performances of the different methods of bunkering at the terminal.

From the simulation results of the proposed model, can be concluded that only vessel and pipe bunkering are suitable for larger scales of ammonia to use. Truck bunkering is not efficient enough for larger volumes. The use of vessel ship to ship bunkering and pipe bunkering at a bunker station is suitable. The use of pipe bunkering as bunker method is found to be the most efficient method to use. With this method ships spend less time at the terminal on average and therefore have less delay in doing so. Furthermore the use of pipe supply to the terminal is the most effective.

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B Verification table

Part of model	Scenario	Expectation	Result	Verified?
Terminal	Different bunkering and supply methods selected	Only the selected method is simulated (for example when truck bunkering is selected no bunker ships should be simulated)	Only correct methods were used	yes
Ship	Increase of ship demand	Longer times in bunkering process and less ships handled	Demand: 1000 gives 44 hours bunkering time and 15 ships handled. Demand: 2000 gives 88 hours bunkering time and 6 ships handled	yes
Ship	Inter arrival time is decreased	Increase in delay	Inter arrival time: 180 gives 1 hour delay at the terminal. Inter arrival time: 80 gives a delay of 3 hours	yes
Bunkerstation	Increase of number bunkerstations	Decreased time at terminal and increase handled ships	3 bunkerstations: 53 ships handled and 50 hours at terminal. 5 bunkerstations: 58 ships handled and 42 hours at terminal	yes
Bunkerstation	No bunkerstation when bunkering method is truck or pipe	No ships will be bunkered and throughput is zero	Shipshandled: 0 and terminal throughput: 0	yes
Truck	No trucks when bunkering method is truck	No ships will be bunkered and throughput is zero	Shipshandled: 0 and terminal throughput: 0	yes
Truck loader	No truck loader when bunkering method is truck	Few ships will be bunkered and throughput is low, trucks cannot refill	Shipshandled: 0 and terminal throughput: 210	yes
Bunkervessel	No vessels when bunkering method is vessel	No ships will be bunkered and throughput is zero	Shipshandled: 0 and terminal throughput: 0	yes
Bunkervessel	Increasing number of bunkervessels	The throughput and handled ships is increased	Number of bunkervessels: 1 gives occupancy of 1 and throughput of 5000; number of bunkervessels: 2 gives occupancy of 0.9 and throughput of 8728	yes
Bunkervessel	Low bunkervessel storage volume	The time in bunkering process will increase	Bunkervessel storage at: 5000 gives 5,8 hours bunkering; storage: 500 gives 18,5 hours bunkering	yes
Vessel loader	No vessel loader	A vessel would only bunker one load	Number of loaders: 1 gives 29 ships handled; 0 loaders gives 2 handled	yes
Storage	Low maximum storage	Greatly increase delay at terminal and low storage occupancy	Max storage: 30000 gives 4,2 hours delay and 0,87 storage occupancy; max storage: 300 gives 33 hours delay and 0,13 storage occupancy	yes
Supply	Inter arrival time of supply is decreased	Higher storage occupancy and higher number of supplies	240 minutes between supply arrival gives storage occupancy 0,32 and number of successful supplies 59; 24 minutes gives occupancy of 0,33 and 89 successful supplies	yes
Terminal	Average demand per ship is equivalent to total throughput divided by number of ships	Uniform distribution of 1000 to 2000 gives average throughput of 1500	Throughput per ship is 1508	yes

Table 17: Verification results

C All simulation results of KPI

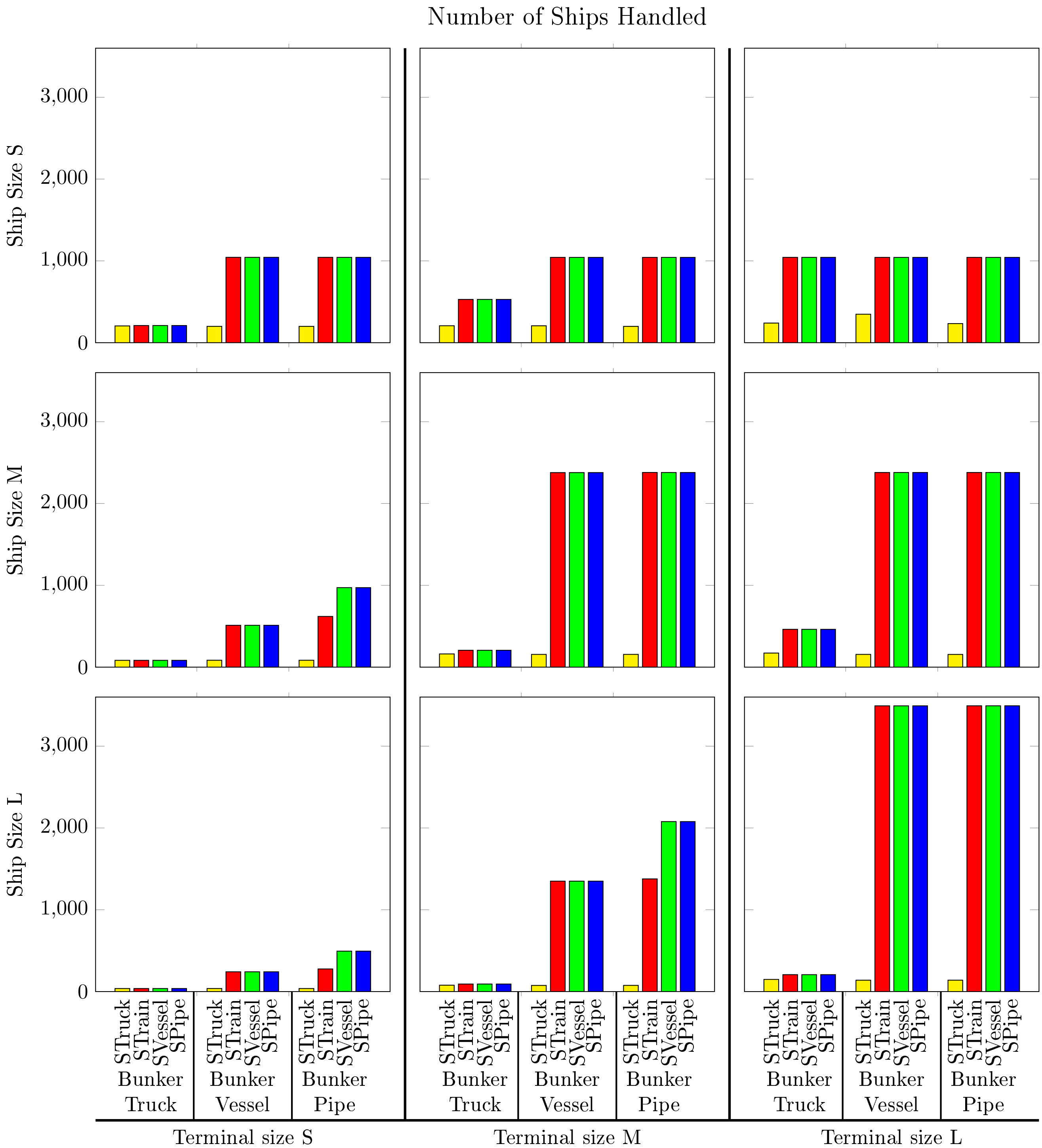

Figure 20: Number of Ships Handled

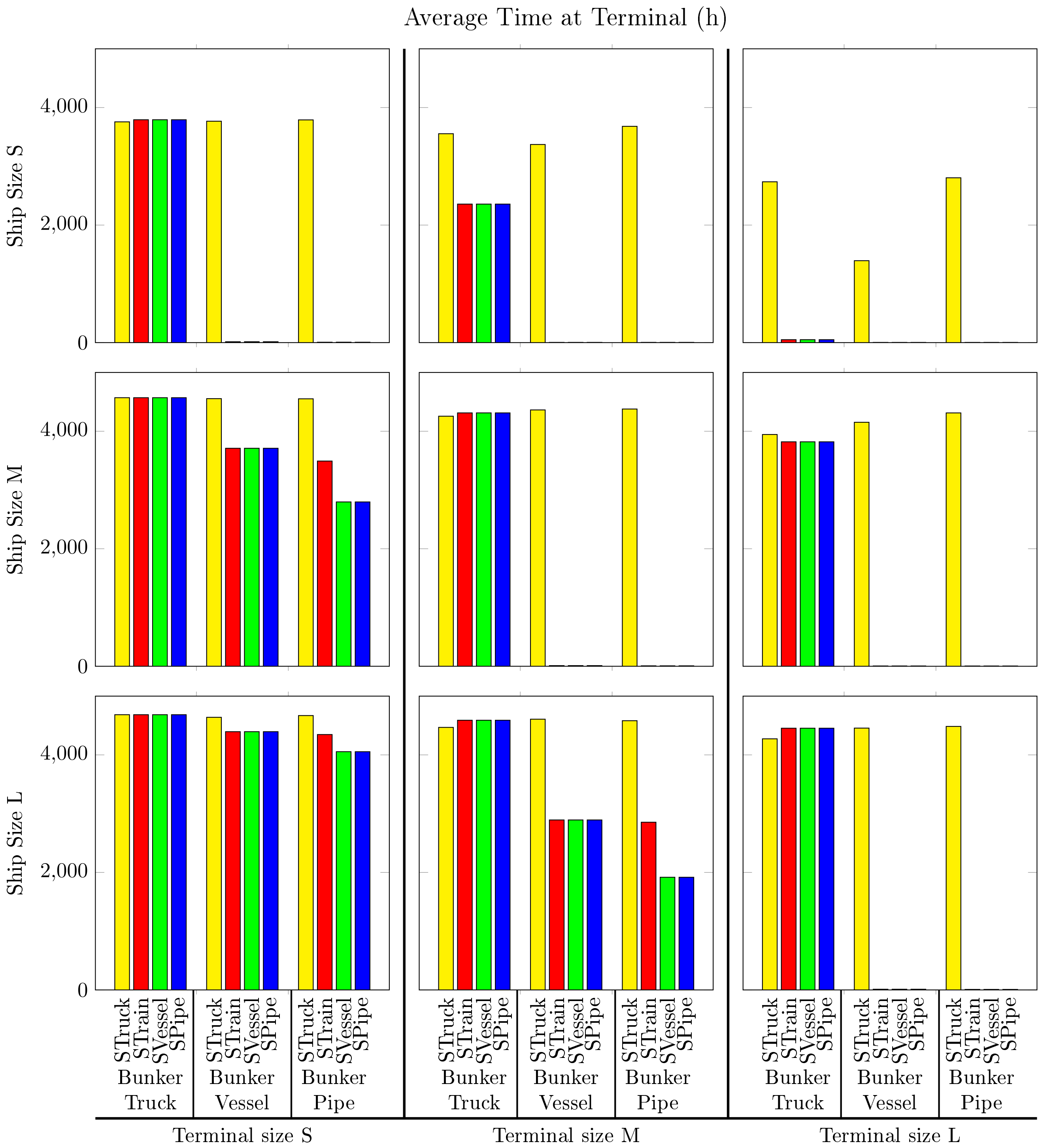

Figure 21: Average Time at Terminal (h)

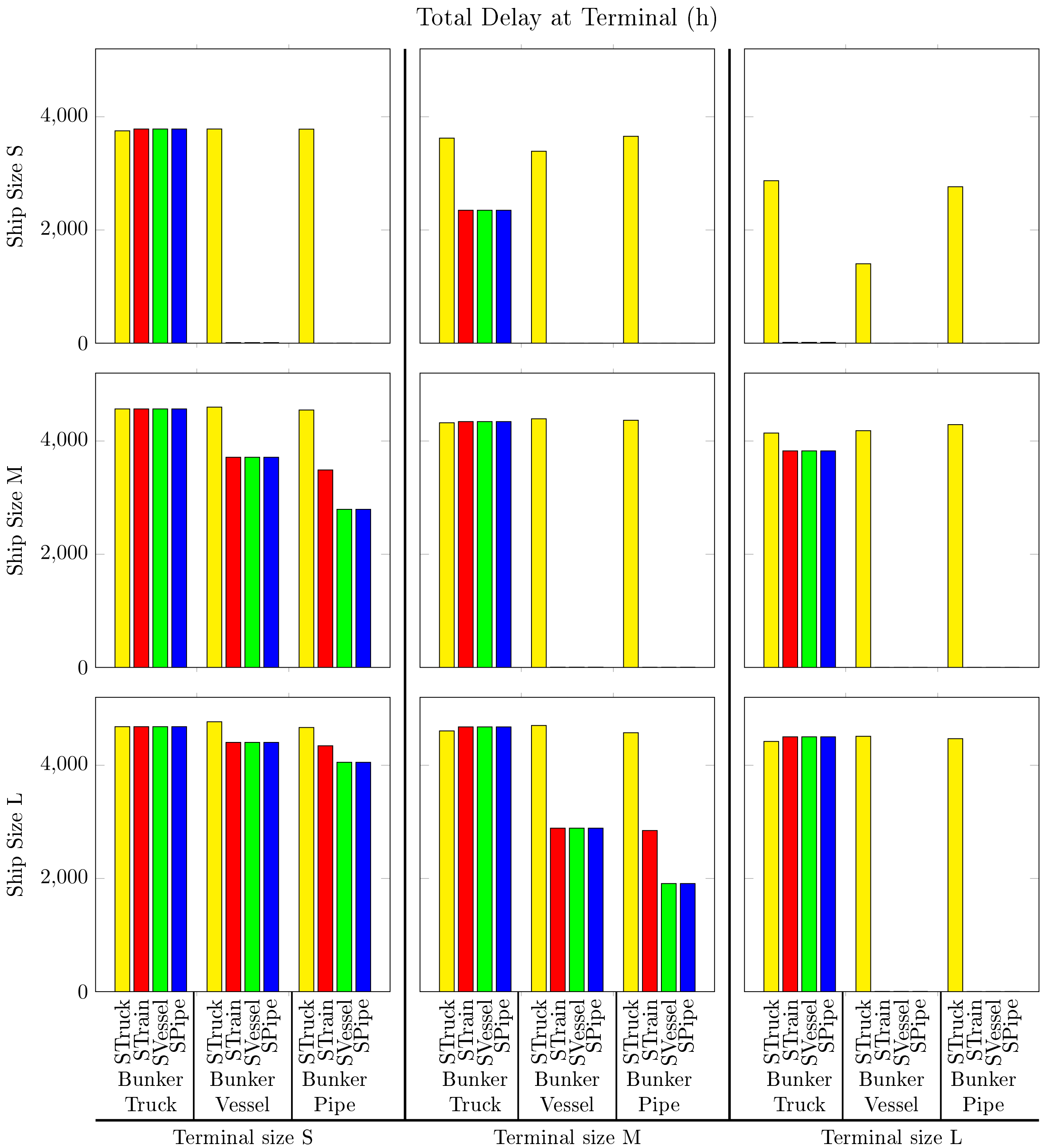

Figure 22: Total Delay at Terminal (h)

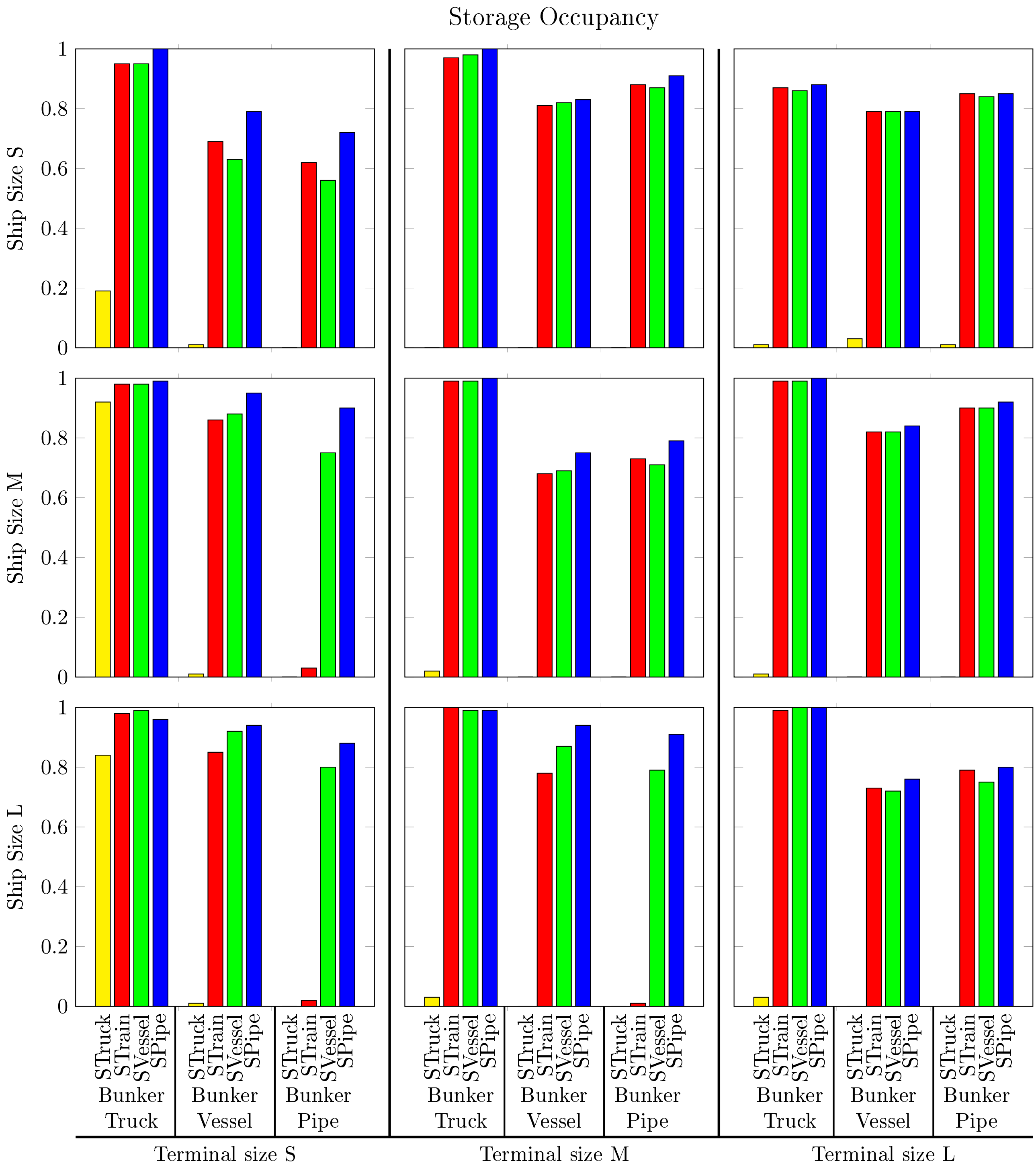

Figure 23: Storage Occupancy

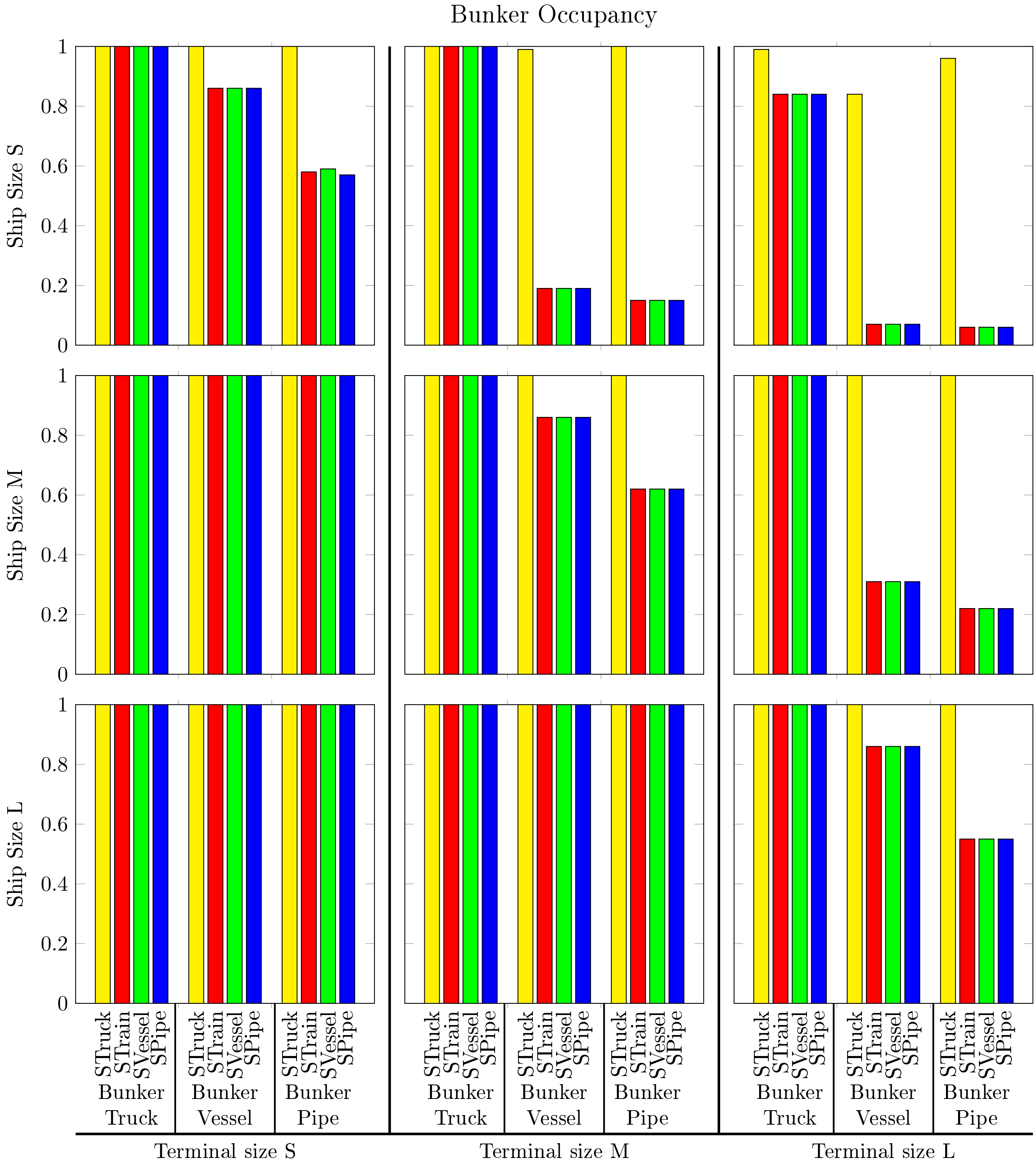

Figure 24: Bunker Occupancy

D KPI all supply and bunker methods

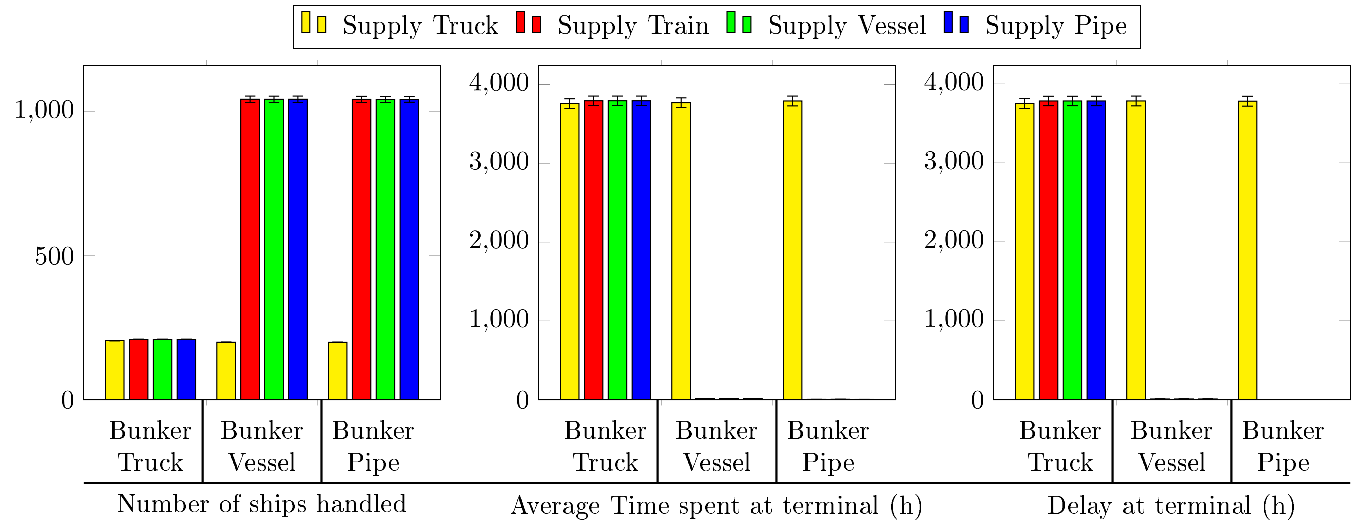

Figure 25: The three KPI shown for a Small terminal with Small ships, showing all bunkering and supply methods

Bunker Method	Supply Method	No. Ships Handled		Average time at terminal (h)		Delay at terminal (h)	
		Mean	SD	Mean	SD	Mean	SD
truck	truck	205.0	0.77	3756.9	60.98	3752	61.32
truck	train	209.8	0.75	3792.4	60.29	3784	60.63
truck	vessel	209.8	0.75	3792.4	60.29	3784	60.63
truck	pipe	209.8	0.75	3792.4	60.29	3784	60.63
vessel	truck	199.8	0.75	3767.7	61.90	3784	62.22
vessel	train	1043.6	10.93	14.3	1.26	10	1.25
vessel	vessel	1043.5	10.79	14.4	1.34	10	1.33
vessel	pipe	1043.6	10.93	14.2	1.24	10	1.23
pipe	truck	199.7	0.64	3790.1	62.53	3782	62.85
pipe	train	1043.4	10.52	6.4	0.56	2	0.46
pipe	vessel	1043.2	10.42	7.0	0.65	2	0.56
pipe	pipe	1043.2	10.03	6.1	0.31	1	0.26

Table 18: Values of the key performance indicators seen in Figure 25 for a terminal size S and ships size S

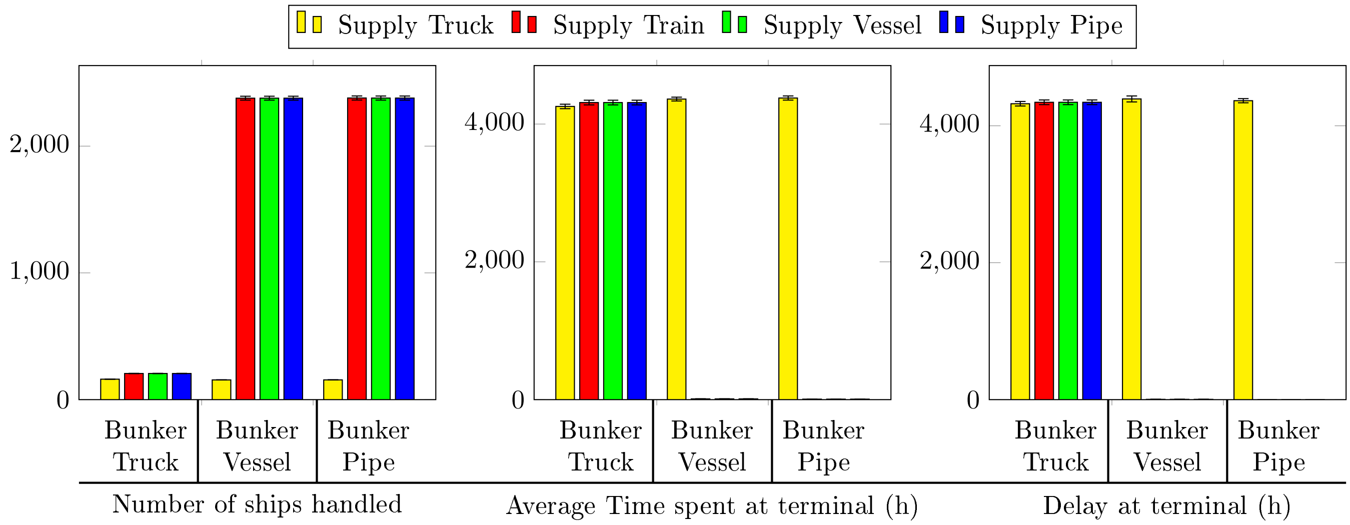

Figure 26: The three KPI shown for a Medium terminal with Medium ships

Bunker Method	Supply Method	No. Ships Handled Mean	No. Ships Handled SD	Average time at terminal (h) Mean	Average time at terminal (h) SD	Delay at terminal (h) Mean	Delay at terminal (h) SD
truck	truck	161.4	0.80	4255.6	32.35	4322	33.02
truck	train	206.2	1.17	4311.9	33.98	4343	34.27
truck	vessel	206.2	1.17	4311.9	33.98	4343	34.27
truck	pipe	206.2	1.17	4311.9	33.98	4343	34.27
vessel	truck	155.6	0.49	4362.5	27.77	4392	43.73
vessel	train	2378.2	15.40	10.9	0.44	4	0.43
vessel	vessel	2378.3	15.47	10.9	0.45	4	0.44
vessel	pipe	2378.3	15.47	10.9	0.45	4	0.44
pipe	truck	155.9	0.54	4377.8	30.23	4367	30.60
pipe	train	2379.7	16.25	7.3	0.09	0	0.06
pipe	vessel	2379.2	16.21	7.3	0.05	0	0.04
pipe	pipe	2379.2	16.21	7.3	0.04	0	0.04

Table 19: Values of the key performance indicators seen in Figure 15 for a terminal size M and ships size M

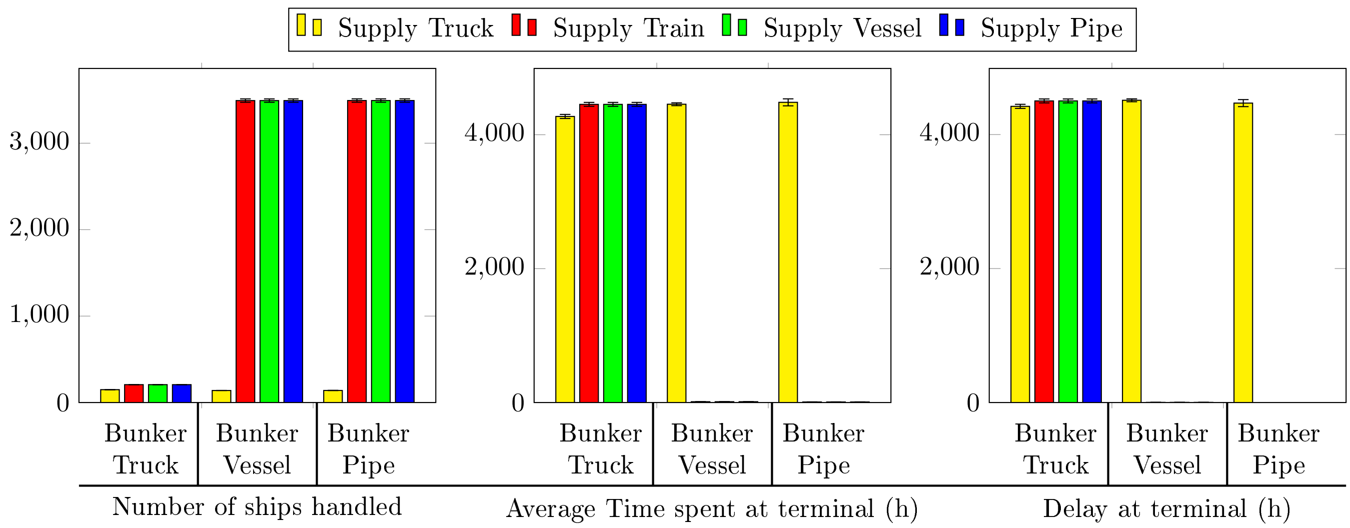

Figure 27: The three KPI shown for a Large terminal with Large ships

Bunker Method	Supply Method	No. Ships Handled		Average time at terminal (h)		Delay at terminal (h)	
		Mean	SD	Mean	SD	Mean	SD
truck	truck	148.9	0.70	4273.3	30.38	4421	30.65
truck	train	206.8	0.87	4453.9	29.44	4502	29.55
truck	vessel	206.8	0.87	4453.9	29.44	4502	29.55
truck	pipe	206.8	0.87	4453.9	29.44	4502	29.55
vessel	truck	139.1	0.70	4456.0	21.29	4511	21.73
vessel	train	3492.8	19.79	12.0	0.42	2	0.41
vessel	vessel	3492.7	19.70	12.0	0.41	2	0.40
vessel	pipe	3492.8	19.79	12.0	0.41	2	0.40
pipe	truck	139.5	1.43	4484.4	52.23	4469	52.50
pipe	train	3493.3	19.83	8.3	0.03	0	0.01
pipe	vessel	3493.3	19.83	8.3	0.04	0	0.01
pipe	pipe	3493.3	19.83	8.3	0.05	0	0.01

Table 20: Values of the key performance indicators seen in Figure 16 for a terminal size L and ships size L

E Bunker Occupancy changes

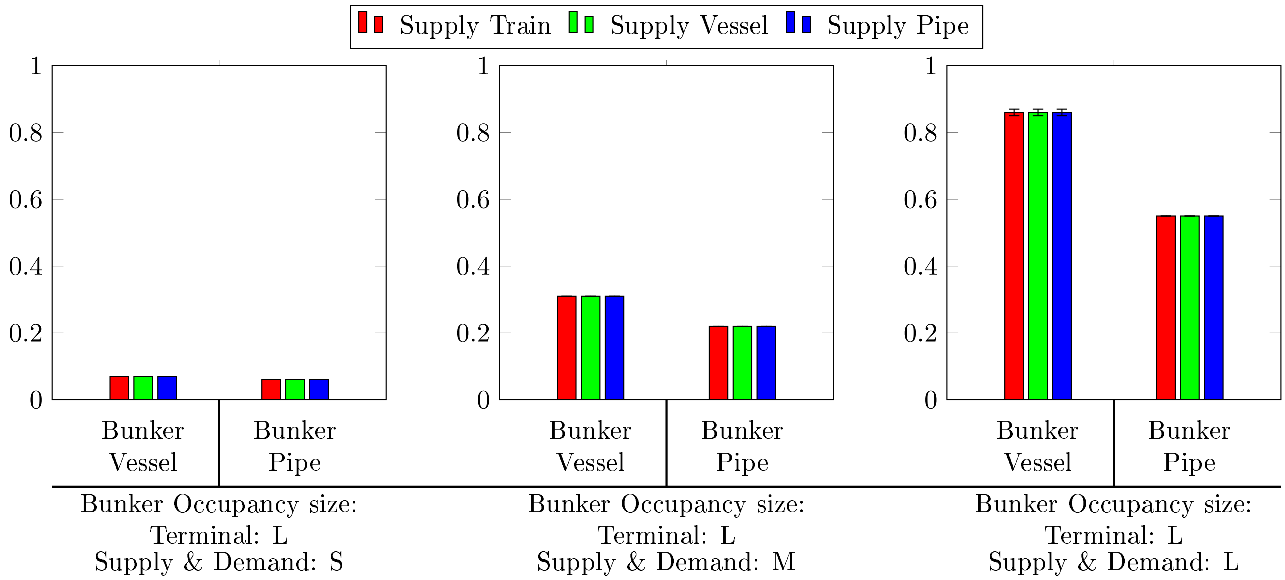

Figure 28: The bunker occupancy for different levels of supply and demand at a large terminal

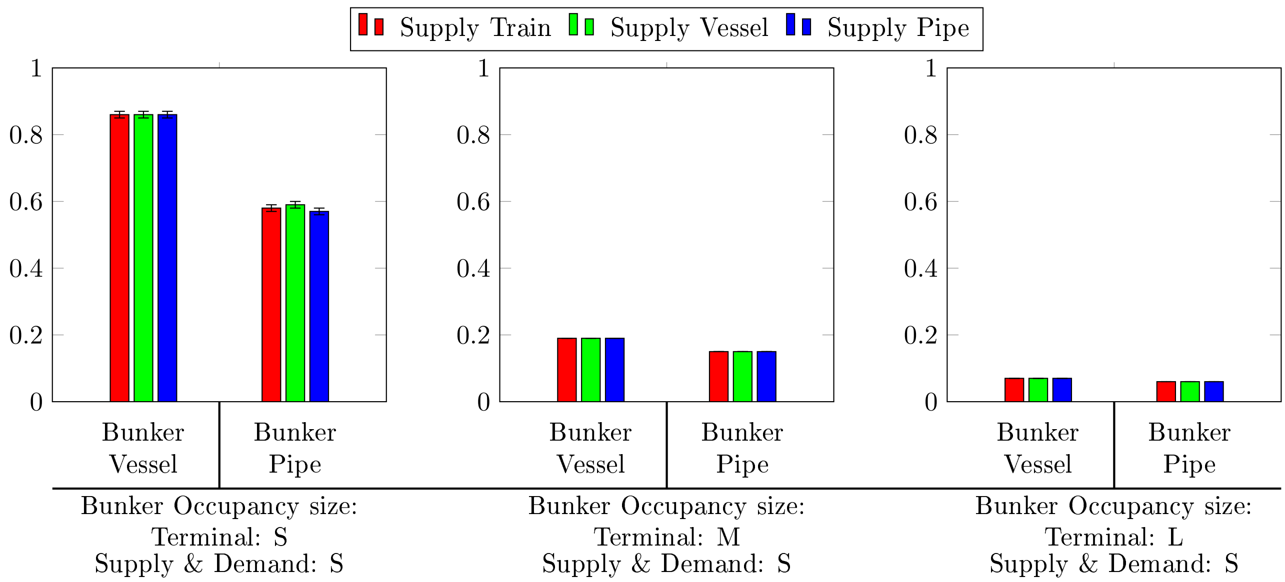

Figure 29: The bunker occupancy for different levels of terminal size at a constant supply and demand

F Costs liquid bulk terminal facilities

Component/ Method	Attributes	EA	CAPEX (M €)	Total CAPEX (M €)	OPEX	Unit	Total OPEX (M €)
Truck, Train, Vessel supply	No. Unloader locations	1	NA	NA	NA	-	NA
Truck supply	Truck unloader	1	0,91	0,91	9%	of CAPEX	0,08
Train supply	No. Carriage Unloaders per location	2	0,40	0,80	9%	of CAPEX	0,07
Vessel supply	Vessel unloader	1	4,54	4,54	9%	of CAPEX	0,41
Pipe supply	Supply pipe per km	20	0,60	12,00	9%	of CAPEX	1,08
Storage	Storage (m3)	10000	30,00	30,00	9%	of CAPEX	2,70
Bunkering Truck & Pipe	No. Bunker Stations	1	15,00	15,00	9%	of CAPEX	1,35
	Construction of quay	1	20,00	20,00	NA	-	NA
Bunkering Pipe	Pipeline to storage	1	0,50	0,50	0,05	M €	0,05
Bunkering Truck	No. Trucks	3	0,20	0,60	0,04	M €	0,12
	No. Truck Loader	1	0,91	0,91	9%	of CAPEX	0,08
Bunkering Vessel	No. Vessels (3000 m^3)	1	28,00	28,00	2,40	M €	2,40
	No. Vessel Loader	1	4,54	4,54	9%	of CAPEX	0,41

Table 21: Costs for terminal size S [10, 48, 53, 71, 72, 73]

Component/ Method	Attributes	EA	CAPEX (M €)	Total CAPEX (M €)	OPEX	Unit	Total OPEX (M €)
Truck, Train, Vessel supply	No. Unloader locations	2	NA	NA	NA	-	NA
Truck supply	Truck unloader	2	0,91	1,82	9%	of CAPEX	0,16
Train supply	No. Carriage Unloaders per location	5	0,40	4,00	9%	of CAPEX	0,36
Vessel supply	Vessel unloader	2	4,54	9,08	9%	of CAPEX	0,82
Pipe supply	Supply pipe per km	20	0,60	12,00	9%	of CAPEX	1,08
Storage	Storage (m3)	50000	80,00	80,00	9%	of CAPEX	7,20
Bunkering Truck & Pipe	No. Bunker Stations	3	15,00	45,00	9%	of CAPEX	4,05
	Construction of quay	3	20,00	60,00	NA	-	NA
Bunkering Pipe	Pipeline to storage	3	0,50	1,50	0,05	M €	0,15
Bunkering Truck	No. Trucks	7	0,20	1,40	0,04	M €	0,28
	No. Truck Loader	3	0,91	2,73	9%	of CAPEX	0,25
Bunkering Vessel	No. Vessels (3000 m^3)	3	41,00	123,00	3,20	M €	9,60
	No. Vessel Loader	2	4,54	9,08	9%	of CAPEX	0,82

Table 22: Costs for terminal size M [10, 48, 53, 71, 72, 73]

Component/ Method	Attributes	EA	CAPEX (M €)	Total CAPEX (M €)	OPEX	Unit	Total OPEX (M €)
Truck, Train, Vessel supply	No. Unloader locations	4	NA	NA	NA	-	NA
Truck supply	Truck unloader	4	0,91	3,64	9%	of CAPEX	0,33
Train supply	No. Carriage Unloaders per location	10	0,40	16,00	9%	of CAPEX	1,44
Vessel supply	Vessel unloader	4	4,54	18,15	9%	of CAPEX	1,63
Pipe supply	Supply pipe per km	20	0,60	12,00	9%	of CAPEX	1,08
Storage	Storage (m3)	180000	290,00	290,00	9%	of CAPEX	26,10
Bunkering Truck & Pipe	No. Bunker Stations	6	15,00	90,00	9%	of CAPEX	8,10
	Construction of quay	6	20,00	120,00	NA	-	NA
Bunkering Pipe	Pipeline to storage	6	0,50	3,00	0,05	M €	0,30
Bunkering Truck	No. Trucks	10	0,20	2,00	0,04	M €	0,40
	No. Truck Loader	6	0,91	5,46	9%	of CAPEX	0,49
Bunkering Vessel	No. Vessels (3000 m^3)	6	80,00	480,00	6,0	M €	36,00
	No. Vessel Loader	3	4,54	13,61	9%	of CAPEX	1,23

Table 23: Costs for terminal size L [10, 48, 53, 71, 72, 73]

G Code of Model

```
# -*- coding: utf-8 -*-
"""
Created on Thu Sep 15 14:38:26 2022

@author: Hans-Pieter
"""

import salabim as sim
import numpy as np
# import pandas as pd
import statistics
import sys
import matplotlib.pyplot as plt
import matplotlib as mpl
mpl.rcParams['figure.dpi'] = 200
import time
sttot = time.time()
from tabulate import tabulate
import os
import pandas as pd

printen = True # if false print to file
Trace = False
Animate = False
Plots = False

if not(printen):
    original_stdout = sys.stdout # Save a reference to the original standard output
    outprint = open('printlog/printlog_v17.txt','w')
    sys.stdout = outprint

SimulationSSTime = 60*24*14
SimulationRunTime = SimulationSSTime + 60*24*365

# REPRandomSeed = [21032023]
# REPShipSize = ['L']      # S M L      i demand
# REPSupplySize = ['S']       # S M L     supply
# REPTerminalSize = ['L']      #S M L   j
# REPBunkerMethod = ['pipe']  #         k
# REPSupplyMethod = ['train']  #         l
################################ reps ################################
mpl.use('Agg')
REPRandomSeed = [4559606, 3121997, 6011998, 14032023, 15032023, 16032023, 17032023, 18032023,
    19032023, 20032023, 21032023]
REPShipSize = ['S','M','L']      #XS S M L      i
# REPSupplySize = ['S','M','L']       # S M L     supply
REPTerminalSize = ['S','M','L']      #S M L   j
REPBunkerMethod = ['vessel','pipe','truck']  #         k
REPSupplyMethod = ['vessel','pipe','truck','train']  #         l

for iseed in REPRandomSeed:
    RandomSeed = iseed
    for i in REPShipSize:
        ShipSize = i
        SupplySize = i
        for j in REPTerminalSize:
            TerminalSize = j
            for k in REPBunkerMethod:
                BunkerMethod = k
                for l in REPSupplyMethod:
                    SupplyMethod = l

                    st = time.time()
                    plt.close('all')
                    sim.reset()
                    # filepathfigure = 'test_output/'
                    filepathfigure = 'results/' +'seed'+ str(RandomSeed) +'/BM'+ BunkerMethod
    +'/Terminal'+ TerminalSize +'/SM'+ SupplyMethod +'/Ship'+ ShipSize +'/'
                    os.makedirs(os.path.dirname(filepathfigure), exist_ok=True)

                    if ShipSize == 'XS':
```

```
                    from parameters.ParametersShipXS import *
                if ShipSize == 'S':
                    from parameters.ParametersShipS import *
                if ShipSize == 'M':
                    from parameters.ParametersShipM import *
                if ShipSize == 'L':
                    from parameters.ParametersShipL import *
                if ShipSize == 'V':                  # verification file
                    from parameters.ParametersShipV import *

                if TerminalSize == 'S':
                    from parameters.ParametersTerminalS import *
                if TerminalSize == 'M':
                    from parameters.ParametersTerminalM import *
                if TerminalSize == 'L':
                    from parameters.ParametersTerminalL import *
                if TerminalSize == 'V':              # verification file
                    from parameters.ParametersTerminalV import *

                if SupplySize == 'S':
                    from parameters.ParametersSupplyS import *
                if SupplySize == 'M':
                    from parameters.ParametersSupplyM import *
                if SupplySize == 'L':
                    from parameters.ParametersSupplyL import *
                if SupplySize == 'V':                # verification file
                    from parameters.ParametersSupplyV import *

                if SupplyMethod == 'truck':
                    if SupplySize == 'S':
                        SupplyInterArrivalTime = 60 #!
                    if SupplySize == 'M':
                        SupplyInterArrivalTime = 30 #!
                    if SupplySize == 'L':
                        SupplyInterArrivalTime = 15 #!
                    if SupplySize == 'V':
                        SupplyInterArrivalTime = 60 #!
                if SupplyMethod == 'vessel':
                    if SupplySize == 'S':
                        SupplyInterArrivalTime = 1720 #!
                    if SupplySize == 'M':
                        SupplyInterArrivalTime = 605 #!
                    if SupplySize == 'L':
                        SupplyInterArrivalTime = 375 #!
                    if SupplySize == 'V':
                        SupplyInterArrivalTime = 375 #!
                if SupplyMethod == 'pipe':
                    SupplyInterArrivalTime = 9999999999999999 # only needed for pipe has
 no use (a value is required)
                if SupplyMethod == 'train':
                    if SupplySize == 'S':
                        SupplyInterArrivalTime = 2050 #!
                    if SupplySize == 'M':
                        SupplyInterArrivalTime = 905 #!
                    if SupplySize == 'L':
                        SupplyInterArrivalTime = 365 #!
                    if SupplySize == 'V':
                        SupplyInterArrivalTime = 365 #!

                # CLASS DEFINITIONS: attributes and process

                class TShipGenerator (sim.Component):
                    def setup (self, Mean, LB, UB, TT, TNTB):                # Attributes
 are defined in setup
                        self.InterArrivalTime = sim.Erlang (2, rate= 2/(Mean))
                        # self.InterArrivalTime = sim.Constant ((Mean))
                        self.DemandOfShip = sim.Uniform (LB, UB)
                        self.TT = TT
                        self.TNTB = TNTB
                    def process (self):
                        while True:
                            myIAT = self.InterArrivalTime.sample ()  # myIAT = time;
 sampled from distribution
```

```
            ShipDemand = self.DemandOfShip.sample()
            TShip (Demand = ShipDemand, TT = self.TT, TNTB = self.TNTB) # create instance of ship with demand
            yield self.hold (myIAT)                     # hold myIAT

class TShip (sim.Component):
    def setup (self, Demand, TT, TNTB):
        self.Demand = Demand
        self.TravelTime = TT
        self.TimeNeededToBerth = TNTB
        self.ShipArrived = sim.State('ShipArrived')
    def process (self):
        self.enter(AtTerminalQ) #only for monitoring terminal times
        TerminalDemandM.tally(TerminalDemandM() + self.Demand)
        self.MyStation = None
        # print(self, 'enters terminal')
        if (BunkerMethod == "truck") or (BunkerMethod == "pipe"):
            self.enter (ShipQ) # enter the terminal queue
            while (StationQ.length() == 0 and self.MyStation == None):
                # print("StationQ empty", self)
                yield self.passivate() #wait for free BS
            if self.MyStation == None:
                self.MyStation = StationQ.pop()
                self.MyStation.ToBunkerShip = self
                self.leave (ShipQ)
            if not(self.MyStation.iswaiting()):
                self.MyStation.activate ()
            self.enter(InBunkerProcessQ) #bunker process started
            DelayForBunkerPosM.tally(ShipQ.length_of_stay.mean())
            yield self.hold(self.TravelTime) #travel time to bunkerstation
            yield self.hold(self.TimeNeededToBerth) #wait time until the ship is tied down to dock
            self.ShipArrived.set(value=True)
            yield self.passivate()
            ShipsHandledM.tally(ShipsHandledM()+1)
            DelayBunkerStationM.tally(sum(StationNTruckQ.length_of_stay.x())/ShipsHandledM())
            DelayAtTerminalM.tally((sum(ShipQ.length_of_stay.x()) + sum(StationNTruckQ.length_of_stay.x()))/ShipsHandledM())
            self.leave(InBunkerProcessQ) #only moniter queue, ship is done bunkering and ready to leave
            self.leave (AtTerminalQ) #only monitoring queue
            TimeAtTerminalM.tally(AtTerminalQ.length_of_stay.mean())
            yield self.cancel() #ship done leaves terminal
        ######################################################################

        if BunkerMethod == 'vessel':
            VesselPriority = 0
            while self.Demand > 0:
                self.MyVessel = None
                self.enter_sorted (ShipQ,VesselPriority)
                while (VesselQ.length() == 0 and self.MyVessel == None):
                    # print("VesselQ empty", self)
                    yield self.passivate() #wait for free BV
                if self.MyVessel == None:
                    self.MyVessel = VesselQ.pop()
                    self.MyVessel.ToBunkerShip = self
                    self.leave (ShipQ)
                if not(self.MyVessel.isscheduled()):
                    self.MyVessel.activate ()
                if(not(InBunkerProcessQ in self.queues())):
                    self.enter(InBunkerProcessQ) #bunker process started
                DelayForBunkerPosM.tally(ShipQ.length_of_stay.mean())
                yield self.wait(self.MyVessel.DoneWithLoading)
                VesselPriority -= 1
            ShipsHandledM.tally(ShipsHandledM()+1)
            DelayAtTerminalM.tally((sum(ShipQ.length_of_stay.x()) + sum(StationNTruckQ.length_of_stay.x()))/ShipsHandledM())
            self.leave(InBunkerProcessQ)
            self.leave (AtTerminalQ)
            TimeAtTerminalM.tally(AtTerminalQ.length_of_stay.mean())
            yield self.cancel() #ship done leaves terminal
```

```python

                class TStorage (sim.Component):
                    def setup(self, IS, MS, SR):
                        self.IntStorage = IS
                        self.MaxStorage = MS
                        self.SupplyRate = SR
                    def process(self):
                        while True:
                            if (SupplyMethod == 'pipe'):
                                LoadSteps = 4
                                if( self.IntStorage + self.SupplyRate/LoadSteps  < self.MaxStorage):
                                    yield self.hold(60/LoadSteps) #supply rate time
                                    self.IntStorage = self.IntStorage + self.SupplyRate/LoadSteps
                                    TerminalStorageM.tally(self.IntStorage)
                                    TerminalSupplyM.tally(TerminalSupplyM() + (self.SupplyRate/LoadSteps))
                                else: yield self.hold(60) #cooldown time

                            else:
                                yield self.passivate() #cooldown time

                class TBunkerStation (sim.Component):
                    def setup (self, ST, DC, LTF, LBT):
                        self.SetupTime = ST
                        self.DecouplingTime = DC
                        self.LoadTimeFactor = LTF
                        self.LeaveBerthTime = LBT
                        self.DoneWithLoading = sim.State('DoneWithLoading')
                    def process(self):
                        while True:
                            self.ToBunkerShip = None
                            self.enter(StationQ)
                            while (ShipQ.length() == 0 and self.ToBunkerShip == None):
                                # print("shipQ empty", self)
                                yield self.passivate() #wait for ship
                            if self.ToBunkerShip == None:
                                self.ToBunkerShip = ShipQ.pop()
                                self.ToBunkerShip.MyStation = self
                                self.leave (StationQ)
                            if not(self.ToBunkerShip.isscheduled()):
                                self.ToBunkerShip.activate () #travel to station
                            # print(self.ToBunkerShip, "goes to", self)

                            # ####################################################################
                            if BunkerMethod == "truck":
                                TruckPriority = 0
                                while self.ToBunkerShip.Demand > 0:
                                    self.MyTruck = None
                                    self.enter_sorted(StationNTruckQ,TruckPriority)
                                    self.DoneWithLoading.set(value=False)
                                    while (TruckAQ.length() == 0 and self.MyTruck == None):
                                        # print("TruckAQ empty", self)
                                        yield self.passivate() #wait for available truck
                                    if self.MyTruck == None:
                                        self.MyTruck = TruckAQ.pop()
                                        self.MyTruck.MyStation = self
                                        self.leave (StationNTruckQ)
                                    self.MyTruck.activate()
                                    yield self.wait(self.MyTruck.AtDestination, self.ToBunkerShip.ShipArrived, all=True) #wait for ship and truck
                                    # print("start loading", self.ToBunkerShip,"with", self.MyTruck, "at", self)
                                    yield self.hold(self.SetupTime)
                                    UnloadTime = min(self.ToBunkerShip.Demand, self.MyTruck.Storage) * self.LoadTimeFactor
                                    yield self.hold(UnloadTime)
                                    self.MyTruck.Storage = self.MyTruck.Storage - (UnloadTime / self.LoadTimeFactor)
                                    self.ToBunkerShip.Demand = self.ToBunkerShip.Demand -
```

```
(UnloadTime / self.LoadTimeFactor)
                                    TerminalTotThroughput.tally(TerminalTotThroughput() + (UnloadTime / self.LoadTimeFactor))
                                    StationTroughput[self.sequence_number()].tally(StationTroughput[self.sequence_number()]() + (UnloadTime / self.LoadTimeFactor))
                                    yield self.hold(self.DecouplingTime)
                                    # print(self.MyTruck, "done offloading to",self.ToBunkerShip ,"at", self, "demand =", self.ToBunkerShip.Demand)
                                    self.DoneWithLoading.set(value=True)
                                    self.MyTruck.activate()
                                    TruckPriority = TruckPriority - 1
                                else:
                                    self.ToBunkerShip.activate ()

                            #
#################################################################
                            if BunkerMethod == 'pipe':
                                while self.ToBunkerShip.Demand > 0:
                                    if Storage.IntStorage > 0:
                                        yield self.wait(self.ToBunkerShip.ShipArrived) # wait for ship to arrive
                                        # print("start pipe loading", self.ToBunkerShip, "at", self)
                                        yield self.hold(self.SetupTime)
                                        UnloadTime = min(self.ToBunkerShip.Demand, max(0, Storage.IntStorage)) * self.LoadTimeFactor
                                        Storage.IntStorage = Storage.IntStorage - (UnloadTime / self.LoadTimeFactor)
                                        TerminalTotThroughput.tally(TerminalTotThroughput() + (UnloadTime / self.LoadTimeFactor))
                                        StationTroughput[self.sequence_number()].tally(StationTroughput[self.sequence_number()]() + (UnloadTime / self.LoadTimeFactor))
                                        TerminalStorageM.tally(Storage.IntStorage)
                                        UnloadBunkerTimeM.tally(UnloadTime)
                                        yield self.hold(UnloadTime)
                                        self.ToBunkerShip.Demand = self.ToBunkerShip.Demand - (UnloadTime / self.LoadTimeFactor)
                                        yield self.hold(self.DecouplingTime)
                                        yield self.hold(self.LeaveBerthTime)
                                        # print("done pipe loading to",self.ToBunkerShip,"at", self, "demand =", self.ToBunkerShip.Demand)
                                    else:
                                        yield self.standby() # cooldown
                                self.ToBunkerShip.activate ()

                class TTruck (sim.Component):
                    def setup(self, TT, S):
                        self.TravelTime = TT
                        self.Storage = S
                        self.AtDestination = sim.State('AtDestination')
                        self.AtDestinationLoader = sim.State('AtDestinationLoader')
                    def process(self):
                        while True:
                            if self.Storage > 0:
                                self.MyStation = None
                                self.enter (TruckAQ)
                                while (StationNTruckQ.length() == 0 and self.MyStation == None):
                                    # print("StationNTruckQ empty", self)
                                    yield self.passivate() #wait for a station that needs a truck
                                if self.MyStation == None:
                                    self.MyStation = StationNTruckQ.pop()
                                    self.MyStation.MyTruck = self
                                    self.leave (TruckAQ)
                                if not(self.MyStation.iswaiting()):
                                    self.MyStation.activate ()
                                # print(self, "goes to", self.MyStation)
                                yield self.hold(self.TravelTime)
                                self.AtDestination.set(value=True)
                                yield self.wait(self.MyStation.DoneWithLoading)
                                self.AtDestination.set(value=False)
                            #Refill
```

```
                            yield self.hold(self.TravelTime)
                            self.AtDestinationLoader.set(value = True)
                            self.MyLoader = None
                            self.enter (TLoaderQ)
                            while (TLoaderNTruckQ.length() == 0 and self.MyLoader == None):
                                # print("TLoaderNTruckQ empty", self)
                                yield self.passivate() #wait for truck that needs a refill
                            if self.MyLoader == None:
                                self.MyLoader = TLoaderNTruckQ.pop()
                                self.MyLoader.MyTruck = self
                                self.leave (TLoaderQ)
                            if not(self.MyLoader.iswaiting()):
                                self.MyLoader.activate ()
                            yield self.wait(self.MyLoader.DoneWithLoading)
                            self.AtDestinationLoader.set(value = False)
                            # print(self, "loaded at storage loader", self.MyLoader)

                class TTruckLoader (sim.Component):
                    def setup(self, ST, DC, LTF):
                        self.SetupTime = ST
                        self.DecouplingTime = DC
                        self.LoadTimeFactor = LTF
                        self.DoneWithLoading = sim.State('DoneWithLoading')
                    def process(self):
                        while True:
                            if Storage.IntStorage > 0:
                                DelayAtLoaderM.tally( np.nansum(TLoaderQ.length_of_stay.mean()) + np.nansum( BVLoaderQ.length_of_stay.mean()))
                                self.DoneWithLoading.set(value = False)
                                self.MyTruck = None
                                self.enter (TLoaderNTruckQ)
                                while (TLoaderQ.length() == 0 and self.MyTruck == None):
                                    # print("TLoaderQ empty", self)
                                    yield self.passivate() #wait for a station that needs a truck
                                if self.MyTruck == None:
                                    self.MyTruck = TLoaderQ.pop()
                                    self.MyTruck.MyLoader = self
                                    self.leave (TLoaderNTruckQ)
                                if not(self.MyTruck.iswaiting()):
                                    self.MyTruck.activate ()
                                yield self.wait(self.MyTruck.AtDestinationLoader)
                                # print(self.MyTruck, 'starts loading at', self)
                                yield self.hold(self.SetupTime)
                                UnloadTime = min(max(0,Storage.IntStorage), (TruckStorageVolume - self.MyTruck.Storage)) * self.LoadTimeFactor
                                Storage.IntStorage = Storage.IntStorage - (UnloadTime / self.LoadTimeFactor)
                                TerminalStorageM.tally(Storage.IntStorage)
                                yield self.hold(UnloadTime)
                                self.MyTruck.Storage = self.MyTruck.Storage + (UnloadTime / self.LoadTimeFactor)
                                yield self.hold(self.DecouplingTime)
                                self.DoneWithLoading.set(value = True)
                                DelayAtLoaderM.tally( np.nansum(TLoaderQ.length_of_stay.mean()) + np.nansum( BVLoaderQ.length_of_stay.mean()))
                            else:
                                yield self.standby() # cooldown

                class TBunkerVessel (sim.Component):
                    def setup(self, ST, DC, LTF, TT, S, LT):
                        self.SetupTime = ST
                        self.DecouplingTime = DC
                        self.LoadTimeFactor = LTF
                        self.TravelTime = TT
                        self.Storage = S
                        self.MaxStorage = S
                        self.LoadThreshold = LT
                        self.DoneWithLoading = sim.State('DoneWithLoading')
                        self.AtDestinationLoader = sim.State('AtDestinationLoader')
                    def process(self):
                        while True:
```

```
                            if self.Storage > 0:
                                self.DoneWithLoading.set(value=False)
                                self.ToBunkerShip = None
                                self.enter(VesselQ)
                                while (ShipQ.length() == 0 and self.ToBunkerShip == None):
                                    # print("shipQ empty", self)
                                    yield self.passivate() #wait for ship
                                if self.ToBunkerShip == None:
                                    self.ToBunkerShip = ShipQ.pop()
                                    self.ToBunkerShip.MyVessel = self
                                    self.leave (VesselQ)
                                if not(self.ToBunkerShip.iswaiting()):
                                    self.ToBunkerShip.activate ()
                                yield self.hold(self.TravelTime) # travel to ship for bunkering
                                # print("start bunkering", self.ToBunkerShip,"with", self)
                                yield self.hold(self.SetupTime)
                                UnloadTime = min(self.ToBunkerShip.Demand, max(0,self.Storage)) * self.LoadTimeFactor
                                UnloadBunkerTimeM.tally(UnloadTime)
                                yield self.hold(UnloadTime)
                                self.Storage = self.Storage - (UnloadTime / self.LoadTimeFactor)
                                self.ToBunkerShip.Demand = self.ToBunkerShip.Demand - (UnloadTime / self.LoadTimeFactor)
                                TerminalTotThroughput.tally(TerminalTotThroughput() + (UnloadTime / self.LoadTimeFactor))
                                VesselTroughput[self.sequence_number()].tally(VesselTroughput[self.sequence_number()]() + (UnloadTime / self.LoadTimeFactor))
                                if self.ToBunkerShip.Demand < 0.0000000001:
                                    self.ToBunkerShip.Demand = 0
                                yield self.hold(self.DecouplingTime)
                                # print(self, "done bunkering to",self.ToBunkerShip , "demand =", self.ToBunkerShip.Demand)
                                # print(self, 'has', self.Storage, 'storage')
                                self.DoneWithLoading.set(value=True)
                            #Refill
                            if self.Storage < self.MaxStorage*self.LoadThreshold:
                                yield self.hold(self.TravelTime)
                                self.AtDestinationLoader.set(value = True)
                                self.MyLoader = None
                                self.enter (BVLoaderQ)
                                while (BVLoaderNVesselQ.length() == 0 and self.MyLoader == None):
                                    # print("BVLoaderNVesselQ empty", self)
                                    yield self.passivate() #wait for truck that needs a refill
                                if self.MyLoader == None:
                                    self.MyLoader = BVLoaderNVesselQ.pop()
                                    self.MyLoader.MyVessel = self
                                    self.leave (BVLoaderQ)
                                if not(self.MyLoader.iswaiting()):
                                    self.MyLoader.activate ()
                                yield self.wait(self.MyLoader.DoneWithLoading)
                                self.AtDestinationLoader.set(value = False)
                                # print(self, "loaded at storage loader", self.MyLoader)
                                # print(self, 'has', self.Storage, 'storage after refill')

                class TBVLoader (sim.Component):
                    def setup(self, ST, DC, LTF):
                        self.SetupTime = ST
                        self.DecouplingTime = DC
                        self.LoadTimeFactor = LTF
                        self.DoneWithLoading = sim.State('DoneWithLoading')
                    def process(self):
                        while True:
                            if Storage.IntStorage > 0:
                                DelayAtLoaderM.tally( np.nansum(TLoaderQ.length_of_stay.mean()) + np.nansum( BVLoaderQ.length_of_stay.mean()))
                                self.DoneWithLoading.set(value = False)
                                self.MyVessel = None
                                self.enter (BVLoaderNVesselQ)
                                while (BVLoaderQ.length() == 0 and self.MyVessel == None):
```

```
                                    # print("BVLoaderQ empty", self)
                                    yield self.passivate() #wait for a station that needs a truck
                                if self.MyVessel == None:
                                    self.MyVessel = BVLoaderQ.pop()
                                    self.MyVessel.MyLoader = self
                                    self.leave (BVLoaderNVesselQ)
                                if not(self.MyVessel.iswaiting()):
                                    self.MyVessel.activate ()
                                yield self.wait(self.MyVessel.AtDestinationLoader)
                                # print(self.MyVessel, 'starts loading at', self)
                                yield self.hold(self.SetupTime)
                                UnloadTime = min(max(0,Storage.IntStorage), (VesselStorageVolume - self.MyVessel.Storage)) * self.LoadTimeFactor
                                Storage.IntStorage = Storage.IntStorage - (UnloadTime / self.LoadTimeFactor)
                                TerminalStorageM.tally(Storage.IntStorage)
                                yield self.hold(UnloadTime)
                                self.MyVessel.Storage = self.MyVessel.Storage + (UnloadTime / self.LoadTimeFactor)
                                yield self.hold(self.DecouplingTime)
                                self.DoneWithLoading.set(value = True)
                                DelayAtLoaderM.tally( np.nansum(TLoaderQ.length_of_stay.mean()) + np.nansum( BVLoaderQ.length_of_stay.mean()))
                            else:
                                yield self.standby() # cooldown

                class TSupplyGenerator (sim.Component):
                    def setup (self, IAT):
                        # self.InterArrivalTime = sim.Erlang (2,rate = 2/IAT) # @@@@@@@@@@@@@@@@@@@@@@@@
                        self.InterArrivalTime = sim.Constant (IAT) # @@@@@@@@@@@@@@@@@@@@@@@@
                    def process (self):
                        while True:
                            if SupplyMethod == 'truck':
                                yield self.hold (self.InterArrivalTime)          # wait IAT
                                TSupplyTruck(TT = TT_SupplyTruck, S = TruckStorageVolume, LTF = LTF_LoaderToTruck)
                            elif SupplyMethod == 'vessel':
                                yield self.hold (self.InterArrivalTime)          # wait IAT
                                TSupplyVessel(TT = TT_SupplyVessel, S = S_SupplyVessel, LTF = LTF_SupplyVToStorage)
                            elif SupplyMethod == 'train':
                                yield self.hold (self.InterArrivalTime)          # wait IAT
                                TSupplyTrain(TT = TT_SupplyTrain, S = S_SupplyTrain, LTF = LTF_SupplyTrainToStorage, NOC = NOC_SupplyTrain, LTT = LTT_SupplyTrain)
                            else:
                                yield self.cancel()

                class TSupplyVessel (sim.Component):
                    def setup(self, TT, S, LTF):
                        self.TravelTime = TT
                        self.Storage = S
                        self.LoadTimeFactor = LTF
                        self.AtDestinationStorage = sim.State('AtDestinationStorage')
                    def process(self):
                        # print(self, 'enters terminal')
                        self.MyStorage = None
                        self.enter (SupplyQ)
                        while (StorageQ.length() == 0 and self.MyStorage == None):
                            # print("StorageQ empty", self)
                            yield self.passivate() #wait for a station that needs a truck
                        if self.MyStorage == None:
                            self.MyStorage = StorageQ.pop()
                            self.MyStorage.MyVessel = self
                            self.leave (SupplyQ)
                        if not(self.MyStorage.iswaiting()):
                            self.MyStorage.activate ()
                        # print(self, "goes to", self.MyStorage)
                        yield self.hold(self.TravelTime)
                        self.AtDestinationStorage.set(value=True)
                        yield self.wait(self.MyStorage.DoneWithLoading)
```

```
                        # print(self, 'done loading at', self.MyStorage)
                        SupplyHandledM.tally(SupplyHandledM()+1)
                        yield self.cancel()

                class TSupplyTruck (sim.Component):
                    def setup(self, TT, S, LTF):
                        self.TravelTime = TT
                        self.Storage = S
                        self.LoadTimeFactor = LTF
                        self.AtDestinationStorage = sim.State('AtDestinationStorage')
                    def process(self):
                        # print(self, 'enters terminal')
                        self.MyStorage = None
                        self.enter (SupplyQ)
                        while (StorageQ.length() == 0 and self.MyStorage == None):
                            # print("StorageQ empty", self)
                            yield self.passivate() #wait for a station that needs a truck
                        if self.MyStorage == None:
                            self.MyStorage = StorageQ.pop()
                            self.MyStorage.MyTruck = self
                            self.leave (SupplyQ)
                        if not(self.MyStorage.iswaiting()):
                            self.MyStorage.activate ()
                        # print(self, "goes to", self.MyStorage)
                        yield self.hold(self.TravelTime)
                        self.AtDestinationStorage.set(value=True)
                        yield self.wait(self.MyStorage.DoneWithLoading)
                        # print(self, 'done loading at', self.MyStorage)
                        SupplyHandledM.tally(SupplyHandledM()+1)
                        yield self.cancel()

                class TSupplyTrain (sim.Component):
                    def setup(self, TT, S, LTF, NOC, LTT):
                        self.TravelTime = TT
                        self.Storage = S
                        self.LoadTimeFactor = LTF
                        self.AtDestinationStorage = sim.State('AtDestinationStorage')
                        self.NumberOfCarriages = NOC
                        self.CarriageStorage = np.full((self.NumberOfCarriages,), self.Storage)
                        self.LeaveTerminalTime = LTT
                    def process(self):
                        # print(self, 'enters terminal')
                        self.MyStorage = None
                        self.enter (SupplyQ)
                        while (StorageQ.length() == 0 and self.MyStorage == None):
                            # print("StorageQ empty", self)
                            yield self.passivate() #wait for a station that needs a truck
                        if self.MyStorage == None:
                            self.MyStorage = StorageQ.pop()
                            self.MyStorage.MyTrain = self
                            self.leave (SupplyQ)
                        if not(self.MyStorage.iswaiting()):
                            self.MyStorage.activate ()
                        # print(self, "goes to", self.MyStorage)
                        yield self.hold(self.TravelTime)
                        self.AtDestinationStorage.set(value=True)
                        yield self.wait(self.MyStorage.DoneWithLoading)
                        # print(self, 'done loading at', self.MyStorage)
                        SupplyHandledM.tally(SupplyHandledM()+1)
                        yield self.cancel()

                class TSupplyUnloader (sim.Component):
                    def setup(self, DC, ST, NOCU):
                        self.SetupTime = ST
                        self.DecouplingTime = DC
                        self.DoneWithLoading = sim.State('DoneWithLoading')
                        self.NumberOfCarriageUnloaders = NOCU
                    def process(self):
                        while True:
                            if SupplyMethod == 'truck':
                                self.DoneWithLoading.set(value = False)
                                self.MyTruck = None
```

```
                    self.enter (StorageQ)
                    while (SupplyQ.length() == 0 and self.MyTruck == None):
                        # print("SupplyQ empty", self)
                        yield self.passivate() #wait for trucks to supply storage
                    if self.MyTruck == None:
                        self.MyTruck = SupplyQ.pop()
                        self.MyTruck.MyStorage = self
                        self.leave (StorageQ)
                    if not(self.MyTruck.iswaiting()):
                        self.MyTruck.activate ()
                    yield self.wait(self.MyTruck.AtDestinationStorage)
                    # print(self.MyTruck, 'starts loading at', self)
                    yield self.hold(self.SetupTime)
                    UnloadTime = min(max(Storage.MaxStorage - Storage.IntStorage,0), self.MyTruck.Storage) * self.MyTruck.LoadTimeFactor
                    yield self.hold(UnloadTime)
                    Storage.IntStorage = Storage.IntStorage + (UnloadTime / self.MyTruck.LoadTimeFactor)
                    TerminalStorageM.tally(Storage.IntStorage)
                    TerminalSupplyM.tally(TerminalSupplyM() + (UnloadTime / self.MyTruck.LoadTimeFactor))
                    self.MyTruck.Storage = self.MyTruck.Storage - (UnloadTime / self.MyTruck.LoadTimeFactor)
                    yield self.hold(self.DecouplingTime)
                    self.DoneWithLoading.set(value = True)

                elif SupplyMethod == 'vessel':
                    self.DoneWithLoading.set(value = False)
                    self.MyVessel = None
                    self.enter (StorageQ)
                    while (SupplyQ.length() == 0 and self.MyVessel == None):
                        # print("SupplyQ empty", self)
                        yield self.passivate() #wait for vessels to supply storage
                    if self.MyVessel == None:
                        self.MyVessel = SupplyQ.pop()
                        self.MyVessel.MyStorage = self
                        self.leave (StorageQ)
                    if not(self.MyVessel.iswaiting()):
                        self.MyVessel.activate ()
                    yield self.wait(self.MyVessel.AtDestinationStorage)
                    # print(self.MyVessel, 'starts loading at', self)
                    yield self.hold(self.SetupTime)
                    UnloadTime = min(max(Storage.MaxStorage - Storage.IntStorage,0), self.MyVessel.Storage) * self.MyVessel.LoadTimeFactor
                    LoadSteps = 10
                    UnloadTimePart = UnloadTime/LoadSteps
                    for _ in range(LoadSteps):
                        if ((UnloadTimePart/self.MyVessel.LoadTimeFactor) < (Storage.MaxStorage - Storage.IntStorage)):
                            yield self.hold(UnloadTimePart)
                            Storage.IntStorage = Storage.IntStorage + (UnloadTimePart / self.MyVessel.LoadTimeFactor)
                            TerminalStorageM.tally(Storage.IntStorage)
                            TerminalSupplyM.tally(TerminalSupplyM() + (UnloadTimePart / self.MyVessel.LoadTimeFactor))
                            self.MyVessel.Storage = self.MyVessel.Storage - (UnloadTimePart / self.MyVessel.LoadTimeFactor)
                    yield self.hold(self.DecouplingTime)
                    self.DoneWithLoading.set(value = True)

                elif SupplyMethod == 'train':
                    self.DoneWithLoading.set(value = False)
                    self.MyTrain = None
                    self.enter (StorageQ)
                    while (SupplyQ.length() == 0 and self.MyTrain == None):
                        # print("SupplyQ empty", self)
                        yield self.passivate() #wait for vessels to supply storage
                    if self.MyTrain == None:
                        self.MyTrain = SupplyQ.pop()
                        self.MyTrain.MyStorage = self
```

```
                                    self.leave (StorageQ)
                                if not(self.MyTrain.iswaiting()):
                                    self.MyTrain.activate ()
                                yield self.wait(self.MyTrain.AtDestinationStorage)
                                # print(self.MyTrain, 'starts loading at', self)

                                for CNum in range(0,self.MyTrain.NumberOfCarriages, self.NumberOfCarriageUnloaders):
                                    yield self.hold(self.SetupTime)
                                    UnloadTime = min(max(Storage.MaxStorage - Storage.IntStorage,0), self.MyTrain.CarriageStorage[CNum]) * self.MyTrain.LoadTimeFactor
                                    if (((UnloadTime/self.MyTrain.LoadTimeFactor)*self.NumberOfCarriageUnloaders) < (Storage.MaxStorage - Storage.IntStorage)):
                                        # print(self, 'unloads', self.MyTrain, 'carriage number', CNum)
                                        yield self.hold(UnloadTime)
                                        Storage.IntStorage = Storage.IntStorage + (UnloadTime / self.MyTrain.LoadTimeFactor)*self.NumberOfCarriageUnloaders
                                        TerminalStorageM.tally(Storage.IntStorage)
                                        TerminalSupplyM.tally(TerminalSupplyM() + (UnloadTime / self.MyTrain.LoadTimeFactor)*self.NumberOfCarriageUnloaders)
                                        self.MyTrain.CarriageStorage[CNum] = self.MyTrain.CarriageStorage[CNum] - (UnloadTime / self.MyTrain.LoadTimeFactor)
                                    yield self.hold(self.DecouplingTime)
                                self.DoneWithLoading.set(value = True)
                                yield self.hold(self.MyTrain.LeaveTerminalTime) # time needed for train to leave and create free spot to unload

                            else:
                                yield self.passivate() # cooldown

                # INITIALIZATION

                env = sim.Environment (trace = Trace, random_seed = RandomSeed, time_unit= 'minutes')

                # Queue
                ShipQ = sim.Queue ('ShipQ') #ship arriving at terminal waiting for spot to bunker
                TruckAQ = sim.Queue ('TruckAQ') #available truck to be used in bunkering (truck supply)
                StationNTruckQ = sim.Queue ('StationNTruckQ') # stations that needs trucks for bunkering (truck demand)
                StationQ = sim.Queue ('StationQ') # queue of free stations
                TLoaderQ = sim.Queue ('TLoaderQ') # queue for trucks waiting for a spot to refill
                TLoaderNTruckQ = sim.Queue ('TLoaderNTruckQ') # queue for TruckLoaders waiting for trucks
                VesselQ = sim.Queue ('VesselQ') # queue of BunkerVessels ready to bunker ships
                BVLoaderQ = sim.Queue('BVLoaderQ') # queue of BunkerVessels needing to refill
                BVLoaderNVesselQ = sim.Queue('BVLoaderNVesselQ') # queue of BunkerVesselLoader that needs vessels to refill
                SupplyQ = sim.Queue ('SupplyQ') # queue for Supply vehicles to load Storage
                StorageQ = sim.Queue('StorageQ') # queue for storage that needs a Supply vehicle

                AtTerminalQ = sim.Queue('AtTerminalQ') # queue to keep track of how long a ship is at the terminal in total
                InBunkerProcessQ = sim.Queue('InBunkerProcessQ') # queue to keep track of how long a ship is in the process of bunkering (in the terminal) until it leaves the terminal

                # Create objects
                if BunkerMethod == "truck":
                    BunkerStation = [TBunkerStation(ST = ST_TruckToShip, DC = DC_TruckToShip, LTF = LTF_TruckToShip, LBT = LBT_Station) for _ in range(NumberOfBunkerStations)] # probleem met 2,3,2  myIAT = 100
                    Truck = [TTruck(TT = TT_Truck, S = TruckStorageVolume) for _ in range(NumberOfTrucks)]
                    TruckLoader = [TTruckLoader(ST = ST_LoaderToTruck, DC =
```

```
DC_LoaderToTruck, LTF = LTF_LoaderToTruck) for _ in range(NumberOfTLoaders)]

                if BunkerMethod == "pipe":
                    BunkerStation = [TBunkerStation(ST = ST_PipeToShip, DC = DC_PipeToShip, LTF = LTF_PipeToShip, LBT = LBT_Station) for _ in range(NumberOfBunkerStations)]

                if BunkerMethod == 'vessel':
                    BunkerVessel = [TBunkerVessel(ST = ST_VesselToShip, DC = DC_VesselToShip, LTF = LTF_VesselToShip, TT = TT_VesselToShip, S = VesselStorageVolume, LT = LT_Vessel) for _ in range(NumberOfBunkerVessels)]
                    BVLoader = [TBVLoader(ST = ST_LoaderToVessel, DC = DC_LoaderToVessel, LTF = LTF_LoaderToVessel) for _ in range(NumberOfVesselLoaders)]

                if SupplyMethod == 'truck':
                    Storage = TStorage(IS = InternalStorage, MS = MaxStorage, SR = 1)
                    SupplyUnloader =[TSupplyUnloader(ST = ST_LoaderToTruck, DC = DC_LoaderToTruck, NOCU = NOCU_SupplyUnloader) for _ in range(NumberOfSupplyUnloaders)]

                if SupplyMethod == 'vessel':
                    Storage = TStorage(IS = InternalStorage, MS = MaxStorage, SR = 1)
                    SupplyUnloader = [TSupplyUnloader(ST = ST_LoaderToVessel, DC = DC_LoaderToVessel, NOCU = NOCU_SupplyUnloader) for _ in range(NumberOfSupplyUnloaders)]

                if SupplyMethod == 'pipe':
                    Storage = TStorage(IS = InternalStorage, MS = MaxStorage, SR = SR_PipeSupplyRate)

                if SupplyMethod == 'train':
                    Storage = TStorage(IS = InternalStorage, MS = MaxStorage, SR = 1)
                    SupplyUnloader = [TSupplyUnloader(ST = ST_TrainToUnloader, DC = DC_TrainToUnloader, NOCU = NOCU_SupplyUnloader) for _ in range(NumberOfSupplyUnloaders)]

                # Generators
                ShipGenerator = TShipGenerator (Mean = ShipInterArivalTime, LB = DemandLB, UB = DemandUB, TT = TT_ShipToBerth, TNTB = TNTB_TimeNeededToBerth)
                SupplyGenerator = TSupplyGenerator(IAT = SupplyInterArrivalTime)

                # Monitors
                TerminalStorageM = sim.Monitor(name='TerminalStorageM',level = True)
                ShipsHandledM = sim.Monitor(name= 'ShipsHandledM', level=True)
                TerminalTotThroughput = sim.Monitor(name='TerminalTotThroughput', level=True)
                StationTroughput = [sim.Monitor(name='StationTroughput', level=True) for _ in range(NumberOfBunkerStations) ]
                VesselTroughput = [sim.Monitor(name='VesselTroughput', level=True) for _ in range(NumberOfBunkerVessels) ]
                SupplyHandledM = sim.Monitor(name= 'SupplyHandledM', level=True)
                TerminalSupplyM = sim.Monitor(name= 'TerminalSupplyM', level=True)
                DelayForBunkerPosM = sim.Monitor(name='DelayForBunkerPosM', level=True)
                DelayBunkerStationM = sim.Monitor(name='DelayBunkerStationM', level=True)
                DelayAtTerminalM = sim.Monitor(name='DelayAtTerminalM', level=True)
                DelayAtLoaderM = sim.Monitor(name='DelayAtLoaderM', level=True)
                TimeAtTerminalM = sim.Monitor(name='TimeAtTerminalM', level=True) # temp test
                TerminalDemandM = sim.Monitor(name= 'TerminalDemandM', level=True)
                UnloadBunkerTimeM = sim.Monitor(name= 'UnloadBunkerTimeM', level=True)

                TerminalStorageM.tally(Storage.IntStorage)
                ShipsHandledM.tally(ShipsHandledM())

                ######################## Steady state reset ####################################
                env.run (SimulationSSTime)

                # print('Simulation in steady state now reset all monitors')
                ShipQ.reset_monitors()
                TruckAQ.reset_monitors()
                StationNTruckQ.reset_monitors()
                StationQ.reset_monitors()
                TLoaderQ.reset_monitors()
                TLoaderNTruckQ.reset_monitors()
                VesselQ.reset_monitors()
                BVLoaderQ.reset_monitors()
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```python
                BVLoaderNVesselQ.reset_monitors()
                SupplyQ.reset_monitors()
                StorageQ.reset_monitors()
                AtTerminalQ.reset_monitors()
                InBunkerProcessQ.reset_monitors()

                TerminalStorageM.reset_monitors()
                ShipsHandledM.tally(0)
                ShipsHandledM.reset_monitors()
                TerminalTotThroughput.tally(0)
                TerminalTotThroughput.reset_monitors()
                for _ in range(NumberOfBunkerStations): StationTroughput[_].tally(0)
                for _ in range(NumberOfBunkerVessels): VesselTroughput[_].tally(0)
                for _ in range(NumberOfBunkerStations): StationTroughput[_].reset_monitors()
                for _ in range(NumberOfBunkerVessels): VesselTroughput[_].reset_monitors()
                SupplyHandledM.tally(0)
                SupplyHandledM.reset_monitors()
                TerminalSupplyM.tally(0)
                TerminalSupplyM.reset_monitors()
                DelayForBunkerPosM.tally(0)
                DelayForBunkerPosM.reset_monitors()
                DelayBunkerStationM.tally(0)
                DelayBunkerStationM.reset_monitors()
                DelayAtTerminalM.tally(0)
                DelayAtTerminalM.reset_monitors()
                DelayAtLoaderM.tally(0)
                DelayAtLoaderM.reset_monitors()
                TimeAtTerminalM.tally(0)
                TimeAtTerminalM.reset_monitors()

                ######################## Run ##############################################
                env.run (SimulationRunTime - SimulationSSTime)

                TerminalStorageM.tally(Storage.IntStorage)
                ShipsHandledM.tally(ShipsHandledM())

                ################## Post sim processing ###########################################
                BSOccupancy = (((SimulationRunTime - SimulationSSTime) - (sum(StationQ.length_of_stay.x())/(NumberOfBunkerStations+0.00000000000001)))/(SimulationRunTime - SimulationSSTime))*(not(BunkerMethod == 'vessel'))
                BVOccupancy = (((SimulationRunTime - SimulationSSTime) - (sum(VesselQ.length_of_stay.x())/(NumberOfBunkerVessels+0.00000000000001)))/(SimulationRunTime - SimulationSSTime))*(BunkerMethod == 'vessel')
                TimeAtTerminal = AtTerminalQ.length_of_stay.mean()/60
                StorageOccupancy = TerminalStorageM.mean()/MaxStorage
                TimeInBunkerProcess = InBunkerProcessQ.length_of_stay.mean()/60
                DelayForBunkerPos = ShipQ.length_of_stay.mean()
                DelayBunkerStation = (sum(StationNTruckQ.length_of_stay.x()))/(ShipsHandledM()+0.0000000000000001)
                DelayAtTerminal = (sum(ShipQ.length_of_stay.x()) + sum(StationNTruckQ.length_of_stay.x()))/(ShipsHandledM()+0.0000000000000001)
                DelayAtLoader = np.nansum(TLoaderQ.length_of_stay.mean()) + np.nansum(BVLoaderQ.length_of_stay.mean())

                #%% Plots and Post sim data
                if Plots == True:
                    #####Plots
                    plt.figure()
                    plt.plot((np.asarray(ShipsHandledM.tx()[0])-SimulationSSTime)/60, ShipsHandledM.tx()[1], drawstyle="steps-post")
                    # plt.plot((np.asarray(ArrivedAtTerminalQ.length.tx()[0])-SimulationSSTime)/60, ArrivedAtTerminalQ.length.tx()[1], drawstyle="steps-post")
                    plt.title('ShipsHandled')
                    plt.ylabel('Number of ships')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    plt.savefig(filepathfigure +'ShipsHandled.png')

                    plt.figure()
```

```
                    plt.plot((np.asarray(TerminalTotThroughput.tx()[0])-SimulationSSTime)/60, TerminalTotThroughput.tx()[1], drawstyle="steps-post")
                    # ##plt.plot(*TerminalTotThroughput.tx(), drawstyle="steps-post")
                    plt.title('Terminal Total Throughput')
                    plt.ylabel('Volume m^3')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    plt.savefig(filepathfigure +'Terminal_Total_Throughput.png')

                    if (BunkerMethod == 'truck' or BunkerMethod == 'pipe'):
                        plt.figure()
                        for i in range(NumberOfBunkerStations):
                            plt.plot((np.asarray(StationTroughput[i].tx()[0])-SimulationSSTime)/60, StationTroughput[i].tx()[1], drawstyle="steps-post", label= 'Station '+str(i))
                        plt.title('Station Throughput')
                        plt.ylabel('Volume m^3')
                        plt.xlabel('Time (hours)')
                        plt.minorticks_on()
                        plt.grid()
                        plt.legend()
                        plt.savefig(filepathfigure +'Total_Station_Throughput.png')

                    if (BunkerMethod == 'vessel'):
                        plt.figure()
                        for i in range(NumberOfBunkerVessels):
                            plt.plot((np.asarray(VesselTroughput[i].tx()[0])-SimulationSSTime)/60, VesselTroughput[i].tx()[1], drawstyle="steps-post", label= i)
                        plt.title('Total Vessel Throughput')
                        plt.ylabel('Volume m^3')
                        plt.xlabel('Time (hours)')
                        plt.minorticks_on()
                        plt.grid()
                        plt.legend()
                        plt.savefig(filepathfigure +'Total_Vessel_Throughput.png')

                    plt.figure()
                    plt.plot((np.asarray(TerminalStorageM.tx()[0])-SimulationSSTime)/60, TerminalStorageM.tx()[1], drawstyle="steps-post", marker= '')
                    # plt.plot(*TerminalStorageM.tx(), drawstyle="steps-post")
                    plt.title('Terminal Storage')
                    plt.ylabel('Volume (m^3)')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    plt.savefig(filepathfigure +'Terminal_Storage.png')

                    plt.figure()
                    # plt.plot((np.asarray(AtTerminalQ.length.tx()[0])-SimulationSSTime)/60, AtTerminalQ.length.tx()[1], drawstyle="steps-post", label= 'At terminal')
                    plt.plot((np.asarray(ShipQ.length.tx()[0])-SimulationSSTime)/60, ShipQ.length.tx()[1], drawstyle="steps-post", label= 'Waiting to bunker')
                    # plt.plot((np.asarray(InBunkerProcessQ.length.tx()[0])-SimulationSSTime)/60, InBunkerProcessQ.length.tx()[1], drawstyle="steps-post", label= 'Bunker Process')
                    plt.title('Bunker Queue length')
                    plt.ylabel('Number of ships')
                    plt.xlabel('Time (hours)')
                    plt.grid()
                    # plt.legend()
                    plt.savefig(filepathfigure +'Bunker_Queue_length.png')

                    plt.figure()
                    plt.plot((np.asarray(DelayAtTerminalM.tx()[0])-SimulationSSTime)/60, DelayAtTerminalM.tx()[1], drawstyle="steps-post", label='Total Terminal')
                    if (BunkerMethod == 'truck'): plt.plot((np.asarray(DelayForBunkerPosM.tx()[0])-SimulationSSTime)/60, DelayForBunkerPosM.tx()[1], drawstyle="steps-post", label='Bunker Position')
                    if (BunkerMethod == 'truck'): plt.plot((np.asarray(DelayBunkerStationM.tx()[0])-SimulationSSTime)/60, DelayBunkerStationM.tx()[1], drawstyle="steps-post", label='At Bunker Station')
                    plt.title('Delay Terminal')
```

```python
                    plt.ylabel('Delay (minutes)')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    # plt.xlim(0, 2200)
                    # plt.ylim(0, 750)
                    if (BunkerMethod == 'truck'): plt.legend()
                    plt.savefig(filepathfigure +'Delay_Terminal.png')

                    if (BunkerMethod == 'truck'):
                        plt.figure()
                        plt.plot((np.asarray(DelayBunkerStationM.tx()[0])-SimulationSSTime)/60, DelayBunkerStationM.tx()[1], drawstyle="steps-post", label='Waiting for Trucks')
                        plt.plot((np.asarray(DelayAtLoaderM.tx()[0])-SimulationSSTime)/60, DelayAtLoaderM.tx()[1], drawstyle="steps-post", label='Delay at loader')
                        plt.title('Delay Bunker Station')
                        plt.ylabel('Delay (minutes)')
                        plt.xlabel('Time (hours)')
                        plt.minorticks_on()
                        plt.grid()
                        plt.legend()
                        plt.savefig(filepathfigure +'Delay_at_bunker_station.png')

                    if (not(SupplyMethod == 'pipe')):
                        plt.figure()
                        plt.plot((np.asarray(SupplyHandledM.tx()[0])-SimulationSSTime)/60, SupplyHandledM.tx()[1], drawstyle="steps-post")
                        plt.title('Supply handled')
                        plt.ylabel('Number of supplies')
                        plt.xlabel('Time (hours)')
                        plt.minorticks_on()
                        plt.grid()
                        plt.savefig(filepathfigure +'Supply_handled.png')

                    plt.figure()
                    plt.plot((np.asarray(TerminalSupplyM.tx()[0])-SimulationSSTime)/60, TerminalSupplyM.tx()[1], drawstyle="steps-post")
                    plt.title('Supplied to terminal')
                    plt.ylabel('Volume (m^3)')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    plt.savefig(filepathfigure +'Supplied_to_terminal.png')

                    plt.figure()
                    plt.scatter((np.asarray(AtTerminalQ.length_of_stay.tx()[0])-SimulationSSTime)/60, AtTerminalQ.length_of_stay.tx()[1], s=3)
                    plt.title('Length of stay at terminal')
                    plt.ylabel('length of stay (min)')
                    plt.xlabel('Time (hours)')
                    plt.minorticks_on()
                    plt.grid()
                    plt.savefig(filepathfigure +'Length_of_stay_at_terminal.png')

                    print ('\n')

                if not(printen):
                    outprint.close()
                    sys.stdout = original_stdout # Reset the standard output to its original value
                # PRINT RESULTS
                print ('\n')

                # KPI's
                KPIdata = [['Bunker station Occupancy:', BSOccupancy],
                    ['Bunker vessel Occupancy:', BVOccupancy],
                    ['Storage Occupancy', StorageOccupancy],
                    ['Ships handled:', ShipsHandledM()],
                    ['Terminal total throughput:', TerminalTotThroughput(), 'm^3'],
                    ['Terminal throughput per ship:', TerminalTotThroughput()/(ShipsHandledM()+0.0000000000001), 'm^3'],
                    ['Terminal supply handled:', SupplyHandledM()],
                    ['Terminal total supply:', TerminalSupplyM(), 'm^3'],
```

```
                    ['Average time at terminal:', TimeAtTerminal, 'hours'],
                    ['Average time in bunker process', TimeInBunkerProcess, 'hours'],
                    ['Delay for bunker position', DelayForBunkerPos, 'minutes'],
                    ['Delay at Bunkerstation', DelayBunkerStation, 'minutes'],
                    ['Delay at terminal', DelayAtTerminal, 'minutes'],
                    ['Delay at loader', DelayAtLoader, 'minutes'],
                    ['Average length ShipQ', ShipQ.length.mean()]]

                # print (tabulate(KPIdata, headers=["Performance Indicators", "Value", "Unit"], numalign="left"))
                # print ('\nREADY')

                et = time.time()
                # get the execution time
                elapsed_time = et - st

                Simdata = [['RandomSeed', RandomSeed],
                    ['SimulationRunTime', SimulationRunTime],
                    ['SimulationSSTime', SimulationSSTime],
                    ['ShipSize', ShipSize],
                    ['TerminalSize', TerminalSize],
                    ['BunkerMethod', BunkerMethod],
                    ['SupplyMethod', SupplyMethod],
                    ['elapsed_time', elapsed_time]]

                print (tabulate(Simdata, headers=["Simulation configuration", "Value"], numalign="left"))
                print ('\nREADY')

                et = time.time()
                # #######get the execution time
                elapsed_time = et - st
                # print('Execution time:', elapsed_time, 'seconds')

                ########################## saving post data ####################################
                df1 = pd.DataFrame(KPIdata)
                df2 = pd.DataFrame(ShipsHandledM.tx()).T
                df3= pd.DataFrame(AtTerminalQ.length.tx()).T
                df4 = pd.DataFrame(TerminalTotThroughput.tx()).T
                df5 = pd.DataFrame(TerminalStorageM.tx()).T
                df6 = pd.DataFrame(DelayForBunkerPosM.tx()).T
                df7 = pd.DataFrame(DelayAtTerminalM.tx()).T
                df8 = pd.DataFrame(SupplyHandledM.tx()).T
                df9 = pd.DataFrame(TerminalSupplyM.tx()).T
                df10 = pd.DataFrame(Simdata)
                df11 = pd.DataFrame(ShipQ.length.tx()).T
                df12 = pd.DataFrame(InBunkerProcessQ.length.tx()).T
                df13= pd.DataFrame(AtTerminalQ.length_of_stay.tx()).T

                with pd.ExcelWriter(filepathfigure + 'data.xlsx') as writer:
                    df10.to_excel(writer, sheet_name='Simdata', index=False, header=False)
                    df1.to_excel(writer, sheet_name='KPIdata', index=False, header=False)
                    df2.to_excel(writer, sheet_name='ShipsHandledM', index=False, header=False)
                    df3.to_excel(writer, sheet_name='AtTerminalQ_length', index=False, header=False)
                    df13.to_excel(writer, sheet_name='AtTerminalQ_length_of_stay', index=False, header=False)
                    df11.to_excel(writer, sheet_name='ShipQ', index=False, header=False)
                    df12.to_excel(writer, sheet_name='InBunkerProcessQ_length', index=False, header=False)
                    df4.to_excel(writer, sheet_name='TerminalTotThroughput', index=False, header=False)
                    df5.to_excel(writer, sheet_name='TerminalStorageM', index=False, header=False)
                    df6.to_excel(writer, sheet_name='DelayForBunkerPosM', index=False, header=False)
                    df7.to_excel(writer, sheet_name='DelayAtTerminalM', index=False, header=False)
                    df8.to_excel(writer, sheet_name='SupplyHandledM', index=False, header=False)
                    df9.to_excel(writer, sheet_name='TerminalSupplyM', index=False, header
```

```
    =False)

    et = time.time()
    # get the execution time
    elapsed_time = et - sttot
    print('Total Execution time:', elapsed_time, 'seconds')
print('Simulation run done for all seeds')
```

G.1 Parameters files

```
# -*- coding: utf-8 -*-
"""
Created on Wed Oct 26 11:47:25 2022

@author: Hans-
"""

# Ship size S
DemandUB = 1500                    # maximum demand per ship
DemandLB = 0.75 * DemandUB          # minimum demand per ship

ShipInterArivalTime = 500   #?     # mean inter arrival time
TNTB_TimeNeededToBerth = 30
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Oct 26 11:49:40 2022

@author: Hans-
"""

# Ship size M
DemandUB = 3850                    # maximum demand per ship
DemandLB = 0.75 * DemandUB          # minimum demand per ship

ShipInterArivalTime = 220   #?     # mean inter arrival time
TNTB_TimeNeededToBerth = 30
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Oct 26 11:49:40 2022

@author: Hans-
"""

# Ship size L
DemandUB = 8616                    # maximum demand per ship
DemandLB = 0.75 * DemandUB          # minimum demand per ship

ShipInterArivalTime = 150   #?     # mean inter arrival time
TNTB_TimeNeededToBerth = 30
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Mar 22 10:21:38 2023

@author: Hans-
"""

######## Supply S ########
# Supply Vessel
S_SupplyVessel = 5000
LTF_SupplyVToStorage = 1/(20)
# Supply Train
S_SupplyTrain = 150
NOC_SupplyTrain = 40
LTF_SupplyTrainToStorage = 1/(3)
ST_TrainToUnloader = 15
DC_TrainToUnloader = 10
# Supply Pipe
SR_PipeSupplyRate = 2.9*60 #? # How much ammonia is added per 60 minutes
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Mar 22 10:21:39 2023

@author: Hans-
"""

######## Supply M ########
# Supply Vessel
S_SupplyVessel = 10000
LTF_SupplyVToStorage = 1/(30)
# Supply Train
S_SupplyTrain = 150
NOC_SupplyTrain = 100
LTF_SupplyTrainToStorage = 1/(3)
ST_TrainToUnloader = 15
DC_TrainToUnloader = 10
# Supply Pipe
SR_PipeSupplyRate = 16.5*60 #? # How much ammonia is added per 60 minutes
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Mar 22 10:21:39 2023

@author: Hans-
"""

######## Supply L ########
# Supply Vessel
S_SupplyVessel = 20000
LTF_SupplyVToStorage = 1/(50)
# Supply Train
S_SupplyTrain = 150
NOC_SupplyTrain = 130
LTF_SupplyTrainToStorage = 1/(3)
ST_TrainToUnloader = 15
DC_TrainToUnloader = 10
# Supply Pipe
SR_PipeSupplyRate = 53*60 #? # How much ammonia is added per 60 minutes
```

```
# -*- coding: utf-8 -*-
"""
Created on Mon Oct 17 14:09:31 2022

@author: Hans-Pieter-PC
"""
# SMALL TERMINAL

# Ship
TT_ShipToBerth = 50

# BunkerStation
NumberOfBunkerStations = 1 #@@@@@@@@@
LBT_Station = 30
# Truck
NumberOfTrucks = 3  #@@@@@@@@@@@
ST_TruckToShip = 5
DC_TruckToShip = 5
LTF_TruckToShip = 1/0.85
TT_Truck = 10 #?
TruckStorageVolume = 30
# Truck Loader/Unloading
NumberOfTLoaders = 1 #@@@@@@@@@
ST_LoaderToTruck = 5
DC_LoaderToTruck = 5
LTF_LoaderToTruck = 1/0.85
# Pipe
ST_PipeToShip = 5
DC_PipeToShip = 5
LTF_PipeToShip = 1/(8)    #?
# Vessel
NumberOfBunkerVessels = 1 #@@@@@@@@@@
ST_VesselToShip = 40
```

```
DC_VesselToShip = 35
LTF_VesselToShip = 1/(8)
TT_VesselToShip = 30    #?
LT_Vessel = 0.3
VesselStorageVolume = 3000
# BVLoader/Unloading
NumberOfVesselLoaders = 1 #@@@@@@@@@@
ST_LoaderToVessel = 60
DC_LoaderToVessel = 60
LTF_LoaderToVessel = 1/(15)
# Storage
InternalStorage =  7500   #storage at start simulation
MaxStorage = 10000
# Supply unloader
NumberOfSupplyUnloaders = 1
NOCU_SupplyUnloader = 2
# Supply Truck
TT_SupplyTruck = 10 #?
# Supply Vessel
TT_SupplyVessel = 30 #?
# Supply Train
TT_SupplyTrain = 10 #?
LTT_SupplyTrain = 15
```

```
# -*- coding: utf-8 -*-
"""
Created on Mon Oct 17 14:09:31 2022

@author: Hans-Pieter-PC
"""
# MEDIUM TERMINAL

# Ship
TT_ShipToBerth = 50

# BunkerStation
NumberOfBunkerStations = 3 #@@@@@@@@@
LBT_Station = 30
# Truck
NumberOfTrucks = 7  #@@@@@@@@@@@
ST_TruckToShip = 5
DC_TruckToShip = 5
LTF_TruckToShip = 1/0.85
TT_Truck = 10 #?
TruckStorageVolume = 30
# Truck Loader/Unloading
NumberOfTLoaders = 2 #@@@@@@@@@
ST_LoaderToTruck = 5
DC_LoaderToTruck = 5
LTF_LoaderToTruck = 1/0.85
# Pipe
ST_PipeToShip = 5
DC_PipeToShip = 5
LTF_PipeToShip = 1/(12)    #?
# Vessel
NumberOfBunkerVessels = 3 #@@@@@@@@@@
ST_VesselToShip = 40
DC_VesselToShip = 35
LTF_VesselToShip = 1/(12)
TT_VesselToShip = 30    #?
LT_Vessel = 0.3
VesselStorageVolume = 10000
# BVLoader/Unloading
NumberOfVesselLoaders = 2 #@@@@@@@@@@
ST_LoaderToVessel = 60
DC_LoaderToVessel = 60
LTF_LoaderToVessel = 1/(30)
# Storage
InternalStorage =  25000   #storage at start simulation
MaxStorage = 50000
# Supply unloader
NumberOfSupplyUnloaders = 2
NOCU_SupplyUnloader = 5
# Supply Truck
```

```
TT_SupplyTruck = 10 #?
# Supply Vessel
TT_SupplyVessel = 30 #?
# Supply Train
TT_SupplyTrain = 10 #?
LTT_SupplyTrain = 15
```

```
# -*- coding: utf-8 -*-
"""
Created on Mon Oct 17 14:09:31 2022

@author: Hans-Pieter-PC
"""
# LARGE TERMINAL

# Ship
TT_ShipToBerth = 50

# BunkerStation
NumberOfBunkerStations = 6 #@@@@@@@@
LBT_Station = 30
# Truck
NumberOfTrucks = 10  #@@@@@@@@@@
ST_TruckToShip = 5
DC_TruckToShip = 5
LTF_TruckToShip = 1/0.85
TT_Truck = 10 #?
TruckStorageVolume = 30
# Truck Loader/Unloading
NumberOfTLoaders = 6 #@@@@@@@@
ST_LoaderToTruck = 5
DC_LoaderToTruck = 5
LTF_LoaderToTruck = 1/0.85
# Pipe
ST_PipeToShip = 5
DC_PipeToShip = 5
LTF_PipeToShip = 1/(20)    #?
# Vessel
NumberOfBunkerVessels = 6 #@@@@@@@@@
ST_VesselToShip = 40
DC_VesselToShip = 35
LTF_VesselToShip = 1/(16)
TT_VesselToShip = 30    #?
LT_Vessel = 0.3
VesselStorageVolume = 25000
# BVLoader/Unloading
NumberOfVesselLoaders = 3 #@@@@@@@@@
ST_LoaderToVessel = 60
DC_LoaderToVessel = 60
LTF_LoaderToVessel = 1/(50)
# Storage
InternalStorage =  90000   #storage at start simulation
MaxStorage = 180000
# Supply unloader
NumberOfSupplyUnloaders = 4
NOCU_SupplyUnloader = 10
# Supply Truck
TT_SupplyTruck = 10 #?
# Supply Vessel
TT_SupplyVessel = 30 #?
# Supply Train
TT_SupplyTrain = 10 #?
LTT_SupplyTrain = 15
```

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