Delft University of Technology

A Simulation-Based Approach to Design a Dry Bulk Transshipment Terminal for Polymetallic Nodule Collection

A Discrete Event Simulation Study

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TUDelft

Allseas

A Simulation-Based Approach to Design a Dry Bulk Transshipment Terminal for Polymetallic Nodule Collection

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by

Chris van der Ree

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Preface

This thesis marks the end of my student life at the TU Delft. I would like to present to you my master's thesis for the study Mechanical Engineering - Multi-Machine Engineering at the TU Delft.

Firstly, I would like to thank my daily supervisors Prof. Dr.ir. Dingena Schott and Dr. Bilge Atasoy for their guidance, feedback and help during the thesis. I would also like to thank Allseas for making this thesis possible. Also a special thanks to my supervisors within Allseas Bram Post and Nitesh Thakoerdajal, for their assistance and mentorship. Furthermore, I am grateful to the employees of both Allseas and TU Delft who offered their expertise and assistance in addressing various questions that arose during the course of my research. Then I would like to thank my girlfriend for her patience regarding withstanding complaints throughout this project. And finally, I would like to thank my parents who made it possible for me to follow this education.

Chris van der Ree
Delft, June 2024

Summary

There is a growing demand of various metals originating from the sustainable energy transition. The current supply and investments plans for these critical minerals are insufficient to enable this green energy transition. Other problems are the dependency of third countries and multiple drawbacks of land-mining. Deep-sea mining could be a great outcome, by collection of nodules on the seabed in the CCZ area. Different mining trials have been executed, but large-scale mining has not started yet. So far, there is no design guideline for a polymetallic nodule dry bulk (transshipment) terminal. The design and construction phase for a dry bulk terminal takes several years, therefore, the design of such a terminal should be investigated.

This thesis will focus on the design of a transshipment terminal to accommodate these large-scale mining activities in the future. The logistics and location determination of this terminal are also taken into account. The thesis contains a case-study which is formed in collaboration with Allseas. For this case-study, the simulation-based approach is chosen to design the transshipment terminal. This approach integrates many stochastic variations, identifies bottlenecks, and allows for sensitivity analysis or 'what if' scenarios. This method was compared to traditional design methods that rely on rules of thumb and practical experiences.

First of all, the appropriate storage technique has been investigated and determined. A conventional longitudinal open stockpile is selected. This option has lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility, although it requires measures to control dust.
A simulation model, containing the majority of the DSM supply chain, was designed to determine the sizing of the stockyard and seaside areas, the number of bulk carriers and their capacity, and the amount of machinery and their specifications.
The location of the transshipment terminal was determined using a weighted criteria method, with Lazaro in Mexico emerging as the most optimal location.
Experiments were performed to simulate the in practice occurring scenarios, to evaluate terminal performance. It was found that smaller capacity bulk carriers were preferred between the production vessel and terminal to have less interruption of mining operations. Experiments also indicated that the processing facility's single berth and limited working hours were bottlenecks, which are mitigated by using self-unloaders to reduce port times at the processing facility.
For berth configuration, it was recommended to have one berth strictly for unloading and one strictly for loading to avoid complex planning, equipment movements and the need for double equipment.
The appropriate handling rates were selected to balance efficiency and cost. Several options are recommended based on the maximum handling rates and knowledge of existing comparable small-scale terminals. Mobile equipment is recommended for its cost-effectiveness, flexibility, and scalability. Redundancy in terminal equipment had a minor impact, as the production vessel, besides the processing facility, proved to be a bottleneck. Speeding up the terminal operations without improving the operations at the production vessel, will only result in longer waiting queues at the production vessel.
Regarding the storage capacity, the lower the terminal capacity, the worse it scores on the key performance indicators. Therefore, a trade-off was chosen to maintain a limited storage capacity while achieving acceptable values for the key performance indicators.
Due to rising energy costs and climate change targets, the energy efficiency within the terminal is also investigated. Experiments have shown that energy reduction strategies and technologies, such as onshore power supply (OPS), alternative power supply (belt conveyor versus diesel trucks) and a shortcut at the terminal can significantly reduce energy consumption and are therefore recommended.
The results of the simulation-based approach were compared with traditional methods, which generally supported the simulation results. However, some differences were noted which have to do with the constant and predictable flow of bulk carriers in the case study.

Overall, the thesis provided a design for a dry bulk transshipment terminal that considers logistics and location. Although, several recommendations for further research can be made. For instance, investigating alternative transshipment methods, such as floating transshipment at sea due to the relatively low required storage capacity. However, challenges such as workable weather windows and the potential need for expensive equipment need further research to assess feasibility and benefits.
Weather influence during STS transfer should also be further investigated and integrated in the model.
Furthermore, additional research is needed to determine the best handling equipment for nodules, as screw or bucket wheel unloaders might cause brittleness and turn nodules into powder.
Finally, coordination among all stakeholders is recommended, including the terminal owner and the processing facility, to implement initiatives like reducing moisture content to lower drying and energy costs during processing.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
BC1	Bulk carrier used for roundtrip 1 - production vessel to terminal
BC2	Bulk carrier used for roundtrip 2 - terminal to processing facility
CCZ	Clarion-Clipperton Zone
CFLP	Capacitated Facility Location Problem
CR	Capacity Ratios
DES	Discrete Event Simulation
DSM	Deep-sea mining
DSNC	Deep-sea nodule collection
DWT	Deadweight tonnage
EV	Electric Vehicle
EV	Empericial Values
FMP	Flow Moisture Point
FPSO	Floating production, storage, and offloading systems
IAT	Inter Arrival time
ISA	International Seabed Authority
kpi	Key Performance Indicator
Mt/year	Million tons per year
OPS	Onshore Power Supply
PDL	Program Design Language
PF	Processing Facility
PIA	Process Interaction Approach
PSD	Particle Size Distribution
RALS	Riser and Lift System
ROV	Remotely Operated Underwater Vehicle
SCD	Storage Capacity Determination
SMT	Seafloor Mining Tool
SSHINC	Saturdays, Sundays and holidays included
STS	Ship-to-ship
SWOE	Sediment, Waste and other Effluents
TD	Terminal Design
TLF	Transport Loss Factor
TMC	The Metals Company
TML	Transportable Moisture Limit
tph	tons per hour
VTS	Vertical Transport System
WoW	Waiting-on-weather

Symbols

Symbol	Definition	Unit
e	Void ratio	[-]
f_{ql}	Quay length factor	[ktm^{-1}y^{-1}]
f_s	Equipment installation factor	[-]
h	Height of the stockpile	[m]
l	Length trapezoidal part stockpile	[m]
$LOA_{average}$	Average calculated vessel length	[m]
m	Mass of the stockpile	[kg]
n	Porosity	[%]
n_b	Number of berths	[m]
s	Stockyard area	[m^2]
w	Water content	[%]
w	Stockpile's width	[m]
w_n	Natural water content	[%]
α	Material's angle of repose	[°]
ρ_d	Dry Density	[kg/m^3]
ρ_s	Mineral Density	[kg/m^3]
ρ_{situ}	Wet Density	[kg/m^3]

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1
Introduction

The renewable energy transition results in a huge demand of various metals, to produce electric cars for example. The green energy sectors will be responsible for 45% of copper demand, 61% of nickel demand, 69% of cobalt demand and 92% of lithium demand by 2040 [1]. An electric car for example requires twice as much copper in comparison to a conventional car. Wind turbines also require 12 times more copper than conventional power generation [2]. Manganese is projected to grow with 40% by 2030, due to a bigger demand for lithium-ion batteries. Furthermore it is widely used in alloys, such as steel [3]. The current supply and investment plans fall short of what is required to transform the energy sector. This imposes the risk of delay or higher prices [4].
Deep-sea mining (DSM), also referred to as deep-sea nodule collection (DSNC) can provide an outcome. Billions of manganese nodules are located at the seabed around water depths of 4000 up to 6000 meter. For example, in the Clarion Clipperton Zone (CCZ), which is located in the Pacific Ocean, in between Mexico and Hawaii. These manganese ('potato-shaped') nodules contain precious metals like cobalt, nickel, copper and manganese. The NORI arera within the CCZ zone alone would enable the production of 140 million electric cars [5].
Geopolitical motivated reasons by states also plays a role for polymetallic nodule collection. Europe is nowadays dependent on China. China dominates the global supply chain for almost all critical mineral resources. It dominates within its own borders, but also through ownership of foreign cobalt mines in Congo for example [6]. The processing of the clean energy metals (Copper, Nickel, Cobalt and Lithium) is also dominated by China [7]. Besides the political reasons to get less dependent on China, child labour in the cobalt mines in Congo is another major issue [8]. That is the reason why the EU is looking for mining opportunities within countries like Portugal and Sweden. However, land-mining still has a 'dirty' image and convincing local residents proved to be very difficult [9],[10]. A comparison between terrestrial mining and deep-sea nodule collection has been made in appendix F, to elaborate on the 'dirty' image of land-mining.
Large-scale mining activities have not started yet, since the International Seabed Authority (ISA) is still working on the 'mining code', which states the conditions to start nodule collection [11].
After the ISA regulations, it will take several years before large-scale nodule collection can take place [9]. A pilot have already been successfully completed by Allseas, but further development and scaling of the technique and overall supply-chain is still required [12].

1.1. Background

In 1978 the first successful trial was already completed, using a nodule collector at the seabed, a surface mining vessel and a vertical riser pipe (pump and air lift were both tested). These techniques and three components are still used.

Nowadays, deep-sea mining is a collective name of three distinct types of ore deposit: cobalt crusts, polymetallic sulphides and (ferro)manganese/polymetallic nodules [13]. This thesis focuses on the collection of polymetallic nodules, so nodules in the rest of this paper refers to polymetallic nodules. These polymetallic nodules are formed over millions of years by precipitation of metals in seawater. The polymetallic nodules contain high grades of nickel, cobalt and manganese. But also other metals like copper, titanium, lithium and molybdenum. All these different metals clarify the name polymetallic nodules. The different metals are a good source to supply environmentally friendly initiatives. Manganese is projected to grow with 40% by 2030, due to a bigger demand for lithium-ion batteries. Furthermore it is widely used in alloys, such as steel [3]. Other metals are also considered to be building blocks for a greener future. Green energy sectors will be responsible for 45% of copper demand, 61% of nickel demand, 69% of cobalt demand and 92% of lithium demand by 2040 [1].

The nodules are generally found in the deepest parts of the oceans, at a water depth between 4000 and 6000 meters. Manganese nodules are also present in shallow seas [14], but have considerably lower amounts of valuable metals [15]. An overview of the locations of different nodules is given in figure 1.1 below.

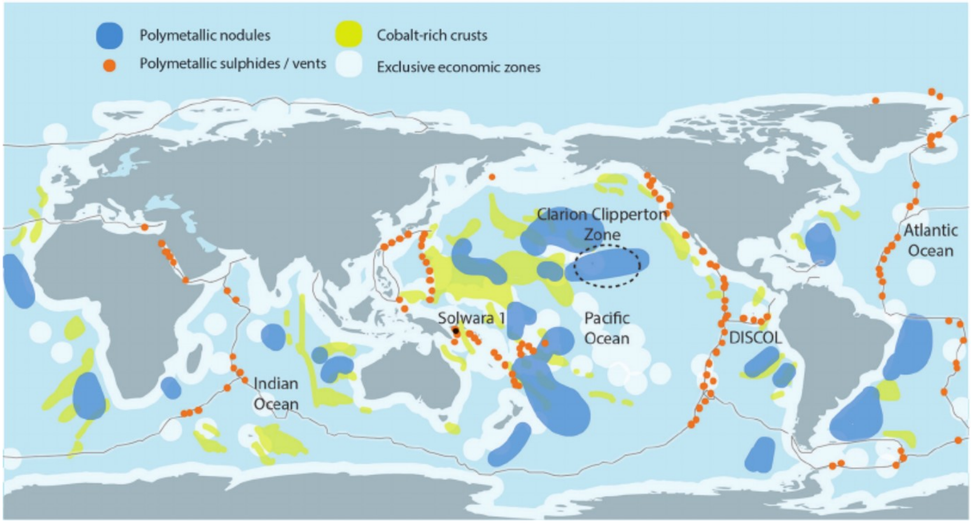


Figure 1.1: World map showing the location of different deposits [16]

The nodules vary in size, from a few millimeters to 20 centimeter, with the common size between two and eight centimeters [17]. The nodules are irregularly shaped but they more or less have the shape of a potato (figure 1.2). They lie scattered across the seabed within the top 50 mm of the seabed sediments [13] [18]. The nodules are formed by precipitation from pore water in sediments (diagenetic) and ambient seawater (hydrogenetic) [19]. 50-60 % of the nodule is hydrogenetic formed, while 35-40 % is formed diagenetic. The remaining 5-10 % consists of sediment in the cracks and pores. They generally grow in the order of 10-20 millimeters per million years [20].

The Clarion-Clipperton Zone (CCZ) is the largest region containing nodules. It is situated in between Hawaii and Mexico (dashed circle in figure 1.1). The nodules are unequally distributed and thus occur in patches. The total amount of nodules within the CCZ is estimated to be 21 billion tons [19]. A current nodule collector of Allseas with The Metals Company (TMC) has a targeted production rate of over 200 tons/hour [21]. Which indicates that the CCZ alone provides decades of mining work for multiple companies.

Figure 1.2: Appearance of a single nodule [5]

The (push) supply chain regarding DSNC is provided in figure 1.3 below. Further (technical) background about seabed harvesting, transport to surface, processing & handling, transshipment, transport at sea and the processing plant will be provided in appendix E.

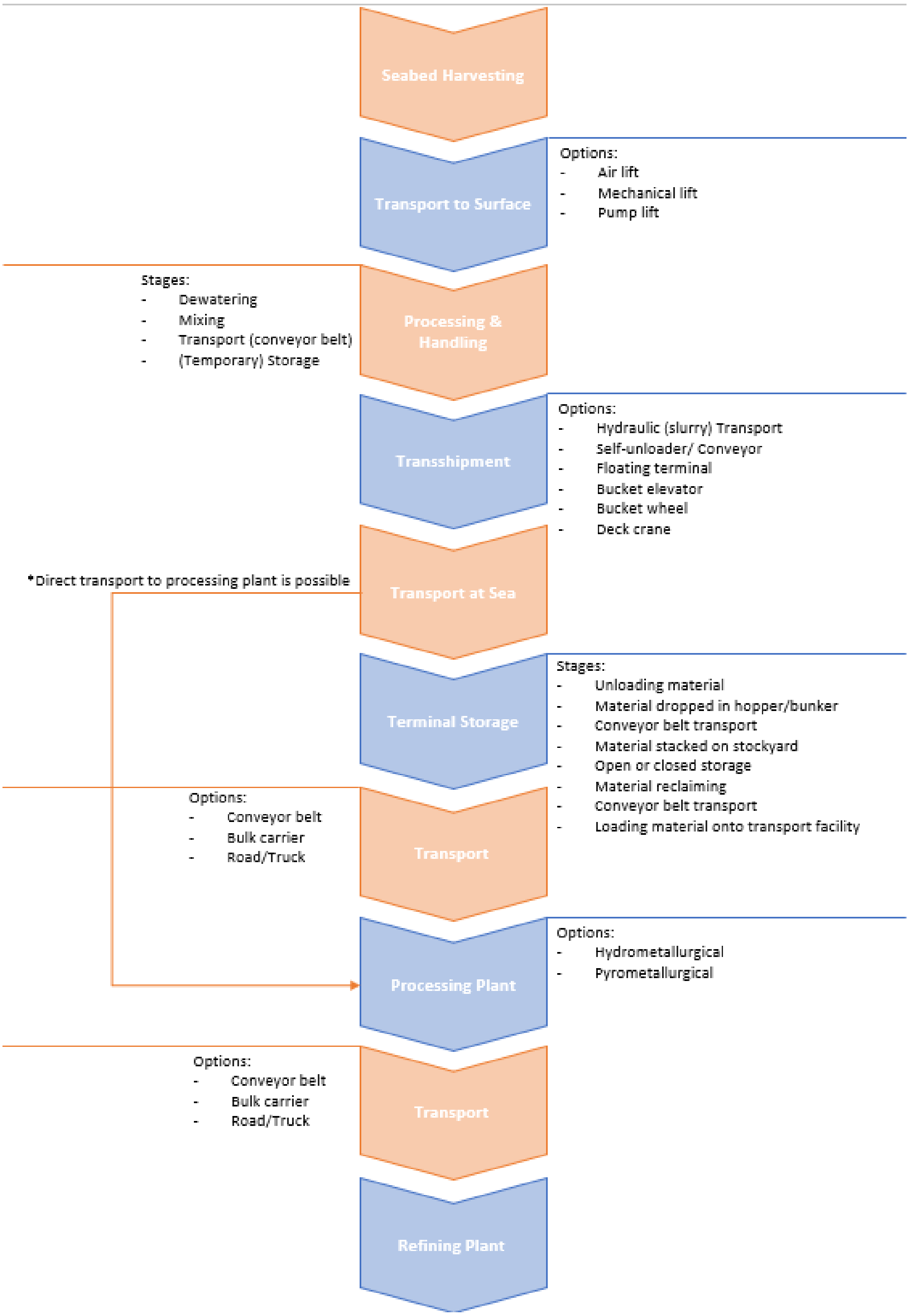


Figure 1.3: Complete supply chain

1.2. Problem Statement

The complete supply chain provides many research opportunities, which are provided in the literature assignment of Ree, Chris van der (2023). The research opportunities are briefly discussed here. For instance, it is unknown which transshipment option is the best? How the transport at sea should look like (regarding the bulk carrier types, sizes and material state)?. Furthermore, more research is required to assess cargo instabilities and the accumulation of radon gas in the holds. The optimal processing technique is also unknown. As well as some material characteristics and environmental impacts. It can be concluded that there are various knowledge gaps left which require further research before the start of large-scale mining activities.
Another very important knowledge gap relates to terminal storage. The design and construction phase for a dry bulk terminal takes several years. The construction for a dry bulk terminal for example is estimated to take 24 till 30 months [22]. The design and regulatory phase also require a significant amount of time. This highlights the importance to start with the design of a dry bulk (transshipment) terminal as soon as possible.

Design of dry-bulk terminals is partly based on rules of thumb and practical experiences. Besides rules of thumb and practical experience, results obtained with simulation tools can be used to design a dry bulk terminal [23]. However, there is currently no design guideline for a polymetallic nodule dry bulk (transshipment) terminal and these simulations have not been executed yet. The dry bulk terminal enables fluctuations between the incoming and outgoing flow of material [24]. These fluctuations will undoubtedly occur when large-scale nodule collection activities take place in the future. A fluctuation could occur in the case of for example maintenance for the production vessel or delay in transport due to weather circumstances. Aspects like equipment, location, equipment capacities, storage method and sizing are undiscovered [25]. There are available studies which address the design of dry bulk terminals, however these studies are focused on an import or export terminal. The polymetallic nodule terminal will be a transshipment terminal. At a transshipment terminal, the commodity is unloaded from a feeder vessel to the shore. Later on, the commodity is loaded to a main line vessel. At a transshipment terminal, the commodity moves over the quay twice, for unloading and loading to another ship [26].

Energy consumption is the final aspect which is not taken into account in these studies. Nowadays, ports and terminals strive to improve energy efficiency, driven by rising energy costs over the past years. Climate change mitigation is also a key target for the port industry [27]. This illustrates why the energy consumption should also be taken into account for the design of a dry bulk terminal.

To conclude, there are many research opportunities regarding deep sea mining. The design of a dry bulk terminal is one of them and should be addressed as soon as possible to accommodate the storage of nodules and thus facilitate large-scale nodule collection. The problem is that there are no design guidelines for a dry bulk transshipment terminal for polymetallic nodule collection. It is unknown whether rules of thumb and practical experiences apply to deep sea mining. Simulations also have not been executed and little is known about the energy consumption of such a dry bulk terminal. This thesis aims to increase the knowledge at an early stage regarding the design of a transshipment terminal for polymetallic nodule collection. This could help to identify constraints and potentially reduce costs and improve performance [28].

1.3. Research Questions

This thesis aims to design a dry bulk transshipment terminal suited for polymetallic nodules. The main research question and sub-questions are listed below:

What should the design be for a dry bulk transshipment terminal to accommodate collected polymetallic nodules, considering logistics and location?

Divided into the following sub-questions:

1. Which storage technique should be used to store the nodules at the dry bulk terminal and which equipment and their respective capacities can be selected regarding the handling of nodules?

2. How should a simulation model be designed to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and the amount of machinery and their specifications?
3. Which factors exert influence on the selection of a transshipment terminal location, and how can these factors be evaluated to identify the optimal location for Allseas?
4. Which experiments should be executed to simulate real-world scenarios, and what will the performance of the terminal be, when these experiments are performed?
5. What strategies and technologies can be implemented to mitigate energy usage at the transshipment terminal?
6. To which extent are the established rules of thumb and practical experiences in the dry bulk terminal domain representative for the design of a dry bulk transshipment terminal for polymetallic nodule collection?

1.4. Scope of Research

The scope of this thesis is defined as:

- Deep-sea mining is a collective name of three distinct types of ore deposit: cobalt crusts, polymetallic sulphides and (ferro)manganese/polymetallic nodules [13]. The focus will be on polymetallic/(ferro)mangese nodules coming from the CCZ area.
- There are three types of dry bulk terminals: export, import and transshipment. This thesis focuses on the design of a transshipment dry bulk terminal. A transshipment terminal is used to accommodate further transport. In this case, there is an incoming stream of nodules from the production vessel in the Pacific Ocean, and an outgoing stream of nodules towards the processing facility.
- Simulation is performed with discrete-event simulation.
- The simulation model will not arrange the equipment at the terminal. Which means that belt conveyor design network is also not taken into account within the simulations.
- The processing facility and mining location are pre-determined for the case study by Allseas. Location determination for transshipment terminal will be required and is performed in chapter 4.
- The transshipment terminal is designed for a yearly production rate between 1 and 3 million tons per year.
- The transshipment terminal is operated 24 hours a day.
- The energy reduction strategies and technologies are only considered for the transshipment terminal itself. Not in other parts of the supply chain such as transport or processing.
- During this thesis, Allseas is the only stakeholder which is taken into account. Where Allseas is the mining company, as well as the owner of the shuttle bulk carriers between the terminal and production vessel. There are multiple other stakeholders within the complete supply chain, like the owner of the terminal, owner of the processing facility, international non-governmental organisations, International Seabed Authority and scientific research institutions [29].

1.5. Methodology

The outline of the research methodology used in this thesis is provided in figure 1.4. In the literature assignment executed on this topic [25], the complete supply chain of deep-sea nodule collection and dry bulk terminals were investigated. Research gaps were found and the research questions were derived for this thesis using the literature assignment. The literature assignment pointed out that that there were different methods to design a dry bulk terminal. On the one hand, the simulation-based approach, and on the other hand the rules of thumb and practical experiences. This thesis will start by using the simulation-based approach, since the suggested values for rules-of-thumb sometimes match poorly with derived terminal characteristics. Furthermore the impact of stochastic variations on terminal designs is hardly considered with rules-of-thumb [23].

Before the model development, the terminal equipment is investigated by talking to experts and perform a desk study. The information from the desk study and expert interviews will result in an overview for different equipment options for each operation at the terminal. Furthermore, the range of handling rates for each equipment option will be provided. This information will be used to make recommendations

for the equipment at the terminal after the experimental phase.
Before the model development, additional literature research is performed to investigate the used simulation techniques and modelling platforms in literature in order to run the simulations.
Next, model development is performed to create a model. By simulating the problem and trying out various terminal designs, we can evaluate the results of different design options. Model testing offers benefits such as reduced time, cost, and risk compared to real-world testing [30]. The model is developed in three stages, where the first stage/model addresses the roundtrip between the mining location and the transshipment terminal. The transshipment terminal only receives nodules. The production vessel is modelled into detail and bulk carriers sail back and forth between the terminal and the production vessel. The second stage/model contains everything from the first stage including the newly added roundtrip between the transshipment terminal and processing facility location. Once again, the terminal is modelled as a black box. Material arrives and leaves at a specific rate. How, when and where are irrelevant. Which means the processes at the terminal are not taken into account. The final stage/model contains every aspect of the first two stages, but now the terminal operations are also taken into consideration. So in the final model, the complete supply chain of the deep-sea nodule collection process is modelled.
After the model development, a final literature study is performed on energy consumption for a dry bulk terminal. Energy consumption is of course very relevant these days regarding climate change. The literature review should provide reduction techniques and strategies to decrease the energy consumption for the imaginary terminal from the case study. The simulation can be used to quantify the outcomes from the literature review. The impact of an energy reduction strategy can be quantified by comparing the old situation to the new situation (where a reduction strategy or technique is used).
Then, a case study is performed for Allseas where a transshipment terminal needs to be designed. The case study shows a real-life example of a complicated problem, although it has limitations since it is only tested on one situation [31]. However, the inputs of the model can be changed to test other scenarios as well. The first part of the case study contains location determination for the transshipment terminal. Many criteria exert influence on the decision-making for a terminal location. Hence the weighted criteria method has been used. This is a method to evaluate a set of options against a set of criteria. It provides a clear structure to choose the best option while considering a wide range of criteria [32].
After the location determination, the experiments are conducted by running simulations. Analytic calculations could provide insight in relationships between parameters on a more abstract level [33]. Simulation studies provide more detail, especially with many interrelated components, which is the case for the supply chain of deep-sea nodule collection [34]. Many stochastic influences is another aspect within the deep-sea nodule collection supply chain. In order to deal with the involved stochasticity, it is widely accepted to work with simulations [35]. Simulation is furthermore appropriate for the design of a new dry bulk terminal. The system performance can be evaluated without doing it in real-life. High investment costs can be postponed until the effectiveness of the investment is proven by the simulation [36]. This might be the case for investing in certain handling equipment for the terminal.
As explained before, the results from the simulation will be used to come up with required handling equipment rates. The handling rates are used to make recommendations for which equipment should be used for various scenarios and operations at the terminal.
The next step is to compare the results from the simulation to the other design methods for dry bulk terminals: rules of thumb and practical experiences. The results from the simulation-based approach will be verified and fine-tuned where necessary. It is important to see when rules of thumb and practical experiences are inline with the simulation results and when not. The similarities and differences are important to study further, in order to obtain insights regarding the potential benefit of using such a simulation approach
Taking all the results into consideration, the thesis will be concluded.

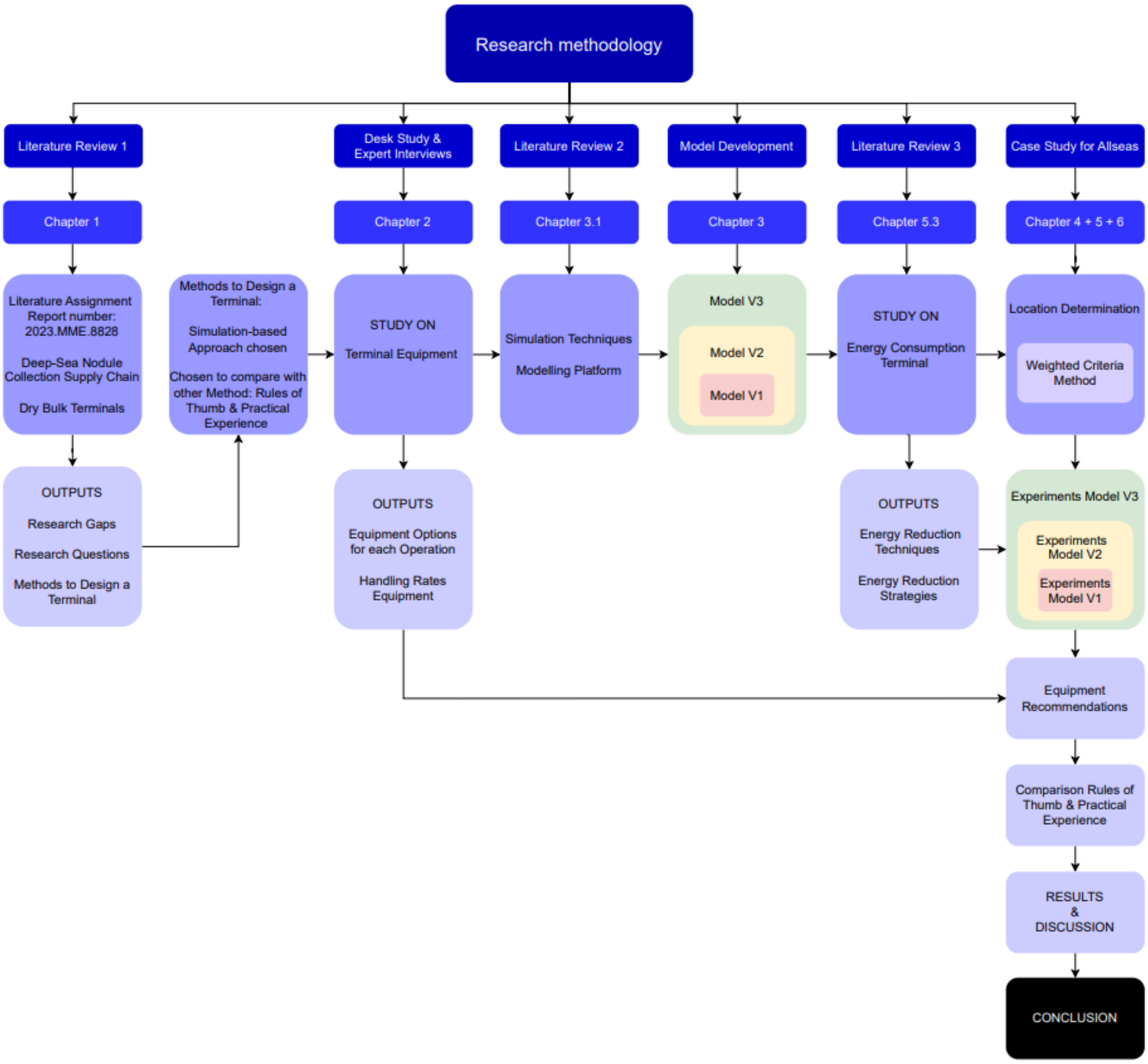


Figure 1.4: Outline methodology

1.6. Layout

The layout of this thesis is visualized in figure 1.5 below.

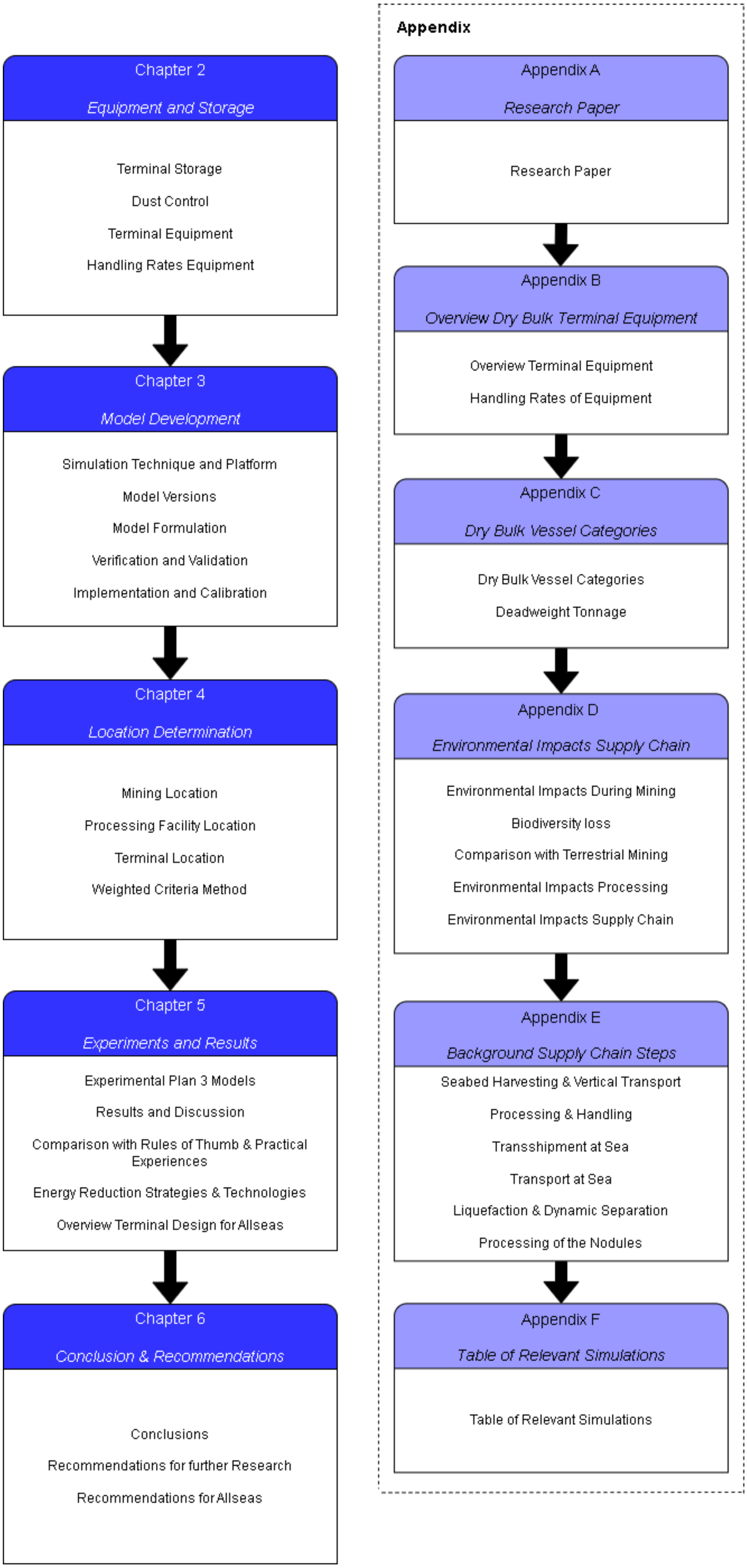


Figure 1.5: Layout of the thesis

2

Equipment and Storage

In this chapter, the following sub-question will be addressed:

Which storage technique should be used to store the nodules at the dry bulk terminal and which equipment and their respective capacities can be selected regarding the handling of nodules?

The different terminal storage options will be reviewed by performing a desk study. For example, factors like moisture permeability, processing technique and alpha radiation will play a role. A storage technique will be chosen which in the end will be used for the case study. Besides the storage of the polymetallic nodules, the equipment used for dry bulk terminals is investigated, as well as their maximum handling rates. Finally, small-scale terminals are investigated to take a look at the equipment being used. In order to make a decision regarding the equipment and their respective capacities, experiments are required to determine the appropriate handling capacities. In section 2.3, a literature and desk study are performed to investigate the equipment and handling rate options, which will be used in chapter 5 to select the appropriate equipment.

2.1. Terminal Storage

First of all, the terminal storage is addressed. There are different storage options possible (also displayed in appendix E). The options are listed below:

- Longitudinal open storage
- Radial open storage
- Conical open storage
- Circular dome storage (closed storage)
- Mammoth silo (closed storage)
- Longitudinal covered storage (closed storage)

The goal of this section is to determine which type of storage will be chosen. First of all, the benefits of open and closed storage need to be investigated. The alpha radiation of the nodules should also be taken into account. Lastly, the moisture permeability and processing technique play a role as well.

2.1.1. Basics Open versus Closed Storage

In this subsection, the (dis)advantages, options and characteristics of open and closed storage options are given.

Open Storage

There are several variations of open storage. These variations are longitudinal, radial and conical (see figure 2.3). The main advantage of open storage are the costs, since there are no investments required for buildings. On the other hand, additional costs might be required to avoid noise and dust pollution, which could result in contamination and environmental problems [37].

Closed Storage

For closed storage there are also multiple options available (illustrated in figure 2.3) [37]:

- Covered stockpile (longitudinal)
- Mammoth silo: cylindrical silo with screw conveyor (first in first out principle)
- (Circular) Dome silo: there are two variations possible here. With and without material pushing against walls.

The advantage of closed storage is that the content is protected against the environment and the other way around. But there are also complications when it comes to closed storage [37]:

- Need for a foundation: silos produce a higher concentrated load (x3) so foundations are required.
- Spontaneous ignition: for example ignition of coal which is stored for long periods is a risk. Tests will have to be performed to determine whether this risk also exists for manganese nodules.
- Less flexibility with a wide product range.
- Higher initial costs/investments
- Closed storage is not suitable for handling capacities of over 8000 t/h.
- Lower reclaim and stacking rates

Comparison

The estimated maximum values of several real-world storage options are given in table 2.1 (based on a bulk density of 1.2 t/m^3). Where the values of the longitudinal stockpiles are based on an existing iron ore stockyard in Rotterdam. A clear disadvantage for closed storage is the lower reclaim and stacking rates. This can be solved by installing multiple silos. Multiple silos are also required to stack and reclaim at the same time. But this will make the logistics more complex. It also results in the need for more equipment since each silo has its own stacking and reclaiming mechanisms. On the other hand, the closed storage options are the clear winner when it comes to capacity per area. This is further elaborated in figure 2.1. However, the height of conventional stacker-reclaimers is something to take into account. These are three times taller than the pile height, so side scrapers, bridge or portal scrapers might be an outcome for closed storage facilities. In the end the choice for open or closed storage also comes down on several criteria like, handling capacity, land use, construction and operating costs [37].

	Max built storage capacity [t]	Footprint [m^2]	Capacity/Area [t/m^2]	Stacking rate [t/h]	Reclaiming rate [t/h]
Open longitudinal stockpiles	3.000.000	450.000	7	4.500	4.500
Dome silos	60.000	3.600	17	2.000	2.000
Dome silos (cover)	180.000	11.310	16	2.300	2.300
Mammoth silo (Eurosilo type)	75.000	3.600	21	1.500	2.500

Table 2.1: Examples of estimated maximum values of different storage facilities [37]

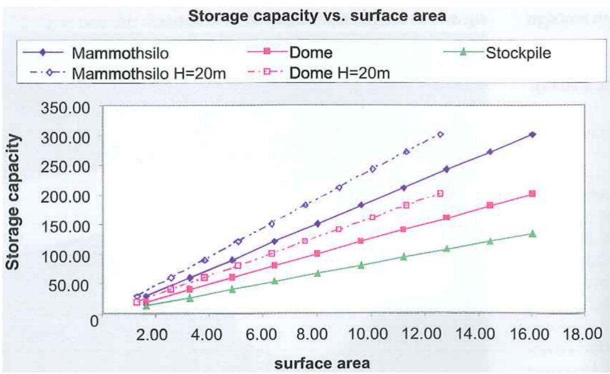


Figure 2.1: Storage capacity versus surface area [37]

2.1.2. Alpha Radiation

A recent paper pointed out the dangers of alpha radiation regarding polymetallic nodules. Volz et al. (2023) [38] states that this alpha radiation could impose health risks. That is the reason why alpha radiation should be taken into account regarding terminal storage. The nodules during handling and processing mainly emit alpha radiation during decay. Alpha particles have a limited travel distance of a few centimeters and a low penetration (most particles do not penetrate the skin). The alpha emitters however, are harmful if they enter the body after inhalation or ingestion. There are two main mechanisms that possibly lead to harmful radiation [38]:

- Inhalation or ingestion of dust or fines from the surface of the nodules:
  Dust and fines could be a serious problem. Once the nodules reach the production vessel, the nodules are dewatered and dried in the storage hold. This decreases the internal strength since sediment layers dry out and lose their cohesiveness. The transport process causes additional disintegration of the dried nodules through abrasion. These fine fractions can be inhaled or ingested by humans. This dust likely consists of abraded material from the surface of the nodules, where Thorium-230, Radium-226 and Protactinium-231 reach the highest values.
  Without masks with particle filters, these fines likely reach into deep lungs and remain there, causing damage to cells. The SWOE discharge is another concern. The discharge plume also contains nodule fines, which can be ingested by marine organisms at great depth. Via this way, it may enter the food chain and ultimately can be ingested by people.
- Inhalation of radon gas from nodules stored in an enclosed space:
  The inhalation of radon gas becomes an issue when nodules are stored in bulk in unventilated and enclosed spaces. This is the case during transport in bulk carriers or closed storage at the terminal. In the case of entering the hold or closed storage facility, adequate ventilation is thus required.

Both inhalation of dust/fines and radon gas should be taken into account in section 2.1.4, where the appropriate storage technique will be selected.

2.1.3. Moisture Permeability

The permeability of water into the stockpiles is another aspect which influences the decision-making for open or closed storage. This is due to the chosen processing method in Japan, which is the use of a rotary kiln. A rotary kiln is a long tube which is rotated at a certain angle. The angle and rotation cause solid reactants to move down the tube. Flue gas could flow in the same or opposite direction (co-current and counter-current). The kiln is operated at high uniform temperatures, which is required for drying, heating, reaction and soaking (keeping the nodules at certain temperature until they reach the desired internal structure) [39]. In case of the polymettalic nodules, all the steps for are visualized in figure 2.2.

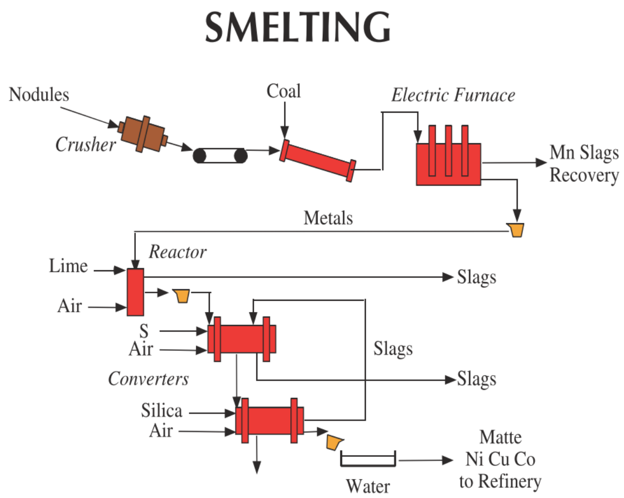


Figure 2.2: Smelting process polymetallic nodules

With the use of a rotary kiln, a lot of energy is required to dry and heat the nodules. Thijssen et al. (2010) investigated the effects of moisture in a stockpile and drying energy and costs. Moisture reduction in a stockpile can have a large influence on for example asphalt production. More energy and costs are required to evaporate the moisture present in the material. This might also be the case for the nodules which will have to be dried in a rotary kiln.

In the paper, the stockpiles are divided into two categories: initial moisture content above the threshold moisture content and initial moisture content below the threshold value. The threshold moisture content is the average moisture content in a stockpile below which no drainage occurs in the residence time [40].

Three effects are analysed in the paper:

- Precipitation prevention by roofing: limiting precipitation by roofing would benefit the materials with a lower initial moisture contents than the threshold moisture contents the most.
- Restrictions on initial moisture content: another method is to restrict the initial moisture content of the material, which results in the obvious outcome of less moisture. Furthermore, by restricting the initial moisture content, the effect of increasing height and reducing capacity becomes amplified.
- Altering pile capacity and height: For stockpiles with an initial moisture content above the threshold moisture content, the drying energy and costs can be reduced by increasing the stockpile capacity and reducing the stockpile height. Because increasing stockpile capacity leads to longer residence times and thus more time for drainage and decreasing height results in a lower drainage curve (thus faster drainage).
  For stockpiles with an initial moisture content below the threshold moisture content, the opposite measures should be taken, thus decreasing the stockpile capacity and increasing the stockpile height.

Another interesting remark from the paper is that materials can be significantly wetter at the bottom of the stockpile.

2.1.4. Chosen Storage Option

To make a decision for the suitable storage technique, all the aspects need to be revised to make a decision:

- Open versus closed storage:
  Open storage requires lower investment costs in comparison to closed storage. However, additional costs might be required to avoid noise and dust pollution. A benefit of closed storage is the capacity per area. The disadvantages of closed storage are not decisive regarding the design of a terminal for this thesis. Less flexibility with a wide product range does not matter, since the terminal will only have one product. The lower reclaim and stacking rates and restricted handling capacities up to 8000 tons per hour are also irrelevant. The experiments with the final model in chapter 5 proved that handling rates of over 8000 tons per hour are not required.
- Alpha radiation:
  The nodules during handling and processing mainly emit alpha radiation. Inhalation of dust or fines should be avoided. Also the inhalation of radon gas from nodules stored in an enclosed space should be avoided. This is crucial information for the open versus closed storage consideration. Open storage is possible, however the inhalation of dust should be avoided, which means additional measures to control the dust. Closed storage is also still possible, however the inhalation of radon gas should be avoided. This will likely result in the need for ventilation systems.
- Moisture permeability:
  The use of a rotary kiln in the processing method, means that the moisture content of the nodules should be as low as possible to reduce drying energy and costs. The initial moisture content will likely be above the threshold moisture content according employees within Allseas. Closed storage has the largest benefit for materials with an initial moisture content below the threshold moisture content which means that closed storage is less attractive. Another measure is to restrict the initial moisture content as much as possible. This would require extra processing steps

on the production vessel which is not attractive for Allseas. A final measure is to increase the capacity and decrease the height of the stockpile. Increasing the stockpile capacity leads to longer residence times (thus more time for drainage) and decreasing the height results in faster drainage.

In the end, open storage is selected for the transshipment terminal. The choice for open storage is mainly due to alpha radiation, where the danger of radon gas in an enclosed space is avoided. The lower investment costs is also an advantage. Although open storage means that additional dust control is required (resulting in extra costs), which will be addressed in the next section. The moisture permeability study furthermore points out that closed storage is not attractive for nodules which have an initial moisture content above the threshold value. An increased capacity and decreased height of the stockpile on the other hand have a positive influence on the moisture content resulting in lower drying energy and costs. A longer residence time is preferred because of the extra time for drainage. This means that the first-in, first-out principle will be used at the terminal to enable more time for drainage.

The final decision which needs to be made is longitudinal, conical or radial open storage. Conical storage would require many separate cones which is very inefficient regarding land use. A longitudinal arrangement (shown in picture 2.3) allows for easy future expansion. A circular arrangement (shown in picture 2.3) requires less space [41]. The ability to expand the terminal in the future is a crucial condition, so the longitudinal open storage option is chosen.

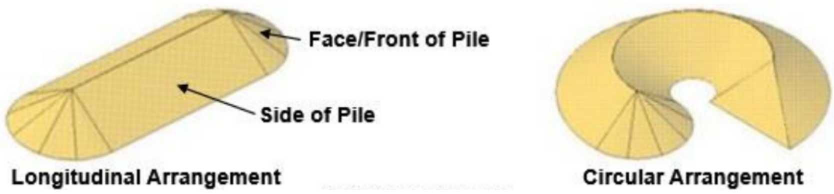


Figure 2.3: Stockpile layouts [41]

2.2. Dust Control

With the choice for open storage, dust control is required to avoid the inhalation of dust and fines. Several dust control techniques are described below:

- Wind screens: Wind screens are an effective solution for the environmental issues caused by bulk material processing at handling [42].
- Cover storage areas where possible [43]: There are three options to cover the storage area: cellulose crust, water sprinklers and the use of a tarpaulin. Cellulose crust provides a reliable, accurate (due to white colour visibility) and cost effectiveness technique. It also has a high resistance to wind erosion [44]. The white flakes made of cellulose fibers to form the crust is displayed in figure 2.4.

Figure 2.4: Cellulose crust on stockpile [44]

Another option is the use of water sprinklers, which should be done frequently. The last option is the use of tarpaulins, which requires extra work for applying.

- Cover handling areas where possible [43]: For example closed belt conveyors can be used [45].
- Install dust suppression mechanisms [43]: For instance a water spray when material is unloaded into a hopper [45]. Although the use of water should be limited as much as possible to lower the moisture content. But preventing dust is more important than a slight decrease in drying energy and costs.
- Use telescoping arms and chutes: The use of telescoping arms and chutes minimizes the free fall of material where usually dust if formed [43].
- Regularly sweep docks and handling areas, truck storage areas, and roadway surfaces. Also use vacuum collectors at dust-generating activities [43].
- Use slurry transport, pneumatic or continuous screw conveyors if possible [43].
- Minimize stockpile heights [43].
- Remove materials from the bottom of piles to minimize dust flying up again [43].

An example of a real iron-ore stockyard area is provided in table 2.2 [44], which shows the used dust control techniques. A combination of the above described techniques will also be required for the transshipment terminal. Especially the need for covered storage areas, since open storage is selected. For the case study in chapter 5, multiple options remain for appropriate terminal equipment. When the final equipment choices are made, the dust control techniques of above should be reminded and selected.

Area	Activity	Controls
Iron Ore Stockpile	Material storage	Dust Suppressant Chemical (Dust Cruster
		Project by using cellulose fibers
		Lower height Stacking
		Wind Fence
		Water Sprinklers
Dead flat area	Yard Entrances	Water Sprinklers
		Minimum Truck Movement
Iron Ore Handling	Material	Moisture content 4-8%
	Discharge/Stockpile	Water Sprinklers
	Reclaim/conveying	
Iron Ore and Pellet Handling	Material	Water Spray system
	conveying	Covered Conveyors
		Spillage Collection System (Flumes)
		Covered transfer towers
Pellet Handling	Material storage	Pellet Coating
	Discharge/Stockpile	Water Sprinklers
	Reclaim/conveying	Lower height Stacking

Table 2.2: Dust control techniques terminal iron ore [44]

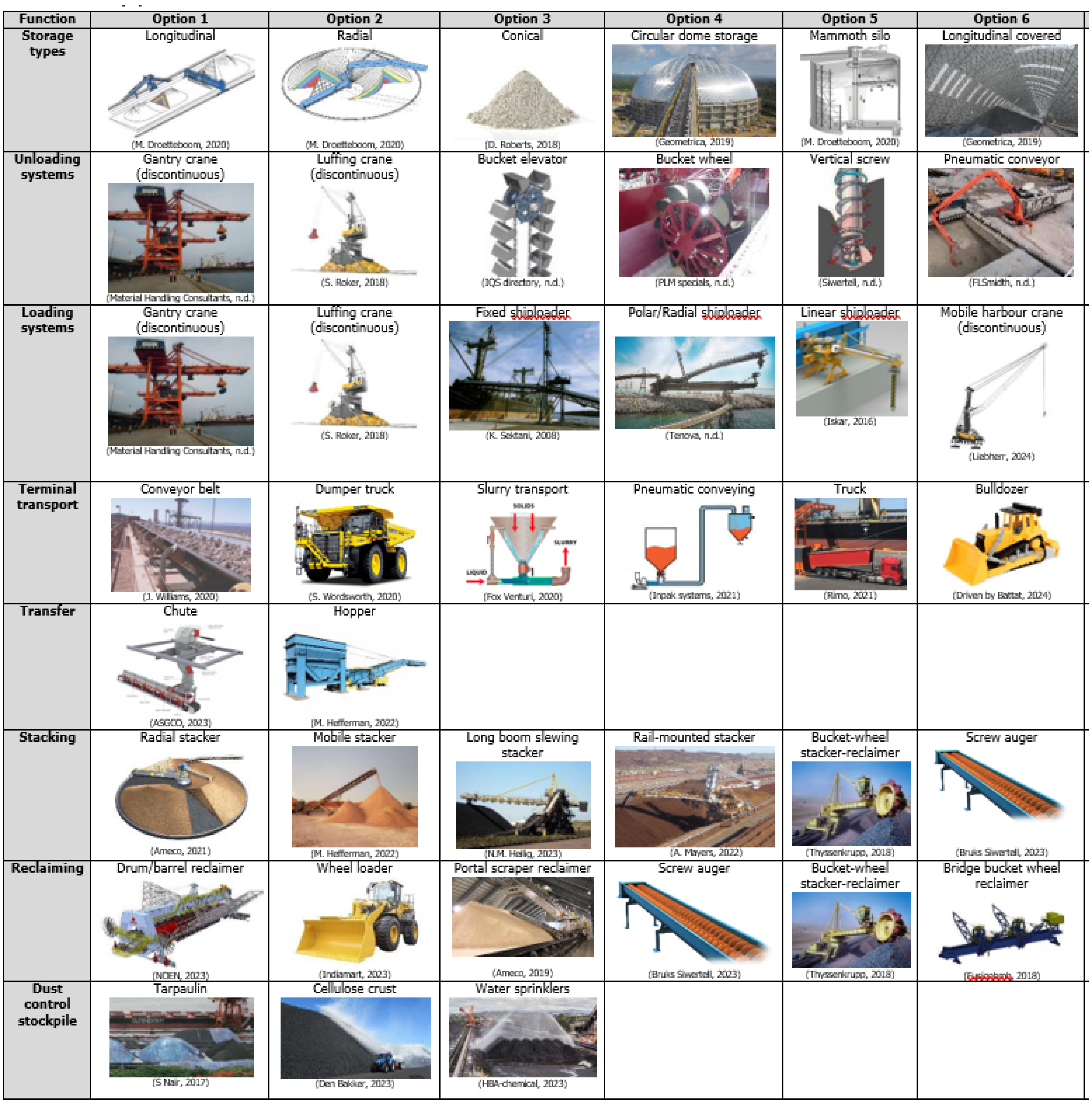
2.3. Handling Equipment

This section investigates the equipment used at dry bulk terminals. An overview of the options is provided in a table. The handling rates of the equipment are also investigated. Finally, small-scale terminals are investigated to get a feeling for which equipment is used at dry bulk terminals with comparable annual throughput rates.

2.3.1. Overview Equipment

A shortened overview of the equipment is provided in table 2.3. The full table is given in appendix B. Regarding the loading systems, not all variations are listed in the table. For example linear, twin-orbiting-slewing and quadrant shiploaders are based on a radial shiploader [46]. Blending and mixing equipment is also not added to the table, since that will not be required at the terminal.
The maximum handling rates for all the equipment is also provided in appendix B. For the unloading equipment, the handling capacity in the table is provided as the rated/free digging capacity. The different stages during unloading with a grab are handled differently in the programming script. This will be explained in the next chapter.

The table in appendix B will support in making decisions for the equipment. Very important is that the transport between the loading and unloading operations should not be a bottleneck. This assumption has also been made by Heuvel, van den S. (2019), which carried out research about the storage requirement of a dry bulk terminal [47]. This means that belt conveyors, stackers and reclaimers should at least have the same handling capacity as the loader and unloading systems.



Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Storage types	Longitudinal (M. Droetteboom, 2020)	Radial (M. Droetteboom, 2020)	Conical (D. Roberts, 2018)	Circular dome storage (Geometrica, 2019)	Mammoth silo (M. Droetteboom, 2020)	Longitudinal covered (Geometrica, 2019)
Unloading systems	Gantry crane (discontinuous) (Material Handling Consultants, n.d.)	Luffing crane (discontinuous) (S. Roker, 2018)	Bucket elevator (IQS directory, n.d.)	Bucket wheel (PLM specials, n.d.)	Vertical screw (Siwertell, n.d.)	Pneumatic conveyor (FLSmidth, n.d.)
Loading systems	Gantry crane (discontinuous) (Material Handling Consultants, n.d.)	Luffing crane (discontinuous) (S. Roker, 2018)	Fixed shiploader (K. Sektani, 2008)	Polar/Radial shiploader (Tenova, n.d.)	Linear shiploader (Iskar, 2016)	Mobile harbour crane (discontinuous) (Liebherr, 2024)
Terminal transport	Conveyor belt (J. Williams, 2020)	Dumper truck (S. Wordsworth, 2020)	Slurry transport (Fox Venturi, 2020)	Pneumatic conveying (Inpak systems, 2021)	Truck (Rimo, 2021)	Bulldozer (Driven by Battat, 2024)
Transfer	Chute (ASGCO, 2023)	Hopper (M. Hefferman, 2022)				
Stacking	Radial stacker (Ameco, 2021)	Mobile stacker (M. Hefferman, 2022)	Long boom slewing stacker (N.M. Hellig, 2023)	Rail-mounted stacker (A. Mayers, 2022)	Bucket-wheel stacker-reclaimer (Thyssenkrupp, 2018)	Screw auger (Bruks Siwertell, 2023)
Reclaiming	Drum/barrel reclaimer (NOEN, 2023)	Wheel loader (Indiamart, 2023)	Portal scraper reclaimer (Ameco, 2019)	Screw auger (Bruks Siwertell, 2023)	Bucket-wheel stacker-reclaimer (Thyssenkrupp, 2018)	Bridge bucket wheel reclaimer ([illegible], 2018)
Dust control stockpile	Tarpaulin (S Nair, 2017)	Cellulose crust (Den Bakker, 2023)	Water sprinklers (HBA-chemical, 2023)			

Table 2.3: Shortened overview of equipment in dry bulk terminals - full overview provided in appendix C

2.3.2. Exploring Small-Scale Terminals

In order to get a feeling for the equipment used at small-scale terminals, comparable small-scale terminals are investigated. The examples are provided in the subsections below.

Port of Tallinn

The dry bulk cargo at the Port of Tallinn is handled at three different harbours. One of these three terminals is visualized in figure 2.5, where fertilizers and gravel is handled. The Port of Tallinn handles 2.3 million tons fertilizers annually [48]. It is unknown whether these 2.3 million tons are all handled at the quay in figure 2.5. The quay shows that trucks are used for terminal transport. Furthermore, a wheel loader, floating crane and rail-mounted luffing cranes are used.

Figure 2.5: Dry bulk terminal at the Port of Tallinn [48]

Malku Ilankos Terminalas

This terminal handles agricultural products and is a specialized timber terminal. The annual throughput is around 2,5 million tons per year of wood, dry bulk, bulk cargo and general cargo combined [49]. The terminal uses a mobile belt conveyor to load the bulk carriers. At the unloading berth, a material handling excavator is used to directly unload the material into trucks. Four of these excavators can be seen which are also used to load train wagons. For the terminal transport, trucks and belt conveyors are used.

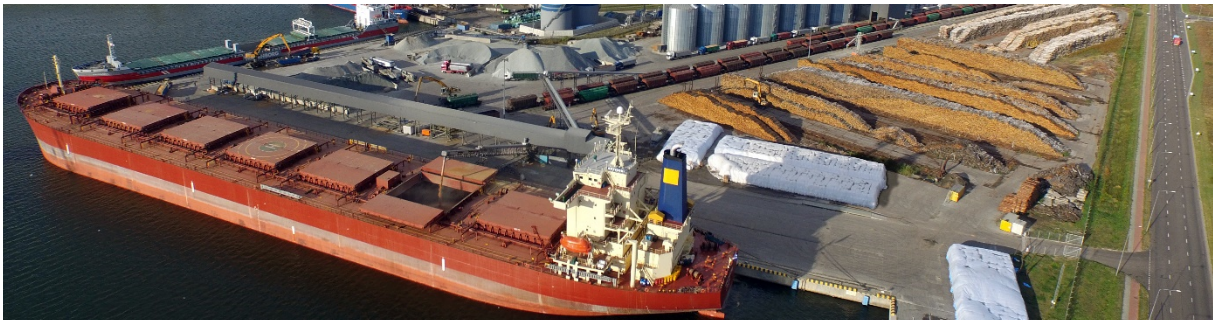


Figure 2.6: Dry bulk terminal at Klaipeda (Lithuania) [49]

Processing facility at Japan

The final example of a small-scale terminal is the terminal of the processing facility which will be used for the case study. More information about the processing facility will be given in chapter 4. It can be seen that a mobile crane is used for unloading of the geared bulk carrier(s). Furthermore, an excavator and multiple wheel loaders can be seen. These machinery are used to load the material on the belt conveyor, which then transports the material towards the stockpiles.

Figure 2.7: Processing facility location Japan

The investigated terminals above correspond with the literature. Minor dry bulk terminals make use of floating and/or mobile equipment. Mobile equipment offers several advantages. First of all, mobile equipment enables flexibility by easily relocating equipment. Furthermore, less infrastructure investments are required, (such as rails for rail-mounted systems or reinforcement to the quay), making mobile equipment a more cost-effective option [50]. Scalability is another advantage, since mobile equipment can deal with future growth, for example enabling expansions of the stockpile. The final advantage is the support in case of breakdowns or planned maintenance, by taking over functions like reclaiming by for instance a mobile crane [51].
Besides the use of mobile equipment, the investigated terminals also indicated that cargo handling operations are supported by yard vehicles such as bobcats, trailers and shovels [52]. The floating crane, trailers, mobile crane, mobile loader and shovels/wheel loaders can also be seen in pictures 2.5, 2.6 and 2.7 above. Stacker-reclaimers are missing in the pictures and are typically used in major dry bulk terminals [52].

2.4. Conclusions

Before answering the sub-question of this chapter, the sub-question will be repeated:

Which storage technique should be used to store the nodules at the dry bulk terminal and which equipment and their respective capacities can be selected regarding the handling of nodules?

The choice for open or closed storage depends on multiple factors like the handling capacity, land use, construction and operating costs [37]. For the storage of nodules, the alpha radiation and moisture permeability should also be taken into account. Especially alpha radiation is very important since the inhalation of dust or fines should be prevented. Also inhalation of radon gas should be prevented, which becomes a problem in unventilated or enclosed spaces [38].
The moisture permeability has to do with the processing method of the nodules. For the case study, a rotary kiln will be used, where the kiln is operated at high uniform temperatures, which is required for drying, heating, reaction and soaking. A lot of energy is required to dry and heat the nodules. The moisture content of the nodules should be as low as possible to reduce drying energy and costs [40]. The initial moisture content of the nodules will likely be above the threshold moisture content when the nodules arrive at the terminal. The threshold moisture content is the average moisture content in a stockpile below which no drainage occurs in the residence time. For materials with an initial moisture content below the the threshold moisture content, closed storage is advised to prevent absorption (for instance of rain water). This does not hold for materials with an initial moisture content above the threshold moisture content. A final measure is to increase the capacity and decrease the height of the stockpile. Increasing the stockpile capacity leads to longer residence times (thus more time for drainage) and decreasing the height results in faster drainage. Although, more research is required to quantify the impact of these measures, regarding the drying energy and costs at the processing facility.

Taking all these aspects into account, longitudinal open storage has been chosen. Open storage has lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility. A drawback of open storage is that additional measures should be taken to prevent inhalation of dust and fines. A combination of measures like wind screens, covered storage areas (for instance cellulose crust, water sprinklers or use of tarpaulin), closed belt conveyors, water sprinklers and minimizing stockpile heights should be considered.

The equipment options and their maximum handling capacities has also been investigated (see results in appendix B). Comparable small-scale terminals (with a relatively low yearly production rate <3 Mt/year) are also shortly investigated to get a feeling for the equipment used at existing small-scale terminals. In the end, there are many equipment options to handle the nodules at the transshipment terminal. Although existing small-scale terminals has proven that mobile equipment is used a lot, since it is cost-effective and offers flexibility and scalability. These aspects can all be used in chapter 5, where experiments will support the decision-making for the appropriate equipment and their respective handling rates.

3 Model Development

In this chapter, the following sub-question will be answered:

How should a simulation model be designed to determine the sizing of the stockyard and seaside areas, terminal capacity and the amount of machinery and their specifications?

In this chapter, the different stages and build up of the models will be explained. The model is developed in three different stages which are displayed in figure 3.1. Figure 3.1 shows one possible scenario where the transshipment terminal is situated in Mexico (blue pinpoint), the processing facility in Japan and the mining location south-west from Mexico. All the yellow pinpoints represent other location possibilities. The final location for the processing facility, mining location and transshipment terminal will be discussed in chapter 4.

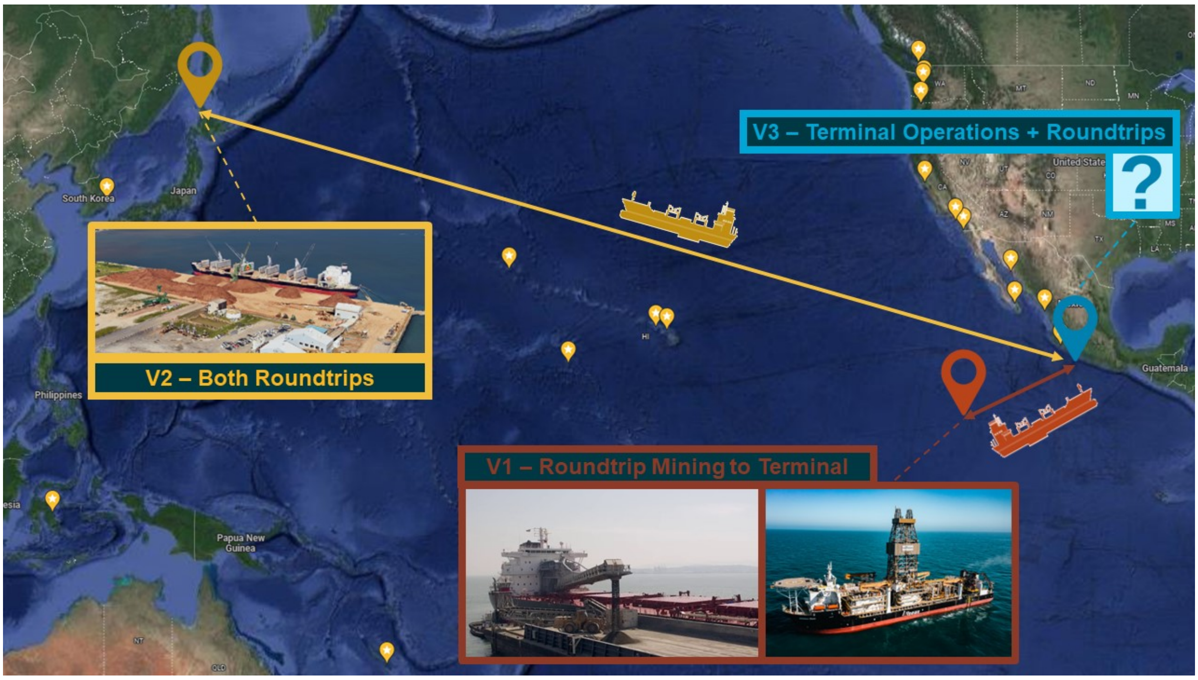


Figure 3.1: Three stages of the model: V1 - Roundtrip Mining to Terminal, V2 - Both Roundtrips, V3 - Terminal Operations + Roundtrips

The first model (V1 - Roundtrip Mining to Terminal) focuses on the roundtrip of the bulk carrier between the mining location and the terminal (section 3.2). The terminal just collects the nodules of

the bulk carrier, but terminal operations such as stacking or transport are not taken into account during this model. The production vessel (Hidden Gem from Allseas) can be seen at the bottom in figure 3.1. To maximize the operational hours of the production vessel, the production vessel is a self-unloader at the same time and unloads the nodules to a (shuttle) bulk carrier by a big conveyor. This process is also depicted at the bottom in figure 3.1. During this thesis, the material losses during different stages of the supply chain are not taken into account, since they are not known yet [28]. Instead of a belt conveyor for ship to ship (STS) transfer, tandem offloading can be used. Tandem offloading is suitable for more severe weather conditions due to the increased distance between vessels, facilitating easier disconnection and departure in case of emergencies. A drawback of tandem offloading is the need for dewatering systems onboard the vessels. This would require extra investments and would in the end decrease the second-hand value of the vessel in the market [28]. For the case study, the use of a belt conveyor will be assumed, which in fact Allseas is also planning to actually use.
The second model (V2 - Both Roundtrips) takes the other roundtrip from the terminal towards the processing facility into account (section 3.3). Again, the terminal is seen as a black box where nodules enter the terminal and nodules leave the terminal.
The final and third model (V3 - Terminal Operations and Roundtrips) takes the terminal processes and their disruptions into account (section 3.4). The models are separately explained in different sections below.
Every model will have its own objective and scope. These scope and objectives are discussed with a diagram at the start of each model section. Furthermore the model formulation, implementation, verification, validation and calibration are described for the three models in section 3.2, 3.3, 3.4.

3.1. Simulation Technique and Platform

In appendix F, an overview can be seen of relevant studies about dry bulk terminal simulations. In this overview, the used programming language and simulation programs are provided. Furthermore it gives information whether Excel, Discrete-event simulation and the process interaction approach are used. Discrete event simulation is a method which is used to model a system as a sequence of events in timec. Each event occurs at a certain timestamp [53]. The process interaction approach/method (PIA) is introduced by Zeigler in 2000 [54]. The method enables to model very close to the real world system.

According to the table in appendix F, discrete event simulation is used in the majority of the studies. Besides the relevance for terminal design, DES is also appropriate for marine systems design applications, due to low computational cost and flexibility in adjusting details and accuracy of the model [28]. Hence, discrete-event simulation is also used for this thesis. Discrete-event simulation models a sequential process by only including distinct events in which a change of state happens, which gives a clear view to see the impact of changes on the process [55], identify bottlenecks and constraints [56]. Each event can be easily adjusted to see the impact of a new change. This provides flexibility to constantly add new processes. Furthermore, many 'what if?' scenarios can be tested, which helps in the decision-making process for the terminal design, where alternative ways can be understand [57]. The final benefit of DES, is the possibility to improve the utilization of resources. The simulation provides insight into the utilization of the use of a machine at the terminal. The optimal utilization of a machine can be determined while minimizing the costs or waiting times [56], which is all very applicable to dry bulk terminals. A challenge with using DES, is the complexity in a representative and accurate model. All the processes require a deep understanding. Furthermore, data collection and validation is another challenge [56]. Luckily, Allseas has extensive knowledge and experience to help to overcome these challenges.

The information in appendix F also points out that the process interaction approach is used in some of the studies. This method will also be used in this thesis. Simulating according the PIA has the advantage to take stochastic influences into account to obtain statistics about traffic flows, stacking volumes and equipment capacities, which are required for initial designs [58]. Furthermore, I have gained some experience with the PIA for a group assignment in the first year of the master Mechanical Engineering, so it makes sense to choose this method since I already have some experience with it. Lastly, as already mentioned, the PIA enables to model very close to the real world system which is exactly what is desired for this thesis to come up with an appropriate terminal design. The first step of the PIA is to decompose the system into relevant element classes. These classes are separately programmed, which means for example that the terminal and bulk carrier are programmed in separate files, which will be shown later on this chapter.

For the programming language, many options are used (see appendix F). For this thesis, Python has been chosen. This programming language is open source and widely used at the TU Delft. Furthermore, Allseas preferred Python since they are already used to work with Python. This is helpful for future simulations. SimPy is added to Python as a discrete-event simulation library. It provides a framework for modeling and simulating complex systems where events occur at specific points in time [59]. A big advantage is that SimPy is a free add on to Python, which prevents Allseas from purchasing an expensive simulation program.

3.2. Model V1 - Roundtrip Mining to Terminal

The first model will address the roundtrip between the mining location and the (transshipment) terminal location. Within this roundtrip, there are many uncertainties. This model is partially based on a research carried out by Bot, P.C. (2012). Bot used the PIA and discrete-event simulation to determine the required storage capacity of an import dry bulk terminal [60]. Bot integrated the following uncertainties to capture the stochastic properties of a dry bulk terminal:

- Inter-arrival times of ships. Terminals do not know exactly when a ship will arrive. The ‘customer is king’ principle applies to terminals: the ships determine when they arrive and when they must be unloaded.
- Ship types. Different types of ships arrive at the terminal. Besides the space each type of ship uses at the quay, larger ships can be unloaded by more quay cranes than smaller ships.
- Ship capacities. Each ship has a different capacity. Therefore, each ship has a different unloading time and the bulk materials on the ship require a different amount of storage on the stockyard.

This indicates that these uncertainties should be taken into account for this thesis. The determination of inter-arrival times, number of ships and ship capacities for the roundtrip between the mining area and the terminal will be addressed in this model. The other objectives and the scope of the model can be found in section 3.2.1. Furthermore, the model formulation, implementation, verification, validation and calibration are described in this section.

3.2.1. Model Formulation

Model V1 - Roundtrip Mining to Terminal is clarified in this subsection. The objective and scope are explained. Then the parameters and inputs are provided, as well as the key performance indicators and outputs. Finally, the stochastic variables are addressed.

Model Objective and Scope

The scope of model V1 is already illustrated with figure 3.1 above. Only the roundtrip with bulk carriers sailing between the terminal and the production vessel is taken into account. The terminal has an infinite capacity and only collects the nodules.
An important remark is that a combination of different bulk carriers within one roundtrip is not taken into account (for example two Handysize and one Panamax bulk carrier). This prevents endless simulations with a lot of possible combinations. The goal of this thesis is not to optimize the roundtrips of the bulk carriers, but to simulate the roundtrip processes to support the decision-making for the terminal design.

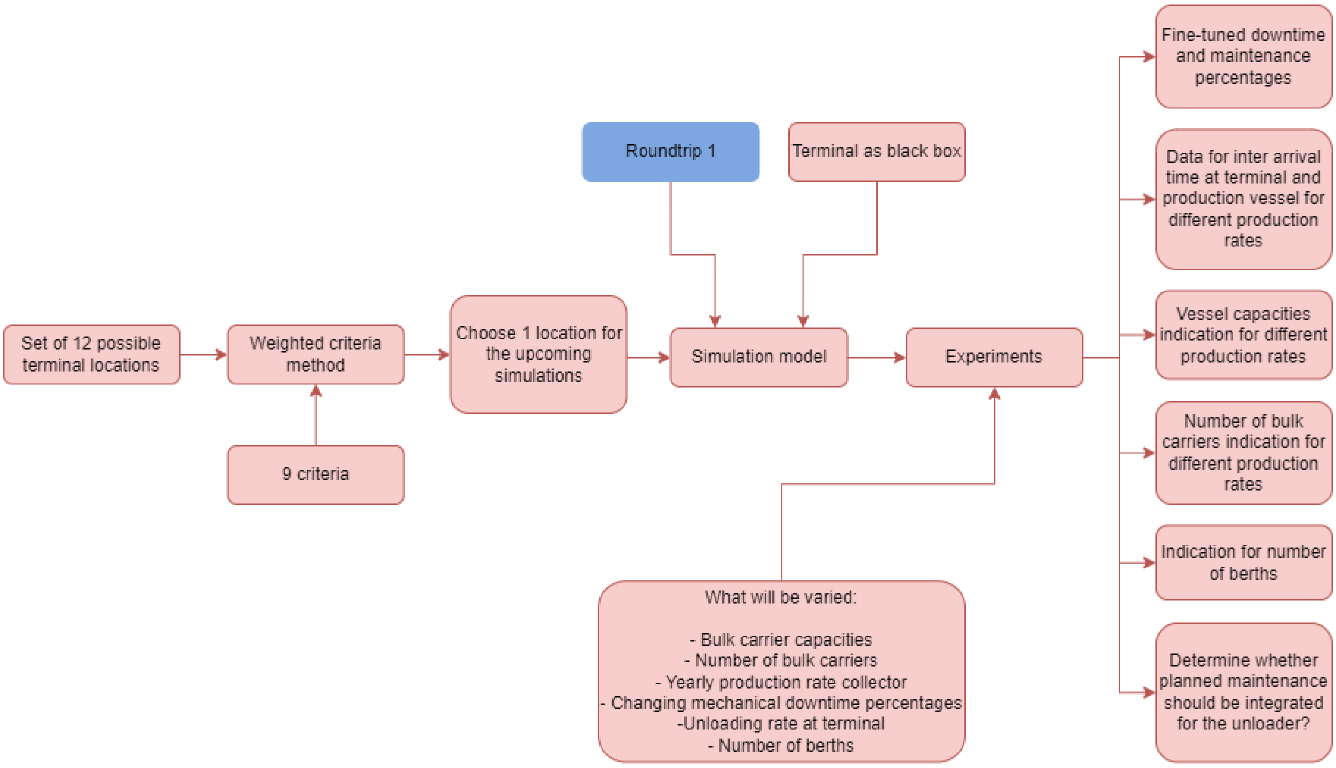


Figure 3.2: Model V1

The objective of model V1 can be seen in figure 3.2 on the right. The most important objective is an indication for the vessel capacities and number of bulk carriers for varying production rates.

Parameters and Inputs

An explanation of the model will be provided in section 3.2.2. All the inputs are provided below.
List of inputs for BC1:

- Sailing speed
- Maximum capacity
- Chance for mechanical downtime
- Amount of bulk carriers
- Planned maintenance interval
- Extensive maintenance interval
- Extensive maintenance duration
- Extensive maintenance duration short

List of inputs for Collector:

- Maximum hold capacity
- Start capacity
- Field efficiency for collecting
- Mechanical downtime chance
- Production rate
- Production rate duration
- Riser planned maintenance interval
- Riser planned maintenance duration
- Collector maintenance duration
- Recovery time of the collector

- Planned maintenance interval of collector

List of inputs for Unloader:

- Unloading rate
- Mechanical downtime unloader chance

List of inputs for Terminal:

- Unloading rate of a bulk carrier at terminal
- Maximum capacity
- Start capacity
- Number of berths

List of stochastic inputs:

- BC1 mechanical downtime duration
- Pre unloading operations at terminal
- Post unloading operations at terminal
- BC1 planned maintenance duration
- Pre loading operations offshore
- Post loading operations offshore
- Collector mechanical downtime duration
- Production rate of the collector
- Unloader mechanical downtime duration
- Position of production vessel

List of simulation parameters:

- Weather downtime percentage: the deep-sea mining operation will be affected by weather downtime: waiting-on-weather (WoW). The wave conditions play an important role during ship-to-ship transfer. Especially the allowable wave limit during STS transfer is a critical parameter which also influences the annual production. When the hold is full, the collector has to wait till the wave conditions are acceptable to empty the hold of the production vessel. A research pointed out that the yearly production without weather restrictions was able to produce 2.46 Mt/year. When an allowable wave limit for STS transfer was set to 3.5 meter, the yearly production decreased to 1.63 Mt/year [28]. Unfortunately this research was carried out for operations within the Norwegian Sea, and not in the CCZ which will be the mining location for the case study of this thesis. Besides the significant wave height, the wave direction, wind direction and wind speed are also essential parameters to take into account.
  For the case study, a total weather downtime of 5% per year is expected by experts within Allseas. This includes weather where the collector is unable to collect nodules, terminal operations have to stop and where the production vessel is unable to transfer nodules to the shuttle bulk carrier. The research from above cannot be used since the weather conditions from the Norwegian Sea differ from the conditions in the CCZ.
  The 5% weather downtime is processed by reducing the simulation duration of 1 year by 5%. Simply reducing the simulation duration by 5% has been chosen since a complete stop of the supply chain is assumed with weather downtime. When the production vessel has to stop, the shuttle bulk carrier will also not leave the port (this assumption is also used in another research about the expected production of a deep-sea mining system [28]). The bulk carrier will not leave the port since it will end up in a waiting queue at the production vessel which does not make sense.
- Number of runs: during this stage, only 1 run will be performed of 1 year, since no crucial decisions are made with this model
- Run/sim duration: each run will represent one full year. However there is a 5% weather downtime so the runtime in hours will be: 365 * 24 * 0.95 = 8322 hours.

KPI's and Outputs

List of outputs:

The outputs are provided in table 3.1 below. In the case of multiple runs, a minimum, maximum and average of the output is provided, hence the three different outputs in each column. The results are purely demonstrative.

Summary	Minimum	Average	Maximum
Collector_production	3.17 Mt/year	3.19 Mt/year	3.21 Mt/year
Collector_days_lost_due_to_hold_full	0.2 days/year	1.6 days/year	4.8 days/year
Collector	**Minimum**	**Average**	**Maximum**
Collector_collecting	68.7 %	69.2 %	69.6 %
PV_hold_full	0.0 %	0.4 %	1.3 %
Collector_mechanical_downtime	14.5 %	18.8 %	21.6 %
Collector_planned_maintenance	4.7 %	6.5 %	9.8 %
Collector_weather_downtime	5.0 %	5.0 %	5.0 %
Unloader	**Minimum**	**Average**	**Maximum**
Unloader_unloading	15.2 %	15.3 %	15.4 %
PV_hold_empty	61.8 %	65.0 %	67.4 %
Unloader_mechanical_downtime	2.1 %	3.4 %	4.2 %
Unloader_no_BC1	12.9 %	16.4 %	20.8 %
Unloader_unloading_speed	0 t/h	467.8 t/h	2500 t/h
BC1	**Minimum**	**Average**	**Maximum**
Sailing_BC1	44.0 %	44.8 %	45.4 %
BC1_unloading	15.9 %	16.1 %	16.3 %
BC1_loading	3.8 %	3.8 %	3.9 %
Total_pre_post_operations_BC1	3.8 %	3.9 %	4.0 %
Total_waiting_and_downtime_BC1	21.6 %	21.9 %	22.6 %
Total_mechanical_downtime_BC1	2.3 %	2.6 %	2.8 %
Total_planned_maintenance_BC1	1.2 %	1.3 %	1.4 %
Total_time_in_waitingQ_PV	7.5 %	8.4 %	9.6 %
Total_time_in_waitingQ_Terminal	0.8 %	1.0 %	1.3 %
Total_time_in_waitingQ_BC1	8.4 %	9.4 %	10.9 %
Terminal	**Minimum**	**Average**	**Maximum**
Terminal_unloading_BC1	15.9 %	16.1 %	16.3 %
Terminal_full	0.0 %	0.0 %	0.0 %

Table 3.1: Output runfile model V1 - Roundtrip Mining to Terminal

Besides the outputs of the runfile, an excel file is also created. In this file, there are many columns which keep track of a status or capacity for example. This file exists of the following columns:

- Time [hours]
- Total nodules collected [tons]
- Current hold capacity production vessel [tons]
- Collector status
- Unloader status
- BC1 waiting queue at production vessel
- BC1 waiting queue at terminal
- Terminal capacity [tons]
- Terminal status
- BC1 hold level (more columns possible when there are more bulk carriers) [tons]
- BC1 status (more columns possible when there are more bulk carriers)
- Roundtrip ID BC1 (more columns possible when there are more bulk carriers)

Below in figure 3.2, an example is given of how the first few columns of the excel file looks like. Every time step represents exactly 1 hour, so the file continues to 8322 hours when a full year is simulated.

Time	total_nodules_collected	Current_hold_capacity_PV	Collector_Status	Unloader_Status
1	1.582.820.613	1.582.820.613	collector_collecting	unloader_no_BC1
2	3.165.641.227	3.165.641.227	collector_collecting	unloader_no_BC1
3	474.846.184	474.846.184	collector_collecting	unloader_no_BC1
4	6.331.282.454	6.331.282.454	collector_collecting	unloader_hold_empty
5	7.914.103.067	7.914.103.067	collector_collecting	unloader_hold_empty
6	949.692.368	949.692.368	collector_collecting	unloader_hold_empty
7	1.107.974.429	1.107.974.429	collector_collecting	unloader_hold_empty
8	1.266.256.491	1.266.256.491	collector_collecting	unloader_hold_empty
9	1.424.538.552	1.424.538.552	collector_collecting	unloader_hold_empty
10	1.582.820.613	1.582.820.613	collector_collecting	unloader_hold_empty
11	1.741.102.675	1.741.102.675	collector_collecting	unloader_hold_empty
12	1.899.384.736	1.899.384.736	collector_collecting	unloader_hold_empty
13	2.057.666.797	2.057.666.797	collector_collecting	unloader_hold_empty
14	2.215.948.859	2.215.948.859	collector_collecting	unloader_hold_empty
15	237.423.092	237.423.092	collector_collecting	unloader_hold_empty
16	2.532.512.981	3.251.298.146	collector_collecting	unloader_unloading
17	2.690.795.043	1.907.950.428	collector_collecting	unloader_hold_empty
18	2.849.077.104	3.490.771.041	collector_collecting	unloader_hold_empty
19	3.007.359.165	5.073.591.655	collector_collecting	unloader_hold_empty
20	3.165.641.227	6.656.412.268	collector_collecting	unloader_hold_empty
21	3.323.923.288	8.239.232.882	collector_collecting	unloader_hold_empty
22	348.220.535	9.822.053.495	collector_collecting	unloader_hold_empty
23	3.640.487.411	1.140.487.411	collector_collecting	unloader_hold_empty
24	3.798.769.472	1.298.769.472	collector_collecting	unloader_hold_empty
25	3.957.051.534	1.457.051.534	collector_collecting	unloader_hold_empty
26	4.115.333.595	1.615.333.595	collector_collecting	unloader_hold_empty
27	4.273.615.656	1.773.615.656	collector_collecting	unloader_hold_empty

Table 3.2: Incomplete output excel file model V1

Key performance indicators:

- Collector days lost due to hold full: During all the experiments, it is crucial that the production vessel is able to mine continuously. When the hold of the production vessel has reached its limit, the collector has to stop. The stream of shuttle bulk carriers at the production vessel should be sufficient to restrict the lost collection days, otherwise the yearly production rate targets will not be met.
- Yearly production rate: When the collector loses too many days because of a full hold, the yearly production rate will be lower. This also gives an indication for a bottleneck within the chain.
- Utilization rate of equipment: The utilization rate of equipment is a common performance indication for terminals [61]. The equipment at the terminal has not been modelled. However the unloading percentage of the unloader is used to make a decision for planned maintenance.
- Berth occupancy: A high berth occupancy results in long vessel waiting times at the terminal [61]. The berth occupancy is the same as Terminal-unloading-BC1 in figure 3.2.
- Time in waiting queue at production vessel: The time in the waiting queue at the production vessel is a very important performance indicator. Too many bulk carriers might result in long waiting times at the production vessel.
- Time in waiting queue at terminal: Normally the waiting-time/service-time ratio is a common performance indicator [61]. However, the terminal is modelled as a black box so the service-time is not very accurate. For now, only the waiting time in the queue at the terminal is taken into account. Possible waiting time must be avoided to avoid demurrage costs. The ship-owner must pay demurrage costs if the expected port time is exceeded [61].

3.2.2. Implementation

As explained in section 1.5, the model is build with Python and SimPy. Within Python, the model is divided into separate files. This results in a clear overview within such a large model. The files and their code are described below:

- **Production vessel:** the processes of the collector and unloader which belong to the production vessel are coded in this file.
  Explanation collector part:
  Firstly, the production rate needs to be determined. The collector rate is partially determined by a lognormal distribution. The varying collector rate simulates the changing conditions at the seabed, where some areas have a larger nodule density than others. The collector will collect nodules at the same rate for 100 hours after which a new collector rate is determined. In the end, the collector rate is multiplied by the field efficiency of 85% which indicates that 85% of the nodules at the seabed is collected. After determining the collector rate, the model checks for mechanical downtime of the collector. Furthermore several planned maintenance scenarios are checked. The maintenance is performed when the right interval has been reached. The maintenance scenarios could be to maintain the riser and/or collector. When the collector experiences mechanical downtime and is already on deck of the production vessel, the planned maintenance on the collector will also be executed when a certain amount of days have passed since the last planned maintenance. This saves time because the recovery of the collector is then performed only once.
  While the collector is collecting nodules, the hold capacity of the production vessel is checked. It of course has to stop collecting when the maximum hold capacity has been reached.
  Explanation unloader part:
  The unloader of the production vessel constantly checks whether a bulk carrier is alongside the production vessel. If there is ship, the unloader has to wait for the pre-loading operations, with a duration picked from a normal distribution with a mean of 4 hours (and a minimum of 2 and maximum of 6 hours). During the pre-loading operations, the bulk carrier has to make sure to sail steady besides the production vessel using dynamic positioning. The belt conveyor also has to be above the right hold of the bulk carrier. Once the unloading can start, the unloader is checked for mechanical downtime. It also checks the hold capacity, since the unloading has to stop once the hold of the production vessel is empty. When the hold of the bulk carrier is full, the post-loading operations occur. Once again picked from a normal distribution but now with a mean time of 2 hours and a minimum of 0.5 and maximum of 3.5 hours.
- **BulkCarrier1:** the bulk carrier which executes the roundtrips from the CCZ (mining location) to terminal is coded in this file:
  Once the bulk carriers are emptied at the terminal, the bulk carrier will be checked for mechanical downtime. The duration is picked from a lognormal distribution with a minimum of 2 hours and maximum of 25 hours. Then the sailing towards the terminal starts. This sailing duration varies due to the varying position of the production vessel. Once arrived at the terminal, the bulk carrier ends up in a waiting queue when the (unloading) berth is already occupied. Once the berth is available, the pre-unloading operations at the terminal start (required for paperwork, sailing from anchorage towards berth, etc). The duration varies and is picked from a normal distribution. During the unloading of the bulk carrier, the unloading operations will stop when the maximum capacity of the terminal has been reached. Further terminal operations are provided in the detailed terminal file used for model V3 - Terminal Operations + Roundtrips. Once the bulk carrier is empty, the post-unloading operations are performed, once again picked from a normal distribution. Before leaving the terminal, a check will be performed whether the bulk carrier requires routine or extensive planned maintenance. This happens when a certain interval has been reached. Before the sailing towards the production vessel, a check is performed whether the bulk carrier is going to experience mechanical downtime. When the bulk carrier arrives at the production vessel, the unloader process takes over, which is described above.
- **Terminal:** the terminal processes are described in this file:
  The terminal is modelled as a blackbox which means the terminal only collects nodules. This is modelled with the use of the SimPy container function.
- **Location file:** this file enables fast and easy adjustments when it comes to the location of the

terminal, mining location and processing facility. This file calculates the distance between these points. There are different methods to calculate distances between points based on longitude and latitude. Examples are the 'great circle formula', 'haversine formula' and 'geodesic distance'. In this model, the geodesic distance is chosen. This method chooses the shortest path along the earth's surface, while accounting for the earth's ellipsoidal shape [62]. This is required in our case because of the large distances between the terminal, mining location and processing facility.

- **Simulation:** this file contains all the simulation variables:
  All the variables and distributions can be quickly adjusted in this file.
- **Run file:** this file is used to run the whole simulation:
  The file creates the output which can be seen in table 3.1 above. This provides a nice overview besides the excel file, where the key performance indicators are provided.

3.2.3. Verification

To verify that the model is right and implemented correctly, verification steps are required [63]. There are plenty of steps in the model to verify. Some checks are generalized to make sure there are not 50 separate verification checks. The verification checks are listed in the subsections below. During the verification phase, the random.seed function was used in the python model. This function ensures that the value picked from a distribution remains the same (instead of creating a new value for each new iteration). This is useful in the verification phase, since I am comparing new test results with previous test results. It is undesired that the new test results are affected by the distributions.

Verification of mechanical downtime and planned maintenance

The verification of mechanical downtime and planned maintenance is explained in table 3.3 and 3.4.

Test	Expectation	Outcome
Mechanical Downtime BC1: See whether mechanical downtime occurs and how long it takes.	Mechanical downtime should happen at around 3% of the time when it's ready for sailing. The duration should be between 2 and 25 hours.	In the simulation, a mechanical downtime of 2.9% for 1 year was found. The mean duration of this mechanical duration took 18 hours, which is as expected.
Planned Maintenance BC1: See whether planned maintenance of BC1 is executed at the right moment, interval and duration.	The planned maintenance should be executed after loading operations at the terminal. The interval should be at least 2200 hours (≈ 90 days) and have a duration between 12 and 72 hours. Routine planned maintenance: every 2200 hours. Duration between 1 and 5 hours. Extensive maintenance: interval of 8000 hours. Duration 84 hours. Except if routine planned maintenance already happened, then the extensive maintenance lasts 80 hours.	The routine planned maintenance is indeed performed before loading at the terminal. Some of the interval examples are 2290, 2356, 2366 and 2250 hours, which is indeed at least 2200 hours. The duration of routine planned maintenance is roughly 4 hours which is indeed between 1 and 5 hours. The extensive maintenance is performed after 8000 hours with a duration of 84 hours. If the extensive maintenance interval is shortened to 4000 hours, the exceptional case with consecutive routine and extensive planned maintenance occurs. The extensive maintenance should last 80 hours instead of 84 hours. This is indeed the case.
Mechanical Downtime Collector: Does the collector experience mechanical downtime and what is the duration of this downtime.	The collector has a chance of 0.95 % of breaking down, so it should not happen too often. The duration should be below 36 hours.	In a test run, the collector had 6.7% time of the year mechanical downtime. This percentage might be finetuned later on. The duration of the downtime was 16 hours which is indeed below 36 hours.

Table 3.3: Verification of mechanical downtime and planned maintenance - first part

Planned Maintenance Collector: See whether the planned maintenance of the collector is executed at the right interval and duration.	The planned maintenance of the collector is fairly complicated. The riser maintenance should happen every 3 months. The collector itself every 15 days. The duration should be at least 18.5 hours when the collector is already on deck. The collector maintenance takes 28.5 hours due to (dis)assembly of the riser. The riser maintenance itself takes 10 days.	The collector experienced in total 10.7% of the time planned maintenance. The riser maintenance took indeed 10 days and occurred for example at an interval of 4258 hours (approximately 177 days). This is all as expected since the interval should be at least 3 months. The collector itself was serviced for 18,5 hours when the collector was already on deck. When the collector was not on deck, the maintenance took 28,5 hours, which is exactly how it should be. Some examples of the intervals were the following: 361, 430, 411 and 506 hours. This is indeed at least 15 days between the planned maintenance, which is again as expected.
Mechanical Downtime Unloader: Does the unloader face mechanical downtime and what is the duration of this downtime.	The unloader has a chance of 1.80 % of breaking down, so it should not happen too often. The duration should be between 0.2 and 12 hours.	In a test run, the unloader had 2.4% time of the year mechanical downtime. This percentage might be finetuned later on. The duration of the downtime was 5 hours which is between the upper and lower band.

Table 3.4: Verification of mechanical downtime and planned maintenance - second part

Verification with capacities

The verification with capacities is explained below in table 3.5.

Test	Expectation	Outcome
Maximum capacity of BC1: See whether the maximum capacity of bulk carrier 1 is not exceeded and check whether the unloading rate of the production is correct.	The maximum capacity of the bulk carrier is set at 50000 tons. So the loading of the bulk carrier should stop when this capacity has been reached. The unloading rate of the production vessel should be 2500 tons per hour.	The loading of the bulk carrier indeed stops at the maximum capacity of the bulk carrier. Furthermore, the rate at which the bulk carrier is filled up is correct.
Hold capacity of collector: Check whether the maximum capacity of the production vessel is not exceeded. Also investigate if the start capacity is correct. Furthermore make sure the collecting rate is correct and varies over time.	The maximum capacity of the production vessel is set at 25000 tons, so it should stay below this value. The start capacity is set at 10000 tons for this test. So the hold capacity of the production vessel should start at this value. Expected collecting rate = 500 * 0.85 * variety in production rate (in between 0.8 and 1.1). So the collecting rate should vary between a minimum of 340 and a maximum of 467.5.	The maximum capacity of the production vessel is not exceeded. In the experiment a maximum value of 24996 tons was reached. The hold capacity of the production vessel indeed had an initial value of 10000. The collecting rate varies indeed between the expected range. Values of 462, 465, 434, 382, 440 were found for example.
Unloading at terminal: Is the unloading rate at the terminal correct and is the bulk carrier fully emptied.	The unloading rate at the terminal should be 600 ton per hour and the bulk carrier should leave the terminal with an empty hold.	The unloading rate is indeed 600 tons per hour. The complete hold of the bulk carrier is empty and added to the terminal capacity.
Capacity of the terminal: Check whether the starting capacity and maximum capacity of the terminal are right and not exceeded.	The start capacity of the terminal is set at 20% of the maximum capacity. The maximum capacity is for now 9.000.000 tons (incredibly large since the terminal only receives nodules in this first model). So the starting capacity of the terminal should start at 1.800.000 tons.	The starting capacity is correct, and the maximum capacity is not exceeded.
Check warm-up period: To check whether the warm-up period works correctly, the capacities can be checked.	If the warm-up period is set at 200 hours, the collector should have already collected 200 hours (without downtimes). To check the warm-up period, the hold capacity of the production vessel should be unequal to zero.	The hold capacity is indeed unequal to zero and the bulk carrier is already partially filled. This means the model is already running during the warm-up period.

Table 3.5: Verification with capacities

Verification waiting queues

The verification of the waiting queues is explained below in table 3.6.

Test	Expectation	Outcome
Waiting queue production vessel: Check whether the waiting queue at the production vessel works correctly. To check this, the amount of bulk carriers is increased. This change in bulk carriers can simultaneously be verified with this test.	Only 1 vessel at the time should be unloaded by the production vessel. The others should be in the waiting queue when they have arrived at the mining scene. If I introduce 4 different bulk carriers, there should be 3 bulk carriers in the waiting queue immediately.	The 4 bulk carriers were created correctly and indeed 3 of them started in the waiting queue at the production vessel.
Waiting queue terminal: Check whether the waiting queue at the terminal works correctly. To check this, the amount of bulk carriers is increased to 4 once again. Furthermore the amount of berths at the terminal is set at 1.	Only 1 vessel at the time should be unloaded by the terminal. To make sure a queue is arising, the unloading rate at the terminal is decreased from 600 to 300 tons per hour. This way, there should be a build up of bulk carriers at the terminal.	The waiting queue at the terminal is indeed working. At some moments there were 2 bulk carriers in the waiting queue. Overall the 4 bulk carriers were 16.2% of the time in the waiting queue at the terminal, which is a significant time.

Table 3.6: Verification waiting queues

Verification location and sailing speed

The verification regarding the location and sailing speed is explained below in table 3.7.

Test	Expectation	Outcome
Terminal location: Check whether a change in terminal location, also represents a larger sailing percentage of BC1 and longer sailing times. For this test, the varying location of the production vessel is switched off.	The location was changed from Lazaro in Mexico to Oakland in the US. This is almost twice as far from the mining location. The sailing percentage and sailing time should go up significantly.	For Lazaro the distance from the mining to terminal = 1807 km. The bulk carrier has a sailing speed of 22 km/u, so it would take roughly 82 hours. This is exactly what the excel file was showing. The total sailing percentage in this case is 43.4% For Oakland the distance from the mining to terminal = 3091 km. The bulk carrier has a sailing speed of 22 km/u, so it would roughly take 140 hours. This is again in accordance with the excel file. The total sailing percentage in this case is 55.3%. This increased sailing percentages is as expected.
Production vessel location: Check the varying sailing times because of the variations in position of the production vessel.	If there is no extra sailing distance added or subtracted to the standard position, the sailing would take roughly 82 hours. With the possibility of an extra 100 kilometers of sailing, a maximum sailing duration of 87 hours would be the case. So the expectation is a varying sailing duration between 77 and 87 hours.	The sailing duration indeed varies between 77 and 87 hours. Sailing durations of 85, 84, 83, 81 and 80 were found.
Sailing speed: An increased sailing speed should result in shorter sailing times and a smaller sailing percentage.	The bulk carrier speed has been increased from 22 to 25 km/u. The traveling time should now be roughly 72 hours instead of 83.	The sailing time decrease was as expected. The sailing percentage has also gone down from 43.3% to 39.2%.

Table 3.7: Verification location and sailing speed

3.2.4. Validation

After the verification phase, the validation comes. The main question during validation is: ”is it the right model?” And: ”is the model an accurate representation of the real system?” [64]. The validation can be divided into three categories: data validation, structural validation and face validation. These three categories will be addressed in the subsections below. Performance validation is not addressed. Performance validation compares the results of the model with results of the actual system in real life. However, there is not an actual system in real life because large-scale mining has not started yet.

Data validation

Data validation focuses on the used data for the model (like distributions or historical data). Important to know about the distributions, is the reasoning behind the choice for a specific distribution, because there are many options possible. An (incomplete) overview of probability distributions is provided in figure 3.3. J. Mun (2008) [65] created a comprehensive overview of which distribution should be used for each case. Based on this information, the decision has been made to use a log-normal and normal distributions in the programming file. B.A. Omondi (2017) stated that a log-normal distribution is suited to generate failure times [66]. The advantage of a log-normal distribution, is the fact that it only generates positive values [65]. Furthermore, a log-normal is suitable for many different occasions [65]. This combination is exactly required to come up with values for the duration of mechanical downtime or planned maintenance. Normal distributions are used for the other distributions, like the duration of pre-loading operations. Normal distributions are suited for these occasions, since the variable could as likely be above the mean as it could be below the the mean. The variable is also likely to be in the vicinity of the mean [65].

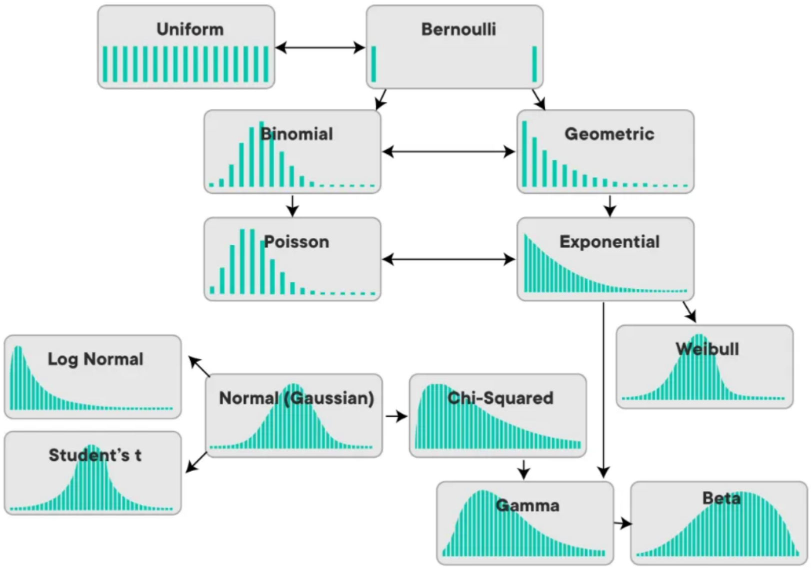


Figure 3.3: Common probability distributions [67]

Regarding the data validation, it can be difficult to validate used data since some of the data is imaginary data. The data which cannot be fully validated with data is listed below:

- Mechanical downtime chance of the collector: up to this point there is no collector which has collected nodules on the seabed for a longer period of time. So there is no data available how often the collector experiences mechanical downtime. Allseas provided an educated guess but this guess cannot be validated with data.
- Mechanical downtime duration of the collector: the same holds for the duration of the mechanical downtime of the collector.
- Planned maintenance interval collector: the same holds for the planned maintenance interval for the collector. Only an estimation can be made, but it is not based on historical data.
- Planned maintenance duration collector: the same holds for the planned maintenance duration of the collector.
- Riser maintenance interval: for the riser holds the same problem. During the 1980s several trials were conducted, but the airlift system which Allseas is planning to use differs from the system used back then [13]. So the maintenance interval cannot be based on historical data.
- Riser maintenance duration: the exact same holds for the maintenance duration of the riser.
- Mechanical downtime chance of the unloader: it proved to be difficult to find sources for the mechanical downtime duration and chance for the unloader itself of a self-unloading vessel. A sensitivity analysis is performed to figure out how much influence the mechanical downtime of the unloader has on the whole system. During this sensitivity analysis, the chance of mechanical downtime was varied, to discover which influence it has on the yearly percentage of mechanical downtime of the unloader, the collecting rate, unloading rate, yearly production, full hold and finnaly the collecting days lost due to a full hold. This data is displayed in table 3.8 below:

Chance of mech. downtime	Mechanical downtime [%]	Collecting collecting [%]	Unloading unloading [%]	Yearly production [Mt/yr]	PV hold full [%]	Collector days lost due to full hold [days/yr]
0.018	1	54.6	10.7	2.23	23.2	84.5
0.027	2.4	52.5	10.2	2.14	23.2	84.6
0.036	3.5	53.6	10.5	2.18	22.9	83.4
0.0405	4.3	54	10.5	2.2	22.1	80.3
0.045	7.3	54.9	10.7	2.24	22.0	80.6
0.54	8.2	52.7	10.3	2.15	23.6	86.1

Table 3.8: Sensitivity analysis unloader mechanical downtime

The chance of mechanical downtime has as expected a big correlation with the yearly mechanical downtime percentage. This is presented in figure 3.4 below. Besides this correlation, there is no correlation between the other columns in table 3.8. This shows that the mechanical downtime of the unloader does not have a big influence on the outcome of the simulation. This means, the mechanical downtime chance and duration of the unloader can safely be estimated. The chance is set at 0.03 which results in a yearly mechanical downtime percentage of roughly 3%.

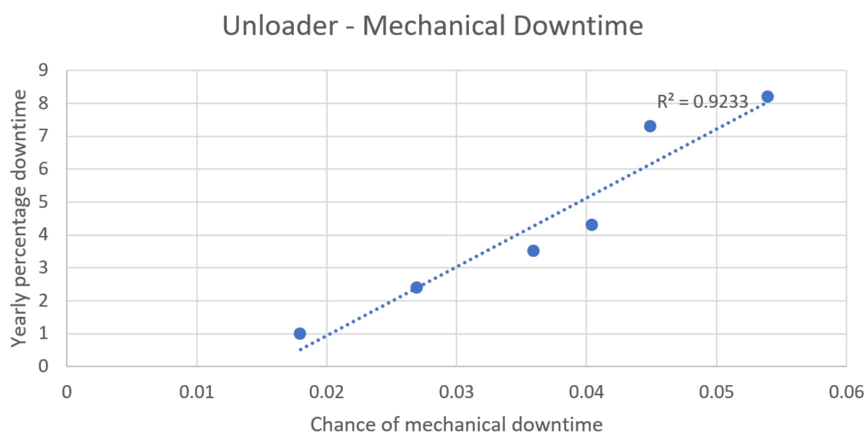


Figure 3.4: Graph of the unloader mechanical downtime chance versus yearly percentage

- Mechanical downtime duration of the unloader: for the duration of the mechanical downtime holds the same as described above. The duration is determined by a lognormal distribution varying between 0.2 and 12 hours.
- Bulk carrier mechanical downtime chance: the mechanical downtime chance and duration of a bulk carrier is the exact same story as the unloader. No references were found, so a sensitivity analysis is performed to see the influence of mechanical downtime of a bulk carrier on the whole simulation. Besides the influence of the chance on the yearly percentage of mechanical downtime, things like the yearly collecting percentage, yearly sailing percentage and yearly production are also investigated (which is displayed in table 3.9). It can be concluded that mechanical downtime of a bulk carrier has a big influence. This is best visualized in graph 3.5 below.

Chance of mech. downtime	Mechanical downtime [%]	Collecting collecting [%]	Sailing BC1 [%]	Yearly production [Mt/yr]
0.125	1.2	54.9	44.0	2.24
0.25	2.8	54.6	44.0	2.23
0.375	4.6	53.3	43.1	2.17
0.5	7.3	52.1	41.6	2.13
0.625	9.8	50.9	40.7	2.07

Table 3.9: Sensitivity analysis bulk carrier mechanical downtime

The yearly production rate has decreased by 170.000 tons per year, if the yearly mechanical downtime percentage has increased from 1.2 to 9.8 %. This meant that it is crucial to still argue the mechanical downtime chance and duration of a bulk carrier. This is done with face validation which will be addressed later.

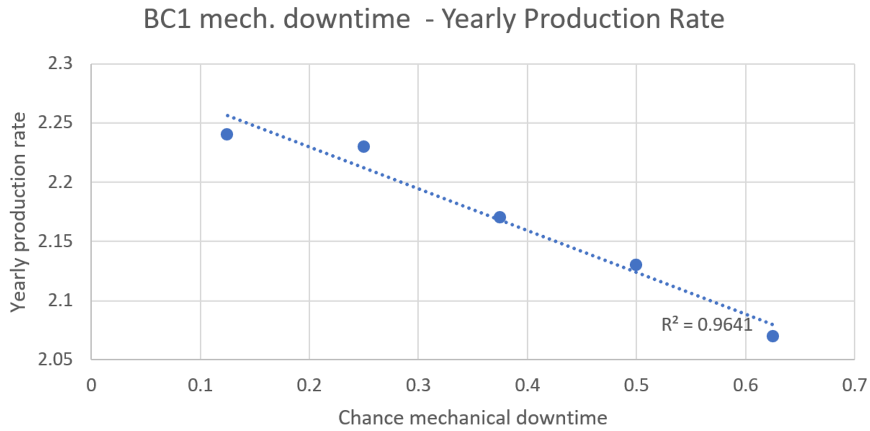


Figure 3.5: Graph of the unloader mechanical downtime chance versus yearly percentage

- Bulk carrier mechanical downtime duration: for the duration of the mechanical downtime holds the same as described above. The duration is determined by a lognormal distribution.

The data which can be fully validated with data is listed below:

- Pre- and post-operations offshore: there is hardly any data available about real-life offshore trans-shipment (in open sea) from a production vessel to a bulk carrier. It has been done but with totally different sea conditions [68]. The structure of the normal distribution which is used in the simulation is explained below:

  Build up of pre loading operations offshore:

  - Berthing: 3 hours
  - Connecting boom: 1 hour

  For the distribution, a normal distribution is chosen with a mean of 4 and a sigma of 0.4 hours. The lower bound is set at 2 hours and the upper bound at 6 hours.

  Build up of post loading operations offshore:

  - Deberthing: 1 hour
  - Disconnecting boom: 1 hour

  For the distribution, a normal distribution is chosen with a mean of 2 and a sigma of 0.4 hours. The lower bound is set at 0.5 hours and the upper bound at 3.5 hours. These numbers are based on another research about the STS transfer with a conveyor belt during deep-sea mining operations. This research came up with an offshore pre-loading duration between 4 and 6 hours and an offshore post-loading duration of 2 hours [28]. The duration of the pre- and post-operations offshore depends on the sea conditions, so in consultation with experts within Allseas, the above distributions are formed.
- Bulk carrier planned maintenance interval: an estimation is required when it comes to bulk carrier planned maintenance interval. Extensive maintenance should occur every 1 or 2 years and routine maintenance should occur every month [69]. These intervals might differentiate from the bulk carriers which will be used in the deep sea nodule collection supply chain, but for now these intervals provide a good indication.

- Bulk carrier planned maintenance duration: the planned maintenance duration is different for every bulk carrier. An estimation was based on two separate sources. P. Selänniemi (2022) [70] came up with a planned maintenance schedule of 9 days at a dry dock every 2 or 3 years. After 15 years of the total lifetime of the ship, this value raised significantly (but this is not taken into consideration for now). Major et al. (1978) [71] showed historical data for the planned maintenance of almost 20 bulk carriers for one whole year. It pointed out that roughly 6 days a year, a bulk carrier requires maintenance (hull damages, stevedore repairs and capital modifications are not included). Based on this historical data, the extensive maintenance is set at 3.5 days at an interval of 1 year. The routine planned maintenance is set at an interval of 1 month with a duration between 1 and 5 hours (determined according a log normal distribution). In total, the maintenance of a bulk carrier should take roughly 6 days a year, which is in line with the historical data.
- Bulk carrier sailing speed: the sailing speed for the bulk carriers in the simulation is set at 12 knots. This is based on the speeds of capesize, handysize and supramax bulk carriers. The sailing speeds of these ships varies from 10 to 14 knots [72] [73]. An extra step of validation is performed with face validation, which is described later.
- Pre and post operations terminals: the duration of the pre and post operations at the terminal is based on historical data from J. Hiltermann (Who gained experience at a large dry bulk terminal before his work at Allseas). The pre and post operations are elaborated below. The minimum and maximum is given for each bullet point, to come up with a reasonable distribution for the simulation.

  Build up of pre-operations:

  - Waiting for assistance like tugs and/or pilots: pilots 0.5 hours. Two other sources showed a time between 10 till 51 minutes [74] or between 0.1 and 0.7 hours [75].
    So Min = 0.1 and Max = 0.8 hours.
  - Sailing from anchorage to berth: 1 hour. Min = 0.5 and Max = 1.5 hours.
  - Berthing time: 0.5 hours. Min = 0.5 and Max = 1 hours.
  - Procedures time like authorities and a shipping agent: 2.5 hours.
    Min = 1.5 and Max = 3.5 hours.
  - Start-up operations of conveyors and processes to convey material: 0.5 hours. No variations assumed

  Minimum: 0.1 + 0.5 + 0.5 + 1.5 + 0.5 = 3.1
  Maximum: 0.8 + 1.5 + 1 + 3.5 + 0.5 = 7.3

  For the distribution, a normal distribution is chosen with a mean of 5.5 and a sigma of 0.667 hours. The lower bound is set at 3 hours and the upper bound at 7.5 hours.

  Build up of post-operations:

  - Procedures time like authorities and a shipping agent: 2.5 hours. Min = 1.5 and Max = 3.5 hours.
  - De-berthing time: 0.5 hours. Min = 0.5 and Max = 1 hours.
  - Waiting for assistance like tugs and/or pilots: 0.33 hours. Two other sources showed a time between 10 till 51 minutes [74] or between 0.1 and 0.7 hours [75].
    So Min = 0.1 and Max = 0.8 hours.
  - Sailing from berth to anchorage: 1 hour. Min = 0.5 and Max = 1.5 hours.

  Minimum: 1.5 + 0.5 + 0.1 + 0.5 = 2.6
  Maximum: 3.5 + 1 + 0.8 + 1.5 = 6.8

  For the distribution, a normal distribution is chosen with a mean of 4.5 and a sigma of 0.667 hours. The lower bound is set at 2.5 hours and the upper bound at 7 hours.
- Unloading rate production vessel: self-unloaders could have unloading speeds up to 5000 tons per hour [76]. The 2500 tons per hour which is now expected for the production vessel is well below that.

- Unloading rate at terminal: there are many unloading systems available with many different unloading rates. For instance, a gantry crane could unload from 150 up to 8000 tons per hour [77]. For now, it is safe to assume an unloading rate of 1000 tons per hour. This is feasible for the majority of the unloading systems.
- Production rate collector: the production rate of the collector can be validated by the trial performed by Allseas in 2022 [12]. Nevertheless, the production rate of the collector is irrelevant. In the end, the collected nodules should match a certain tonnage for a whole year (for example 3 million tons per year).

Structural validation

Structural validation addresses the structure of the model and whether the simplifications that have been made do not impact the results excessively.

List of simplifications:

- Bulk carrier sailing:
  The sailing of the bulk carrier is assumed to be constant and in a direct line. The sailing speed of a bulk carrier is never constant. For example the deceleration when the bulk carrier is near the terminal is not taken into account. Also for terminal locations which are more land inwards, a direct line is assumed. In real life, the bulk carrier might have to deal with corners which increase the sailing time slightly. The impact on the results of all this is minor. The part of deceleration and acceleration of a bulk carrier is a small percentage compared to the whole trip. The straight line could have a bigger impact, especially for locations which are not directly near the sea. But for Lazaro, which is really close to open sea, it has a minor impact. Especially if the whole trip is taken into account, the last few kilometers will not make a huge difference.
- Weather downtime:
  The downtime caused by extreme weather conditions is simplified by adjusting the runtime of a simulation. In real life the weather disruptions would be randomly divided over the whole year. A yearly weather downtime percentage of 5% is used in this thesis. The runtime is adjusted to 0.95 * 365 days = 346.75 days. This simplification should not have a big impact on the results. The most important is the yearly weather downtime percentage, and that is still 5% with this simplification. The only potential drawback of this simplification might be the omission of start-up operations, such as those of a terminal or collector, for example.
- Crew changes:
  The crew change on the production vessel is not taken into consideration. This might have a very small influence on the production rate for a short period of time. Such a small change will not impact the results of course.
- Fueling of production vessel:
  The fueling of the production vessel is also neglected. This might also have an influence on the production rate but again, this is likely to be a very small impact for a full year of collecting.
- Planned maintenance bulk carrier:
  P. Selänniemi (2022) [70] came up with a planned maintenance schedule of 9 days at a dry dock every 2 or 3 years. In model V1, the simplification was made to perform planned maintenance for 3.5 days each year. This is small simplification without big influence.
- Route production vessel:
  The route of the production vessel is heavily simplified. The production vessel will be within the NORI D area for all the simulations. The NORI D area is the yellow square on the right in figure 3.6.

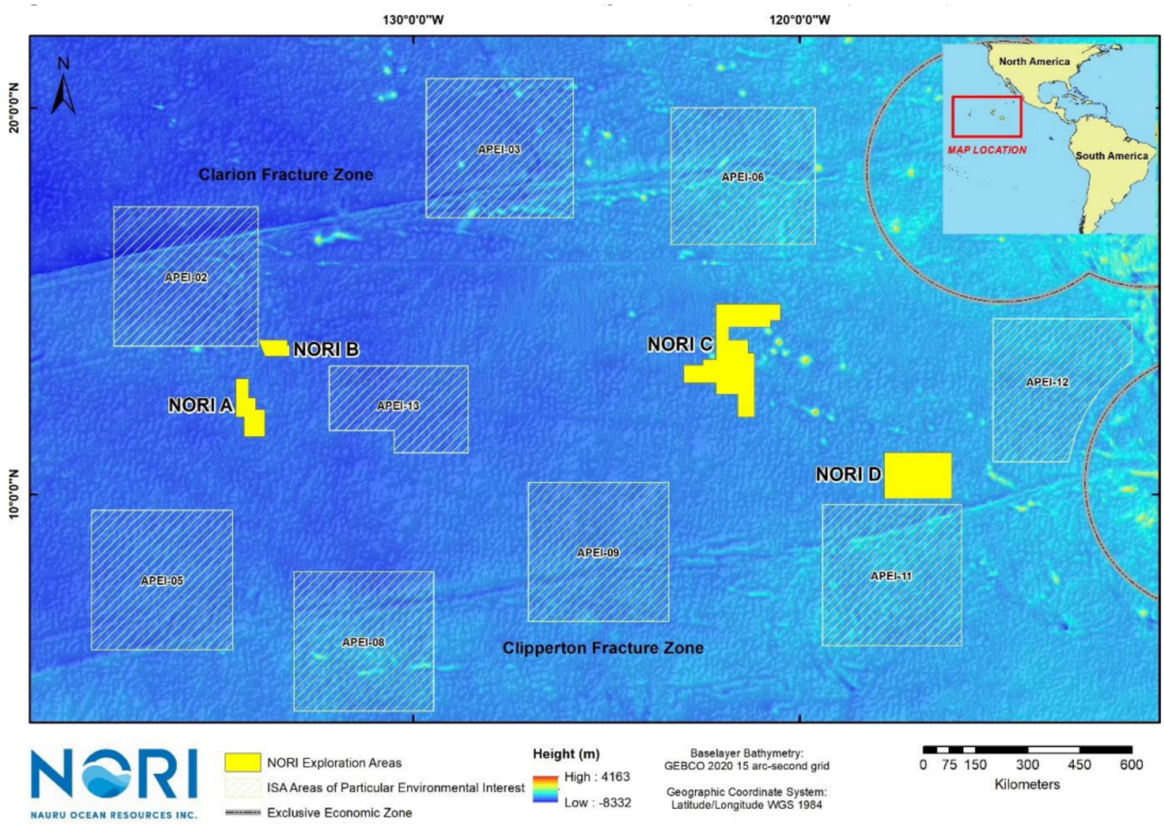


Figure 3.6: NORI D [78]

The standard location of the production vessel is assumed to be exactly in the middle of this yellow square and is roughly 1800 kilometers away from Lazaro in Mexico. The exact route of the production vessel is very complicated so a simplification has been made. The route of the production vessel is confidential, but it basically means that the production vessel can be at a maximum 100 kilometers further from the terminal or 100 kilometers closer to the terminal (because the NORI D area is in total 200 km wide). A normal distribution determines whether an extra 100 kilometers are added or subtracted from the 1800 kilometers route. The distance to return to the terminal is assumed to be equal to the distance towards the production vessel.
Another simplification is that corners of the production vessel are not taken into account. During these corners, the unloading towards the bulk carrier might temporarily stop.

- Production rate collector:
  The collector rate of the collector varies and is determined by a lognormal distribution and the field efficiency. A simplification is made when the collector rate is sampled by the lognormal distribution. The collector rate will namely stay the same for 100 hours. In real life the collector rate might change more often due to the different nodule densities at the seabed.
- Anchorage points:
  Another simplification is made regarding the acnhorage points. A minimum of 0.5 hours and a maximum of 1.5 hours is assumed to sail from the anchorage to the berth. In reality this could be a bit more or less, since the exact location of the anchorage point is unknown.
- Tidal variations:
  Tidal variations are neglected, which might occasionally have influence on entering the harbour.
- Mechanical downtime bulk carrier:
  It is assumed that mechanical downtime of the bulk carrier occurs before the start of the sailing journey (so at the terminal or production vessel). Mechanical downtime however often occurs while sailing, which often results in a lower sailing speed to manage the problem according to practical experience of Carlo Floor [79]. Although the lost time will likely come down to the same duration as when the mechanical downtime occurs at the terminal.

- Unlimited terminal capacity:
  The terminal capacity is set at infinity for this model, which means the terminal always has available storage left. The terminal only collects nodules in this model so it would not make sense to set a limited capacity for the terminal.
- Bulk carrier waiting spot:
  In the case of a waiting queue for bulk carriers at the production vessel, the bulk carriers wait nearby the production vessel. In reality, waiting near the coast is cheaper in terms of fuel consumption because dynamic positioning is not required in that case. For example when the collector requires extensive maintenance and a waiting queue is foreseen at the production vessel, the bulk carriers wait on anchorage near the coast instead of in the mining field.
- Unloading rate at terminal constant:
  The unloading rate at the terminal is assumed to be constant in this model. Later on, the different stages like free digging are added. The unloading rate is now a mean value for the whole ship. This should not matter since the terminal operations are not modelled in this version.

Face validation

Face validation is a form of validation that relies on an individual. I have used the experience of Carlo Floor, who is master mariner with more than 30 years of worldwide sea-going experience on various vessel types [79]. Carlo Floor helped me to validate the following things:

- Mechanical downtime bulk carrier: A bulk carrier experiences 2.5% yearly mechanical downtime.
- Mechanical downtime bulk carrier duration: The duration for repairing mechanical downtime for a bulk carrier varies between 3 and 20 hours, with a mean repair time of 8 hours.
- Planned maintenance bulk carrier: Planned maintenance of a bulk carrier takes up 6 days each year.

3.2.5. Calibration

The calibration is used to estimate and adjust/fine-tune parameters and constants. The following parameters and constants are calibrated:

- Mechanical downtime of a bulk carrier
- Mechanical downtime of the unloader at the production vessel
- Collector production per year

The yearly production rate of the collector is adjusted by varying the collector rate. A certain collector rate given in tons per hour, results in a total yearly production rate given in million tons per year. Several runs have been performed to calibrate the collector rate to correspond with the desired yearly production rates.
The mechanical downtime parameters are calibrated by adjusting the chance for mechanical downtime. The duration of mechanical downtime is determined by a lognormal distribution. During the calibration phase, the duration stays the same throughout the various simulations with the build in random.seed function in Python. The chance needs to be calibrated to end with the desired yearly mechanical downtime percentage. Face validation indicated that a bulk carrier should roughly experience 2.5% of yearly mechanical downtime. Mechanical downtime occurs randomly, so the mechanical downtime percentage cannot be exactly 2.5% each year. Table 3.10 below shows the chance for mechanical downtime to happen and the corresponding yearly mechanical downtime percentage in the first two columns. The chance for mechanical downtime is set at 0.25 to roughly reach the desired 2.5%.

Chance of mech. downtime	Mechanical downtime [%]	Collecting collecting [%]	Sailing BC1 [%]	Yearly production [Mt/yr]
0.125	1.2	54.9	44.0	2.24
0.25	2.8	54.6	44.0	2.23
0.375	4.6	53.3	43.1	2.17
0.5	7.3	52.1	41.6	2.13
0.625	9.8	50.9	40.7	2.07

Table 3.10: Calibration for the mechanical downtime of a bulk carrier

3.3. Model V2 - Both Roundtrips

This second model will address the roundtrip between the mining location and the transshipment terminal, as well as the roundtrip between the transshipment terminal and processing facility. The terminal operations are not taken into consideration, but will be implemented in model V3. Just like model V1, the model formalization, implementation, verification, validation and calibration are described in separate subsections below.

3.3.1. Model Formulation

Model V2 is clarified in this subsection. The objective and scope are explained. Then the parameters and inputs are provided, as well as the key performance indicators and outputs. Finally, the stochastic variables are addressed.

Model Objective and Scope

The scope of model V2 is illustrated in figure 3.1 above. Besides the inputs of model V1 - Roundtrip Mining to Terminal, the processing facility is added, as well as the second roundtrip loop, which are bulk carriers sailing between the terminal and processing facility. The terminal is still regarded as a black box with incoming and outgoing nodules.

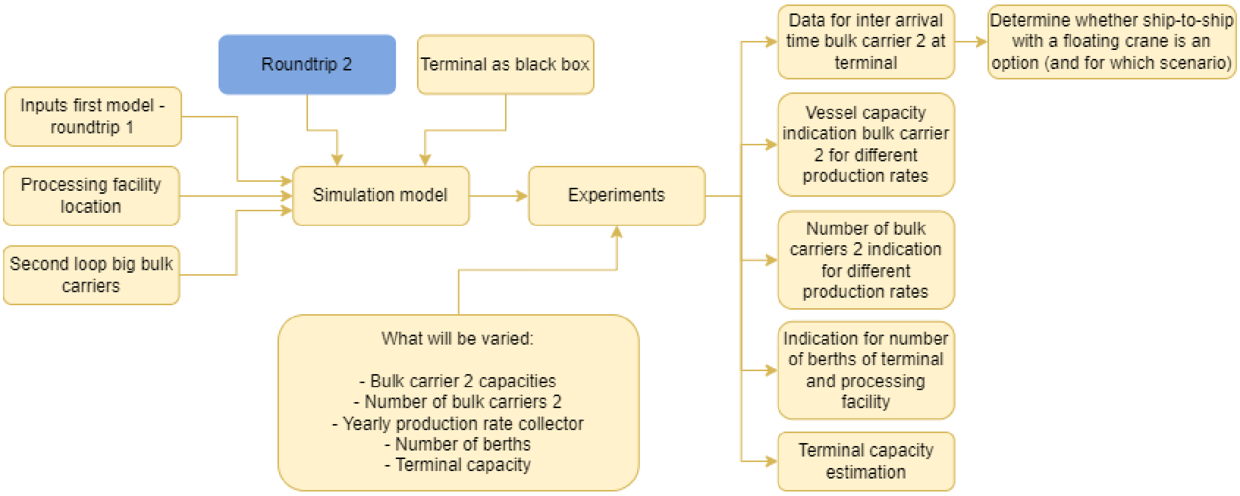


Figure 3.7: Model V2

The five objectives of model V2 can be seen in figure 3.7 on the right. The most important objective is indication for all the vessel capacities and number of bulk carriers for varying production rates. Vessel recommendations can be made to for the final model V3 - Terminal Operations and Roundtrips, which prevents performing long simulations with unapproriate bulk carriers.
Once again, an important remark is that a combination of different bulk carriers within one roundtrip is not taken into account (for example two bulk Handysize and one Panamax bulk carrier). This prevents endless simulations with a lot of possible combinations. The goal of this thesis is not to optimize the roundtrips of the bulk carriers, but to simulate the roundtrip processes to support the decision-making for the terminal design.

Parameters and Inputs

The parameters and inputs which are already provided for model V1 will not be repeated below.

List of new inputs for BC2:

- Sailing speed
- Maximum capacity
- Chance for mechanical downtime
- Amount of bulk carriers

- Planned maintenance interval
- Extensive maintenance interval
- Extensive maintenance duration
- Extensive maintenance duration short

List of inputs for processing facility:

- Unloading rate of a bulk carrier at the processing facility
- Maximum capacity
- Start capacity
- Number of berths

New input for terminal:

- Loading rate of BC2 at terminal

List of new stochastic inputs:

- BC2 mechanical downtime duration
- BC2 planned maintenance duration
- Pre unloading operations at processing facility
- Post unloading operations at processing facility

List of simulation parameters:

- Weather downtime percentage: the same yearly weather downtime percentage of 5% is used, which has already been explained for the first model.
- Number of runs: during this stage, only 1 run will be performed of 1 year, since no crucial decisions are made with this model
- Run/sim duration: each run will represent one full year. However there is a 5% weather downtime so the runtime in hours will be: 365 * 24 * 0.95 = 8322 hours.

KPI's and Outputs

List of outputs:

The outputs are provided in table 3.11 below. In the case of multiple runs, a minimum, maximum and average of the output is provided, hence the three different outputs in each column. The results are purely demonstrative.

Summary	Minimum	Average	Maximum
Collector_production	9.40 Mt/year	9.77 Mt/year	9.96 Mt/year
Collector_days_lost_due_to_hold_full	0.3 days/year	0.7 days/year	1.3 days/year
Collector	**Minimum**	**Average**	**Maximum**
Collector_collecting	70.8 %	73.6 %	75.1 %
PV_hold_full	0.0 %	0.1 %	0.1 %
Collector_mechanical_downtime	14.4 %	14.6 %	14.8 %
Collector_planned_maintenance	5.2 %	6.7 %	9.8 %
Collector_weather_downtime	5.0 %	5.0 %	5.0 %
Unloader	**Minimum**	**Average**	**Maximum**
Unloader_unloading	15.2 %	15.8 %	16.1 %
PV_hold_empty	68.4 %	69.9 %	71.4 %
Unloader_mechanical_downtime	4.2 %	4.5 %	4.7 %
Unloader_no_BC1	9.1 %	9.8 %	10.7 %
Unloader_unloading_speed	0 t/h	460.8 t/h	2500 t/h
BC1	**Minimum**	**Average**	**Maximum**
Sailing_BC1	48.1 %	50.2 %	51.3 %
BC1_unloading	6.9 %	7.2 %	7.3 %
BC1_loading	4.0 %	4.2 %	4.3 %
Total_pre_post_operations_BC1	4.1 %	4.3 %	4.4 %
Total_waiting_unloader_BC1	19.4 %	19.7 %	19.9 %
Total_mechanical_downtime_BC1	2.8 %	2.9 %	3.1 %
Total_planned_maintenance_BC1	0.9 %	0.9 %	0.9 %
Total_time_in_waitingQ_PV	12.9 %	14.2 %	16.9 %
Total_time_in_waitingQ_Terminal	0.0 %	0.0 %	0.0 %
Total_time_in_waitingQ_BC1	12.9 %	14.3 %	16.9 %
Waiting_due_capacity_terminal_or_PV	18.2 %	18.5 %	18.8 %
BC2	**Minimum**	**Average**	**Maximum**
Sailing_BC2	87.9 %	88.9 %	90.2 %
BC2_unloading	2.6 %	2.8 %	2.9 %
BC2_loading	3.2 %	3.9 %	4.3 %
Total_pre_post_operations_BC2	1.2 %	1.7 %	1.9 %
Total_mechanical_downtime_BC2	1.9 %	2.5 %	3.3 %
Total_planned_maintenance_BC2	0.5 %	0.9 %	1.3 %
Total_time_in_waitingQ_PF	0.7 %	1.6 %	2.2 %
Total_time_in_waitingQ_Terminal	0.4 %	0.7 %	0.9 %
Total_time_in_waitingQ_BC2	0.3 %	0.9 %	1.3 %
Waiting_due_capacity_terminal_or_PF	0.0 %	0.1 %	0.2 %
Terminal	**Minimum**	**Average**	**Maximum**
Terminal_unloading_BC1	6.9 %	7.2 %	7.3 %
Terminal_loading_BC2	3.2 %	3.9 %	4.3 %
Terminal_full	0.0 %	0.0 %	0.0 %
Terminal_empty	0.0 %	0.0 %	0.0 %
PF	**Minimum**	**Average**	**Maximum**
PF_unloading_BC2	2.6 %	2.8 %	2.9 %
PF_full	0.0 %	0.0 %	0.0 %

Table 3.11: Output runfile model V2 - Both Roundtrips

Besides the outputs of the runfile, an excel file is once again created. The following columns are added to the excel file:

- Processing facility status
- Processing facility capacity [tons]
- BC2 hold level (more columns possible when there are more bulk carriers) [tons]
- BC2 status (more columns possible when there are more bulk carriers)

- Roundtrip ID BC2 (more columns possible when there are more bulk carriers)
- Waiting queue at processing facility

The following key performance indicators have been utilized:

- Collector days lost due to hold full: During all the experiments, it is crucial that the production vessel is able to mine continuously. When the hold of the production vessel has reached its limit, the collector has to stop. The stream of shuttle bulk carriers at the production vessel should be sufficient to restrict the lost collection days, otherwise the yearly production rate targets will not be met.
- Yearly production rate: When the collector loses too many days because of a full hold, the yearly production rate will be lower. This also gives an indication for a bottleneck within the chain.
- Berth occupancy: A high berth occupancy results in long vessel waiting times at the terminal [61]. Although, this key performance indicator is more important for the next model, since the terminal operations are not simulated yet, which means the berth occupancy could change significantly.
- Time in waiting queue at production vessel: The time in the waiting queue at the production vessel is a very important performance indicator. Too many bulk carriers might result in long waiting times at the production vessel.
- Time in waiting queue at terminal: Normally the waiting-time/service-time ratio is a common performance indicator [61]. However, the terminal is modelled as a black box so the service-time is not very accurate. For now, only the waiting time in the queue at the terminal is taken into account. Possible waiting time must be avoided to avoid demurrage costs. The ship-owner must pay demurrage costs if the expected port time is exceeded [61].
- Terminal capacity: The terminal capacity also says something about the performance. Especially the terminal capacity at the end of a simulation. The terminal capacity could slowly become zero or stay at a constant level. The case where the terminal capacity slowly becomes zero is of course more beneficial, since the terminal capacity can be much lower.
- Time in waiting queue at processing facility: The time in the waiting queue at the processing facility is a very important performance indicator. The processing facility only has one berth, and too many bulk carriers might result in long waiting times at the processing facility.

The utilization rate of equipment is a common performance indication for terminals [61], but not taken into account during experiments with this model, since the terminal is modelled as a black box.

3.3.2. Implementation

This version is like model V1 - Roundtrip Mining to Terminal, also divided in separate files. The following files are added to Python for model V2 - Both Roundtrips:

- **BulkCarrier2:** the bulk carrier which executes the roundtrips from the terminal to the processing facility is coded in this file:
  The BC2 bulk carriers are generated at the terminal and added to the waiting queue if the loading berth is occupied. Once arrived at the loading berth, the pre-loading operations at the terminal are executed. The terminal is still modelled as a black box so the terminal operations are not taken into account. The loading of course stops when the terminal capacity is zero. When the bulk carrier is filled, the post-loading operations are executed at the terminal. Before the sailing towards the processing facility starts, a check is performed whether the bulk carrier faces mechanical downtime. After the sailing towards the processing facility, the bulk carrier is added to the waiting queue when the berth is occupied. Once a berth is available, the pre-unloading operations are executed. The bulk carrier is unloaded till the hold is empty. Then the post-unloading operations are executed. Before sailing back towards the terminal, a check is performed for mechanical downtime of the bulk carrier. At the terminal another check is executed whether the bulk carrier requires routine and/or extensive planned maintenance.
- **Processing facility:** the processing facility is described in this file:
  It is a relatively simple file since the processing facility only unloads bulk carrier 2 and then stores the nodules. Pre- and post-unloading operations are taken into account, but additional unloading processes are not simulated. The processing facility has an infinite capacity and is modelled using the SimPy container function. Furthermore, it has one berth which will be explained and visualized in section 4.2.

3.3.3. Verification

The verification of model V2 is based on the verification of model V1, where some checks are generalized to make sure there are not 50 separate verification checks. The random.seed function is once again used during the verification. The verification checks are listed in the subsections below.

Verification of mechanical downtime and planned maintenance

The verification of mechanical downtime and planned maintenance is explained below in table 3.12.

Test	Expectation	Outcome
Mechanical Downtime BC2: See whether mechanical downtime occurs and how long it takes.	Mechanical downtime should happen at around 3% of the time when it's ready for sailing. The duration should be between 4 and 40 hours.	In the simulation, a mechanical downtime of 2.4% for 1 year was found. The duration was sometimes more than 40 hours. For each roundtrip, there can be sampled twice for mechanical downtime before the start of the sailing trip. To get close to the 3% of mechanical downtime over the full year, a larger probability of 0.45 is required in comparison to 0.25 for BC1. This means, that it could happen that mechanical downtime happens two or three times after each other. This means, that it might take 53 hours for example.
Planned Maintenance BC2: See whether planned maintenance of BC2 is executed at the right moment, interval and duration.	The planned maintenance should be executed after loading operations at the terminal. The interval should be at least 2200 hours (≈ 90 days) and have a duration between 12 and 72 hours. Routine planned maintenance: every 2200 hours. Duration between 1 and 5 hours. Extensive maintenance: interval of 8000 hours. Duration 84 hours. Except if routine planned maintenance already happened, then the extensive maintenance lasts 80 hours.	The routine planned maintenance is indeed performed before loading at the terminal. Some of the interval examples are 2354, 2400, 2428, 2282 and 2340 hours, which is indeed at least 2200 hours. The duration of routine planned maintenance is roughly 3 hours which is indeed between 1 and 5 hours. The extensive maintenance is performed at 8187 hours with a duration of 84 hours. If the extensive maintenance interval is shortened to 4000 hours, the exceptional case with consecutive routine and extensive planned maintenance occurs. The extensive maintenance should last 80 hours instead of 84 hours. This is indeed the case.

Table 3.12: Verification of mechanical downtime and planned maintenance

Verification with capacities

The verification with capacities is explained below in table 3.13.

Test	Expectation	Outcome
Maximum capacity of BC2: See whether the maximum capacity of bulk carrier 2 is not exceeded.	The maximum capacity of the bulk carrier is set at 35000 tons. So the loading of the bulk carrier at the terminal should stop when this capacity has been reached.	The loading of the bulk carrier indeed stops at the maximum capacity of the bulk carrier.
(Un)loading at terminal and processing facility: Is the unloading rate at the processing facility correct and is the bulk carrier fully emptied? The same holds for the terminal where the bulk carrier is loaded with a certain loading rate.	The unloading rate at the processing facility should be 1000 ton per hour and the bulk carrier should leave the processing facility with an empty hold. The loading rate at the terminal is 1000 ton per hour and the bulk carrier should leave the terminal completely full.	The unloading rate is indeed 1000 ton per hour. The complete hold of the bulk carrier is empty and added to the processing facility capacity. The loading rate is also 1000 ton per hour at the terminal. The complete bulk carrier capacity is subtracted from the terminal capacity.
Capacity of the terminal and processing facility: Check whether the starting capacity and maximum capacity of the terminal and processing facility are right and not exceeded.	The start capacity of the terminal is set at 50% of the maximum capacity. The maximum capacity is for now 400.000 tons. So the starting capacity of the terminal should start at 200.000 tons. The maximum capacity of the processing facility is set at 3.500.000 tons. This is very large since there is no outflow taken into account for now. The start capacity is set at 0.	The starting capacity of the terminal and processing facility are correct, and the maximum capacities are not exceeded.

Table 3.13: Verification with capacities

Verification waiting queues

The verification of the waiting queues is explained below in table 3.14.

Test	Expectation	Outcome
Waiting queue processing facility: Check whether the waiting queue at the processing facility works correctly. To check this, the amount of bulk carriers is increased. This change in bulk carriers can simultaneously be verified with this test.	Only 1 vessel at the time should be unloaded at the processing facility. The others should be in the waiting queue when they have arrived.	The waiting queue at the processing facility works as expected. For this test, 3 bulk carriers were used and only 1 berth at the processing facility. This resulted in a small waiting queue at the processing facility.
Waiting queue terminal: Check whether the waiting queue at the terminal still works correctly. Besides 2 bulk carriers for roundtrip 1, 3 bulk carriers are added for roundtrip 2.	The amount of berths is set to 2 for this test. With 3 bulk carriers of roundtrip 2, which all start at the terminal, there should be immediately 1 bulk carrier in the waiting queue.	The waiting queue at the terminal is indeed working. At the beginning, there is indeed one bulk carrier in the waiting queue. In the rest of the simulation, the waiting queue also performs as expected.

Table 3.14: Verification waiting queues

Verification location and sailing speed

The verification regarding the location and sailing speed is explained below in table 3.15.

Test	Expectation	Outcome
Processing facility location: Check whether a change in PF location, also represents a shorter sailing percentage of BC2 and shorter sailing times.	The location was changed from Japan to the island Midway Atoll (which is a lot closer to the terminal in Lazaro). The sailing percentage and sailing time should go down significantly.	The old situation from Lazaro to Japan took 525 hours of sailing. The total sailing percentage was almost 90% in this case. From Lazaro to Midway Atoll takes 384 hours of sailing. The sailing percentage decreased to almost 85%. So the expectations are met.
Sailing speed BC2: An increased sailing speed of BC2 should result in shorter sailing times and a smaller sailing percentage.	The bulk carrier speed has been increased from 22 to 25 km/u.	The sailing time decrease was as expected. The sailing percentage has also gone down.

Table 3.15: Verification location and sailing speed

3.3.4. Validation

The validation is again divided into three categories: data validation, structural validation and face validation. The data, structural and face validation which are described for model V1 - Roundtrip Mining to Terminal, also hold for this model. For example:

- Bulk carrier mechanical downtime chance
- Bulk carrier mechanical downtime duration
- Pre and post operations processing facility
- Unloading and loading rate
- Bulk carrier planned maintenance
- Mechanical downtime chance of a bulk carrier
- Mechanical downtime duration of a bulk carrier

For the bulk carrier obviously holds the same. For the pre- and post-operations at the processing facility, it is assumed to be the same as the terminal. The same holds for the unloading and loading rate at the terminal and processing facility. The bulk carrier planned maintenance and mechanical downtime are already adressed in the face validaiton section of model V1 - Roundtrip Mining to Terminal.

3.3.5. Calibration

The following parameters and constants are calibrated:

- Mechanical downtime for the bulk carrier sailing between terminal and processing facility
- Planned maintenance for the bulk carrier sailing between terminal and processing facility

The parameters are once again calibrated by adjusting the chance and duration, to reach a desired yearly percentage. This method has been explained in section 3.2.5.

3.4. Model V3 - Terminal Operations + Roundtrips

Model V3 - Terminal Operations and Roundtrips is addressed in this section. This model is the final version which will be used to answer the following sub-question:

How should a simulation model be designed to determine the sizing of the stockyard and seaside areas, as well as to quantify the equipment?

The most important change in comparison with the previous models is that terminal operations are simulated with this model. The roundtrips however of model V1 and V2 are similar to the previous models. Besides the terminal operations, energy consumption is also investigated with this model. As discussed before, the rising energy prices and climate change encourage energy efficiency within the terminal [27].

3.4.1. Model Formulation

Model V3 is clarified in this subsection. The objective and scope are explained. Then the parameters and inputs are provided, as well as the key performance indicators and outputs. Finally, the stochastic variables are addressed.

Model Objective and Scope

The scope of model V3 is also illustrated in figure 3.1 above, where both roundtrips and the terminal operations are taken into account. The model objectives are provided in figure 3.8

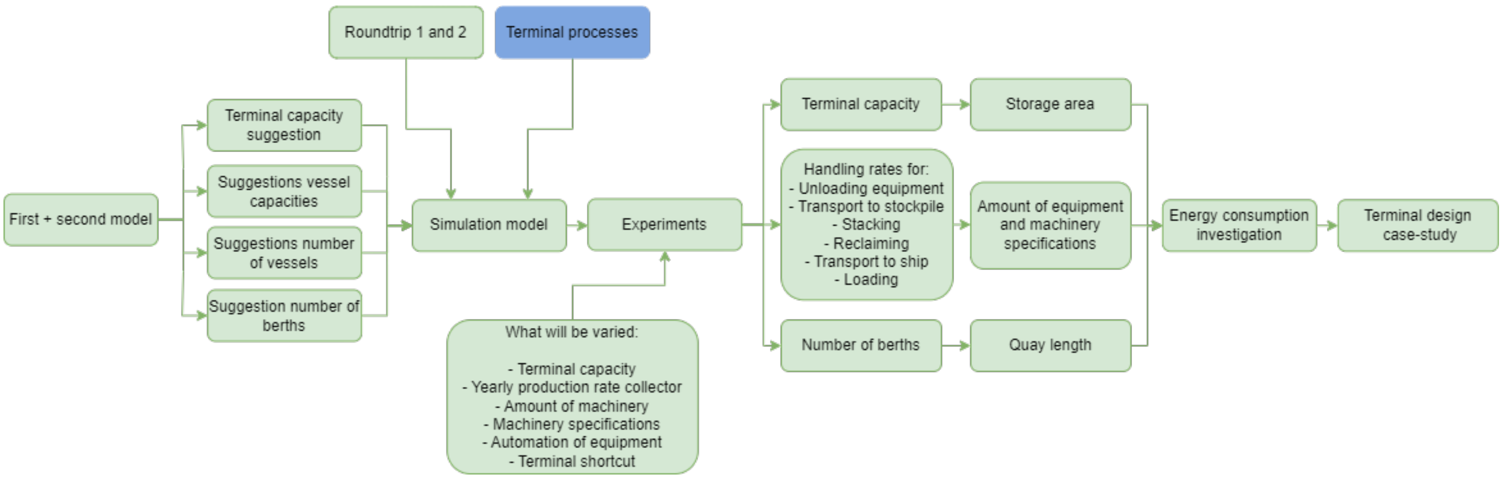


Figure 3.8: Model V3 - Terminal Operations and Roundtrips

The most important objective of this model is to find handling rates for the terminal equipment. Based on these handling rates, decisions can be made regarding equipment. The required terminal capacity can be used to determine the required amount of storage area, and thus give an indication for the total size of the terminal.

The number of berths will determine the required quay length of the terminal. The quay length and quay length factor are associated to the number of berths and can be determined by a formula [26].

Parameters and Inputs

The parameters and inputs which are already provided for the previous models will not be repeated below.

List of new inputs for terminal:

- Sailing speed
- Maximum capacity
- Chance for mechanical downtime
- Amount of bulk carriers

- Planned maintenance interval
- Extensive maintenance interval
- Extensive maintenance duration
- Extensive maintenance duration short

List of inputs for processing facility:

- Unloading rate of a bulk carrier at the processing facility
- Maximum capacity
- Start capacity
- Number of berths

List of new stochastic inputs:

- BC2 mechanical downtime duration
- BC2 planned maintenance duration
- Pre unloading operations at processing facility
- Post unloading operations at processing facility

List of simulation parameters:

- Weather downtime percentage: the same yearly weather downtime percentage of 5% is used, which has already been explained for the first model.
- Yearly operational hours terminal: The terminal will operate according to the SSHINC principle. SSHINC means that saturdays, sundays and holidays are included [80]. According to J. Hiltermann (who gained experience at a large dry bulk terminal before his work at Allseas), 360 working days at the transshipment terminal is feasible. However there is still a 5% weather downtime so the runtime in hours will be: 360 * 24 * 0.95 = 8208 hours.
- Warm up period: a warm up period is used to have more accurate results. The starting situation with all the BC2 bulk carriers at the terminal, results in an artificial situation. This phenomenon can be seen in figure 3.9 (the time in hours on the x-axis is linear, which will also hold for all the other graphs regarding the terminal capacity as a function of time). A starting capacity can be seen of 150.000 tons at the terminal. All the BC2 bulk carriers are instantly loaded after each other. The terminal capacity then experiences a peak because all the BC2 bulk carriers are still at the processing facility or sailing, while the three BC1 bulk carriers are unloaded at the terminal. This situation will never happen in reality. The BC2 bulk carriers are then more scattered. In some simulations, the effect of all the BC2 bulk carriers starting at the terminal could still be recognized after 6000 hours (see figure 3.10 below, where a clear pattern (increasing terminal capacity) starts to evolve after 6700 hours). A warm up period of one year (8202 hours) has been selected to make sure the starting situation does not influence the results.

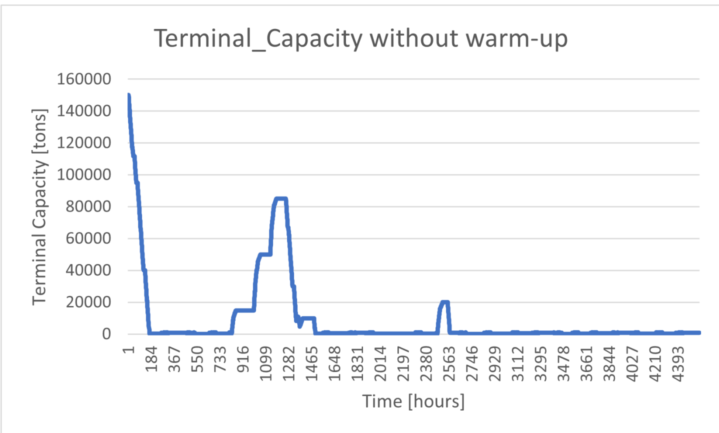


Figure 3.9: Terminal capacity without a warm up period

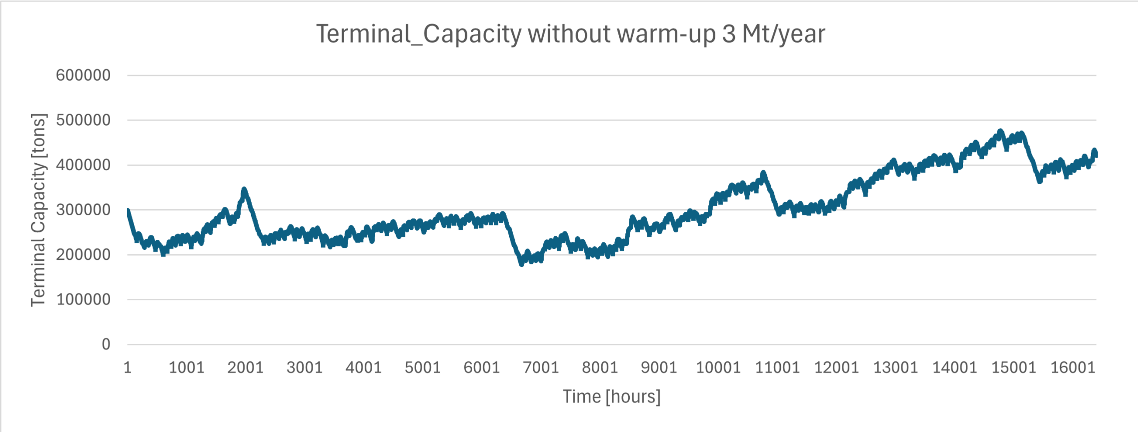


Figure 3.10: Influence of starting position BC2 bulk carriers can be seen till 6700 hours without a warm up period

- Number of runs and duration: The model has many random variables, which means that many iterations can be generated with a different outcome because of the randomness. By collecting the data from multiple runs, the behaviour of the model can be analyzed [81]. Making decisions based on a single simulation is not very wise when the randomness of the simulation is high. That is the reason why different run variations are executed to find the right balance between total runtime and a representative output. The stochasticity means that decisions cannot be made on a run of one single year. The following variations are investigated (all performed with a warm up period of 1 year):
  - 10 iterations of 5 years (41010 hours)
  - 10 iterations of 3 years (24606 hours)
  - 5 iterations of 5 years (41010 hours)
  - 3 iterations of 5 years (41010 hours)
  - 3 iterations of 3 years (24606 hours)

  There is a very small difference in the outcome of all the variations. For this thesis, iterations of 5 years are more efficient. For example, 15 years of simulation require 3 simulations of 5 years or 5 simulations of 3 years. But each iteration requires a full year of a warm up period so 3 simulations of 5 years are more efficient. The difference between 3 and 10 simulations of 5 years has proven to be negligible. One single run of 5 years generally takes 30 minutes (including 1 year of warm up). Many experiments will be executed so 3 simulations of 5 years is more practical regarding the time it takes to run the experiments, while still having a representative result.
- Starting capacity terminal: several simulations with an annual throughput of 2 Mt/year have been performed to find an appropriate starting capacity of the terminal. In figure 3.11 a starting capacity of 0 has been tested. This results in an unrealistic behaviour of the terminal capacity. The BC2 bulk carriers are all in the waiting queue at the start which results in a terminal capacity of 0 for the first 1,5 years. This is of course unrealistic so a starting capacity of 0 is not used. The second option, a starting capacity of 10% of the annual throughput, is visualized in figure 3.12. This is based on a research of Lodewijks et al. (2009), which stated that a storage capacity of 10% of the annual throughput is acceptable for the dry bulk industry [23]. Figure 3.12 shows that the terminal capacity has a steady development shortly after the beginning of the simulation. A starting capacity of 10% of the annual throughput seems acceptable. The last simulation is performed with a starting capacity of 20% of the annual throughput, which can be seen in figure 3.13. Once again the terminal capacity quickly has a steady course, however, the terminal capacity is constantly above 200.000 tons. The high starting capacity thus results in an unrealistic storage capacity. A starting capacity of 10% of the annual throughput does not have this problem and will thus be used for the remaining simulations.

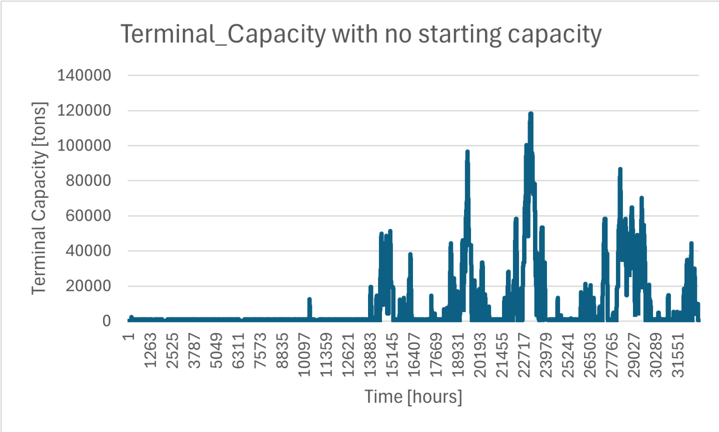


Figure 3.11: Simulation without a starting capacity

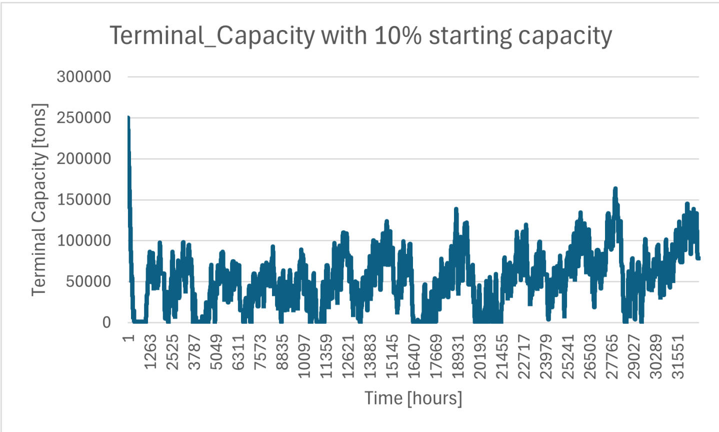


Figure 3.12: Simulation with a starting capacity of 10% annual throughput

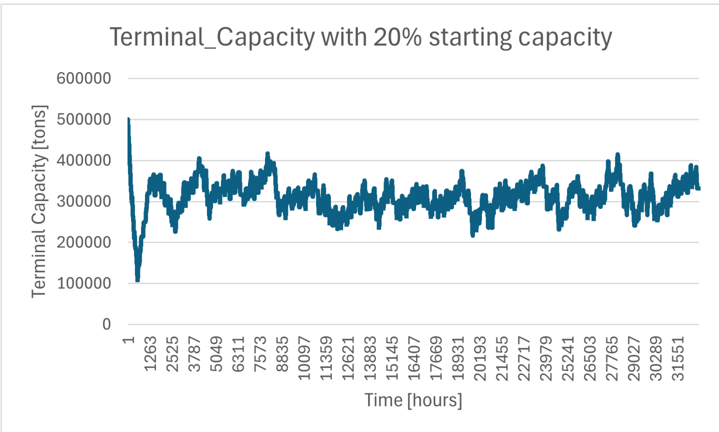


Figure 3.13: Simulation with a starting capacity of 20% annual throughput

KPI's and Outputs

List of outputs:

The outputs are provided in table 3.16 below. In the case of multiple runs, a minimum, maximum and average of the output is provided, hence the three different outputs in each column. The results are purely demonstrative.

Summary	Minimum	Average	Maximum
Collector_production	3.06 Mt/year	3.16 Mt/year	3.21 Mt/year
Collector_days_lost_due_to_hold_full	1.0 days/year	2.0 days/year	2.6 days/year
Collector	**Minimum**	**Average**	**Maximum**
Collector_collecting	74.7 %	77.3 %	78.7 %
PV_hold_full	0.3 %	0.5 %	0.7 %
Collector_mechanical_downtime	9.9 %	10.4 %	11.0 %
Collector_planned_maintenance	5.3 %	6.8 %	9.7 %
Collector_weather_downtime	5.0 %	5.0 %	5.0 %
Unloader	**Minimum**	**Average**	**Maximum**
Utilization_rate_unloader	14.9 %	15.4 %	15.7 %
PV_hold_empty	67.6 %	69.7 %	70.9 %
Unloader_mechanical_downtime	1.8 %	1.9 %	2.0 %
Unloader_no_BC1	11.5 %	13.0 %	14.8 %
Unloader_unloading_speed	0 t/h	451.9 t/h	2500 t/h
BC1	**Minimum**	**Average**	**Maximum**
Sailing_BC1	44.0 %	44.8 %	45.4 %
BC1_unloading	15.9 %	16.1 %	16.3 %
BC1_loading	12.7 %	13.1 %	13.4 %
Total_pre_post_operations_BC1	12.8 %	13.5 %	13.9 %
Total_waiting_unloader_BC1	60.9 %	61.9 %	62.8 %
Total_mechanical_downtime_BC1	4.9 %	5.0 %	5.1 %
Total_planned_maintenance_BC1	4.1 %	4.2 %	4.3 %
Total_time_in_waitingQ_PV	25.9 %	30.9 %	38.6 %
Total_time_in_waitingQ_Terminal	1.91 %	2.26 %	2.96 %
Total_time_in_waitingQ_BC1	28.8 %	33.2 %	40.5 %
Waiting_due_capacity_terminal_or_PV	62.8 %	63.4 %	64.1 %
Mean_time_per_visit_at_PV	21.8 h	23.6 h	26.0 h
Waiting-time/service-time_ratio_at_PV	4.90 %	5.41 %	6.15 %
BC2	**Minimum**	**Average**	**Maximum**
Sailing_BC2	74.4 %	76.6 %	77.9 %
BC2_unloading	8.9 %	9.2 %	9.4 %
BC2_loading	11.6 %	11.9 %	12.0 %
Total_pre_post_operations_BC2	4.5 %	4.7 %	4.7 %
Total_mechanical_downtime_BC2	7.8 %	7.9 %	8.1 %
Total_planned_maintenance_BC2	3.4 %	3.5 %	3.6 %
Total_time_in_waitingQ_PF	2.56 %	3.09 %	3.69 %
Total_time_in_waitingQ_Terminal	3.0 %	6.4 %	12.3 %
Total_time_in_waitingQ_BC2	6.7 %	9.5 %	14.8 %
Waiting_due_capacity_terminal_or_PF	6.13 %	7.38 %	8.68 %
Terminal	**Minimum**	**Average**	**Maximum**
Unloading_berth_occupancy	59.3 %	63.9 %	67.8 %
Loading_berth_occupancy	77.2 %	79.2 %	79.8 %
Utilization_rate_unloading_equipment	35.2 %	39.2 %	41.2 %
Utilization_rate_loading_equipment	67.2 %	69.2 %	69.8 %
Terminal_full	0.0 %	0.56 %	1.69 %
Terminal_empty	0.0 %	2.57 %	7.72 %
Mean_port_time_per_visit_BC1	67.1 h	67.9 h	69.6 h
Waiting-time/service-time_ratio_BC1	7.3 %	9.2 %	11.9 %
an_port_time_per_visit_BC2	110.0 h	133.4 h	168.7 h
Waiting-time/service-time_ratio_BC2	53.8 %	69.7 %	79.7 %
Downtime_unloading	0.0 %	0.7 %	2.2 %
Downtime_transport_to_terminal	0.0 %	0.3 %	0.9 %
Downtime_stacking	0.0 %	0.1 %	0.4 %
Downtime_reclaiming	0.0 %	0.2 %	0.6 %
Downtime_transport_from_terminal	0.0 %	0.4 %	1.1 %
Downtime_loading	0.0 %	0.1 %	0.2 %
Shortcut_utilization_BC1	63.3 %	66.2 %	67.7 %
Shortcut_utilization_BC2	85.8 %	89.9 %	92.1 %
Full_shortcut_stockpile	1.1 %	1.1 %	1.2 %
Empty_shortcut_stockpile	0.9 %	0.9 %	1.0 %
PF	**Minimum**	**Average**	**Maximum**
Berth_occupancy_PF	85.8 %	87.5 %	88.5 %
Utilization_rate_unloading_equipment	0.0 %	3.0 %	8.9 %
Downtime_unloading_equipment	0.0 %	0.6 %	1.8 %
Mean_port_time_per_visit_BC2_PF	713.6 h	752.6 h	786.5 h
Waiting-time/service-time_ratio_BC2_PF	10.6 %	12.4 %	14.4 %

Table 3.16: Output runfile model V3 - Terminal Operations + Roundtrips

The following key performance indicators have been utilized:

- Collector days lost due to hold full: During all the experiments, it is crucial that the production vessel is able to mine continuously. When the hold of the production vessel has reached its limit, the collector has to stop. The stream of shuttle bulk carriers at the production vessel should be sufficient to restrict the lost collection days, otherwise the yearly production rate targets will not be met.
- Yearly production rate: When the collector loses too many days because of a full hold, the yearly production rate will be lower. This also gives an indication for a bottleneck within the chain.
- Berth occupancy: A high berth occupancy results in long vessel waiting times at the terminal [61].
- Time in waiting queue at production vessel: The time in the waiting queue at the production vessel is a very important performance indicator. Too many bulk carriers might result in long waiting times at the production vessel.
- Time in waiting queue at terminal: The waiting-time/service-time ratio is a common performance indicator [61]. Possible waiting time must be avoided to avoid demurrage costs. The ship-owner must pay demurrage costs if the expected port time is exceeded [61].
- Terminal capacity: The terminal capacity also says something about the performance. Especially the terminal capacity at the end of a simulation. The terminal capacity could slowly become zero or stay at a constant level. The case where the terminal capacity slowly becomes zero is of course more beneficial, since the terminal capacity can be much lower.
- Time in waiting queue at processing facility: The time in the waiting queue at the processing facility is a very important performance indicator. The processing facility only has one berth, and too many bulk carriers might result in long waiting times at the processing facility.
- Utilization rate of equipment: The utilization rate of equipment is a common performance indicator for terminals [61].
- Waiting-time/service-time ratio: The waiting-time/service-time ratios (wt/st ratios) are widely used as a measure of the level of service provided by a terminal. It is usually considered that waiting time should be not more than 50 per cent of working time. When the plan has been based on investing for the economic optimum, the wt/st ratio should be generally less than 30 to 40 per cent [61].
- Port time: Another widely used measure of port performance is the pre-mentioned port time, which includes the vessels time at the berth and the vessels waiting time for a berth. [61]

3.4.2. Implementation

Like the previous models, this model is divided in seperate files. A full list is provided below:

- Production vessel: the processes of the collector and unloader which belong to the production vessel are coded in this file.
- BulkCarrier1: the bulk carrier which executes the roundtrips from the CCZ (mining location) to terminal is coded in this file.
- BulkCarrier2: the bulk carrier which executes the roundtrips from the terminal to the processing facility is coded in this file.
- Location file: this file enables fast and easy adjustments when it comes to the location of the terminal, mining location and processing facility. This file calculates the distance between these points.
- Simulation: this file contains all the simulation variables. All the variables can be changed quickly in this file.
- Run file: this file is used to run the whole simulation (resulting in an output which can be seen in table 3.1).
- Terminal: the terminal processes for a BC1 and BC2 bulk carrier are described in this file:
  BC1 terminal operations (unloading berth):
  Once a berth is available, the bulk carrier leaves the waiting queue at the anchorage point to sail towards the berth. An important note is that the waiting queue at the terminal is still divided into a waiting queue for roundtrip 1 with BC1 and roundtrip 2 with BC2. The reasoning for this

has already been provided in section 3.3. The sailing towards the berth is incorporated in the pre-unloading operations at the terminal, as well as the pilots, administration, etc. In the case of running experiments with the 'shortcut' function, a constant check is performed whether a BC2 bulk carrier is also present at the terminal. If that is the case, the unloading will be performed via the shortcut, which means terminal transport to and from the stockpile, as well as stacking and reclaiming is unnecessary. A separate stockpile has been modelled for the shortcut. In case of mechanical downtime of the loader or transport towards the loader, the unloading can continue, but the nodules will not be directly transported to the other bulk carrier, but temporarily stored at the small stockpile. This size of stockpile is for example three times the maximum unloading rate. This enables continuation of unloading for 3 hours when the loader or shortcut terminal transport experiences mechanical downtime. This should be sufficient for the majority of mechanical downtime. Furthermore, when mechanical downtime occurs at unloading stage 3 (will be explained below), the buffer of the shortcut stockpile enables for many more hours repairing time without interrupting the unloading operations.
The unloading will take place in various stages. These unloading stages are displayed in figure 3.14 [23]. The stages are divided into three stages:

- Free digging: maximum unloading rate for a hold capacity between 100 and 50 %
- Intermediate digging: between 100 and 66% of the unloading rate for a hold capacity between 50 and 15%.
- Trimming stage: between 66 and 16% of the unloading rate for a hold capacity between 15 and 0%.

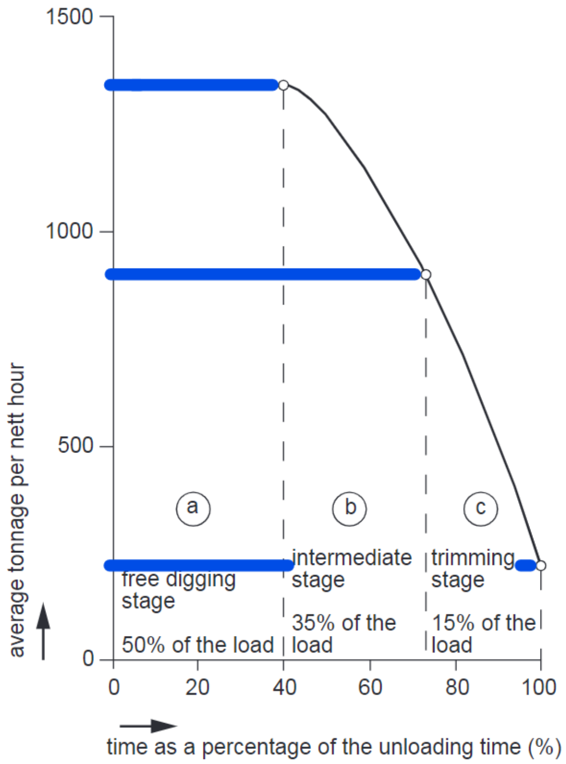


Figure 3.14: Unloading stages - blue bars indicate the 100%, 66% and 15% mark of the rated unloading rate (reworked from Ligteringen, 2017, by TU Delft - Ports and Terminals)

In the programming file, the unloading rate is constantly calculated due to the unloading stages. This is done according to the formulas which are displayed in figure 3.15. The unloading rate is calculated by multiplying the unloading rate percentage with the rated unloading rate used at the free digging stage.

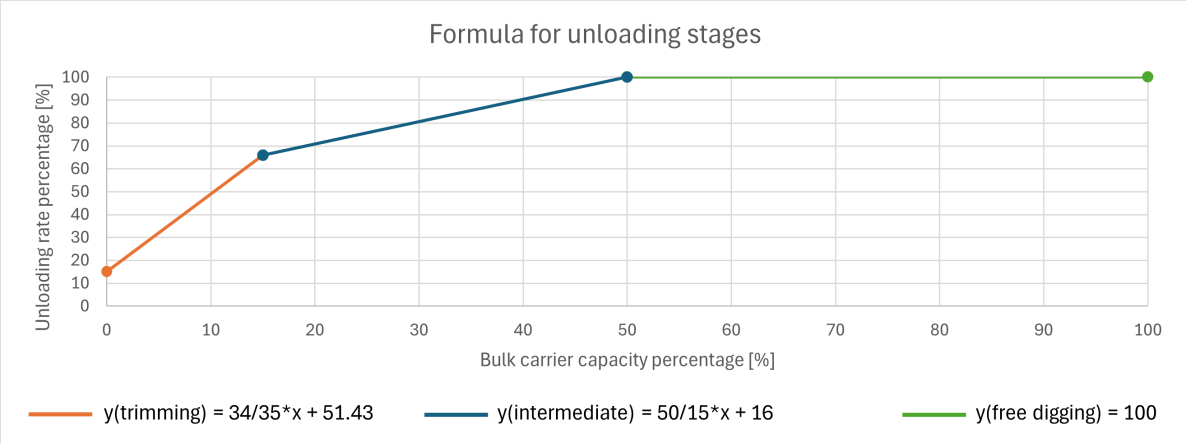


Figure 3.15: Unloading rate formulas for trimming, intermediate and free digging stage

During the unloading with the shortcut, checks are performed for mechanical downtime of the unloader, terminal shortcut transport and the loader of the BC2 bulk carrier. Crew changes are also performed every 8 hours. After 7.5 hours, 0.5 hours are required for a crew change, which means the terminal operations are terminated.
If the BC2 bulk carrier berth is not occupied, the unloading shortcut is not used. The unloading then stays the same, apart from the fact that mechanical downtime of the stacker and transport towards the stockpile is now taken into account. The unloading operations are stopped when the maximum capacity of the terminal has been reached. When the BC1 bulk carrier is empty, the post-unloading operations (such as deberthing) are executed.
BC2 terminal operations (loading berth):
Once a berth is available, the bulk carrier leaves the waiting queue at the anchorage point to sail towards the berth. This is incorporated in the pre-unloading operations at the terminal, as well as the pilots, administration, etc. Then a constant check is performed whether a BC1 bulk carrier is also present at the terminal. If that is the case, the shortcut will be used. The BC2 bulk carrier is then loaded with two streams. One stream directly from the BC1 bulk carrier and one conventional stream from the stockpile.
If the BC1 bulk carrier berth is not occupied, the shortcut is not used. This results in one stream nodules coming from the terminal which will be loaded at a constant rate into the BC2 bulk carrier. While loading, checks are performed for mechanical downtime of the reclaimer, transport from the stockpile and the loader. Crew changes are also performed every 8 hours. After 7.5 hours, 0.5 hours are required for a crew change, which means the terminal operations are terminated. The loading will be stopped when the terminal capacity equals zero. When the holds of the BC2 bulk carrier are filled, the loading will also be stopped and the post-loading operations are executed.

- Processing facility: In this file, the terminal operations at the processing facility are simulated:
  Once a berth is available, the bulk carrier leaves the waiting queue at the anchorage point to sail towards the berth. This is incorporated in the pre-unloading operations at the terminal, as well as the pilots, administration, etc. The bulk carrier is then unloaded with a varying unloading rate because of the unloading stages explained in figure 3.14. When the arriving bulk carrier is a self-unloader, the unloading rate will be constant throughout the hold capacity of the ship. During the unloading, checks are performed whether the unloader experiences mechanical downtime. Downtime for the stacker and terminal transport are not taken into account at the processing facility due to the buffer zone at the quay, where the material can be temporary stored. The temporary stored material will then be moved by wheelloaders towards the conveyor belt for transport towards the stockpile in the hinterland. When the bulk carrier is empty, the post-unloading operations are executed. The processing facility is operated 7 days a week for 8 hours a day and will be further explained in section 4.2.

3.4.3. Verification

The verification of model V3 - Terminal Operations and Roundtrips is based on the verification of model V1 and V2, where some checks are generalized to make sure there are not 50 separate verification checks. The random.seed function is once again used during the verification. The verification checks are listed in the subsections below.

Verification of mechanical downtime and planned maintenance

The verification of mechanical downtime and planned maintenance is explained below in table 3.17.

Test	Expectation	Outcome
Mechanical Downtime Terminal Equipment: See whether mechanical downtime of the terminal equipment occurs at the terminal and how long it takes to repair.	The repair time (diagnose included) duration should be between 0.5 and 48 hours for the loader, unloader, transport to and from terminal, stacker and reclaimer.	The mechanical downtime of the terminal equipment is indeed in between 0.5 and 48 hours.
Mechanical Downtime Processing Facility Equipment: See whether mechanical downtime of the processing facility equipment occurs and how long it takes to repair.	The repair time (diagnose included) duration should be between 0.5 and 48 hours for the unloader at the processing facility	The mechanical downtime of the unloader at the processing facility is indeed in between 0.5 and 48 hours.
Extensive Planned Maintenance Bulk Carrier: Does the bulk carrier experience mechanical downtime and what is the duration of this downtime.	The bulk carriers for both roundtrips should experience extensive planned maintenance at a random moment in time within the first year. After the first extensive maintenance event, an interval of at least 7500 hours is managed. The duration should be 84 hours or 80 hours in case the routine planned maintenance already has been executed.	All the bulk carriers experience extensive planned maintenance at a random instance during the first year. After the first occurrence, the interval of at least 7500 hours is managed. The duration is also as expected with 84 hours, and sometimes 80 hours when the routine planned maintenance is recently executed.
Planned maintenance Terminal Equipment: Planned maintenance is not taken into account. It is assumed that the utilization rate of the terminal and processing facility equipment is low enough to assume planned maintenance is executed in the remaining hours.	There should be plenty of intervals where the terminal equipment is not used. These intervals should also be several hours to make sure the planned maintenance can be executed. This happens when the loading or unloading berth is empty for example.	A test has been performed with a yearly production rate of 3 million tons per year. The unloader at the terminal has the highest utilization rate with roughly 50%. In the remaining 50%, there should be plenty of time for planned maintenance. Furthermore, in the simulations, big intervals can be seen where the unloader and other equipment are standby.

Table 3.17: Verification of mechanical downtime and planned maintenance

Verification of shortcut usage

The verification of shortcut usage is explained below in table 3.18.

Test	Expectation	Outcome
Shortcut Utilization: Check whether the shortcut is used at the right instances.	The shortcut should be used when the condition is set at True in the simulation file and both bulk carriers are present at the terminal.	The shortcut is indeed used when the condition is set at True and when both bulk carriers are at the terminal.
Shortcut Stockpile Capacity: See if the maximum shortcut capacity is not breached.	A small stockpile is generated in order to compensate for mechanical downtime in the shortcut chain. This stockpile should be zero at the end of the shortcut use and the maximum capacity should not be breached.	The stockpile is indeed zero after the shortcut utilization. The maximum capacity is also not breached.

Table 3.18: shortcut

Verification of the unloading stages

The verification of the unloading stages is explained below in table 3.19.

Test	Expectation	Outcome
Unloading Stages at Terminal: Check if the unloading stages are used correctly	The unloading should be divided into three stages. Where the first 50% should be the free digging stage where the unloading rate is at its maximum. For the remaining 50% of the hold capacity the unloading rate gradually decreases.	The unloading stages are indeed used correctly. The unloading rate indeed decreases after the first 50% of the hold of the bulk carrier.
Unloading Stages at Processing Facility: Check if the unloading stages are used correctly	The unloading should be divided into three stages. Where the first 50% should be the free digging stage where the unloading rate is at its maximum. For the remaining 50% of the hold capacity the unloading rate gradually decreases.	The unloading stages are indeed used correctly. The unloading rate indeed decreases after the first 50% of the hold of the bulk carrier.

Table 3.19: unloading

Verification of energy consumption

The verification of energy consumption is explained below in table 3.20.

Test	Expectation	Outcome
Energy Consumption: See whether the energy consumption is correctly calculated during (un)loading at the terminal	Every unloading or loading step results in a specific energy consumption. The energy consumption depends on the (un)loading rate and the use of the shortcut. The bulk carrier at the terminal also consumes energy while docked.	For traditional loading or unloading, the energy consumption is correctly calculated where all the terminal equipment is taken into account. For shortcut loading and unloading, the energy consumption of only the loader, unloader and shortcut terminal transport are taken into consideration. Furthermore, the energy consumption of the bulk carriers is calculated correctly when the bulk carrier utilizes the berth.

Table 3.20: energy

Verification of the crew changes

The verification of the crew changes is explained below in table 3.21.

Test	Expectation	Outcome
Crew Changes Terminal: See whether the crew changes at the terminal are executed corrected.	Crew changes at the terminal should occur every 7.5 hours (while unloading or loading) and should last 0.5 hours. A crew change during mechanical downtime of certain terminal equipment should be executed but does not slow down the repairing time.	In the simulation, the crew changes are indeed executed at the right interval. The duration is also correct. Crew changes during mechanical downtime indeed do not influence the repairing time.
Crew Changes Processing Facility: See whether the crew changes at the processing facility are executed corrected.	Crew changes at the processing facility should occur every 8 hours (while unloading) and should last 16 hours. The employees at the processing facility work 7 days a week but only for 8 hours per day. A crew change during mechanical downtime of certain terminal equipment should be executed but does not slow down the repairing time.	The crew changes are executed at the right interval and have the correct duration. Crew changes during mechanical downtime indeed do not influence the repairing time.

Table 3.21: crew

3.4.4. Validation

The validation which will be used can be divided into three categories: data validation, structural validation and face validation. These three categories will be addressed in the subsections below.

Data validation

Data validation focuses on the used data for the model (like distributions or historical data). The data validation is provided below:

- Energy consumption of a bulk carrier: In order to calculate the energy usage at the terminal, the power consumption of a bulk carrier while docked should be calculated. This power consumption will be later used to compare a diesel generator versus onshore power supply. The literature states that for the majority of the bulk carriers, the power consumption should be between 100 and 500 kW [82]. Allseas assumes 250 kW for now (ship size does not matter), which fits in the range. So for the simulations, an energy consumption of 250 kW per hour has been used.
- Shortcut stockpile capacity: the capacity of the temporary stockpile which is used at the shortcut should be validated. This stockpile cannot be too big, since this would take up too much quay space. The storage area is calculated below and a conclusion has been drawn whether that is a feasible storage area.
  For the calculation, an apparent density is taken of 1200 kg/m3, which has been researched in the literature assignment of Ree, Chris van der (2023). In this literature assignment, the angle or repose has also been investigated. Values between 30 and 37 degrees were found. A test with intact nodules found an angle of repose between 31 and 33 degrees [83]. The nodules at the terminal will not be intact and thus have a smaller particle size. A smaller particle size generally results in an increase of the angle of repose [84]. Because of the smaller particle size, an angle of repose of 37 degrees is assumed. Below in figures 3.16 and 3.17, a test case is visualized. The maximum shortcut stockpile capacity is set at 3 times the maximum unloading rate, which is 3*1500 = 4500 tons. A tool has been used to estimate the size of the stockpile in case the shortcut stockpile reaches its maximum of 4500 tons. A coned pile with a diameter of 35 meters and a height of 12 meters should be sufficient. This results in a slope of 34.4 degrees, which is

less than the angle of repose of 37 degrees. A diameter of 35 meters is assumed to be feasible for the terminal and does not take up too much quay space.

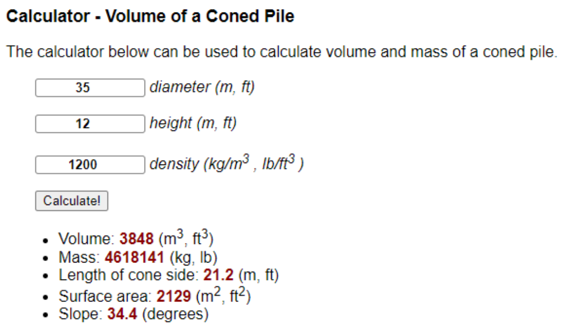


Figure 3.16: Calculation for a coned pile [85]

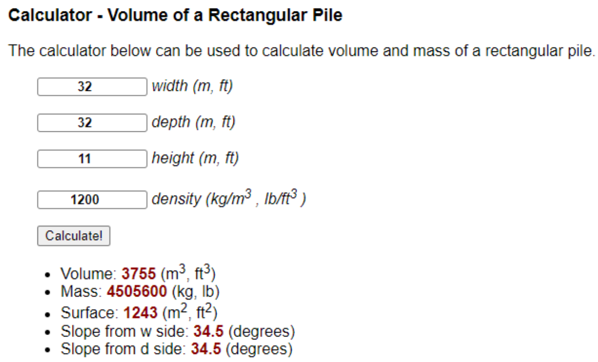


Figure 3.17: Calculation for a rectangular pile [85]

- Energy consumption calculation terminal equipment:

  The energy consumption of the terminal equipment is determined by using tables 3.22 and 3.23. A conversion coefficient of equipment operational quantity is used. This coefficient helps in standardizing energy consumption so a comparison can be made how much energy each piece of equipment uses relative to the operational quantity intensity and the throughput [86].

Handling production process	**Main energy consumption equipment**	**Conversion coefficient of equipment operational quantity.**
Shore-side handling	Mobile ship loader	0.5
	Bridge grab ship unloader	0.5
	Trimming bulldozer (for hold cleaning)	0.05
Horizontal transport	Belt conveyor	1.0
Storage area operation	Bucket-wheel stacker reclaimer	2.0
Truck handling operation	Truck loader	0.5
	Screw unloader	0.5

Table 3.22: Main energy consumption equipment [86]

Handling production step	**Main energy consumption equipment**	**Conversion coefficient of equipment operational quantity.**
Shore-side handling	10t/16t gantry crane	0.5
	25t/40t gantry crane	0.5
	Single-bucket loader (for hold cleaning)	0.05
Horizontal transport	Traction trailer	1.0
Storage area operation	Single-bucket loader	1.0

Table 3.23: Main energy consumption equipment [86]

The most accurate equipment to calculate are the mobile shiploader and belt conveyor. This can be done by simple hand calculations with potential and kinetic energy. Calculation tools can also be used to calculate the required power. In the end, a calculation sheet has been used which is based on a handbook of Rulmeca [87], which is specialized in belt conveyors. The calculation can be used to determine the energy consumption of a belt conveyor and a mobile shiploader. A handling rate of 1500 tons per hour has been selected as a base case. The required power for a belt conveyor and a mobile shiploader is strongly related to the tonnage rate in tons per hour. To simplify the programming code, this relation is assumed as linear. The calculation tool shows that a doubling in the tonnage rate does not result in a doubling of the required power. It results in less required power but this is not taken into account. This is because running an empty belt already requires significant power.

The other inputs for the calculation are provided below:

- Total belt conveyor length horizontal: 1500 meter. This is based on other terminal examples and simulations ([88], [86]). This means that 750 meter of belt conveyor is used to transport material towards the stockpile and 750 meter is used to facilitate reclaiming operations. The transport towards and from the stockpile is divided into three conveyors of each 250 meters. One parallel to the quay, one perpendicular to the quay and one parallel to the stockpile.
- belt conveyor length shiploader: 40 meter. The 40 meter is based on an existing mobile shiploader with a loading capacity between 100 and 3000 tons per hour [89]. The working length is between 25 and 58 meters due to a telescopic arm.
- Material lift height shiploader: 12.5 meter. This value is also based on the existing mobile shiploader [89], where the Discharging height can be varied between 9.3 and 19.6 meter.
- Belt speed: for both calculations a belt speed of 3 m/s is selected. This is based on a study which investigated active belt control. The minimum belt speed is 2 m/s and the nominal belt speed is set at 4 m/s at a tonnage rate of 2000 tons per hour [90]. For the calculation, a handling rate of 1500 tons per hour is selected, so the belt speed is also lowered to 3 m/s.
- Belt cleaners: for the short mobile shiploader, 1 belt cleaner has been selected. For the longer horizontal belt conveyor, 3 belt cleaners has been selected. Both conveyors have one return belt scraper.
- Non-driven pulleys: for the short mobile shiploader, 1 non-driven pulley is selected. For the longer horizontal belt conveyor, 4 non-driven pulleys has been selected.
- Condition of idlers and pulleys: for both calculations well maintained has been selected.
- Ambient temperature: for both calculations a minimum ambient temperature of -10 degrees and a maximum ambient temperature of 40 degrees Celsius has been selected.

With the inputs which are provided above, the required power for the mobile shiploader equals 73.3 kW. The required power for the horizontal belt conveyor with a total length of 750 meter equals 156.1 kW. This confirms the outcomes of table 3.22, where the horizontal transport consumes two times more energy compared to a mobile ship loader. The required power of the horizontal transport can now be safely used to estimate the required power of other terminal equipment. The required power is linked to the loading and unloading rate at the terminal. For horizontal transport of the nodules towards the stockpile, the formula becomes:
energy-terminal-transport = (156.1/1500) * unloading-rate-terminal

- Energy consumption shortcut terminal transport:

  With the same method as above, the energy consumption of the shortcut terminal transport has been calculated. The belt conveyor length is set at 300 meter. This is based on the expected vessel length for a bulk carrier [91] from the table in appendix C. An expected vessel length of 150 to 300 meters is expected. 300 meter is chosen to also account for the mooring lines. 2 belt cleaners are expected and 2 non-driven pulleys. The other variables are the same as the calculation above. The formula for energy consumption at the shortcut equals:
  energy-shortcut-terminal-transport = (71.9/1500) * unloading-rate-terminal

Structural validation

Structural validation addresses the structure of the model and whether the simplifications that have been made do not impact the results excessively.

List of simplifications:

- Planned maintenance equipment:
  The planned maintenance of the terminal equipment is not taken into account. This should not have influence on the outcome of the experiments. The utilization rate of the equipment is investigated in table 3.17 above. This shows that there should be plenty of time remaining for planned maintenance outside the operational time.
- Energy consumption simplification:
  The energy consumption of the terminal has been simplified with the use of tables 3.22 and 3.23. For example, the energy consumption of the loader should be the same as the 500 meter belt conveyor, but it can be seen there is a small difference. Undoubtedly, there will also be small differences for the energy consumption of the other terminal equipment such as the stacker. This means that the final energy consumption output is less accurate. However, the main goal is to

quantify energy reduction techniques and strategies, not to calculate the exact energy consumption.

- Idling energy consumption not taken into account:
  The idling energy consumption of equipment has not been taken into account. The same holds as the point above: the main goal is to quantify energy reduction techniques and strategies, not to calculate the exact energy consumption. So this simplification should not give any problems.
- Distance between stockpile and berth:
  For the calculation of the energy consumption, a standard distance between the stockpile and berth is assumed. In reality, this distance depends on the terminal capacity at that moment. When the terminal is almost full, the material needs to be stacked further away, which means slightly more energy is used. So the energy consumption of the terminal transport varies constantly. The should not have a big impact on quantifying energy reduction techniques and strategies. It is also unknown how the final terminal layout will look like, so this is the best option for now.
- Belt conveyor lengths:
  For the calculation of the energy consumption of the terminal transport, 6 conveyors are assumed with each having a length of 250 meters. In reality, one conveyor could have a length of 400 meters and another one of 50 meters. As explained above, the terminal layout is unknown and as long as the total distance of the terminal transport is more or less accurate, this should not have a big impact on the outcomes of the experiments.

Face validation

Face validation is a form of validation that relies on an individual. I have used the experience of Jan Hiltermann, who has over 14 years of experience in the dry bulk handling industry [92]. Jan Hiltermann was able to help regarding mechanical downtime of terminal equipment, which validates the numbers used for mechanical downtime of all terminal equipment (unloader, loader, stacker, reclaimer and terminal transport) and the unloading equipment at the processing facility.
Finding what causes mechanical downtime is doable with existing literature, although finding values for the yearly mechanical downtime percentage and duration proved to be very difficult to find. Jan Hiltermann pointed out that loaders, terminal transport and stackers generally have an operational uptime of 98%. An important remark, is that his operational uptime for terminal transport is per element. For example, if four belt conveyors are used for terminal transport, the operational uptime is 0.98^4. An unloader is a bit more fragile and typically have an operational uptime of 95%. A reclaimer has an operational uptime of 97%. This confirms the literature, which states that a (bucketwheel) reclaimer is very sensitive to changes in balance, resulting in more likelihood for failures [93].
The mean time to repair is equal for all the terminal equipment. Three scenarios of mechanical downtime have been taken into account. The scenarios and corresponding repair time duration are listed below:

- 0.5-2 hours: mechanical downtime which happens on a weekly basis. The minimum diagnose and repairing time is 0.5 hours
- 6-8 hours: mechanical downtime which happens for example 3 times a year.
- 30-48 hours: mechanical downtime which happens for example once a year.

One scenario is not taken into consideration, due to the rareness. This scenario happens once every 10 years and the duration equals 1 or 2 weeks. The three scenarios are captured in a lognormal distribution which is visualized in figure 3.18.

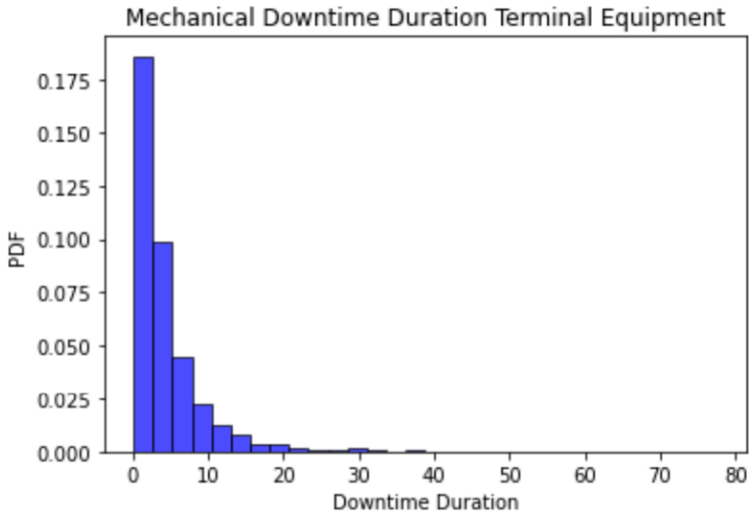


Figure 3.18: Distribution of mechanical downtime duration terminal equipment

3.4.5. Calibration

The calibration is used to estimate and adjust/fine-tune parameters and constants. The following parameters and constants are calibrated:

- Mechanical downtime for the unloader at the terminal
- Mechanical downtime for the transport towards the stockpile at the terminal
- Mechanical downtime for the stacker at the terminal
- Mechanical downtime for the loader at the terminal
- Mechanical downtime for the transport from the stockpile at the terminal
- Mechanical downtime for the reclaimer at the terminal
- Mechanical downtime for the shortcut transport at the terminal
- Mechanical downtime for the unloader at the processing facility

The duration of the mechanical downtime of all the equipment is known. The yearly mechanical downtime percentages are also known. The chance for the mechanical downtime to happen should be calibrated to match the desired yearly mechanical downtime percentages. This is done by running the simulations multiple times and fine-tuning the chances for mechanical downtime to happen. The chances change when the terminal shortcut is used, which results in less utilization of the reclaimer, which has to be compensated by adjusting the chance. This not only holds for the reclaimer, but also for the stacker and terminal transport to and from the stockpile.

3.5. Conclusions

In this chapter, the following sub-question is answered:

How should a simulation model be designed to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and the amount of machinery and their specifications?

To develop the desired model, a literature research have been executed about the design of dry bulk terminals using the simulation-based approach. Discrete event simulation (DES) is used in the majority of the simulations. DES offers many advantages, such as low computational costs, flexibility in adjusting, high accuracy, identifying utilization of equipment and finally the ability to identify bottlenecks and constraints [56]. Python in combination with the free add on SimPy will be used as a programming language.

The simulation model will be used to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and lastly, the amount of machinery and their specifications at the terminal. The majority of the supply chain is integrated within the model. Starting with the production vessel and the collection process. The production vessel will use the principle of a self-unloader to transfer the nodules to the shuttle bulk carrier which sails between the transshipment terminal and the production vessel. At the transshipment terminal, the operations to handle the nodules, like unloading, loading, transport, stacking and reclaiming are modelled. Important to mention is that the unloading rate decreases as the hold capacity of the bulk carrier decreases. This is not the case for the unloading of the production vessel, since a self-unloader is able to maintain a constant unloading rate. The terminal will operate according the SSHINC principle: saturdays, sundays and holidays included. Practical experience points out that 360 working days at the terminal is feasible (minus the weather downtime which will be addressed that later on). Besides the roundtrip of bulk carriers between the production vessel and the transshipment terminal, there is another roundtrip between the terminal and processing facility. Bulk carriers will be filled at the terminal and sail towards at the processing facility where the unloading takes place, after which the bulk carriers will sail with an empty hold back towards the terminal. The processing facility is operated 8 hours a day.

Within the model, there are many stochastic influences. For instance planned maintenance and mechanical downtime for the bulk carriers, vertical transport system, unloader, collector and the terminal equipment. Furthermore pre- and post-loading and unloading operations at the production vessel and the terminal, due to waiting for tugs and/or pilots, (de)berthing operations, sailing from anchorage to berth, procedures time like authorities and a shipping agent and finally the start-up operations of equipment to handle the material. The varying density of nodules at the seabed has also been taken into account. Log-normal distributions are suited to generate failure times [66], so log-normal distributions are used to determine the duration of mechanical downtime and planned maintenance. Normal distributions are used for the remaining distributions, like the duration of pre- and post-loading operations. Waiting-on-weather is also taken into account. The wave conditions play an important role during ship-to-ship transfer [28]. For the case study, a total weather downtime of 5% per year is expected by experts within Allseas. This includes weather where the collector is unable to collect nodules, terminal operations have to stop and where the production vessel is unable to transfer nodules to the shuttle bulk carrier.

Multiple key performance indicators are used to assess the outcomes of the experiments. The obvious ones are the waiting times at the terminal, processing facility, and production vessel. The port time and waiting-time/service-time ratio are also used. As well as the utilization rate of equipment and berth occupancy at the terminal and processing facility. Finally the 'collector days lost due to full hold of production vessel' and linked yearly production rate are used. The 'collector days lost due to full hold of production vessel' is a very important key performance indicator. When the hold of the production vessel has reached its limit, the collector has to stop. The stream of shuttle bulk carriers at the production vessel should be sufficient to restrict the lost collection days, otherwise the yearly production rate targets will not be met.

4
Location Determination Transshipment Terminal

In this chapter, the following sub-question will be answered:

Which factors exert influence on the selection of a transshipment terminal location, and how can these factors be evaluated to identify the optimal location for Allseas?

First, the factors used for terminal location selection will be investigated by a literature study. Then a method will be selected to evaluate these factors. Finally, the method will come up with an appropriate location for Allseas, which will later on be used for the experiments in the next chapter (5).

As can be seen in figure 4.1, there are many options for a transshipment terminal (highlighted with coloured pins). Figure 4.1 shows one possible scenario where the yellow lines indicate the sailing route of the bulk carriers between mining location, terminal and processing facility. In this scenario, the transshipment terminal is situated in Mexico, but this chapter might point out that Hawaii for example is a better option. Furthermore, the criteria for location determination are discovered in this chapter. With these criteria, a decision can be made which terminal location is optimal for Allseas. The mining facility and processing facility are also shortly addressed in this chapter. However, these locations are predetermined for the case-study with Allseas.

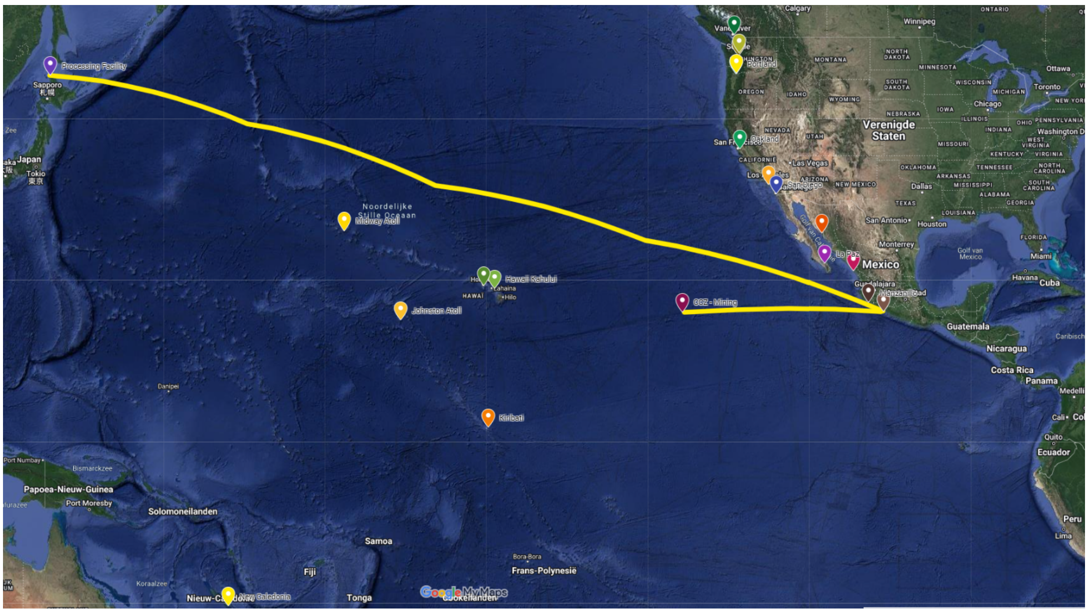


Figure 4.1: Complete overview of the possible mining, terminal and processing location in a top-view of the Pacific Ocean

4.1. Mining Location

The mining location will be within the NORI D area, which is situated within the The Clarion-Clipperton Zone (CCZ). The CCZ is the largest region containing nodules and is situated in between Hawaii and Mexico (see top right of figure 4.2). The NORI D area is the yellow square on the bottom right in figure 4.2. The production vessel will be located within the NORI D area and will unload the nodules at a constant rate with a belt conveyor into bulk carriers.

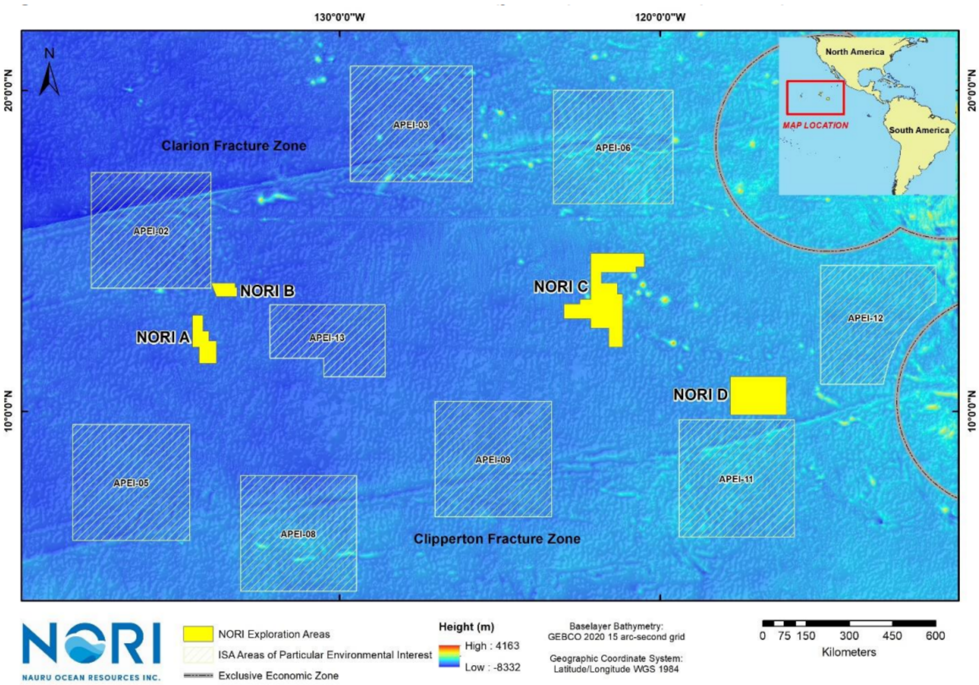


Figure 4.2: NORI D area within the CCZ [78]

4.2. Processing Location

There are several processing locations possible. For now, Allseas has decided to choose Hachinohe in the north of Japan for now. A top view of the processing facility location is depicted in figure 4.3 below. In the top right, the berth is illustrated and in the bottom left, the processing facility itself is depicted. The berth itself is also depicted in figure 4.4. There is one mobile crane at the berth. The material is then transported to a belt conveyor with wheel loaders. The belt conveyor transports the material towards the processing facility. The terminal is operated 7 days a week for 8 hours per day. Geared bulk carriers will be required at this terminal since the berth is equipped with only one mobile crane. The mobile crane will unload one hold at the time. A geared bulk carrier is able to use two additional deck-cranes (not all cranes can be operated at the same time due to a lack of qualified personnel and due to safety reasons). The deck-cranes are able to unload at a maximum rate of roughly 600 tph and this rate is followed by the mobile crane according to practical experience from Jan Hiltermann. Three cranes unloading at a rate of 600 tph equals a maximum unloading rate of 1800 tph. This value will be used in the experiments of chapter 5.3.1, and will not be exceeded since the remaining equipment at the processing facility is likely not designed for higher unloading rates.
For this thesis, the assumption has been made that other operations at the current processing facility quay will not exert influence on the experiments performed in chapter 5.

Figure 4.3: Top-view processing facility location Japan

Figure 4.4: Overview of the terminal at the processing facility location Japan

4.3. Terminal Location

The location determination for the terminal is performed with the weighted criteria method. This is a decision-making tool which evaluates the different options against weighted factors. The steps of this method are explained below.

4.3.1. Weighted Criteria Method

The first step is to determine the relevant criteria. The relevant criteria for the best terminal location are:

- **Infrastructure costs:** Assess the investing and operating costs of developing necessary infrastructure (e.g., berths, conveyor systems, storage silos) at the chosen location [94], [95]. An island is for example very expensive since all the construction materials need to be transported there by sea.

- **Environmental impact:** The environmental impact should also be taken into consideration [94]. Things like transportation pollution, noise and visual intrusion should be avoided [95]. So close to residents or a wildlife park or nature areas receive a lower grade in the decision-making tables.
- **Land accessibility:** Land accessibility is important for the transport of employees, maintenance or equipment. A huge impact on local traffic with road congestion should be avoided [94], [95].
- **Labour availability:** Labour availability should also be taken into account [95].
- **Water accessibility:** Water access is a crucial aspect. Things like the accessibility for big bulk carriers and distance from the sea are examples. If the terminal is situated inland, a lower score is provided due to added sailing time.
- **Land availability:** A high score is provided when the land availability is high to build the new transshipment terminal [94]. There should also be enough land available for future terminal expansion when the yearly production rates rise [94], [95].
- **Availability quay space:** Available quay space is a huge advantage. Existing quay space reduces the costs and time to build a terminal and expands the range of service [95].
- **Distance to CCZ:** Proximity to production is also mentioned as a criteria [95]. In this case the production location is situated in the CCZ. The smaller the distance, the lower the sailing time of course.
- **Distance to processing facility:** Besides the proximity to production, the proximity to another logistics platform is also key [95]. In this case, another logistic platform is the processing facility.

To prevent to go too much into detail and due to a lack of data, the following criteria are not taken into consideration:

- **Regulation and permitting requirements:** Research for compliance with zoning laws, permits, and other regulatory requirements [94] for bulk cargo handling are not taken into account.
- **Safety or weather resilience:** Resistance against natural disasters such as tsunamis, hurricanes, and global warming.
- **Labour costs:** Labour costs of local employees.
- **Economic regulations:** The return to the local government (taxes e.g.) is an example of economic regulatory [95]. Some countries will be more expensive, with possible tax per handled ton nodules.
- **Possibility to be close to new processing facilities/market demand:** The proximity to key markets and potential customers to reduce delivery lead times and transportation costs are not considered. There might be a processing facility in America in the future to get less dependent on other countries, but this results in too much uncertainties for the decision-making now.
- **Environmental regulations:** Compliance with local environmental regulations [95] is not taken into account.
- **Draft restrictions:** The draft restrictions for each waterway or harbour are not taken into account.
- **Tide influence:** The tide influences on each waterway or harbour are not taken into account.
- **Tug requirements:** The need for tugs for a certain waterway or harbour is not considered.

The second step is to classify these criteria. This is executed by using table 4.1 below. It can be seen that the distance from the mining location within the CCZ towards the terminal is considered more important than the distance towards the processing facility. This is because of crew changes at the production vessel. A shorter distance is beneficial for crew changes.

	Distance CCZ	Distance PF	Land access	Water access	Available quay space	Land availability	Labour availability	Environmental impact	Infrastructure costs	**Score**
Distance CCZ		+	+	+	+	+	+	+	+	**8**
Distance PF	-		+	+	+	+	+	+	+	**7**
Land access	-	-		-	-	-	-	+	+	**2**
Water access	-	-	+		-	-	+	+	+	**4**
Available quay space	-	-	+	+		+	+	+	+	**6**
Land availability	-	-	+	+	-		+	+	+	**5**
Labour availability	-	-	+	-	-	-		+	+	**3**
Environmental impact	-	-	-	-	-	-	-		+	**1**
Infrastructure costs	-	-	-	-	-	-	-	-		**0**

Table 4.1: Classify criteria

The third step is to determine the weighted factors (illustrated in table 4.2, where the difference in classification is quantified using the weighted factors. A weighted factor of 10, means that the distance from terminal to CCZ is very important. On the other hand, the weighted factor of 1 for infrastructure costs, indicates that infrastructure costs are not that important. 9 relevant criteria are selected so one weighted factor will not be used.

Weight	**Criterium**
1	Infrastructure costs
2	Environmental impact
3	Land access
4	Labour availability
5	Water access
6	
7	Land availability
8	Available quay space
9	Distance PF
10	Distance CCZ

Table 4.2: Weighted factors

The final step is to fill in the table, to finally determine which location should be chosen. The scores are given according a five-point scale:

1. Very poor
2. Poor
3. Average
4. Good
5. Excellent

There is a total of 19 possible locations. These are divided in the three tables below. Where the first table represents the locations in Mexico (table 4.3), the second table the locations in America and Canada (table 4.4) and finally the islands are displayed in the third table (table 4.5).

Criterium	Weight	La Paz		Guaymas		Mazatlán		Manzanillo		Lazaro Cardenas	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Infrastructure costs	1	5	5	5	5	5	5	5	5	5	5
Environmental impact	2	3	6	3	6	2	4	2	4	4	8
Land access	3	5	15	5	15	4	12	5	15	5	15
Labour availability	4	5	20	5	20	5	20	5	20	5	20
Water access	5	3	15	3	15	5	25	5	25	5	25
Land availability	7	4	28	2	14	2	14	2	14	4	28
Available quay space	8	1	8	4	32	5	40	5	40	5	40
Distance PF	9	2	18	2	18	2	18	2	18	2	18
Distance CCZ	10	5	45	4	40	5	50	5	50	5	50
Total score		**160**		**165**		**188**		**191**		**209**	

Table 4.3: Weighted criteria method score table for locations in Mexico

Criterium	Weight	Los Angeles		San Diego		Oakland		Portland		Tacoma		Seattle		Vancouver WA		Vancouver Canada	
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Infrastructure costs	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Environmental impact	2	5	10	2	4	3	6	4	8	4	8	3	6	4	8	3	6
Land access	3	5	15	5	15	5	15	5	15	5	15	5	15	5	15	5	15
Labour availability	4	5	20	5	20	5	20	5	20	5	20	5	20	5	20	5	20
Water access	5	5	25	5	25	5	25	3	15	4	20	4	20	3	15	4	20
Land availability	7	2	14	2	14	4	28	4	28	5	35	2	14	3	21	2	14
Available quay space	8	5	40	4	32	5	40	4	32	4	32	3	24	3	24	3	24
Distance PF	9	3	27	3	27	3	27	3	27	3	27	3	27	3	27	3	27
Distance CCZ	10	4	40	4	40	3	30	2	20	2	20	2	20	2	20	2	20
Total score		**196**		**182**		**196**		**170**		**182**		**151**		**155**		**151**	

Table 4.4: Weighted criteria method score table for locations in America and Canada

Criterium	Weight	Midway Atoll		Johnston Atoll		Hawaii Kahului		Hawaii Honolulu		Kiribati		New Caledonia	
		Score	Weighted	Score	Weighted	Score	Score	Score	Weighted	Score	Weighted	Score	Weighted
Infrastructure costs	1	1	1	1	1	2	2	2	2	1	1	2	2
Environmental impact	2	3	6	3	6	3	6	3	6	1	2	3	6
Land access	3	1	3	1	3	2	6	2	6	1	3	2	6
Labour availability	4	1	4	1	4	4	16	4	16	1	4	5	20
Water access	5	5	25	5	25	5	25	5	25	5	25	5	25
Land availability	7	5	35	5	35	3	21	2	14	5	35	2	14
Available quay space	8	3	26	2	16	2	16	5	40	1	8	3	24
Distance PF	9	5	45	4	36	4	36	4	36	3	27	3	27
Distance CCZ	10	2	20	3	30	4	40	4	40	3	30	1	10
Total score		**163**		**156**		**168**		**185**		**135**		**134**	

Table 4.5: Weighted criteria method score table for island locations

According to the three score tables above (tables 4.3, 4.4, 4.5), a top 10 with the highest scores is formed, where Lazaro has the highest score:

1. Lazaro
2. Los Angeles
3. Oakland
4. Manzanillo
5. Mazatlán
6. Hawaii Honolulu
7. Tacoma
8. San Diego

9. Portland
10. Hawaii Kahului

The next step was to figure out whether these locations actually have the potential for a transshipment terminal. This is done by using Google Earth and looking for available land and existing quay length or berth places. The ten locations are then listed from high potential to low potential in table 4.6. In this table the geographical coordinates are also provided.

Ranking	Location	Latitude	Longitude
1	Lazaro	17.930785	-102.168934
2	Portland	45.615250	-122.782817
3	Tacoma	47.276592	-122.397549
4	Los Angeles	33.770331	-118.244888
5	Oakland	37.780809	-122.258309
6	Hawaii Kahului	20.897637	-156.478077
7	Hawaii Honolulu	21.318974	-157.880325
8	Manzanillo	19.072915	-104.286429
9	San Diego	-	-
10	Mazatlán	-	-

Table 4.6: Ranking of locations after investigation for available land, existing quay length and berth places

The decision making is very straightforward in this case. Lazaro comes in both tests out on top. The assigned weights in table 4.2 are not based on literature. So a different weight distribution could result in another outcome regarding the weighted criteria method. However, the top 10 scores of the weighted criteria method are investigated by using Google Earth (to check available land and existing berths or quay length), to make the final decision. Changing the weights could result in a different order of the top 10 ranking, but Google Earth is still used as a second step in the decision-making process. So changing the weights would not necessarily change the chosen location in the end.

A 3D top view of the location in the port of Lázaro Cárdenas is shown below in figure 4.5 with the help of Google Maps [96]. The colour areas in the figure are explained below:

- Yellow area: the two yellow areas are currently used for coal storage. A power plant is located A few kilometers north of this storage location. A huge advantage is that it might be easier to get a permit for the building of a new dry bulk terminal. Since a coal terminal is nearby, the location should be fine with respect to, for example, distance to residential neighbourhoods.
- Blue area: the three blue areas indicate berth places. The available of existing berth places is another big plus. An ideal scenario might be to use these berth places in the beginning stage, but it also shows that the making of a quay wall is possible. The top and lower blue berths are equipped with an unloader, belt conveyor and hopper to process the coal.
- Red line: the red arrow indicates the belt conveyor. This belt conveyor is used to transport the coal form the berth towards the storage area. At the top of the figure, another red arrow can be seen. This arrow indicates the outgoing flow of the storage facility towards the power plant.
- Green area: the green area shows a potential terminal location. This area is flat and unused at the moment. An online tool was used to determine the total surface area, which equals 0.9 km^2 [97].

Figure 4.5: Current situation terminal location Lazaro

The suggested area above of 0.9 km^2 might not be sufficient for the future or is (partially) unavailable. Research has been executed to look for other possibilities within the port of Lázaro Cárdenas. Again, with the use of the online tool, figures have been made and the areas are calculated. The first expansion possibility is displayed in figure 4.6. The green areas represent the potential space for the dry bulk transshipment terminal. The left area is the same area as figure 4.5. The right area represents the possible enlargement. The total area has now increased to a total of 1.8 km^2.

Figure 4.6: Possible expansion to 1.8 km^2

When the 1.8 km^2 of figure 4.6 is insufficient or unavailable, there are other possibilities for the positioning of the dry bulk terminal. All the possible locations are provided in figure 4.7. This has a total surface area of 7.5 km^2. This should be more than enough, since one of the largest dry bulk terminals of Europe (EMO in Rotterdam) has a surface area of 1.6 km^2 [98]. But it is very unlikely the total 7.5

km^2 is available, since land ownership and legislation was not taken into account. Think of a minimum distance from other companies or highways. Although, figure 4.7 shows that there is a lot of potential for the transshipment terminal. Especially because of the already existing coal terminal and container terminal. This shows that the waterways are suited for large ships and quay space is available or can be realized.

Figure 4.7: Possible expansion to 7.5 km^2

4.4. Conclusions

In this chapter the following sub-question is answered:

Which factors exert influence on the selection of a transshipment terminal location, and how can these factors be evaluated to identify the optimal location for Allseas?

There are 9 factors/criteria which are taken into consideration in this thesis for the selection of a transshipment terminal location. These 9 factors are: infrastructure costs, environmental impact, land access, labour availability, water access, land availability, available quay space, distance from terminal towards processing facility, distance from terminal to mining location. The criteria are ranked from least to most important respectively. There are many more criteria such as economic regulations. These are not taken into account due to a lack of available data or information. This would require an additional extensive research.

The weighted criteria method has been used as a multi-criteria decision making method. This method pointed out that Lazaro in Mexico is the optimal transshipment terminal location for now. On all the criteria it ended up with an excellent score. The only disadvantage is the distance towards the processing facility in Japan in comparison to especially island locations such as Hawaii. On the other hand, another advantage is the presence of an existing coal terminal. This takes away some uncertainties about certain environmental regulations, draft restrictions and tide influence. Since the existing coal terminal is also able to deal with these criteria.

Changing the weights could result in a different order of the top 10 ranking of the weighted criteria method, although the top 10 is further investigated regarding available land and existing berths or quay length. So changing the weights would not necessarily change the chosen location in the end.

5 Experiments and Results

In this chapter, multiple sub-questions will be answered. The first sub-question which will be addressed is the following:

Which experiments should be executed to simulate real-world scenarios, and what will the performance of the terminal be, when these experiments are performed?

As described in chapter 3, the model is divided into three versions (see figure 5.1). The experiments are also divided according these versions. A separate experimental plan is determined for each model. The experiments are performed for the case study of Allseas. For all the experiments, 5 scenarios for the yearly production rate are tested. Allseas is planning to linearly increase the production rate over the years. The first year, a production rate of 1 million tons per year is aimed for. The final goal is to reach a production rate of 3 million tons per year. The 5 scenarios are: 1, 1.5, 2, 2.5 and 3 Mt/year.

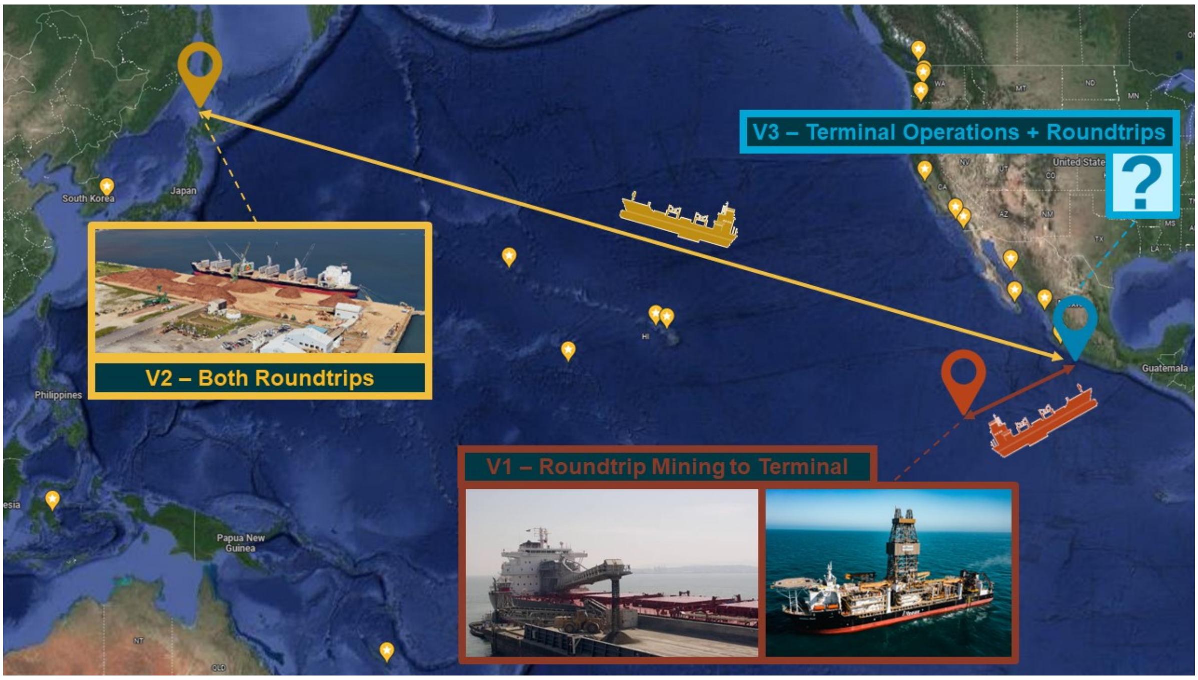


Figure 5.1: Three stages of the model: V1 - Roundtrip Mining to Terminal, V2 - Both Roundtrips, V3 - Terminal Operations + Roundtrips

The second sub-question in this chapter is:

What strategies and technologies can be implemented to mitigate energy usage at the transshipment terminal?

With a literature study, the energy reduction techniques and strategies will be investigated. Thereafter experiments are executed to quantify the impact of the reduction strategies and techniques.

The final sub-question that will be answered is:

To which extent are the established rules of thumb and practical experiences in the dry bulk terminal domain representative for the design of a dry bulk transshipment terminal for polymetallic nodule collection?

A literature study and expert interviews are used to investigate the rules of thumb and practical experiences. The results of the experiments for the case study will be compared to these rules of thumb and practical experiences.

5.1. Experimental Plan V1 - Mining to Terminal

Besides the varying yearly production rate, the bulk carrier capacities are also varied. Not every bulk carrier type is taken into account (an overview of the bulk carrier categories is provided in appendix C). This is because very large bulk carriers like the Chinamax (400 kDWT) the dynamic positioning system will be big and complex (and thus expensive) for sizes above Capesize. The availability of donorships is also difficult for bulk carriers above 200/250 kDWT according to experts within Allseas. These donorships are required since Allseas is not planning to build their own bulk carriers for now. The maneuverability is another disadvantage of such large bulk carriers, which is undesired during the STS transfer at the production vessel [99].

The bulk carriers which will be taken into account during the experiments with model V1 are:

- Handysize - 35 kDWT
- Handymax - 55 kDWT
- Panamax - 80 kDWT
- Post-panamax - 110 kDWT
- Capesize - 180 kDWT

The term deadweight tonnage (DWT) is simplified during this thesis. In reality, the deadweight tonnage of ship is the carrying capacity plus the fuel, crew, ballast water, fresh water and provisions. According to Dr.Ir. J.F.J. Pruijn, Associate Professor at the TU Delft [100], the additional numbers besides the carrying capacity account for a maximum of 5% of the DWT. For this thesis, the DWT is simplified to carrying capacity, which means for instance, a Handysize bulk carrier is able to carry 35.000 tons of nodules. The term DWT is still used in this thesis since it is a well-known measure within the maritime sector for the general dimensions of a ship and how much a ship can carry.
All the bulk carriers are bigger than the hold capacity of the production vessel, which equals 25000 tons for the case study. This has also been a recommendation in another research, which pointed out that transportation vessels are the cheaper asset, and should be able to allow for complete emptying of the production vessel when ship-to-ship transfer is used [28]. This reduced the chance of a full hold for the production vessel which prevents unwanted time-outs for the collector.

The following experiments will be executed:

- Varying the number of bulk carriers for the different yearly production rates and the different bulk carrier sizes.
- Varying the number of berths

5.1.1. Amount and Capacity of Bulk Carriers

For the experiments, the collector rate is adjusted to reach the desired yearly production rate of 1, 1.5, 2, 2.5 or 3 million tons per year. The production rate still slightly varies due to all the stochastic influences within the supply chain.

The production rate of the collector is varied as following:

- 1 mt/year - production rate = 170 tons/hour
- 1.5 mt/year - production rate = 265 tons/hour
- 2 mt/year - production rate = 355 tons/hour
- 2.5 mt/year - production rate = 440 tons/hour
- 3 mt/year - production rate = 550 tons/hour

The results of the required amount of bulk carriers and their corresponding capacities are shown in figure 5.2 below. It can be seen that for a yearly production rate of 1 and 1.5 million tons per year, two Handysize bulk carriers (35000 DWT) are sufficient to reach the desired yearly production rate.

For a yearly production rate of 1 mt/year, the two Handysize bulk carriers (35000 DWT) experienced 7 % of their total time in the waiting queue at the production vessel. When the bulk carrier size is increased to a Handymax (55000 DWT), this waiting queue percentage increased to 17.9 %. Which means it does not make sense to chose a larger bulk carrier than 35000 DWT. An extra test was conducted whether a Chinamax with a capacity of 400 kDWT could reach the yearly production rate of 1 mt/year with just 1 bulk carrier, but it reached 0.91 mt/year which is insufficient.
The experiment with a yearly production rate of 2 mt/year shows that three instead of two bulk carriers with a capacity of 35 and 55 kDWT are required to reach the desired production rate.
The same holds for a yearly production rate of 2.5 and 3 mt/year. For instance with 3 mt/year, there are four Handysize bulk carriers required, while there are only 2 Capesize (180 kDWT) are required. A remarkable difference between both situations, are the lost collecting days. With 2 Capesize bulk carriers, 9 days in total were lost due to a full hold of the production vessel. With the 4 Handysize bulk carriers, 0 days were lost in total. On the other hand, with more ships, there is a bigger chance of ending up in a waiting queue. For the 4 Handysize bulk carriers, the total time in the waiting queue at the production vessel and terminal combined was 12.8%. For the two Capesize bulk carriers, this number is significantly lower with 3.3%.
The experiments also point out that the tests with a single Chinamax bulk carrier (400 kDWT) is in none of the cases sufficient to reach the yearly production rate.
In the end a final decision cannot be made regarding the bulk carriers for the roundtrip between the production vessel and the terminal. More information like the terminal operations and the influence of the other roundtrip is still required. However, some bulk carrier appear to be less interesting. For example the use of Post-panamax vessels (110 kDWT). For 1, 1.5, 2 and 3 Mt/year, 2 Post-panamax are over-classified since the same amount of bulk carriers can be used while having a lower capacity. This can be seen at the 3 Mt/year scenario where three Handymax (55 kDWT) are sufficient. The use of three Post-panamax vessels is less interesting since the total waiting queue percentages increases from 7 to 23%.

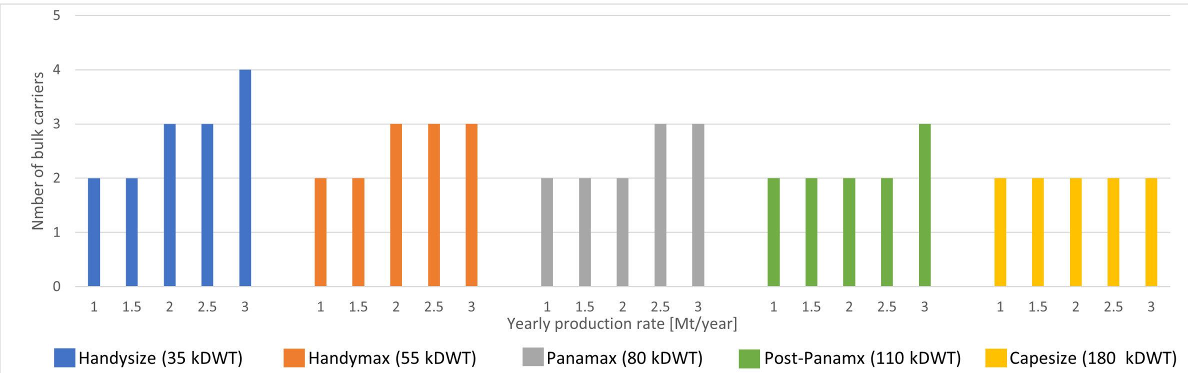


Figure 5.2: Number of required BC1 bulk carriers for different yearly production rates and different vessel types

5.1.2. Number of Berths

One of the goals of model V1 was to get an indication for the amount of berths. Of course, this is just an indication since the second roundtrip has not been added in model V1 and the terminal operations are not taken into account. During the experiments the amount of berths was set at 1. A berth occupancy of 65% was found with a yearly production rate of 3 Mt/year and 4 Handysize bulk carriers. The use of 2 Capesize bulk carriers resulted in a berth occupancy of 60%. This has to do with the pre- and post-operations which take up less time for 2 vessels instead of 4. However, the most important kpi for the amount of berths is the waiting queue percentage at the terminal. The waiting queue percentage at the terminal was between 0 and 0.7 % for all vessels. Such a low percentage in the waiting queue is definitely acceptable, and proved that just one berth for the bulk carriers executing roundtrip 1 is sufficient. The waiting queue percentage will of course raise when terminal operations are added but for now, a single berth for this roundtrip is definitely sufficient.

5.1.3. Inter-Arrival Times

The average and median inter-arrival times were calculated during all the experiments. The results are shown in table 5.1 below. It shows that the bigger bulk carriers are more 'time efficient' at transport the nodules. The inter-arrival times for a Capesize (180 kDWT) bulk carrier is roughly 2.5 times higher than the inter-arrival times for a Handysize (35 kDWT) bulk carrier, while it is transporting roughly 5 times the amount of nodules. This has to do with the lower waiting queue percentages. For 3 Mt/year, the two Capesize vessels each wait 3.3% of the total time in the waiting queue the production vessel and 0% at the terminal. The three Handymax vessels each wait 7% of total time at the production vessel and 0.2% at the terminal. The four Handysize bulk carriers each wait 12.2 % at the production vessel and 0.7% of the time at the terminal. It can be concluded that smaller bulk carrier experience more waiting queues at the production vessel and the terminal, which declare why bigger bulk carriers are more 'time efficient' concerning the inter-arrival times and their carrying capacity. The pre- and post-operations at the terminal and production vessel also contribute to the time efficiency. For instance, a smaller Handysize bulk carrier requires for every 35.000 tons pre- and post operations at the terminal and production vessel, while a Capesize vessel only need these operations for every 180.000 tons.

Yearly production rate [mt/year]	Bulk carrier capacity [DWT]	Number of bulk carriers	Mean IAT [hours]	Median IAT [hours]
1	35000	2	573.9	570.0
1.5	35000	2	394.0	374.5
2	35000	3	443.2	411.5
2	80000	2	688.0	626.5
2.5	35000	3	354.1	331.0
2.5	110000	2	766.7	719.0
3	35000	4	394.9	368.5
3	55000	3	645.1	606.5
3	180000	2	989.1	954.5

Table 5.1: IAT experiment with model V1 - Mining to Terminal

5.1.4. Planned Maintenance Unloader

With the use of Model V1, a decision can be made about the planned maintenance of the unloader, since the operations at the production vessel are already simulated. It was uncertain how much of the time, the unloader is operational or on standby. The kpi 'utilization rate of equipment' can be used to discover the operational time of the belt conveyor from the production vessel. The experiments pointed out that with a yearly production rate of 3 mt/year and a production rate of 550 ton per hour, the utilization rate of the unloader is roughly 15% of the time. It is assumed that there is plenty of time left to perform planned maintenance in the remaining 82%, which means that planned maintenance should not be integrated in model V2 or V3. This decision has also been made by another research about deep-sea mining, which also concluded that the conveyor belt is used sporadically. Which means the assumption has been made to execute the planned maintenance when the belt conveyor is on standby [28].

5.2. Experimental Plan V2 - Both Roundtrips

For the experiments with model V2, the same bulk carriers are taken into account:

- Handysize - 35 kDWT
- Handymax - 55 kDWT
- Panamax - 80 kDWT
- Post-panamax - 110 kDWT
- Capesize - 180 kDWT

The following experiments will be executed:

- Varying the number of bulk carriers for the different yearly production rates and the different bulk carrier sizes. The results of experiment V1 are taken into account. For example for a yearly production rate of 1 million tons per year, two bulk carriers with a capacity of 35000 proved to be the most optimal solution. For other yearly production rates, there were more than 1 optimal solutions for BC1. These options are all considered and used to determine the amount and capacity of BC2 bulk carriers.
- Varying the number of berths at the terminal and processing facility for BC2 bulk carriers.

With the data generated by these experiments, the other goals depicted in figure 3.7 can be reached. Such as an estimation for the terminal capacity. With the data of the inter-arrival times, it can also be determined whether a floating ship-to-ship crane might be an outcome for the terminal.

During the experiments, the terminal capacity is set at infinity so it will not influence the results, since the terminal capacity will be determined later on.

5.2.1. Amount and Capacity of Bulk Carriers

Below, the results for the varying capacity and amount of bulk carriers are provided in figure 5.3. The collector rates are equal to experiment V1 to match the same yearly production rates.

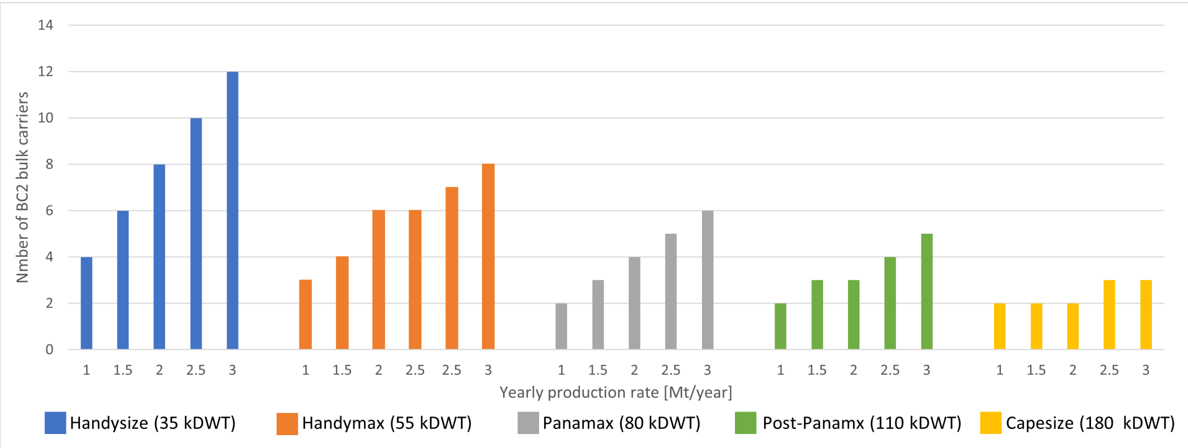


Figure 5.3: Number of required BC2 bulk carriers for different yearly production rates and different vessel types

The remarks for the varying amount and capacity of bulk carriers is provided below. These remarks above can be used to make a recommendation for the bulk carrier configuration for the final model.

- One BC2 bulk carrier can make a huge difference. This is illustrated with the terminal capacities in figure 5.4 and 5.5, where a simulation has been executed with a yearly production rate of 2.5 Mt/year and 2 BC1 bulk carriers with a capacity of 110.000 DWT. With 3 bulk carriers the terminal capacity keeps rising throughout the year with a capacity of over 400.000 tons at the end of the simulation. With just one BC2 bulk carrier extra, the terminal capacity does not exceed 20.000 tons at the terminal.

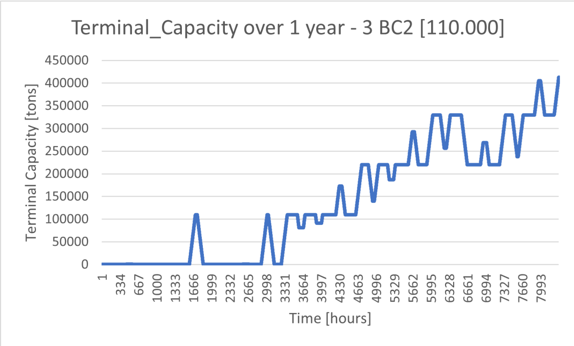


Figure 5.4: Terminal capacity over time with 3 bulk carriers

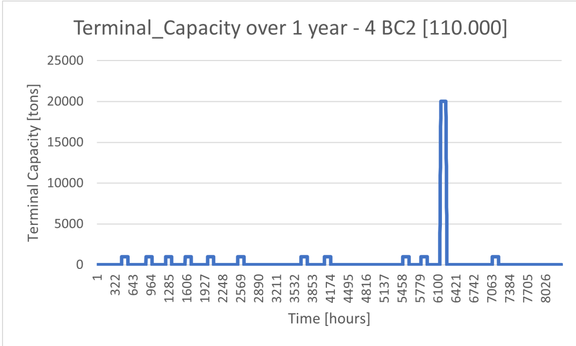


Figure 5.5: Terminal capacity over time with 4 bulk carriers

- Besides the amount of bulk carriers, the capacity of the bulk carrier can also have a big impact. For the simulation with 3 Mt/year, regardless the capacity of the BC1 bulk carrier, there were 12 BC2 bulk carriers required with a capacity of 35.000 DWT (Handysize). Instead of 12 Handysize bulk carriers, 8 Handymax (55.000 DWT) were sufficient (see figure 5.3). A difference of 4 bulk carriers, while the capacity increase is not even that big.
- The BC1 capacity does not change the situation for the amount of BC2 bulk carriers. For the 2, 2,5 and 3 Mt/year simulations, the amount of BC2 bulk carriers did not change when other combinations of BC1 bulk carriers has been chosen.
- The impact of extensive planned maintenance might have a big influence. In figure 5.6, a peak can be seen just before 8000 hours. This is due to the extensive planned maintenance (duration of 80 or 84 hours) all the bulk carriers experience at the terminal location after at least 7500 hours. The effect of planned maintenance can sometimes have impact on the rest of the simulation. This is clearly seen in figure 5.7. After the extensive planned maintenance took place, the maximum terminal capacity never got below 100.000 tons. While during the first year this was most of the time the case. So the effect of extensive planned maintenance can not be clearly seen within one year, which indicates the simulation duration should be extended for the final model.
  Besides the simulation duration, the moment at which the extensive planned maintenance takes place should also be changed. Now all the bulk carriers experience extensive planned maintenance after at least 7500 hours when they are at the terminal. In real life, the extensive planned maintenance is distributed randomly over the year for all bulk carriers, while the interval of 7500 hours stays the same. This adjustment will be implemented in model V3.

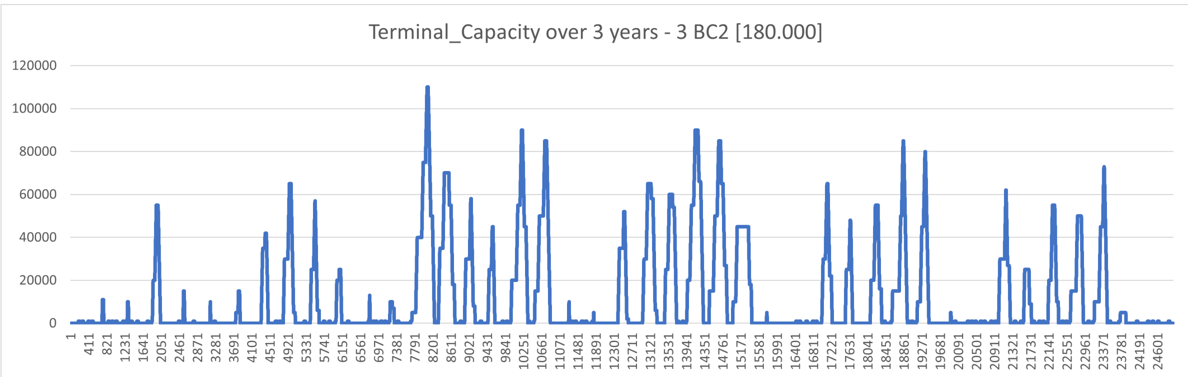


Figure 5.6: Simulation of 3 years with a yearly production rate of 2.5 Mt/year

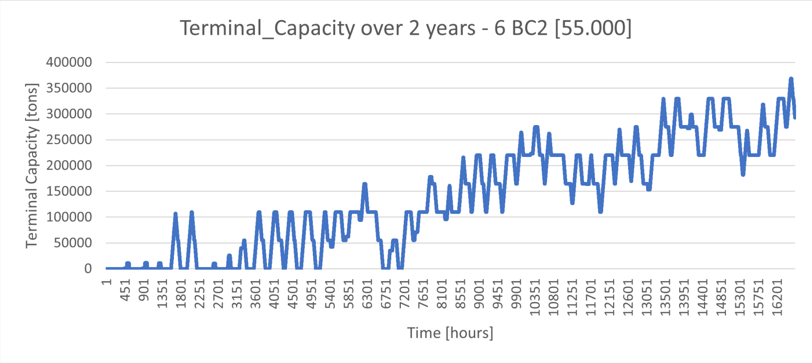


Figure 5.7: Simulation of 2 years with a yearly production rate of 2.5 Mt/year

- A BC1 bulk carrier with a big capacity might result in a larger maximum terminal capacity. This can be seen in figure 5.8 where the three different BC1 bulk carrier capacities are displayed for a yearly production rate of 3 Mt/year. For a yearly production rate of 2 and 2.5 Mt/year no correlation has been found between big BC1 bulk carriers and a higher maximum terminal capacity. Although a BC1 capacity of 180 kDWT does not occur in these simulations. The correlation between big BC1 bulk carriers and a higher maximum terminal capacity in figure 5.8 is not that overwhelming. For the bigger BC2 capacities, the difference in maximum terminal capacity is significant. When there is no BC2 bulk carrier waiting at the terminal and the BC1 Capesize (180 kDWT) bulk carrier starts unloading, an enormous amount is added to the terminal. This results in very large variations for the terminal capacity which is illustrated in figure 5.9.

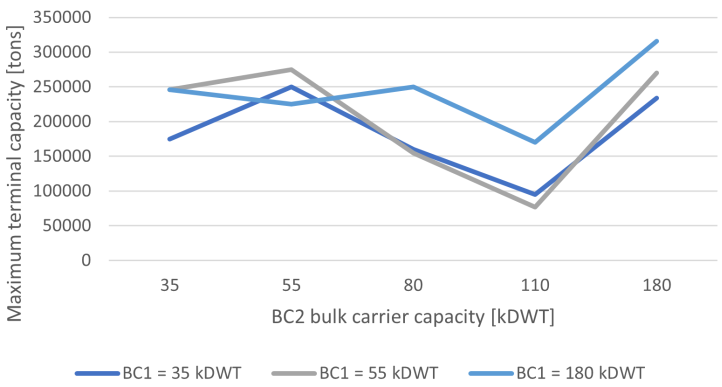


Figure 5.8: Maximum terminal capacity for different BC1 capacities with a yearly production rate of 3 Mt/year

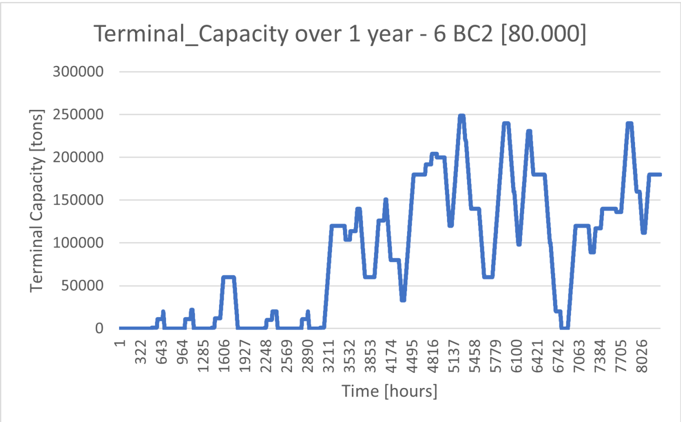


Figure 5.9: Large variations in maximum terminal capacity due to large BC1 bulk carriers

Suggestion for Model V3

Below in figure 5.10, an overview is given for each bulk carrier type. These provide a nice overview to have a bulk carrier indication for model V3.

For the use as a BC1 bulk carrier, the Handysize is an excellent choice. The Capesize should be avoided as explained above. This results in huge variations in the terminal capacity which is undesired. The Post-Panamax and Panamax both require 3 vessels for a yearly production rate of 3 Mt/year. The Handymax also requires 3 vessels for the same yearly production rate, so the Panamax and Post-Panamax are unnecessary big. This means that a decision has to be made between the Handymax and Handysize. The Handysize is more optimal for the lower yearly production rates. For 1 and 1.5 Mt/year, 2 Handysize or 2 Handymax vessels are required. The experiments showed a waiting queue percentage of 17.9% for the Handymax versus 7% of the Handysize, which is clear in favour of the Handysize. Furthermore, a Handysize bulk carrier has better manoeuvrability in comparison to a Handymax vessel [99], which is desired for the loading operations at the production vessel. The Handysize bulk carrier is thus the best option and will be used within the experiments of model V3 - Terminal Operations + Roundtrips.

The decision-making for a BC2 bulk carrier is more complicated. The processing facility plays an important role here. The processing facility in Japan has one mobile unloading crane. This means that the arriving bulk carriers will have to be geared or self-unloading bulk carriers. This narrows done the possibilities for a BC2 bulk carrier. Geared bulk carriers are usually Handysize and Handymax [101]. A few Panamax vessels are geared bulk carriers but that is unconventional [102]. When a Panamax vessel is desired, self-unloaders can provide an outcome, since the biggest self-unloader has a DWT of 100.000 [103]. But the need for a geared bulk carrier or self-unloader means that Post-Panamax and Capesize vessels are out of reach. Another important aspect regarding the processing facility, is that the quay and harbour are not suitable for Panamax vessels. This narrows down the opportunities to a Handysize or Handymax vessel. The final decision for the BC2 bulk carrier type will be made with model V3 - Terminal Operations + Roundtrips.

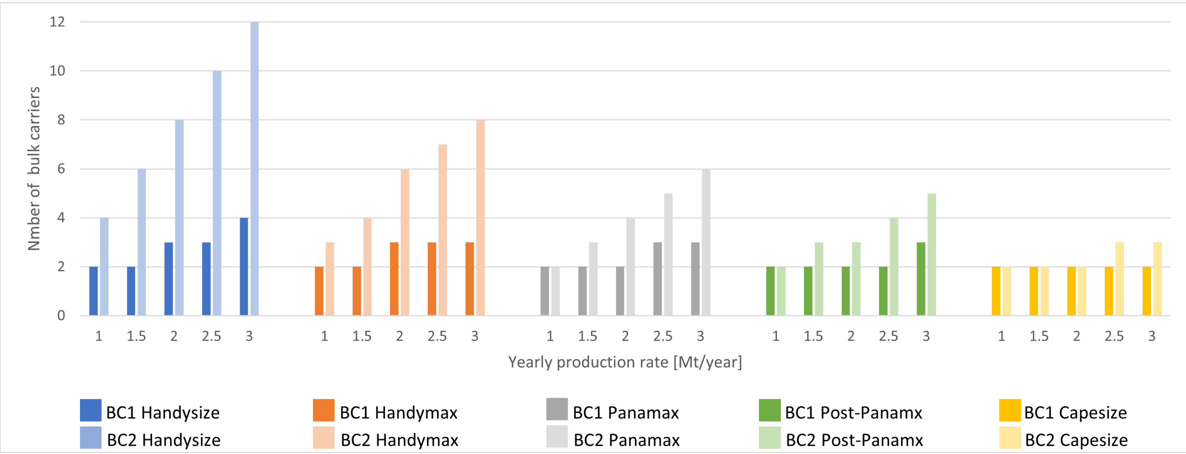


Figure 5.10: Number of required BC1 and BC2 bulk carriers for different yearly production rates and different vessel types

5.2.2. Number of Berths

Regarding the berths at the transshipment terminal, two options are considered: 1 versatile berth (where both loading and unloading can take place) or 2 dedicated berths (there is one berth for loading operations and one for unloading operations). A test has been executed with 2 dedicated berths for a yearly production rate of 3 Mt/year. This indicates berth occupancies at the loading and unloading berth of over 70%. Thoresen (2003) points out that for an average level of arrival control by a port's administration, berth occupancies should typically be below 65% for a terminal with five or less berths, and may, in some instances, reach up to 70% in the case of terminals with 6 or more berths and a higher level of arrival control by the port's administration [104]. However, in a high berth occupancy scenario, ships will likely experience longer queues and more time waiting for service due to the terminal's decreasing ability to operate efficiently, thus increasing the likelihood of higher demurrage costs [104].

Furthermore for this thesis, a maximum yearly production rate of 3 Mt/year is picked. This yearly production rate might be even higher in the future, which indicates that 1 versatile berth will not be sufficient. So for this thesis, 2 dedicated berths will be programmed and used during the experiments. Another research, which investigated the required storage capacity [47], also made the assumption to have 2 dedicated berths, where the terminal is modelled as a system with two handling stations which means the loading and unloading is strictly separated. For the case study in this thesis, 1 versatile berth might be sufficient for lower yearly production rates, but if 2 berths are required in the future, costly retrofitting or expansions are prevented by starting with 2 berths from the beginning.
So 2 dedicated berths are for now preferred in comparison with 2 versatile berths. The use of dedicated berths has several advantages:

- Movement of equipment: if the unloading and loading equipment differs, the equipment needs to be changed at a berth when loading has to take place directly after the unloading of another vessel. This means that equipment needs to be moved which takes up time.
- The planning is less complicated: BC1 bulk carriers always have priority to make sure the production vessel will not be restricted by a full hold because there are no bulk carriers available. The situation where two BC2 bulk carriers are loading at the terminal and a BC1 bulk carrier will have to wait should be prevented. This will result in a complicated planning where BC2 bulk carriers are dependent on the arrival times of BC1 bulk carriers.
- No double equipment required: when unloading can take place at several berths, unloading equipment is required for each of those berths. While one single berth for unloading means that only one set of unloading equipment is needed. This is a huge advantage for Allseas to keep the investment costs low (especially in the beginning phase).

5.2.3. Inter-Arrival Times

For every bulk carrier configuration, the roundtrip duration of BC1 and BC2 bulk carriers is determined. With the mean roundtrip duration of the BC1 and BC2 bulk carriers, a decision can be made whether a floating ship-to-ship crane 5.11 is helpful.

Figure 5.11: Floating ship-to-ship crane [77]

In figure 5.12 and 5.13 the mean roundtrip duration for a Handysize BC1 and BC2 are displayed. For now, the perfect scenario is taken into consideration where a BC1 and BC2 bulk carrier have the same capacity. The BC1 roughly has a mean roundtrip duration of 400 hours and a BC2 bulk carrier of roughly 1200 hours. This results in the fact that a BC2 bulk carrier completes 1 roundtrip and then faces the same BC1 bulk carrier, which has then completed 3 roundtrips in the same time. Furthermore, a simulation with 3 Mt/year and 4 BC1 and 12 BC2 Handysize bulk carriers points out that 30% of the whole year, both vessels are at terminal. This all does not tell the whole story but it shows that the use of a floating crane could be interesting, so it will be further investigated.

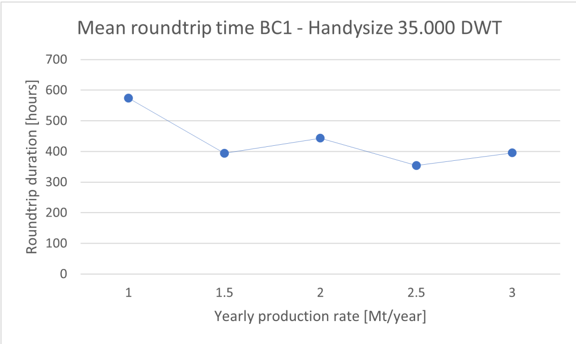


Figure 5.12: Mean roundtrip duration for a BC1 Handysize

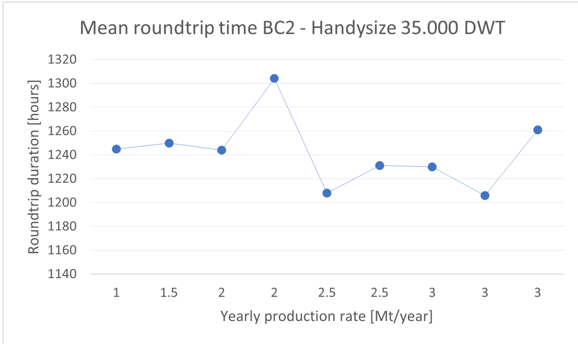


Figure 5.13: Mean roundtrip duration for a BC2 Handysize

Table 5.2 shows that a floating crane is often used to unload the load of large bulk carriers into multiple smaller barges [105]. This is also the case at the EMO terminal in Rotterdam [106]. Although, this will not work for the transshipment terminal in the case study. The suggestion is made above to use Handysize bulk carriers for the roundtrip between the production vessel and the terminal. The bulk carriers used for the roundtrip between the terminal and the processing facility will be bigger or the same size. Even the most favorable scenario for the floating crane when the BC2 bulk carriers have the same size, the floating crane will likely cause delay. Since the BC2 ship which will be loaded, will have to be loaded with a single BC1 ship. It does not make sense to load the BC2 ship for 50% after which the ship has to de-berth and re-berth at the terminal to load the remaining 50%. Another option is to wait for another BC1 bulk carrier to load the remaining 50% but that will significantly increase the port time of a BC2 bulk carrier due to the potential waiting for the arrival of a BC1 bulk carrier and the post- and pre-unloading operations of the BC1 bulk carriers. So the floating crane can only be used when there already is an empty BC2 bulk carrier at the terminal and it has the same size. This condition is definitely not met 30% of the time since the 30% described above, does not take the ship capacities into account. The chance of a waiting empty BC2 bulk carrier at the terminal can be increased by adding a BC2 bulk carrier. Although that would result in longer waiting queues at the terminal and the processing facility, as well as higher costs. Another solution would be to let BC1 bulk carriers wait for BC2 bulk carriers to arrive. However, this will increase the port time of the BC1 bulk carriers resulting in a higher chance for lost collector days due to a full hold of the production vessel.
Another important drawback are the costs of a floating crane according to dry bulk terminal expert J. Hiltermann. Furthermore it will make the planning more complicated, since the timing of the ships should be properly coordinated to use the floating crane. The operations of a floating crane are also time-consuming because of the crane barge towing operations, mooring lines and parallel movement of the crane barge itself to move to another hold [105]. It is also unknown whether the use of a floating crane is possible in the port of Lazaro. Other ships still require sufficient space to sail through the channel.

Phase	Action
1	Capesize berthing
2	Crane barge towing
3	Bulk barge towing
4	Crane barge mooring
5	Bulk barge mooring
6	**Production phase**
7	**Hatch switching**
8	**Bulk barge substitution**
...	...
9	Towing back floating crane & bulk barge
10	Capesize de-berthing

Table 5.2: Overview operations floating crane [105]

To conclude, the use of a floating crane is not recommended for the case study. The bulk carrier configuration is not appropriate for the use of a floating crane. Furthermore, the costs of a floating crane and the possible need for extra bulk carriers are a downside. Especially for the case study for Allseas, where the investment costs at the start should be taken into account. However, it has been discovered that for 3 Mt/year, 30% of the time both bulk carriers are at the terminal. So it is still interesting to to take a look at other ways to transport the unloaded nodules directly to a BC2 bulk carrier. If it is possible to directly transfer the nodules to the BC2 bulk carrier, it is way more efficient instead of stacking and reclaiming the nodules from the stockpile on the terminal. An example of this method will be investigated and tested in section 5.3.

5.2.4. Terminal Capacity

With the generated data of the previous experiments, a first indication for the terminal capacity can be determined. There was often a clear indication for what the terminal capacity should be. Take the simulations in figure 5.14 and 5.15. 2 BC2 bulk carriers were clearly not enough to handle the inflow of BC1 bulk carriers. The terminal capacity kept rising throughout the simulation. Whereas 3 BC2 bulk carriers is sufficient to keep the terminal capacity somewhat stable and below 140.000 tons. The terminal capacity of course depends on the yearly production rate and the amount of BC2 bulk carriers. Experiments with model V3 will point out a general indication for each yearly production rate, although for now it seems that the terminal capacity will be significantly below the 10 percent of the annual throughput (which is sometimes used as a rule of thumb [47]).

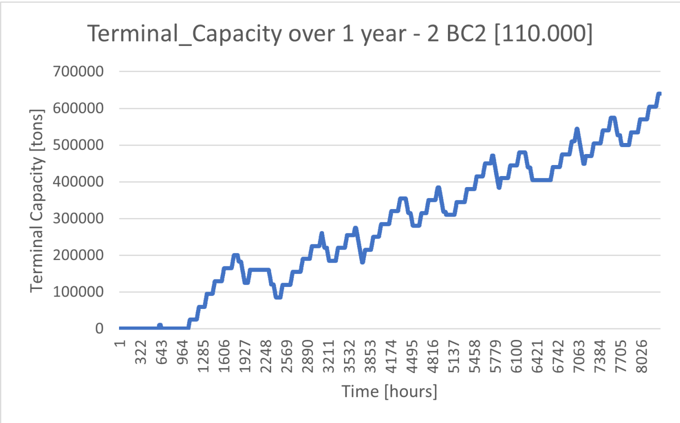


Figure 5.14: Terminal capacity of a simulation with a 2 Mt/year production rate and 2x 110.000 BC2 bulk carriers

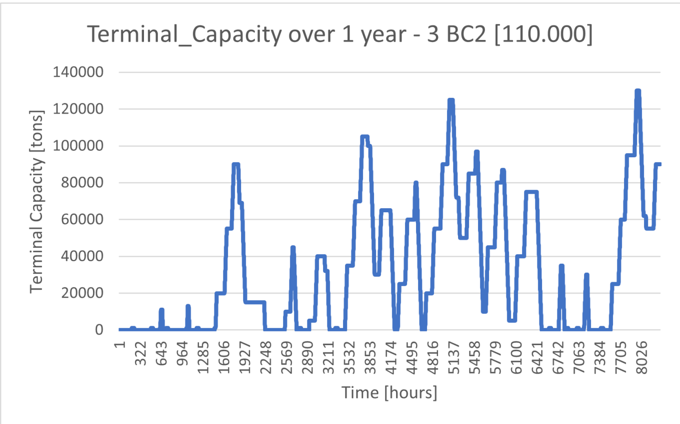


Figure 5.15: Terminal capacity of a simulation with a 2 Mt/year production rate and 3x 110.000 BC2 bulk carriers

5.3. Experimental Plan V3 - Terminal Operations + Roundtrips

This section addresses the experiments with the final model, where the roundtrips from prior models are combined with the terminal processes. This section will outline the decisions made for the case study. For instance the terminal capacity will be determined, after which the storage area can be determined. The handling rates will also be selected, which enables the making of decisions regarding terminal equipment. The number of berths is also verified and used to determine the required quay length. Finally, energy reduction strategies and technologies are investigated and partially implemented to quantify the difference.

5.3.1. Bulk Carriers

First of all, checks are performed whether the amount of BC2 bulk carriers stays the same after modelling the terminal operations. The amount of required BC2 bulk carriers is slightly changed. In general, one or two bulk carriers extra are required to prevent accumulation of the nodules at the terminal. Although, a problem was found at the processing facility. The processing facility could not keep up with the amount of BC2 bulk carriers for the 3 Mt/year yearly production rate. When the amount of berths at the processing facility was changed from 1 to 2 this problem was solved (see figure 5.16). However, the amount of berths at the processing facility cannot be increased easily. This would require significant adjustments in Japan and it is unknown whether that is possible. So the scenario of 2 berths at the processing facility will not be used for the remaining experiments. Another solution might be to increase the unloading rate, but this is not an option due to the use of geared bulk carriers and one mobile crane at the processing facility (this has been explained in chapter 4).

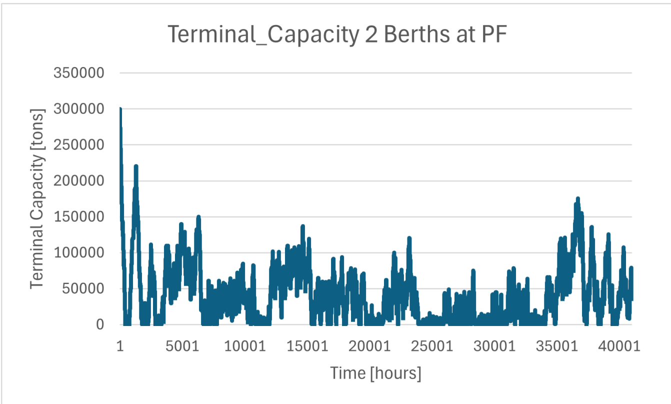


Figure 5.16: Terminal capacity with 2 berths at the processing facility for 3 Mt/year

Instead of 2 berths at the processing facility, two other options have been investigated. The first one is a change in working hours per day. The processing facility now operates 8 hours a day. When the working hours per day are increased to 12 hours, the problem was solved. The other option was the use of a self-unloader (while keeping 8 working hours a day). A self-unloader is able to continuously unload at a constant rate. The unloading stages (previously showed in figure 3.14) take up a lot of time. Especially at the final trimming stage, the unloading rate is much lower.

Simulations have been performed to see which option is more attractive. Both simulations are performed with a yearly production rate of 3 Mt/year. Furthermore 4 BC1 Handysize (35 kDWT) and 9 BC2 Handymax (55 kDWT) vessels are used. The simulations point out that the use of a self-unloader is more attractive. The self-unloader has a lower port time due to the constant unloading rate. This resulted in a smaller waiting queue percentage at the processing facility of 0.87% versus 4.01% for the 12 hour shifts. The processing facility berth occupancy is also significantly lower with the use of self-unloaders: 74.3% versus 94.4%. Finally, the terminal capacity was also significantly lower with the use of self-unloaders. This can be seen in figures 5.17 and 5.18.
A short comparison was also made between the use of a self-unloader and 2 berths at the processing facility. The average and maximum terminal capacity were lower with the use of a self-unloader. No

significant other changes are found, besides the obvious differences in berth occupancy at the processing facility. With 2 berths, the waiting queue at the processing facility also decreased to almost zero with 0.07%. However, this waiting queue percentage for the self-unloader equals 1%, which is also fine. The extra berth at the processing facility was also not enough to decrease the amount of BC2 bulk carriers from 9 to 8 Handymax vessels.

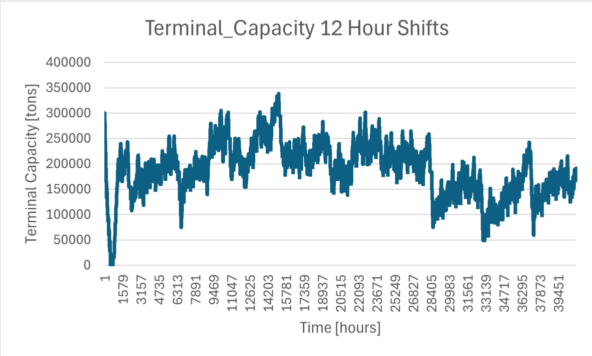


Figure 5.17: Terminal capacity with 12 hour shifts at PF

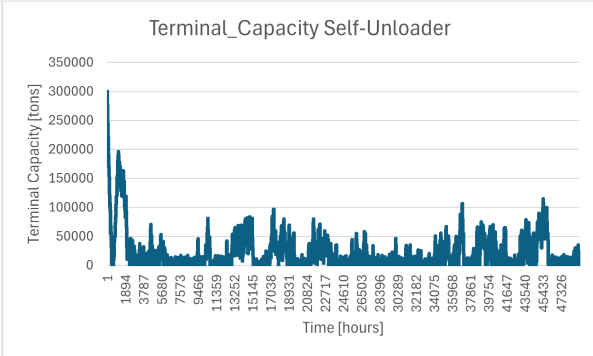


Figure 5.18: Terminal capacity with BC2 self-unloaders

From now on, a self-unloader will be used as a BC2 bulk carrier. Now a decision has to be made whether a Handysize or Handymax should be chosen as a BC2 bulk carrier. This has been investigated with a yearly production rate of 1.5 Mt/year and 3 Mt/year. Panamax vessels are also taken into account to have extra verification of the results. This might be helpful to see certain patterns. The results for a yearly production rate of 3 Mt/year are shown below in table 5.3.

	13 Handysize	9 Handymax	7 Panamax
PF Berth occupancy [%]	76.7	74.3	74.9
Unloading Berth occupancy [%]	71.3	70.4	71.2
Loading Berth occupancy [%]	54.6	73.0	89.0
BC2 Time in waiting queue terminal [%]	1.0	3.2	5.2
BC2 Time waiting queue PF [%]	2.0	0.9	0.6
Utilization rate unloading equipment [%]	51.5	51.0	51.5
Utilization rate loading equipment [%]	33.2	32.3	32.5
Average terminal capacity [tons]	102982	20361	8926
Maximum terminal capacity [tons]	270000	120000	65000

Table 5.3: Results of different BC2 bulk carriers with a yearly production rate of 3 Mt/year

The results for a yearly production rate of 1.5 Mt/year are shown in table 5.4 below.

	7 Handysize	5 Handymax	4 Panamax
PF Berth occupancy [%]	37.1	37.8	37.9
Unloading Berth occupancy [%]	34.7	35.7	35.5
Loading Berth occupancy [%]	81.4	83.0	94.3
BC2 Time in waiting queue terminal [%]	4.1	3.8	5.1
BC2 Time waiting queue PF [%]	0.05	0.03	0.0
Utilization rate unloading equipment [%]	25.1	25.8	25.7
Utilization rate loading equipment [%]	16.3	16.3	16.3
Average terminal capacity [tons]	4017	4193	2317
Maximum terminal capacity [tons]	45000	50000	37000

Table 5.4: Results of different BC2 bulk carriers with a yearly production rate of 1.5 Mt/year

Several conclusions can be drawn from these results. First of all the results do not differ much. However, the loading berth occupancy does show a clear pattern: a bigger vessel size results in a higher loading berth occupancy. On the one hand this was unexpected, since the pre- and post-operations for 7 Panamax vessels in total take up less time than 13 Handysize vessels. On the other hand, bigger vessels spend more time waiting at the berth to be completely filled while the terminal is empty. For the 3 Mt/year scenario with 7 Panamax vessel, 25% of the total time the terminal is empty. While with 13 Handysize vessels, only 4% of the total time the terminal is empty. In the end a higher berth occupancy is not a big deal as long as the waiting queue percentages are acceptable.
Besides the loading berth occupancy, there is no clear winner between the Handysize and Handymax. Sometimes a certain amount of bulk carriers for a certain DWT matches exactly to have a more or less steady terminal capacity from the beginning. In other cases, the amount of vessels is 'over-classified' and results in a constantly low terminal capacity. This results in a higher waiting queue percentage at the terminal and a lower average and maximum terminal capacity. When the amount of bulk carriers is then decreased with one bulk carrier, the terminal capacity suddenly rises very fast. This has already been concluded after the experiments with V2 - Both Roundtrips, which pointed out that one extra or less bulk carrier, can make a huge difference.
In the end, a Handymax vessel will be selected for the roundtrip between the terminal and the processing facility. The higher loading berth occupancy is a disadvantage in comparison to the Handysize vessels, but the waiting queue percentage at the terminal is still acceptable. Furthermore the use of Handymax vessels result in a significantly lower average and maximum terminal capacity, which will beneficial for the required storage area. Furthermore, a bigger bulk carrier is more cost effective: the bigger the ship, the smaller the cost. For instance, a 170,000 DWT bulk carrier has 5.7 times the storage capacity of a 30,000 DWT bulk carrier, but costs only 2.1 times more [107]. Although cost effectiveness is not considered as a kpi in this thesis. In the end it is also not the main goal to choose the perfect vessel. Optimization is required to determine the optimal amount of bulk carriers with the optimum DWT.
The chosen amount of Handymax bulk carriers is visualized below in table 5.19. The terminal capacity is also shown below in figures 5.21, 5.22, 5.24, 5.26 and 5.28. These results are obtained with a handling rate of 1500 tph at the unloading berth and 1200 tph at the loading berth. The right column of all these figures will be used in section 5.3.3 where the appropriate handling rate is selected.

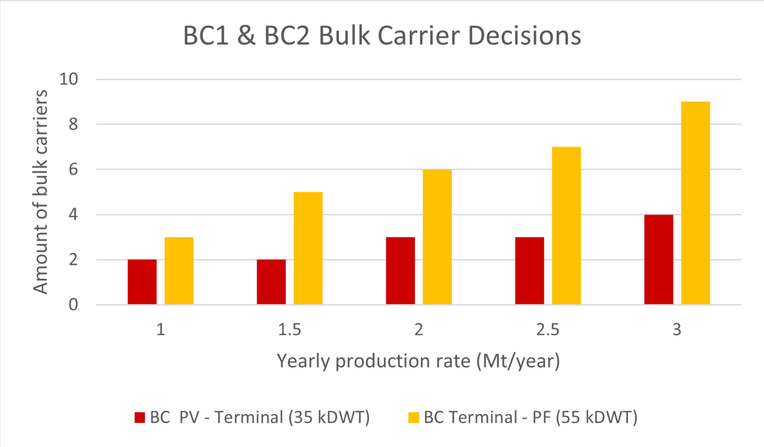


Figure 5.19: Amount of bulk carriers for different yearly production rates where BC1 = 35 kDWT and BC2 = 55 kDWT

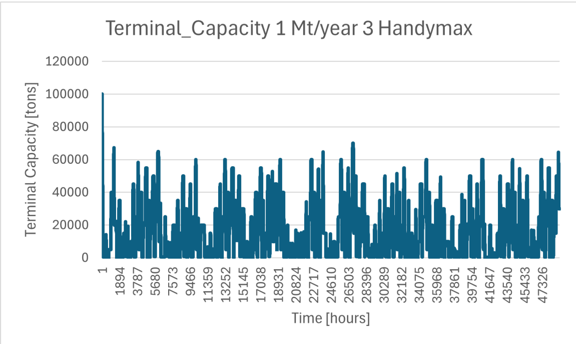


Figure 5.20: Terminal capacity with 3 Handymax bulk carriers

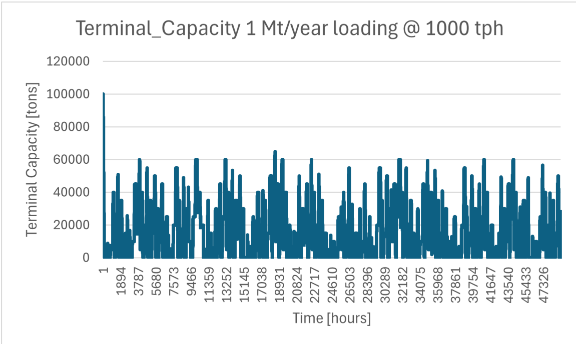


Figure 5.21: Terminal capacity with a loading rate of 1000 tph

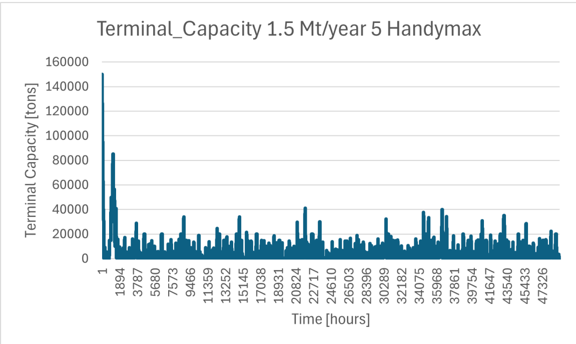


Figure 5.22: Terminal capacity with 5 Handymax bulk carriers

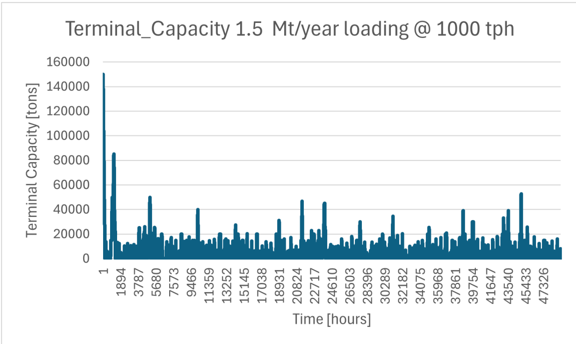


Figure 5.23: Terminal capacity with a loading rate of 1000 tph

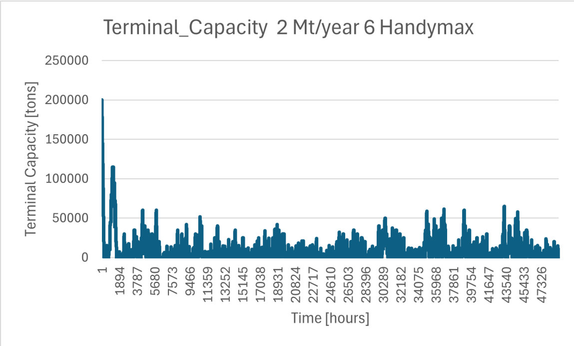


Figure 5.24: Terminal capacity with 6 Handymax bulk carriers

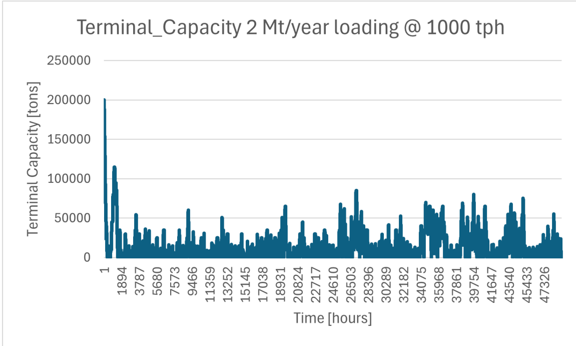


Figure 5.25: Terminal capacity with a loading rate of 1000 tph

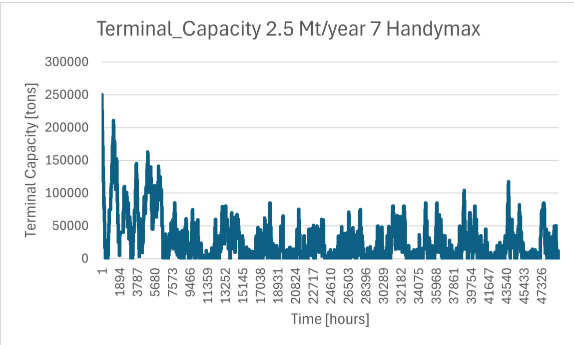


Figure 5.26: Terminal capacity with 7 Handymax bulk carriers

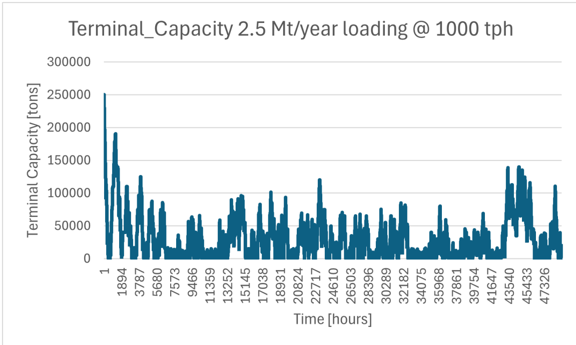


Figure 5.27: Terminal capacity with a loading rate of 1000 tph

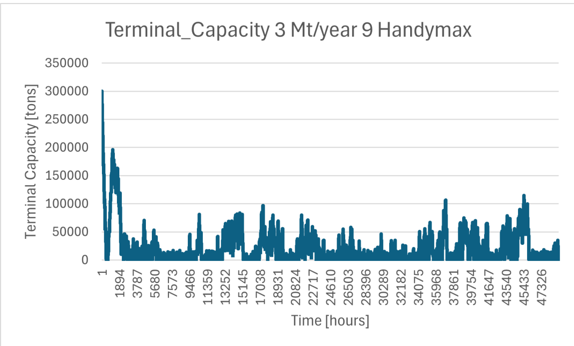


Figure 5.28: Terminal capacity with 9 Handymax bulk carriers

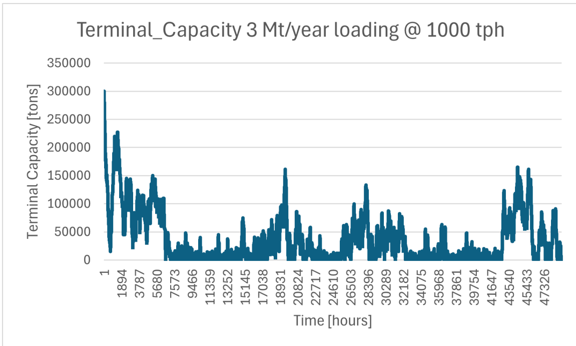


Figure 5.29: Terminal capacity with a loading rate of 1000 tph

5.3.2. Number of Berths

This section will address the number of berths at the transshipment terminal and the corresponding quay length. The number of berths at the processing facility equals one and will remain unchanged (as shortly discussed in section 5.3.1). The base-case of the number of berths is one berth for loading operations and one berth for unloading operations. The choice for two dedicated berths has been clarified in the model implementation section of model V2 - Both Roundtrips in chapter 3.

A new test has been executed to see the difference between two and one loading or unloading berth. For the unloading berth, no outstanding differences were found. One extra berth did not result in less 'collector days lost due to full hold', so the yearly production rate was exactly the same. One extra berth resulted in no waiting queue at all. However, the waiting queue percentage for BC1 bulk carriers with one unloading berth was already very low with 0.57% (equal to roughly 50 hours per year per bulk carrier). Furthermore, the unloading berth occupancy was roughly divided by two, but one single berth experienced an unloading berth occupancy of 70.6% which proved to be sufficient judged by the

waiting queue percentages. So it does not make sense to upgrade the unloading berth facility from one to two berths.
For the loading berth the same test was conducted by increasing the amount of loading berths from one to two. The loading berth occupancy obviously decreased by roughly 50%, but the loading berth occupancy with one berth was roughly 55% which is appropriate judged by the waiting queues. The waiting queues at the terminal did show a notable decrease from 3.2% to 0.7%. On the other hand, the waiting queue percentage at the processing facility doubled from 1% to almost 2%. This can be declared by the fact that two ships can leave the terminal and thus arrive at the processing facility at more or less the same time, where one bulk carrier then ends up in the waiting queue. An interesting event occurred regarding the terminal capacity. The terminal capacity proved to be more constant, with less outliers, compared to one berth. The maximum terminal capacity decreased from 170 kton to 125 kton. However, an empty terminal was seen more often, resulting in unwanted delay and thus a longer port time for BC2 bulk carriers. With one berth, the unwanted delay due to an empty terminal happened 2.1% of the time, versus 3.5% of the time with two berths. All in one, there are some up- and downsides with using two loading berths. But the minor advantages do not outweigh the drawbacks and additional costs of extra quay length for this case study, which means the number of berths remains unchanged with 2: one berth strictly used for loading and one berth strictly used for unloading.

The number of berths will determine the required quay length of the terminal. The quay length and quay length factor are associated to the number of berths. M. Patel (2021) used equation 5.1 (developed by Ligteringen (1999)) to determine the quay length:

$$\textbf{Quay length} = \mathbf{1.1} \times \boldsymbol{n_b} \times (\mathbf{LOA}_{\boldsymbol{average}} + \mathbf{15}) + \mathbf{15}$$

where n_b is equal to the number of berths and $\mathrm{LOA}_{average}$ is the average calculated vessel length (5.1)

The average vessel length are picked from the table in appendix C. The vessel dimensions for a Handysize and Handymax are respectively 140 and 175 meter. An important remark is that the Handymax vessels are self-unloaders. Self-unloaders generally have a bigger length. An example is a self-unloader with a 50 kDWT, which has an overall length of 190 meter [108]. The 190 meter is copied for the Handymax vessels. Using equation 5.1 above, the required quay length equals 411 meter.
It is assumed that the water depth along the quay is sufficient at all times and will not hinder seaside operations. One thing to take into account for Allseas, is that increased water depths are expensive to realize and maintain [23]. This highlights another advantage for the use of Handysize and Handymax vessels due to their limited vessel draft (see appendix C).

5.3.3. Handling Rates Equipment

In this section, the handling rates will be varied. The maximum handling rate which shall be tested is 4500 tons per hour, since 4500 tons per hour is the maximum stacking and reclaiming capacity for a longitudinal stockpile [37]. The following handling rates will be tested:

- 500 tons per hour
- 1500 tons per hour
- 3000 tons per hour
- 4500 tons per hour

The handling rates will be tested for scenarios with a yearly production rate of 3 Mt/year. The other scenarios are temporary steps towards the end-goal of 3 Mt/year.It is also the scenario where the biggest amount of bulk carriers is required. This scenario should be optimized to make sure the amount of bulk carriers is optimized as much as possible. For example, if it is possible to have one bulk carrier less with a handling rate of 4500 tph, this could be interesting from a cost perspective for Allseas. Another possibility is that a handling rate of 500 tph is sufficient. It does not make sense to have terminal equipment which is capable of 4500 tph because of the 2 Mt/year scenario, while for the 3 Mt/year scenario, the equipment is heavily over-classified.

BC1 bulk carriers

Several options are tested for the handling rate of the BC1 bulk carriers, which sail between the production vessel and the terminal. The base-case is 4 Handysize bulk carriers with a handling rate at the unloading berth of 1500 tph (this has also been used in section 5.3.1).
First of all the scenario has been tested to see whether 5 Handysize bulk carriers with a handling rate of 500 tph is possible. It does not sound attractive to add an extra bulk carrier, but the kpi's might point out interesting things. The experiment has shown that 5 Handysize bulk carriers with a handling rate of 500 tph is impossible. The average yearly production rate was 1.91 Mt/year and almost 128 days were lost due to a full hold capacity of the production vessel.
The second scenario is to check whether 4 Handysize bulk carriers are sufficient when the handling rate is decreased to 500 tph. Once again, the yearly production rate was insufficient, with 1.83 Mt/year and almost 136 days lost due to a full hold of the production vessel.
The last scenario is to check whether 3 Handysize bulk carriers are sufficient when the handling rate is increased to 3000 or 4500 tph. Once again, the collector days due to full hold of the production vessel raised significantly from 3.4 days (base-case with 4 Handysize vessels and 1500 tph) to 16.8 and 22.3 days for 3000 and 4500 tph respectively. This also meant that the yearly production rate was roughly 0.2 Mt/year lower. The unloading berth occupancy and utilization rate of unloading equipment on the other hand decreased massively: 28.4% and 15.8% respectively for 3 Handysize bulk carriers with a handling rate of 4500 tph versus 70.4% and 51.0% for 4 Handysize bulk carriers with a handling rate of 1500 tph. This is due to the lower amount of bulk carriers and the higher handling rate, which also results in a decrease in port time. With 3 Handysize bulk carriers, the waiting time percentage and waiting-time/service-time ratios at the production vessel and terminal also decreased. The waiting queue percentage at the production vessel and terminal is roughly 4% and 0.03% for 3 Handysize vessels compared to 9% and 0.57% for 4 Handysize vessels. However, the waiting queue percentages for 4 Handysize vessels are still considered appropriate.
Another option to check whether 3 Handysize bulk carriers are sufficient, is to look into the use of other equipment. The unloading rate with the use of a grab decreases as the hold capacity also decreases (see section 3.4.2). Equipment like a self-unloader or screw-type ship unloaders are able to unload the ship at a more constant unloading rate, which would result in faster unloading operations in comparison to the use of a grab [109]. Several tests has been performed to verify whether 3 Handysize bulk carriers with a constant unloading rate would be sufficient since it would reduce the waiting-time/service-time ratio and the overall port time. A constant unloading rate of 1500 tph has proven to be insufficient, since the lost collector days increased to 17 days on average, which meant the yearly production rate target of 3 Mt/year was not reached. A constant unloading rate of 2000 and 2500 tph decreased the amount of lost collector days to 11.6 and 10.2 days respectively. This also resulted in a yearly production decrease of 0.14 and 0.10 Mt/year respectively. However, the use of 3 Handysize vessels resulted in a lower waiting queue percentage at the terminal and production vessel. The unloading berth occupancy also massively decreased from roughly 75% to only 30%, which is as expected since the bulk carrier is now emptied in 14 hours when there is no delay or downtime. But still, the lost collector days is an issue with 3 bulk carriers. The increase from 2000 to 2500 tph did not make a huge impact. The use of a self-unloader is also more expensive and the bulk carrier will be bigger which is undesired in terms of maneuverability and the dynamic positioning system during the STS transfer in the CCZ [99]. The use of a vertical screw unloader or bucket type unloader remains as an option, but the material interaction with nodules is unknown. The particle size might be influenced, so further recommendation is required to determine whether the use of a screw or bucket unloader is appropriate. This means that the option of 3 Handysize bulk carriers with a constant unloading rate is dropped for the remaining simulations. A decision still has to be made whether 4 Handysize bulk carriers with a handling rate of 1500 tph will be used, or 3 Handysize bulk carriers with a handling rate of 3000 or 4500 tph. On all the performance indicators, the 3 Handysize bulk carriers score significantly better. However, even with a handling rate of 4500 tph, almost 17 days a year are lost due to a full hold capacity of the production vessel. The 'collector days lost due to full hold of the production vessel' is regarded as one of the most important performance indicators by Allseas. For the remaining experiments of the case study, the 4 Handysize bulk carriers with a handling rate of 1500 tph will be chosen.

BC2 bulk carriers
The base-case is 9 Handymax with a handling rate of 1200 tph at the loading berth (this has also been used in section 5.3.1). The scenario has been tested whether 8 Handymax vessels can be used at a handling rate of 4500 tph. The result are depicted in figure 5.30. The terminal capacity keeps rising. In real life, there is a maximum storage capacity, which would be reached quickly in this case. This results in the fact that BC1 bulk carriers have to wait till they are able to unload. This would be a bottleneck in the BC1 roundtrip process, which means the collector has to stop on a regular basis because the BC1 bulk carriers are in the waiting queue at the terminal, resulting in a much lower yearly production rate. So the option of 8 Handymax vessels with a handling rate of 4500 tph is dropped. The same applies to 9 Handymax bulk carriers with a handling rate of 500 tph.

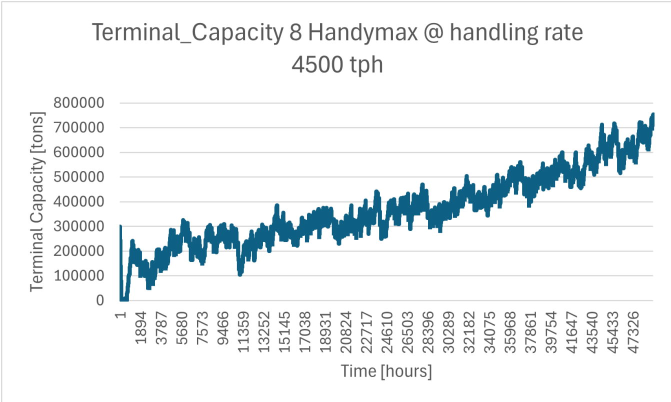


Figure 5.30: 8 Handymax vessels at a handling rate of 4500 tph

In section 5.3.1, it can be seen that the terminal capacity is quite low for every scenario with a handling rate of 1200 tph. Two other handling rates (1000 and 1500 tph) have also been tested to find the appropriate handling rate. The differences in waiting queue percentages at the terminal and processing facility is negligible. A significant difference can be seen regarding the loading berth occupancy and utilization rate of loading equipment: respectively 54.7% and 38.8% for 1000 tph and 39.7% and 25.8% for 1500 tph. The maximum and average terminal capacity also show a difference: respectively 160 and 35 ktons for 1000 tph and 100 and 18 ktons for 1500 tph. The benefit of a higher handling rate with the same amount of bulk carriers is clear and as expected. A handling rate of 4500 tph would obviously score even better with the performance indicators.
For the remaining experiments of the case study, 1000 tph is selected as a handling rate at the loading berth. A lower handling rate should result in lower costs. Furthermore, the berth occupancy of 54.7% and average/maximum terminal capacity with 1000 tph are considered as appropriate and doable. The comparison between 1200 tph and 1000 tph can be seen in figure 5.20 till 5.29. On the left side, the 1200 tph scenario is depicted and on the right side the 1000 tph handling rate.

Now that the handling rates are investigated, a selection can be made for appropriate equipment. In appendix B, the overview of the equipment is provided. Colours are used to indicate which equipment can be used. No colour indicates that the handling rate is not sufficient. For instance, a pneumatic conveyor with a maximum handling rate of 1000 tph is not sufficient for the desired 1500 tph at the unloading berth. An orange colour indicates that the handling rate is sufficient, but the use of the specific equipment is highly unlikely. For example a bucket-wheel stacker-reclaimer has a very high maximum handling rate, but is typically used in major dry bulk terminals [52]. A radial stacker is also highly unlikely because of the longitudinal stockpile configuration.
There are still many options left. At the end of section 5.4, a smaller selection of recommended terminal equipment will be provided, since the experiments in section 5.4 influence the decision-making concerning terminal equipment.

5.3.4. Storage Capacity

The required storage capacity and connected storage area will be investigated in this section. According to Kleinheerenbrink (2012), the storage capacity is determined by trial and error. The simulations are run with different storage capacities, and the simulation which led to acceptable values for the key performance indicators, is the right storage capacity [61].
The right column of the figures (5.20 till 5.29) in section 5.3.1 show the terminal capacity with respect to time without a maximum terminal capacity.
For the experiments, a warm up period of 5 years is used. The warm up has been increased because the starting capacity of the terminal now equals the maximum storage capacity. This could be 5000 tons, which means the artificial starting situation of all the BC2 bulk carriers in the waiting queue at the terminal takes up a lot more time. A warm up period of 5 years has been assumed to be sufficient (10 years has also been tested but did not show a significant difference).
The yearly production rate of 3 Mt/year is first used to determine an appropriate maximum storage capacity. Various maximum storage capacities (5000 till 100.000) are tested and multiple patterns are found. The lower the storage capacity, the higher the loading and unloading berth occupancies. The terminal percentage of a full and empty terminal also increased. Because of this increase, the port time increased, which then also resulted in higher waiting queue percentages for both ships. Thus, the lower the terminal capacity, the worse it scores on the key performance indicators. For very low maximum storage capacities, 5000 ton for example, the loading berth occupancy increased to 94% in comparison to 54% for no maximum capacity. Although, other maximum storage capacities such as 45000 tons, show no extremely negative influences on berth occupancies or waiting queue times. The key performance indicator which is then used, is the 'collector days lost due to full hold'. The relation between this performance indicator and the maximum storage capacity is provided in figure 5.31 below. Without a maximum storage capacity, the collector days lost due to full hold equals 2.5 days. This value is important since it is about the difference between lost days with and without a maximum terminal capacity. For example, a yearly production rate of 2.5 Mt/year already has 11.4 lost days due to the nature of the amount of BC1 bulk carriers and their capacity.

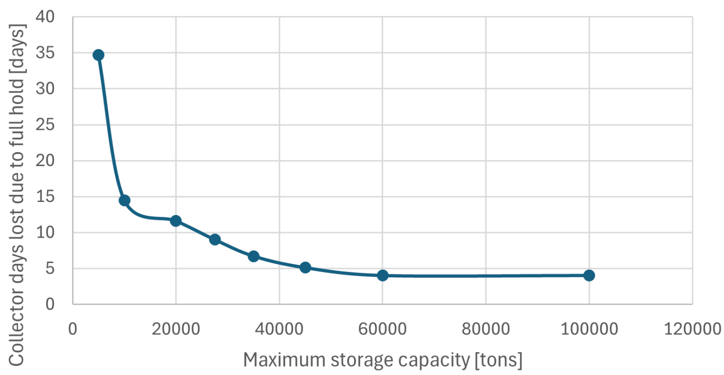


Figure 5.31: Maximum storage capacity versus collector days lost due to full hold for a yearly production rate of 3 Mt/year

Experiments were also conducted for the other yearly production rate scenarios. The decisions are mainly based on the 'collector days lost due to full hold' and the corresponding yearly production rate. The 2.5 Mt/year scenario is decisive for the maximum storage capacity. A maximum of 60,000 tons resulted in an additional full day of 'collector days lost due to full hold'. In contrast, a maximum of 52,500 tons resulted in an additional 5.4 days of 'collector days lost due to full hold'. This shows that a relatively small difference in maximum storage capacity, could result in a significant increase of lost collection days. 3 days is considered as a maximum amount of lost collection days. It has been decided to have the same maximum storage capacity of 30.000 tons for the yearly production rates of 1, 1.5 and 2 Mt/year, with 2.2, 0.5 and 2.3 lost collection days respectively. A maximum storage capacity of 60.000 tons is selected for the yearly production rates of 2.5 and 3 Mt/year, with 1 and 1.5 lost collection days respectively. These values will be applied in the subsequent experiments of the case study. It is a big advantage for Allseas to have a maximum storage capacity for multiple yearly production scenarios. This prevents potential costly retrofittings for every yearly production change. Furthermore, for some yearly production rates, like 1.5 Mt/year, the stockpile capacity is over-classified. This should result in longer residence times, and thus more time for drainage, which results in a lower moisture content (and thus less required energy during processing at the processing facility).

Storage Area
With the known required maximum storage capacity, the required storage area can be determined. This will be down with the following equations 5.2 and 5.3 [110] (with clarification of the variables in figure 5.32):

$$m = hl\,\rho\left(w - \frac{h}{\tan(\alpha)}\right) + \frac{1}{3}\rho\pi\left(\frac{h^3}{\tan^2(\alpha)}\right) + \rho h\left(w - \frac{2h}{\tan(\alpha)}\right)\frac{h}{\tan(\alpha)} \tag{5.2}$$

$$h_{\max} = \frac{1}{2} w \tan(\alpha) \tag{5.3}$$

Where m is the pile's mass [ton], h is the pile's height [m], l is the length of the trapezoidal part [m], ρ is the dry bulk's density [t/m3], w is the pile's width [m] and α is the material's angle of repose [°].

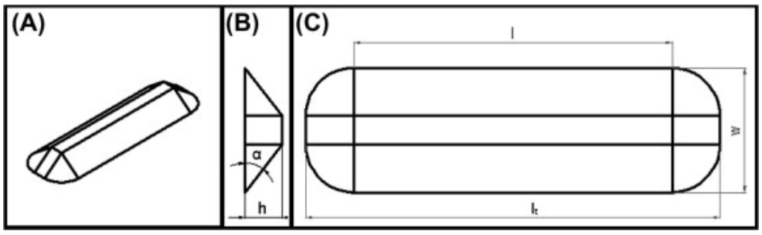


Figure 5.32: Variables used in the formula to calculate the mass of a pile [110]

With equations 5.2 and 5.3 above, the length of the stockpile can be determined. The other variables can be determined by investigating literature. The pile width usually varies between 40 and 100 meter. A common lane's width is 50 meter [23], which will also be used in equations 5.2 and 5.3 above. The height of the pile is normally limited by the stacking height of the stacker and/or reclaimer. Most stacking machines are able to stack up to a maximum of 23 meters [111]. Equation 5.3 indicated a maximum height of 18.8 meter so a height of 18 meter will be used to be on the safe side. A lower height is also beneficial in terms of dust control. A slightly lower height helps to reduce dust forming [43]. The final advantage of a lower height has to do with the moisture permeability described in chapter 2. Decreasing the height results in faster drainage [40]. This in the end will likely result in less energy consumption during the processing of the nodules.
For the calculations, an apparent density is taken of 1200 kg/m3 and an angle of repose of 37 degrees, which has been researched in the literature assignment of Ree, Chris van der (2023).

The stockpile length for a storage capacity of 30.000 tons equals 65 meter.

The stockpile length for a storage capacity of 60.000 tons equals 120 meter.

A pile is often limited to a certain weight. This is 105 kton for coal piles and 175 kton for iron ore piles [23]. The 30 and 60 kton of the stockpiles above are below these limits, so one continuous stockpile will be used.

5.3.5. Redundancy in Equipment

In this section, the influence of redundancy for equipment will be investigated. Till this point, the terminal has been simulated with one piece of equipment for every terminal operation. This could result in undesired extra port time for a bulk carrier when the unloader experiences mechanical downtime. The downtime for the unloader is now sampled from a lognormal distribution (see figure 5.33). The maximum downtime duration (time for diagnose and repairing) now equals 48 hours for the unloader. The exceptional cases above 48 hours are not taken into account, since these situations occur very rarely. However, 48 hours is still a long time for a vessel to wait to be unloaded. This might also result in additional waiting time for the BC2 bulk carrier because of an empty terminal. This points out that redundancy in equipment might be really beneficial for the terminal. With spare equipment, the result of mechanical downtime is minimized to one hour. This is because there is still time required to make a diagnose for what is broken. After the diagnose, there is additional time needed for start-up operations and for the new equipment to get into the right position. So the influence of mechanical downtime will not be zero, but will be limited to one hour for all the terminal equipment.

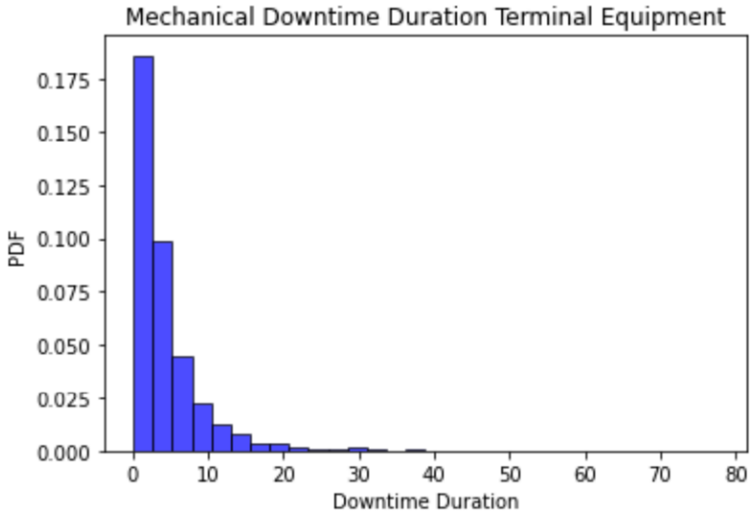


Figure 5.33: Distribution of mechanical downtime duration terminal equipment

An experiment has been performed for the 3 Mt/year scenario. This scenario has the highest berth occupancies and utilization rates of terminal equipment. The redundancy of equipment resulted in a lower average port time for BC1 bulk carriers (64.5 hours with redundancy versus 72 hours without redundancy). The unloading berth occupancy also decreased with roughly 5% to 70% with redundancy. Furthermore, the waiting queue at the unloading berth decreased from 3.1% to 1.7%, resulting in a lower waiting-time/service-time ratio (7.8% versus 5.9%). These are all significant decreases, although it did not influence the lost collector days due to a full hold. This is due to the fact that the waiting queue at the production vessel increased from 29.2% (without redundancy) to 33.6% (with redundancy). This means that the unloading at the production vessel is the main bottleneck. It does not make sense to improve the terminal operations on the unloading berth side, because this highlights the bottleneck at the production vessel even more.
For the loading berth, no significant changes were discovered regarding waiting queue times and loading berth occupancy. The average terminal capacity is also equal to the situation without redundancy, as well as the utilization rate of the equipment. The port time surprisingly also did not change. This is has to do with an increase of the waiting times because of an empty terminal. With redundancy, a BC2 bulk carrier has to wait 9.2% of the total time because the terminal is empty. This used to be 8.1% for the situation without redundancy of equipment. So the gained up-time of the equipment has been nullified by waiting for an empty terminal.
To conclude, the redundancy of equipment does not have an enormous impact. On the loading berth side no significant changes were discovered due to the increase of waiting time for an empty terminal. The unloading berth did show some positive changes, but this resulted in a negative outcome concerning the waiting queue at the production vessel. This shows that it does not make sense to improve the terminal operations without improving the operations at the production vessel, since this is the weakest link in the chain.

5.4. Energy Reduction Strategies & Technologies

Ports and terminals strive to improve energy efficiency, driven by rising energy costs over the past years. Climate change mitigation is also a key target for the port industry [27]. The energy efficiency within a terminal brings up the second sub-question of this chapter:

What strategies and technologies can be implemented to mitigate energy usage at the transshipment terminal?

One measure which can be used has already been discussed in section 2.1.3, with increasing the stockpile capacity and decreasing the height of the stockpile. Increasing the stockpile capacity leads to longer residence times (thus more time for drainage) and decreasing the height results in faster drainage [40]. This in the end will likely result in less energy consumption during the processing of the nodules. Dedicated strategies and techniques for terminal operations are described below:

- Onshore Power Supply (OPS): onshore power supply is also called cold-ironing. During docking, the main engines are turned off and the auxiliary engines provide power for things such as power system maintenance, lighting and refrigerating. These auxiliary engines burn fuel in idle position and emit CO2, SO2 and NOx depending on the fuel type [27]. Onshore power supply makes sure the ship is connected to the energy grid and thus using electricity instead of burning fuel. This can reduce operating costs and energy consumption by up to 75% [112], helping port authorities and shipowners. Cold-ironing comes with technological challenges, such as the proper voltage, correct connection type, capabilities of power supply companies, grid characteristics and security [113].
- Alternative Power Supply: Emissions from electricity are substantially lower compared to fossil fuels. Furthermore it is economical to use electrified equipment in many ports. This resulted in an increasing number of new electrified equipment in recent years [27]. Besides the electrification of equipment, the use of energy storage devices can be implemented. For instance, supercapacitors, batteries and flywheels can all be used to store potential energy and consume the stored energy for hoisting [27].
- Shortcut at terminal: When a BC1 and BC2 bulk carrier are both at the terminal, a shortcut at the terminal can be used. As usual, the nodules are unloaded from the BC1 bulk carrier. Instead of transporting the nodules to the stockpile, the nodules are directly transported to the BC2 bulk carrier. This results in less terminal transport and no need for stacking and reclaiming the nodules from the stockpile. This will result in an energy reduction.
- Lighting: Lighting consumes 3-5% of the total energy in ports. The use of LED lamps in storage facilities, buildings and outdoor terminal high mast lighting contributes to an energy reduction [114].
- Stockpile positioning: The closer the stockpile to the unloading and loading berth, the less terminal transport is required. This means that the stockpiles should be positioned as close as possible to the berth(s).
- Belt conveyor speed control: When belt conveyors will be selected to transport the material on the terminal, the energy consumption can be decreased by applying speed control. Belt conveyors have a throughput capacity that is determined for peak material flows. The actual material flows are often considerably lower in practice. As a result, the belt conveyor is not optimally filled during normal use. The throughput capacity can be adjusted to the current material flow by reducing the belt speed (speed variation). This increases the load of the belt optimally at the lowest possible belt speed [115]. This would be applicable to the transshipment terminal, since the actual material flow on the belt conveyor is often lower than the peak material flow, since the unloading rate of a bulk carrier decreases as the hold capacity of the bulk carrier decreases.

Not all techniques are taken into consideration. For example automated mooring systems. With this system, ships are mostly moored using vacuum and they lock to berth without many maneuvers. This reduces the energy consumption from the engines. However, the investment costs are too high to be interesting for the case study of Allseas [116].

Peak shaving is not considered as a energy reduction strategy in this thesis. Peak shaving is an operational strategy that aims to reduce the peak energy consumption at a port. This is because the peak electricity consumption accounts for roughly 25-30% of the monthly electricity bill for a terminal [117]. There are 3 methods for peak shaving (also illustrated in figure 5.34):

- Power sharing: using stored energy at peaks
- Load shifting: shifting the energy demand in peak periods to non-peak periods
- Load Shedding: turning off non-critical loads at peaks

Peak shaving does not necessarily reduce energy usage, so it is not taken into account for the terminal design. However, it can be interesting for Allseas to reduce energy costs.

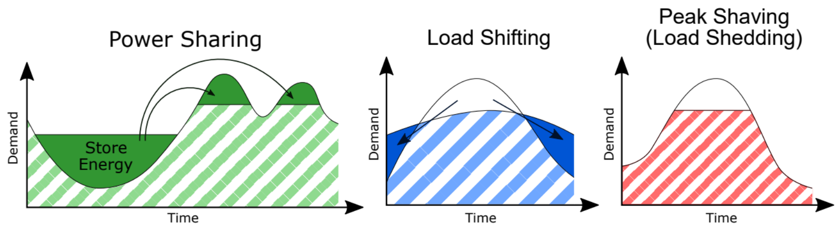


Figure 5.34: Peak shaving methods [27]

Besides energy reduction strategies at the terminal, there are also strategies during the transport of the nodules. Two strategies are explained below:

- Permanent speed reduction bulk carriers: A speed reduction of 10%, 20%, and 30% reduce fuel consumption by 27.1%, 48.8%, and 60.3% and CO2 emissions by 19%, 36%, and 51% respectively. The bigger the ship, the more impact the speed reduction has [118].
- Speed reduction near ports: instead of a permanent speed reduction, the speed of a bulk carrier can also be decreased when a bulk carrier is likely to end up in a waiting queue at the terminal. The energy savings by reducing the speed near ports can reach up to 25.4% [119].

The influence of the permanent speed reduction and the speed reduction near ports will not be investigated, since energy reduction strategies during transport are not within the scope.

Some energy reduction strategies/technologies, described above, will not be used for experiments. For instance the energy reduction regarding lighting and belt conveyor speed control will not be quantified by performing experiments. However, the use of LED lamps in buildings and terminal high mast lighting is recommended, as well as speed control for the belt conveyors. The energy reduction by moving the stockpile as close as possible to the quay also will not be quantified by experiments. It is of course recommended to have the stockpiles as close as possible to the loading and unloading berth to minimize terminal transport.

The non-working energy consumption of the equipment is not taken into account during the experiments below. The non-working energy consumption is about auxiliary units and lightning [27].

5.4.1. Cold-Ironing

The first energy reduction technology that will be investigated is 'onshore power supply' (OPS), also called cold-ironing (see figure 5.35). In the validation section of model V3 - Terminal Operations + Roundtrips, the energy consumption of a bulk carrier is estimated to be 250 kW for either a Handysize or Handymax bulk carrier. For this test, the assumption will be made that energy used for cold-ironing comes from renewable energy sources. The fuel is 'free' and delivery is not measured, which means the power is assumed to be delivered with 100% efficiency [120]. When the energy does not come from renewable sources, the grid efficiency of roughly 40% plays a role [121], which would result in hardly an energy reduction.

Two cases have been tested. The first case is the base case where the auxiliary diesel engines are used to provide power while docked. The efficiency of a diesel ship engine is between 30 and 45% [122]. A relatively modern engine is assumed, so an efficiency of 45% is used [123]. This means that the required input roughly equals 550 kW. The second case is where onshore power supply is used from renewable energy, which means a required input of 250 kW.

The first case with the use of diesel engines resulted in a mean energy consumption of 3.87 GW (gigawatt) in 5 years. The use of cold-ironing resulted in a mean energy consumption of 2.21 GW in 5 years. This means a massive reduction of almost 43%, when renewable energy is used. However, even if renewable energy is not used, there is the advantage of reducing local emissions. The use of onshore power supply also results in a reduction of 27% on CO2, 59% on NOx, 19% on SOx and 55% on particulate matter [124].

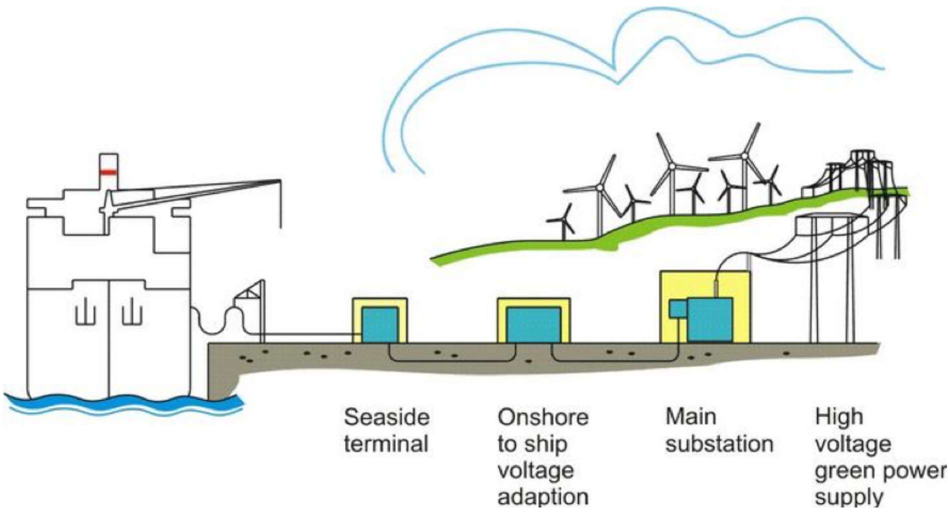


Figure 5.35: Onshore power supply in combination with renewable energy [125]

5.4.2. Alternative Power Supply

The second energy reduction technology that will be investigated is the use of an alternative power supply. Electrification is the most obvious option will result in less local emissions. Electrification also enables the ability to regenerate energy. However, the use flywheels can also be used to store potential energy and consume the stored energy for hoisting [27].
Based on the available equipment options, which have already been discussed in section 5.3.3, the decision has been made to compare the use of (diesel) trucks versus a belt conveyor for terminal transport. A comparison between two terminal transport options has been chosen because the terminal transport will have a significant impact on the terminal overall. For example the need for a road infrastructure because of trucks, but also the loading system depends on the terminal transport. A mobile truck shiploader will of course not be used when a belt conveyor is used for terminal transport.
The transport loss factor (TLF) can be used to compare the specific mechanical energy consumption between a truck and a belt conveyor [126]. Although, to quantify the exact difference in energy consumption, the TLF cannot be used. In chapter 3, the energy consumption of a belt conveyor has already been calculated. For the comparison, the energy consumption of a truck also needs to be calculated. To do this, an estimation has to be made regarding the fuel consumption of a diesel truck. A diesel truck with a payload of 23.5 tons uses on average 38 litres of diesel every 100 kilometers. However, the trucks at the terminal will be used for small distances and lots of low speed maneuvering. This will increase the fuel consumption (garbage trucks can use 80 L/100 km from my own practical experience). The payload of the trucks used at the terminal will also be 28 tons instead of 23.5 tons, so a fuel consumption of 50 litres for every 100 kilometer is assumed. This means that one single truck will use 0.75 liter of diesel for the roundtrip of 1500 meter. 1 liter diesel roughly contains 10 kWh [127], so 7.5 kWh is used for a single roundrip. 36 roundtrips are required for a tonnage rate of 1000 tph, which means 270 kWh is used every hour for the terminal transport with trucks. The energy consumption will be related to the tonnage rate, so the following formula is used during the experiment:

Energy-usage-per-hour-truck = (270/1000) * handling rate = (405/1500) * handling rate
For the belt conveyor, the formula equals:
Energy-usage-per-hour-belt-conveyor = (156.1/1500) * handling rate

For this experiment, the energy consumption of the bulk carriers is not taken into account. This is because of the large impact of the energy usage of the bulk carriers. Without this impact, the focus is limited to the terminal equipment.
The use of trucks resulted in an average energy consumption of 1.34 GW per 5 years. The use of belt conveyors resulted in a 39% lower energy consumption (solely terminal equipment) of 0.82 GW per 5 years. The energy consumption of a belt conveyor is significantly lower, although the energy consumption is not the only reason to opt for a belt conveyor. For example the need for a road infrastructure, handling stations for trucks and drivers are a drawback. Expansion in the future might also be more difficult with trucks, because the road infrastructure also has to be adjusted, as well as an increase in handling stations to prevent waiting queues. Another drawback of trucks are environmentally related, since diesel trucks contribute to local pollution. The terminal planning with trucks might also be complicated. With an unloading rate of 1000 tph, roughly 6 trucks are required (each truck performing 6 roundtrips of 10 minutes every hour). But the unloading rate actively changes depending on the hold capacity of the bulk carrier, resulting in less required trucks. This will make the planning for the truck drivers complicated. The use of trucks on the other hand has one advantage regarding downtime. In case of unexpected downtime for a truck, there are still 5 other trucks available which make sure the (un)loading of the bulk carrier is able to continue. But, as shown in section 5.3.5 on redundancy in equipment, the use of a belt conveyor is not disastrous in the case of downtime.

5.4.3. Shortcut at Terminal

The final energy reduction strategy that will be investigated is the use of a shortcut at the terminal. The shortcut is visualized in figure 5.36. The shortcut allows for onshore direct ship to ship transshipment, which means the transport at the terminal is reduced and the stacking and reclaiming operations are bypassed. Another advantage of the use of a shortcut is an increase of the number of connections within the terminal transport network. The more connections within a belt conveyor network, the higher the terminal performance [23]. For instance, the shortcut can be used in the case of maintenance or downtime for the transport towards the stockpile. When the loading berth is not occupied, the material can still be stacked on the stockpile by following another route. A bi-way transport mechanism would then be required.
For the shortcut example in figure 5.36, a mobile harbour crane is used to unload the Handysize vessels arriving from the production vessel. The material is then unloaded into the blue hopper. Instead of using the belt conveyor towards the stockpile, the belt conveyor towards the other hopper is used. The material is then loaded with a mobile belt conveyor into a Handymax vessel which is used to sail towards the processing facility.
The use of a temporary stockpile at the quay will be investigated. The temporary stockpile is able to account for downtime of the shortcut belt conveyor and the loader, since the unloader can dump the material onto a small stockpile on the quay. This idea has been partially based on processing facility at Japan. The quay at Japan functions as a temporary stockpile, since all the material is dumped onto the quay to probably unload the vessel as quickly as possible.
The capacity of the temporary stockpile in our case will have a maximum of 4500 tons (3 * maximum-unloading-rate), which enables the crew at least 3 hours (even more when the unloading is at a later stage which means the unloading rate decreases) to solve the downtime, maintenance or delay on the loader or shortcut belt conveyor. An excavator is then used to remove the temporary stockpile on the quay by dumping it into the hopper, after which the material will be loaded via the shortcut route. An experiment later on will investigate whether the use of a temporary stockpile in combination with an excavator is more energy efficient than just transporting the nodules towards the stockpile when the shortcut belt conveyor or loader experiences downtime.

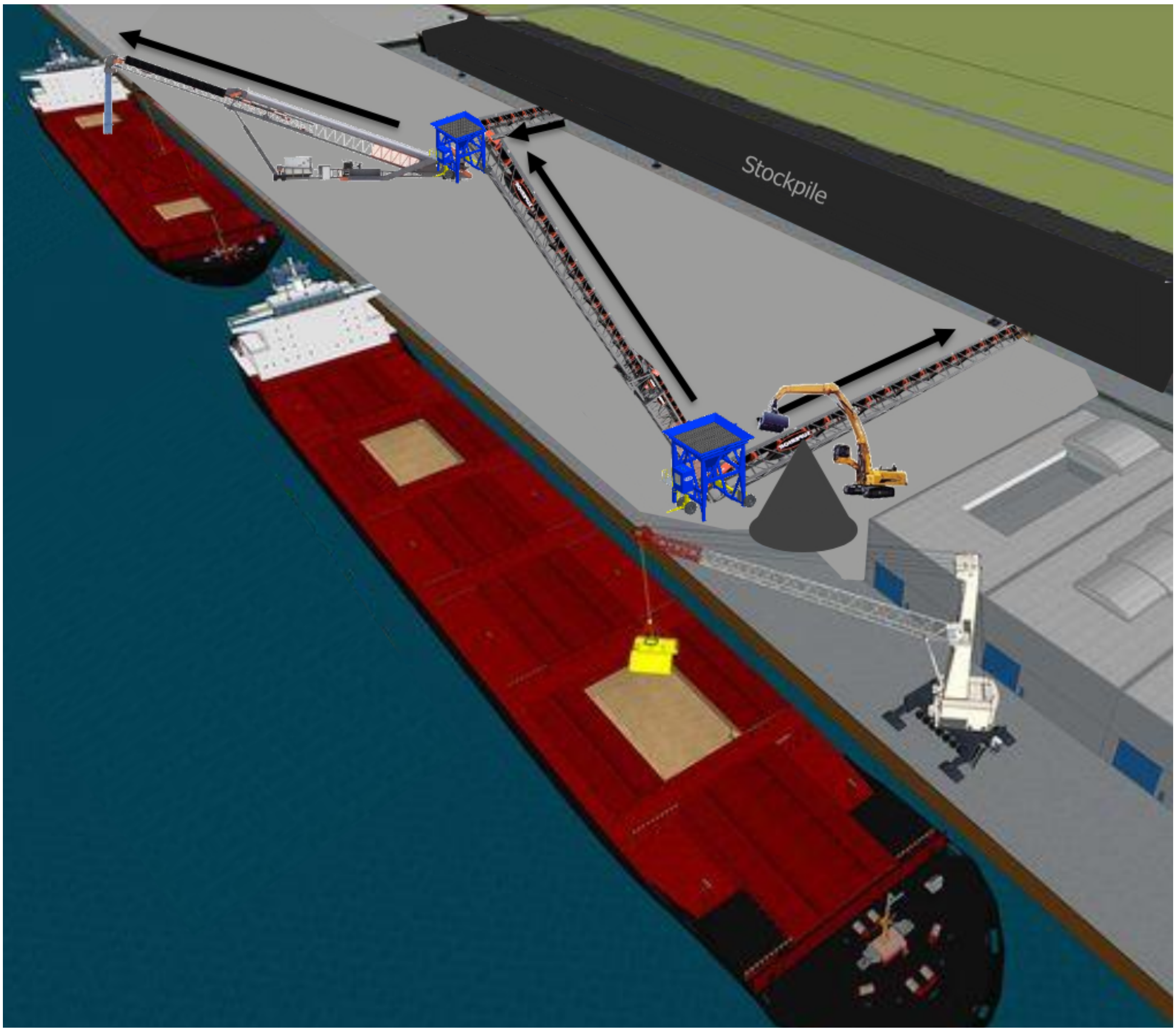


Figure 5.36: Shortcut at terminal (reworked from [128])

Concerning the temporary stockpile on the quay, a small experiment has been executed whether the unloader and loader should take the capacity of the temporary stockpile into account. For instance, the unloader can wait because the temporary stockpile is at its maximum. On the other hand, the nodules can be transported to the stockpile which is less energy efficient but prevents undesired waiting times for the unloader and BC1 bulk carrier. For the loader holds the same. The loader can wait because of an empty temporary stockpile. The other option is to load the BC2 bulk carrier by nodules coming from the stockpile. Once again, less energy efficient but undesired waiting times for the loader and thus BC2 vessel are prevented.
A run of 5 years showed a total of 475 hours of waiting of the unloader because of a full temporary stockpile. This seems like a small amount on a total of 5 years. However, the BC1 bulk carrier and unloader had to wait for up to 10 hours on some occasions. For the loading berth, 1255 hours were lost in total due to waiting for an empty stockpile. For the remaining experiments, the loader and unloader will wait because of the capacity of the temporary stockpile. It is unlikely to stall terminal operations because of a gain in energy usage. Losing 10 hours is not worth the energy reduction, so in case of an empty or full temporary stockpile, the normal stockpile route will be used.

Three scenarios will be tested with the use of the shortcut at the terminal:

- Increasing loading rate: the first scenario is focused on increasing the loading rate and thus try to have a lower port time for BC2 bulk carriers. With this scenario, nodules from the stockpile and nodules arriving by the shortcut are simultaneously loaded onto the BC2 bulk carrier. The BC2 bulk carrier is always loaded from the 'conventional' stockpile at a handling rate of 1000 tph (this also used to be the case without the use of a shortcut). When a BC1 bulk carrier is also at the terminal, the shortcut will be used, and the stream of nodules which is unloaded from the BC1 bulk carrier will be added to the loader of the BC2 bulk carrier. This means that the loading rate of the BC2 bulk carrier varies between 1000 and 2500 tph (depending on the hold capacity and thus unloading rate of the BC1 bulk carrier).

- Maximizing utilization shortcut: the second scenario is to always and only use the shortcut when the unloading and loading berth are occupied. This means that the loading rate equals the unloading rate and thus does not exceed 1500 tph. The loading rate could also be significantly lower, at 240 tph, when the trimming stage of the BC1 bulk carrier is reached.
- Compromise: the final scenario is a mix of the two scenarios above. As long as the unloading rate of the BC1 bulk carrier is between 1000 and 1500 tph, the loading rate for the BC2 bulk carrier is exactly the same, which means the BC2 bulk carrier is only loaded by a stream of nodules with the shortcut. When the unloading rate of the BC1 bulk carrier is below 1000 tph, the loading rate will be complemented by a stream of nodules from the stockpile. This means the loading rate of the BC2 bulk carrier will at least be 1000 tph (when the stockpile has enough capacity of course).

The experiments help in determining which option will be recommended for Allseas. Without the simulation it is very difficult to assess the trade-off between fast handling rates, and thus short port times, which mean less energy consumption of the BC2 bulk carrier. Or on the other hand, maximizing the use of the shortcut, which means stacking and reclaiming operations are bypassed, and the terminal transport is reduced, which also should result in a reduction of the energy consumption.

Temporary Stockpile

The first experiment will investigate the influence of the temporary stockpile at the quay. Two situations will be compared with each other: the situation where the temporary stockpile has a capacity of three times the maximum unloading rate (in this case 4500 tons) and the situation where there is no temporary stockpile. The advantage of the temporary stockpile is when the shortcut transport or loader experience delay, maintenance or downtime, the unloading operations can still continue for at least 3 hours (depending on the unloading rate stage). Normally the conventional route towards the terminal would then be used which uses more energy.
Without a temporary stockpile, no remarkable differences in key performance indicators or energy consumption were seen. The temporary stockpile was used once or twice a week on average. Although the use of the temporary stockpile proved to be not ideal in all cases. For instance when the unloading rate is 1500 tph and the stacker experiences 6 hours of mechanical downtime, the temporary stockpile only enables 3 hours of continuation of the unloading operations, before using the conventional route towards the stockpile. So the temporary stockpile is unable to cover all downtime or delay scenarios. Furthermore, no significant decrease in energy consumption was discovered.
Despite no difference in energy consumption, the temporary stockpile could in real life be very practical. The 3 hours (or more) are very useful to make a diagnose in the case of mechanical downtime. Then a decision can be made whether it is worth to use the conventional route towards the stockpile. It does make less sense to use the conventional route for just one hour, because of start-up operations for the transport and stacker, as well as arranging employees. So for the remaining experiments, the temporary shortcut will be used with a capacity of 4500 tons. Instead of using a stockpile with an excavator, one or multiple silos can be used. Although that would require higher investment costs. Furthermore the excavator can function as a stand-in for stacker and reclaimer operations in the case of downtime or maintenance.

Maximizing Utilization Shortcut

The results of this scenario are relatively simple. When the shortcut is always used without addition from the stockpile, the loading rate for the BC2 bulk carrier is too low. The trimming stage results in a very low loading rate which means the port time of the BC2 bulk carriers is too long. Because of the increased roundtrip duration, the BC2 bulk carriers are unable to handle the incoming stream of nodules at the terminal, which means the terminal soon reaches the maximum capacity. When the maximum capacity of the terminal is reached, this also impacts the BC1 bulk carriers which sometimes have to wait for room at the terminal in order to unload the nodules. This results in way too many collection days, which means the targets of the yearly production rate are not reached. This in accordance with the results of the experiments regarding the handling rate at the loading berth. A handling rate of 500 tph instead of 1000 tph was tested, but proved to be insufficient.

Minimizing Port Time

The results of increasing the loading rate are promising. The total energy consumption of the terminal without the use of a shortcut is 37.97 GWh over a time span of 5 years. With the use of the shortcut to increase to loading rate occasionally to 2500 tph, the energy consumption over 5 years decreased to 32.89 GWh. The energy consumption of the excavator is not taken into account here. A small calculation will be executed to see whether the energy consumption of the excavator exerts a big influence. First of all, the energy consumption of an excavator needs to be determined. The energy consumption is based on an investigation about the energy consumption of material handling by an hydraulic excavator, where crushed stone with a bulk density of 1750 kg/m3 is used as a reference. An energy consumption was found of 75.88 kJ/t [129]. Equation 5.4 points out that the excavator uses 20.8 W per ton per hour. With the outputs of the simulation, it can be determined how many tons the excavator moved during the 5 years of simulation. This all resulted in an energy consumption of 27500 kWh for the excavator over 5 years. This amount is assumed to be negligible in comparison to the total of 32.89 GWh.

$$E = P * t \tag{5.4}$$

Where E is the energy in Joule, P the power in Watt and t the time in seconds.

Besides the decrease in energy consumption, the use of the shortcut resulted in additional advantages. For instance a 3.5% lower loading berth occupancy of 69.8%. The utilization rate of the equipment also decreased. The transport towards the terminal and stacker were previously used 51% of the time, and are now used 18% of the time, since the shortcut route is used 32% of the time for the unloading berth. The utilization rate at the loading berth experienced a smaller decrease, since the conventional route is still used in this scenario. However the utilization rate of the reclaimer and transport from the stockpile still decreased from 39% to 34%. On average, the BC2 bulk carrier spent 8.5 hours less at the loading berth. This resulted in a very small waiting queue percentage of 0.6% at the loading berth. Regarding the terminal capacity, no clear reduction can be concluded. The average terminal capacities correspond very well to the base case without the use of a shortcut. This might be due to the randomness of the shortcut utilization. When the shortcut is extensively used for several bulk carriers after each other, the terminal capacity does not change much. When the terminal capacity is at the moment by chance very high, the average terminal capacity will be also higher.

Compromise

During this experiment, the loading rate is always above 1000 tph with a maximum of 1500 tph. The use of the shortcut once again showed a significant decrease in energy consumption in comparison to the base case: 33.35 GWh versus 37.97 GWh. The energy consumption on the other hand is higher in comparison to the previous scenario 'Minimizing Port Time'. This has to do with the higher berth occupancy. The loading berth occupancy is 74.9% versus 69.8% for the previous shortcut experiment. This means more energy is required for the bulk carriers. The bulk carriers are by far the biggest energy consumption sources (since they consume 550 kW per hour when berthed). When the bulk carrier energy consumption is not taken into account, the results are as following:

- Energy Consumption Base Case: 7.95 GWh
- Energy Consumption 'Increasing Loading Rate Scenario': 3.95 GWh
- Energy Consumption 'Compromise Scenario': 3.82 GWh

As expected, the compromise scenario now consumes the least energy, since the utilization rates of the transport to stockpile + stacker and transport from stockpile + reclaimer are respectively 2% and 2.5% lower.

5.5. Equipment Recommendations

Appropriate equipment can be selected for the transshipment terminal, by combining the information of the desired handling rates, investigation of existing small-scale terminals in chapter 2 and the results of the energy reduction strategies & technologies. The recommended equipment options for each function are provided in table 5.5 below.

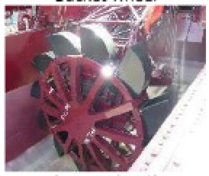
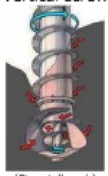
Function	Option 1	Option 2	Option 3	Option 4	Option 5
Storage types	Longitudinal open storage  (M. Droetteboom, 2020)				
Unloading systems	Mobile harbour crane  (Liebherr, 2024)	Material handling excavator  (PortCraneOperator, 2023)	Bucket elevator  (IQS directory, n.d.)	Bucket wheel  (PLM specials, n.d.)	Vertical screw  (Siwertell, n.d.)
Loading systems	Mobile shiploader (linear)  (Superior Industries, 2024)	Mobile shiploader (radial)  (Telestack, 2017)			
Terminal transport	Belt conveyor  (J. Williams, 2020)	Mobile belt conveyor  (Superior Industries, 2024)			
Stacking	Mobile stacker  (Metso, 2024)				
Reclaiming	Material handling excavator  (PortCraneOperator, 2023)	Wheel loader  (Indiamart, 2023)			
Support vehicle	Wheel loader  (Indiamart, 2023)	Bulldozer  (Driven by Battat, 2024)			

Table 5.5: Equipment recommendations

As described in chapter 2, mobile equipment offers several advantages such as cost-effectiveness, flexibility and scalability.
Because of the benefits of mobile equipment, a rail-mounted luffing crane as an unloading system is not recommended. The use of bucket and screw unloader types is also recommended due to clear advantage over grab type unloaders in controlling environmental dust, noise emissions and a lower energy consumption. However, continuous type of unloaders are more prone to downtime/breakdowns, require more maintenance and repair times will be higher in comparison to grab type unloaders [130]. It us unknown whether the use of a screw or bucket wheel unloader is appropriate. The nodules are

very brittle which might result in powder after handling the nodules with the wrong equipment. So more research will be required to make a final decision regarding the unloading systems.
For the loading systems, the rail-mounted luffing crane and fixed shiploaders are also not recommended since it is no mobile equipment. The use of mobile truck loader is also not recommended since trucks are not recommended for terminal transport. Due to the recommendation for the use of a shortcut at the terminal, the mobile harbour crane and material handling excavator are also not recommended since this equipment is unable to handle 2500 tph.
For the transport at the terminal, the use of a bulldozer, truck or dumper truck is not recommended due to the outcomes of the 'Alternative Power Supply' experiment. A belt conveyor or mobile belt conveyor on the other hand is recommended. A combination of these two options is also possible. For instance mobile belt conveyors can be used for the shortcut route at the terminal (see figure 5.37 below).

Figure 5.37: Mobile belt conveyors used for the shortcut [89]

Regarding the stacking operations for the stockpile, a mobile stacker is advised. Once again the rail-mounted stacker and long boom slewing stacker are not recommended since it is no mobile equipment. A rail-mounted stacker and reclaimer would also cause difficulties when they have to pass each other. A wheel loader and material handling excavator are recommended to reclaim material from the stockpile. A side and portal scraper are rail-mounted and thus undesired.
When a wheel loader is not selected for reclaiming operations, a wheel loader or bulldozer is advised as a support vehicle. The investigated terminals at chapter 2 also indicated that cargo handling operations are supported by yard vehicles such as wheel loaders [52].

5.6. Comparison with Rules of Thumb & Practical Experiences

Besides the use of simulations as a design tool, rules of thumb and practical experience are also used in the process of designing dry-bulk terminals [24]. In this section, the final sub-question of this chapter will be answered:

To which extent are the established rules of thumb and practical experiences in the dry bulk terminal domain representative for the design of a dry bulk transshipment terminal for polymetallic nodule collection?

A literature study and expert interviews are used to investigate the rules of thumb and practical experiences. The results of the experiments for the case study will be compared to these rules of thumb and practical experiences. The rules of thumb and practical experiences are listed below, as well as a comparison with the results of the experiments performed for the case study.

- **Quay length factor:**
  The quay length factor relates strongly to the terminal capacity. It is the annual throughput divided by the quay length, where the annual throughput $\dot{m}$ is given in [kt/y]. The formula for the quay length factor f_{ql} [ktm^{-1}y^{-1}] is given in equation 5.5 below:

$$f_{ql} = \frac{\dot{m}}{L_q} \tag{5.5}$$

  A value between 25 and 75 is suggested for coal and a value for iron ore between 50 and 150 [24]. In a paper of T.A. van Vianen, 49 existing dry bulk terminals (import and export) were examined [24]. Real-world quay length factors are displayed in figure 5.38.

  For the case study, the quay length is the same for all the yearly production rate scenarios (411 meter). For the lowest yearly production rate of 1 Mt/year, the quay length factor equals 2.43 kt/m. For the highest yearly production rate of 3 Mt/year, the quay length factor equals 7.30 kt/m. In comparison to the existing dry bulk terminals in figure 5.38, the quay length factor for this case study is comparable and in line with import terminals. Export terminals tend to have a larger quay length factor.

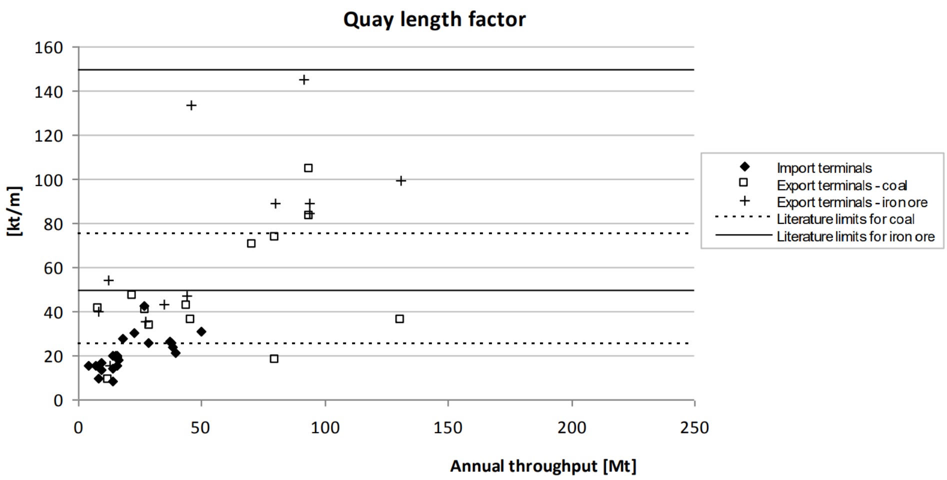


Figure 5.38: Quay length factors of existing terminals [24]

- **(Un)loading ship capacities:**
  The total installed (un)loading capacities strongly relate to the annual throughput. The (un)loading

capacity is always a certain factor larger than the minimum required (un)loading capacity to account for potential downtime for example. This has already been integrated for the simulations performed in this thesis. Two graphs for (un)loading capacities are shown in figure 5.39.

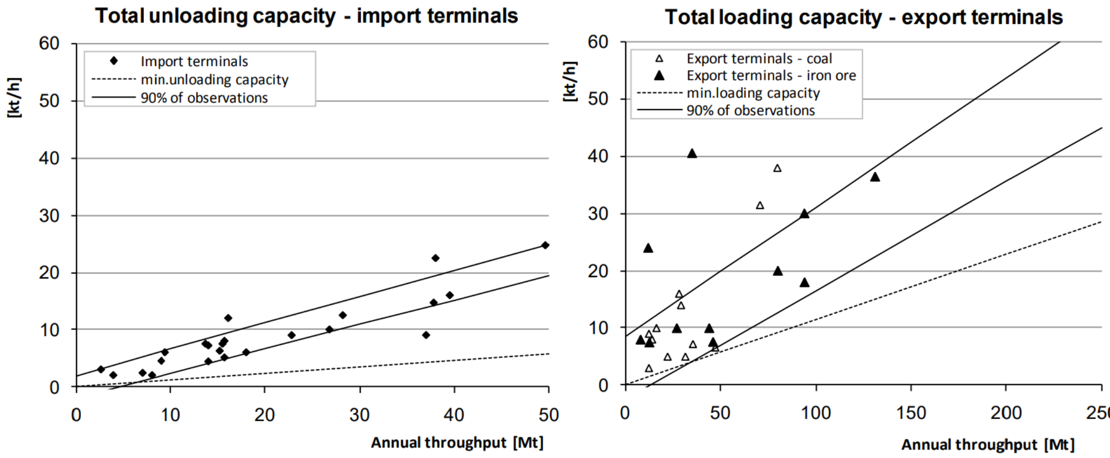


Figure 5.39: (Un)loading capacity of an import and export terminal [24]

The transshipment terminal has a maximum unloading capacity of 1.5 kt/h. This is in line with the results of the import terminals since this value is within the borders of 90% of the observations of the 49 existing dry bulk terminals [24]. Furthermore, the transshipment terminal has a maximum loading capacity of 2.5 kt/h (when the shortcut at the terminal is operational) or 1.0 kt/h (when the shortcut at the terminal is not used). This is again in line with 90% of the observations, however the annual throughput of most of the investigated dry bulk terminals is significantly higher.

- **Storage factor:**
  Due to differences in density between dry bulk materials, the required storage area differs per ton. The storage factors for import and export terminals are in figure 5.40.

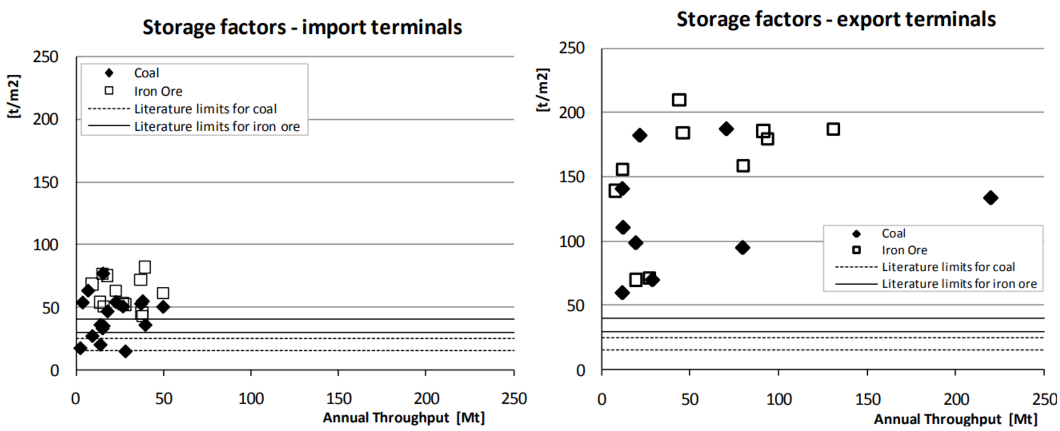


Figure 5.40: Storage factors for import and export terminals [24]

In figure 5.40, it can be seen that storage factors for export terminals is way higher. This has several reasons, of which one of them is that blending and homogenizing is done at import terminals which requires extra storage space. The material is also stored for a longer period at an import terminal [24].

The storage area for the transshipment terminal of the case study equals the stockpile's width multiplied by the stockpile's length which is 50 * 65 = 3250 or 50 * 120 = 6000 m^2. The stockpile is used to accommodate 30.000 or 60.000 tons of nodules, which means the storage factor equals

9.23 or 10 respectively. Since only one commodity is handled at the terminal, the utilization rate of the storage area is 100%. For multiple commodities, it is important to prevent cross contamination between stockpiles. As a consequence the storage area cannot be fully utilized, which results in a common utilization rate of 80% [61]. The storage factor of 9.23 or 10 is still very low in comparison to the storage factors of import terminal and export terminals (even blending and homogenizing is not required at the transshipment terminal). Table 5.6 also shows that the values of the case study are quite low for literature and real life values.
The low storage factor has to do with the stockpile dimensions. The width of 50 meter is on the low side, since some stockyard lanes have a width up to 100 meter. Wider piles result in higer storage factors [23]. The height is also on the safe side with 18 meter. Furthermore, a short stockpile has relatively a lower storage factor in comparison to a longer stockpile due to the beginning and end of a stockpile. The 'lost' storage at the beginning and end of a stockpile relatively has a larger impact on a small stockpile in comparison to a long stockpile.

Unit: [t/m^2]	Import Terminal		Export Terminal	
	Coal	Iron Ore	Coal	Iron Ore
Analyzed terminals	15 – 75	45 – 80	60 – 185	70 – 210
Literature values (Ligteringen, 2000)	15 – 25	30 – 40	15 – 25	30 – 40

Table 5.6: Storage factors real-world versus literature values [24].

- **Utilization rate of equipment:**
  According to practical experience, most terminal equipment today has a minimum utilization rate of around 40% to 50% and a maximum utilization rate of around 80% [61]. Without the use of the shortcut, the utilization rate of the unloader, transport to stockpile and stacker is 51.5%, which is slightly above the minimum of above. The utilization rate of the reclaimer, transport from stockpile and loader is 38.4%, which is slightly below the minimum value of 40%. When the shortcut is used, the utilization rate of the unloader stays the same. The transport to the stockpile and stacker however decreases to only 17.7%. The decrease for the loader, transport from stockpile and reclaimer is minimal: from 38.4 to 34.6%. The utilization rate of the transport equipment of the shortcut itself equals 32.3%. This means the utilization rate of the equipment without the use of a shortcut corresponds with the minimum utilization rates of around 40% to 50%. The use of the shortcut made sure the utilization rate of the equipment dropped significantly (except the unloading equipment).
- **Storage capacity:**
  The maximum storage capacity has to do with the extent of fluctuations between import and export. Regarding the storage capacity, multiple rules of thumb are suggested. First of all, Lodewijks et al. (2009) suggested a rule-of-thumb that a possible stock of about 10% of the annual throughput seems to be accepted in the dry bulk industry. K. van Hemert (1984) suggested a minimum storage capacity of two months of the annual throughput, which equals about 17% of the annual throughput. UNCTAD (1985) provided guidelines for export stockpile dimensioning and concluded 16% of the annual throughput. Another research pointed out that the storage capacity of import terminals varies between 5 and 22% of the annual throughput, and for export terminals these values are between 3 and 10% [24]. Yet another research came up with again 10 percent of the annual throughput or between 2 and 4 times the largest shipload per commodity as storage capacity [47].
  The corresponding graphs for 49 investigated real life dry bulk terminals are given in figure 5.41.

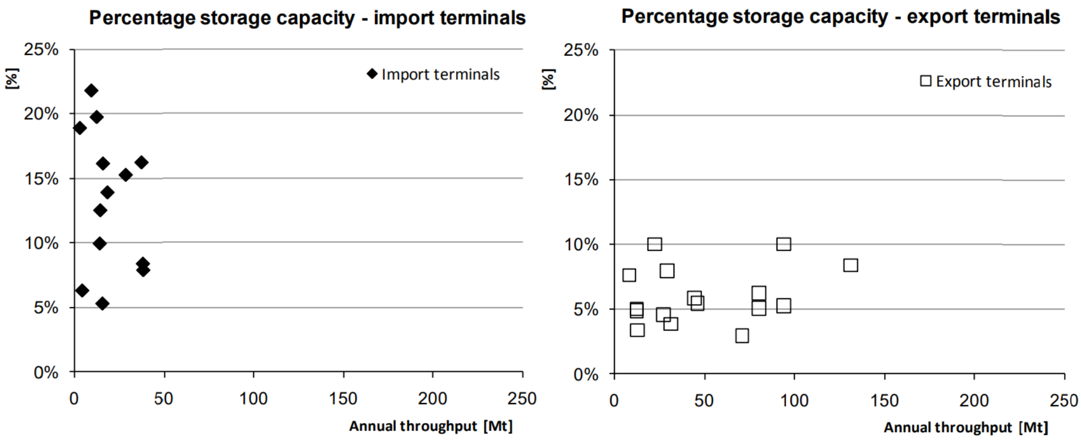


Figure 5.41: Storage capacity for import and export terminals [24]

In this thesis, the terminal has a storage capacity of 30.000 tons for 1, 1.5 and 2 Mt/year (respectively 3%, 2% and 1.5% of the annual throughput). This is lower than the suggested rules of thumb. Also the guideline between 2 and 4 times the largest shipload is not applicable, since the storage capacity would then at least be 110.000 tons.
For the 2.5 and 3 Mt/year scenario, the same can be seen. Both scenarios having a storage capacity of 60.000 tons which equals 2.4% and 2% of the annual throughput respectively. The low storage capacities has to do with the fact that the inter-arrival times are relatively constant. There are a lot of random influences but in general the flow within the supply chain is constant and predictable. Vianen (2015) also concluded that the values used in figure 5.41 will lead to oversized stockyards, so a storage capacity of 2% does seem acceptable.

- **Wt/st ratio:**
  A rule of thumb is that the waiting time should be not more than 50 per cent of service time. For the economic optimum, a maximum of 30 to 40% as a wt/st ratio is acceptable [61]. The bulk carriers for the case study are well below these figures with 6.3 and 9.4% for the BC1 and BC2 bulk carriers respectively.
- **Stacking and reclaiming capacities:**
  The capacities of stackers and reclaimers have a correlation with the annual throughput. The graphs are given in figure 5.42 and 5.43.

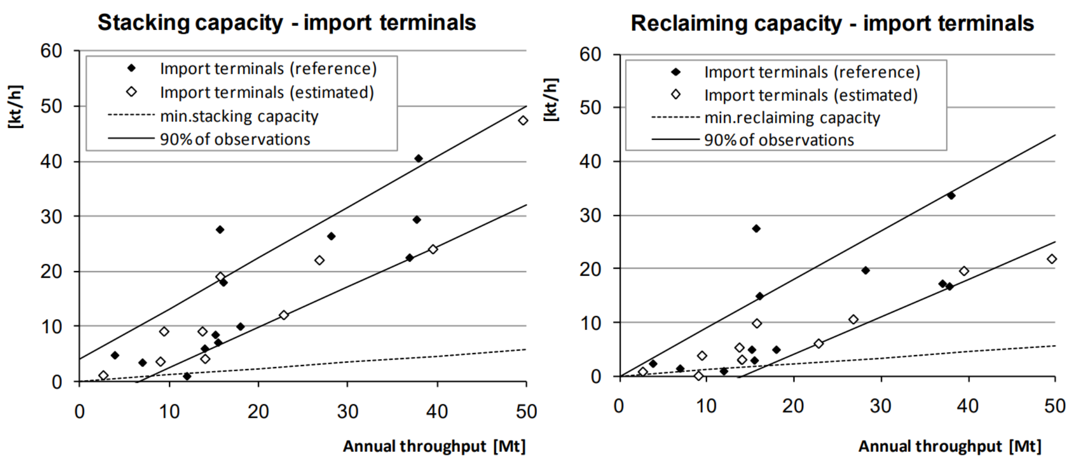


Figure 5.42: Stacking and reclaiming capacity for import terminals [24]

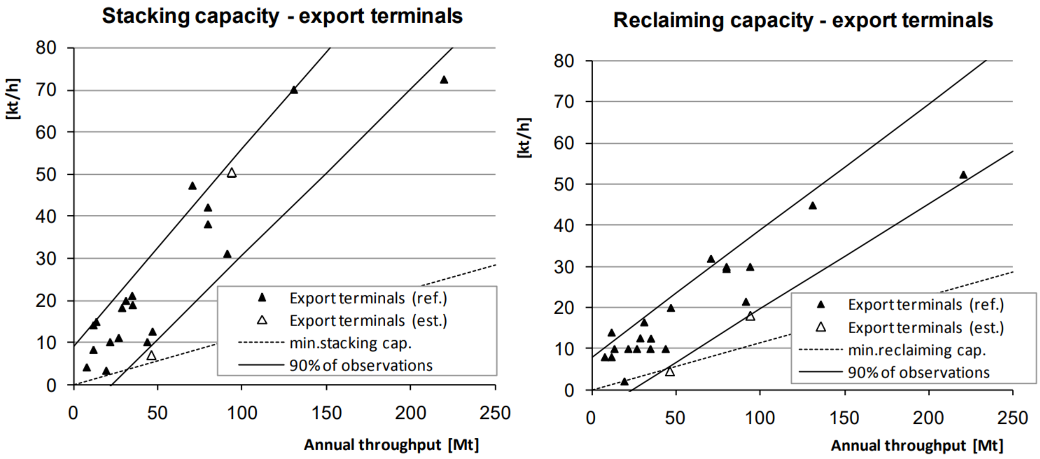


Figure 5.43: Stacking and reclaiming capacity for export terminals [24]

The stacker used in the case study has a maximum stacking capacity of 1.5 kt/h. This is in line with the results of stacking capacities for import and export terminals shown above. The reclaimer has a maximum reclaiming capacity of 1.0 kt/h which also correlates with the figures above.

- **Berth utilization:**
  According to practical experiences, the berth utilization should be below 65% for a terminal with five or less berths. For 6 or more berths, the berth utilization may reach up to 70% [104]. Since the transshipment terminal will have two berths, the berth utilization should be ideally below 65%. For the highest yearly production rate of 3 Mt/year, the unloading berth utilization equals 76.5% and the loading berth utilization equals 73.5% (or 69.8% in the case of shortcut utilization), which is well above the recommended value of 65%. Although, the average waiting queue percentages at the terminal of 4.8% and 6.9% were very low for the bulk carriers of both roundtrips. The higher berth utilization for this case study without consequences has to do with the predictable supply chain. The roundtrip durations do not vary that much which makes the arrival times of the bulk carriers predictable. The production vessel and processing facility can both handle one ship at the time, which also reduces the chance of arrivals of multiple bulk carriers at the terminal at the same time.
- **Equipment installation factor:**
  The equipment installation factor is a measure of the over-dimensioning of the installed equipment [23]. The higher the equipment installation factor, the more over-dimensioning of the installed equipment. The formula for the equipment installation factor is given in equation 5.6 below. Which is the installed terminal (un)loading rate [kt/h] divided by the terminal (un)loading rate when (un)loading machines are 100% of the time in operation.

$$f_s = \frac{Q_{installed}}{Q_{100\%}} \tag{5.6}$$

Graphs for real-world seaside, landside and stockyard equipment installation factor are given in figures 5.44 and 5.45.
For the case study, the handling rate of the equipment is the same for all yearly production rates. The equipment installation factor for 1 Mt/year at the unloading berth equals 1500 / 114 = 13.1 and at the loading berth 1000 / 114 = 8.8. These values are very high in comparison to the results in figures 5.44 and 5.45. The equipment installation factor for 3 Mt/year at the unloading berth equals 1500 / 342 = 4.4 and at the loading berth 1000 / 342 = 2.9. It can be concluded that the equipment installation factor for the lowest yearly production rate is very high, which means the equipment is over-dimensioned. This is logical since the handling rates of the equipment are selected for 3 Mt/year. For 3 Mt/year, the equipment installation factor corresponds very well to the real life terminals below. Especially, the loader and unloader values in figure 5.44 match very well. The stacking and reclaiming equipment in figure 5.45 is in general more over-dimensioned, however 2.9 and 4.4 are still very respectable values which correspond to existing terminals.

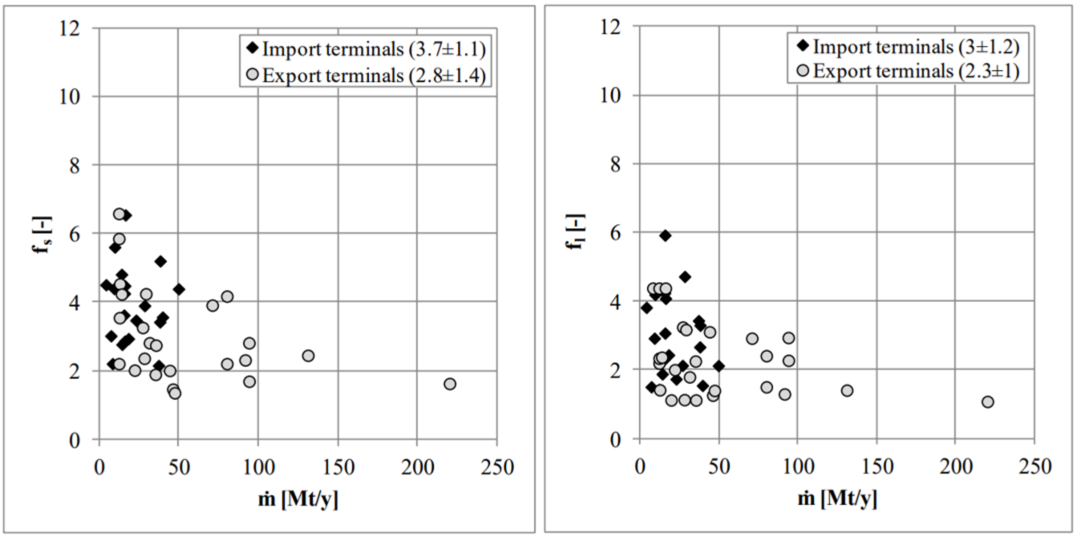


Figure 5.44: Seaside and landside equipment installation factor versus annual throughput [24]

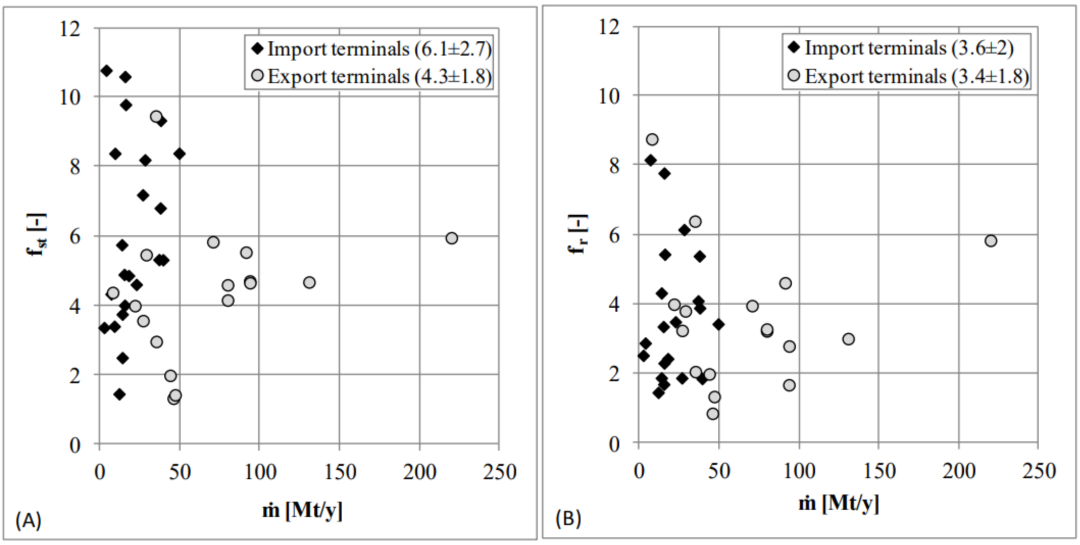


Figure 5.45: Stacking (A) and reclaiming (B) equipment installation factor versus annual throughput [24]

5.7. Conclusions

In this chapter, multiple sub-questions were addressed. Starting off with the following sub-question:

Which experiments should be executed to simulate real-world scenarios, and what will the performance of the terminal be, when these experiments are performed?

The experiments are divided into three versions (see figure 5.46). The first version is focused on the roundtrip between the production vessel and the transshipment terminal. In the second version, the other roundtrip is added to the first version, which is the sailing between the transshipment terminal and the processing facility. The final version combines the roundtrips of the previous models with the terminal processes.

A definitive decision is reached regarding the quantity and capacity of bulk carriers. The processing facility proved to be a bottleneck due to one berth and 8 working hours a day. The use of self-unloaders and thus significantly lower port times provided an outcome.

After the bulk carrier selection, the optimal number of berths is determined. More than 2 berths had very little influence and is thus not worth the additional costs. 1 berth is highly unlikely due to the already high berth occupancies at the 3 Mt/year scenario. The yearly production rate might be even higher in the future. To prevent costly retrofittings or expansions, 2 berths are advised from the beginning. While having two berths might seem excessive for lower annual production rates, such as 1 Mt/year, it provides valuable flexibility for familiarizing with all the operations. During the first year, maximum efficiency is unlikely as there will be a learning curve involved. With two berths available, the supply chain can better accommodate initial inefficiencies, ensuring smoother operations. Using a berth strictly for unloading and one strictly for loading operations is also highly recommended, due to less movement of equipment, less complicated planning and no need for double equipment. By knowing the average vessel sizes and the number of required berths, the required quay length has been calculated.

Next, handling rates for terminal equipment are chosen, with various rates tested to see their impact. For the chosen bulk carrier configuration it was not possible to have one bulk carrier less by increasing the handling rates. However, for the shuttle bulk carriers between the production vessel and the terminal, one bulk carrier less possible when the handling rate is increased and kept constant (for instance by using a self-unloader, bucket or screw type unloader). A drawback of one bulk carrier less is a significant increase in lost collection days. So increasing the handling rates at the unloading berth of the terminal to have one shuttle bulk carrier less is not recommended. In the end, the handling rates are selected to have acceptable results regarding the kpi's, while not being over-classified. Over-classification of equipment would result in unnecessary costs because of more expensive equipment.

After the selection of the right handling rates, the appropriate terminal equipment is selected, which is primarily based on their maximum handling rates. Because the required handling rates are 1000 and 1500 tph, many terminal equipment options remain since these handling rates are not extremely high.

Variations in maximum terminal capacity are then explored to gauge their effects. The lower the terminal capacity, the worse it scores on the key performance indicators and the more lost collection days it has. A trade-off was found to have little lost collector days on the one hand, and an as low as possible storage capacity on the other hand. With the chosen storage capacity, the storage area is determined, building on prior investigation into storage types in chapter 2.

Finally, the influence of redundancy for terminal equipment has also been investigated, which did have a small impact. At the loading berth, no significant changes were observed despite the increased port time caused by waiting for an empty terminal. However, the redundancy of equipment at the unloading berth led to several improvements, such as a reduced average port time for the shuttle bulk carriers. This, in turn, increased the waiting queue at the production vessel, indicating that the production vessel, along with the processing facility, is a bottleneck. This bottleneck at the production vessel is actually desirable for this case study. It is preferable for bulk carriers to wait at the production vessel rather than having no waiting queue, as the last-mentioned scenario increases the likelihood of more lost collection days. Therefore, the bulk carrier configuration and terminal should be designed to ensure that mining operations at the production vessel remain uninterrupted.

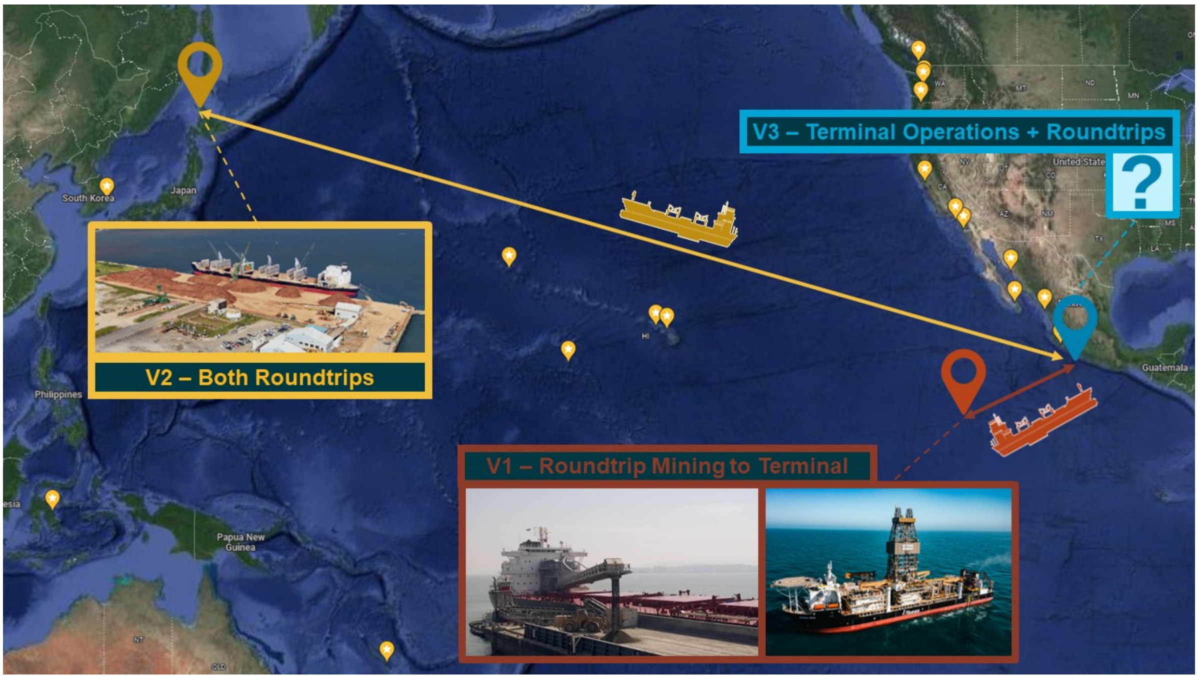


Figure 5.46: Three stages of the model: V1 - Roundtrip Mining to Terminal, V2 - Both Roundtrips, V3 - Terminal Operations + Roundtrips

The next sub-question of this chapter is:

What strategies and technologies can be implemented to mitigate energy usage at the transshipment terminal?

Various energy reduction strategies and technologies were found. Firstly the use of LED lamps at the terminal, since lighting consumes 3-5% of the total energy in ports. Another strategy is the positioning of the stockpile, which should be as close as possible to the berths to minimize terminal transport. Both the use of LED lamps and a stockpile position as close as possible to the berth are recommended to implement for the transshipment terminal. Belt conveyor speed control is also highly recommended at the unloading berth, since the material flow is 50% of the time lower than the peak handling capacity (due to the intermediate and trimming stage during unloading). Belt conveyor speed control is not recommended for the loading berth, since the loading berth will have a constant material flow of 1000 tph, which means that belt conveyor speed control will likely have a small impact.
Furthermore, the use of onshore power supply is recommended as well. The use of onshore power supply however is simulated to quantify the reduction in energy. When renewable energy sources are used, almost 43% of energy can be saved in the case of a yearly production rate of 3 Mt/year. Besides the energy reduction, local pollution is also significantly decreased.
The second energy reduction strategy is the use of alternative power supply, such as electrification of equipment or energy storage devices. An experiment has been performed to quantify the electrification of terminal transport, by replacing diesel trucks by conveyor belts. Again a significant energy consumption can be realized, although that is not the only reason to opt for belt conveyors. Other factors like the need for a road infrastructure, future expansions, local pollution and the need for handling stations for trucks and drivers are a drawback regarding the use of diesel trucks.
The final energy reduction strategy is the use of a shortcut at the terminal, which is also a very effective energy reduction strategy. The experiments with V2 already showed that some way of direct ship to ship transshipment could be interesting. Different scenarios have been tested, for instance increasing the loading rate to a maximum of 2500 tph or having a loading rate between 1000 and 1500 tph. The main reason for the energy reduction is the lower berth occupancy and the lower utilization rate of the transport to and from the stockpile, stacker and reclaimer. The scenario where the loading rate is increased to a maximum of 2500 tph results in a total energy reduction of 13.4%. A drawback is the need for a loader which is able to handle occasionally at 2500 tph. This means that the possible

loading equipment options decrease, since a material handling excavator, mobile harbour crane and screw type loaders are not sufficient concerning their handling capacity.
The compromise scenario where the handling rate is between 1000 and 1500 tph also showed a significant energy reduction of 12.2%. The higher loading berth occupancy results in less energy consumption due to the bulk carrier energy consumption. When the bulk carriers are not taken into consideration, the compromise scenario uses the least energy. The handling rate of the loader again needs an upgrade, however this time 1500 tph is required which means the material handling excavator, mobile harbour crane and screw type loaders are still an option to use. The scenario where the loading rate is increased to a maximum of 2500 tph is recommended since it results in a bigger total energy reduction. The only drawback is the need for loading equipment which is able to handle 2500 tph.
In the end, the six energy reduction strategies and technologies are all recommended to implement. The use of LED lamps and a stockpile position as close as possible to the berths speak for itself. Belt conveyor speed control is also highly recommended at the unloading berth, since the material flow is 50% of the time lower than the peak handling capacity (due to the intermediate and trimming stage during unloading). Belt conveyor speed control is not recommended for the loading berth, since the loading berth will have a constant material flow of 1000 tph, which means that belt conveyor speed control will likely have a small impact. The other energy reduction strategies and technologies, such as onshore power supply, alternative power supply and a shortcut at the terminal all resulted in a significant reduction in energy consumption. Besides the energy reduction, local pollution is also diminished, so these strategies and techniques are recommended as well.
By combining the information of the desired handling rates, investigation of existing small-scale terminals in chapter 2 and the results of the energy reduction strategies & technologies, the appropriate equipment can be selected for the transshipment terminal. Mobile equipment is mainly recommended due to the several advantages such as cost-effectiveness, flexibility and scalability. For the unloading equipment, five options remain. It us unknown whether the use of a screw or bucket wheel unloader is appropriate. The nodules are very brittle which might result in powder after handling the nodules with the wrong equipment. So more research will be required to make a final decision regarding the unloading systems.

The final sub-question within this chapter is:

To which extent are the established rules of thumb and practical experiences in the dry bulk terminal domain representative for the design of a dry bulk transshipment terminal for polymetallic nodule collection?

Overall the results indicate to align with the rules of thumb and practical experiences. Factors like the equipment installation factor, stacking and reclaiming capacities, (un)loading ship capacities and quay length factor are all within the boundaries of the rules of thumb or practical experience. Other factors like the storage factor and utilization rate of equipment were on the low side. This could also be due to the low annual throughput. The comparisons where the research of T. van Vianen (2015) are used like the graph in figure 5.45 above require a side note. The majority of the 49 investigated terminals have a way higher annual throughput. Only 6 terminals were investigated with an annual throughput between 0 and 10 Mt/year. This made it more difficult to compare the results sometimes. Only the berth utilization was high in comparison to practical experiences, but this has to do with the predictable and constant flow of bulk carriers within the supply chain of the case study. The equipment installation factor for low yearly production rates was also divergent, since the handling rates of the equipment are selected for 3 Mt/year. For 3 Mt/year, the equipment installation factor was indeed in line with the existing terminals.

6 Discussion

In this chapter, the limitations of this study and the generalisation of the results are discussed.

6.1. Limitations

The first limitation of this study is that the financial aspect is hardly considered during this thesis. Regarding the bulk carrier configuration, bigger bulk carriers are more cost-effective regarding transport costs per ton [107]. Furthermore, the use of self-unloaders between the terminal and processing facility is not desired from a financial point of view. Besides the bulk carrier configuration, the costs for the terminal equipment are also not taken into account. It might be helpful in the future to use the following rule of thumb used by several experts within the dry bulk terminal field to estimate stockyard machine's investment cost: a machine fully installed at the stockyard has 6-8 times more costs than the machine's weight in kilograms [23]. Another point where financial considerations are overlooked is in the decision to opt for two berths. Return on investment is not considered when two berths are chosen for all annual production rates. Using a single versatile berth for low annual production rates might offer a better return on investment. The final limitation regarding the financial aspect has to do with the option to use floating transshipment. The relatively low storage capacity of 60.000 tons for a yearly production rate of 3 Mt/year opens up opportunities for other transshipment options. For instance floating transshipment at sea, since this would decrease the total sailing distance significantly. Which is beneficial from a cost and environmental point of view. There are several options when it comes to floating transshipment at sea. The first option is direct floating transshipment (see figure 6.1) or self-unloading transshipment. The bulk carriers will be loaded by the production vessel (self-unloading transshipment) and sail directly towards the processing facility. Because of the large sailing distance and processing facility, the production vessel is likely to be more vulnerable to 'lost collector days due to a full hold'. This can be solved by having an over-capacity in bulk carriers but this would result in longer waiting queues at the production vessel and processing facility. Another option is the use of indirect floating transshipment (see figures 6.2, 6.3, 6.4). Then there is still a storage capacity to account for fluctuations in the flow of nodules. The main drawback of the solutions above is the workable weather window. Experts within Allseas mentioned it could be very difficult to use these types of transshipment in the case of rough sea conditions.

Another limitation is the use of a total weather downtime of 5% per year. Research shows that the influence of waiting-on-weather can have a significant impact on the yearly production rate [28]. With the help of weather data and the workable weather window, the waiting-on-weather occasions can be simulated more into detail, instead of using an annual weather downtime percentage.

The final limitation has to do with the movement of equipment during hold changes. The loading and unloading operations temporarily have to stop when the equipment has to move to another hold of the bulk carrier. This phenomenon is not taken into account within the model.

Figure 6.1: Direct floating transshipment [105]

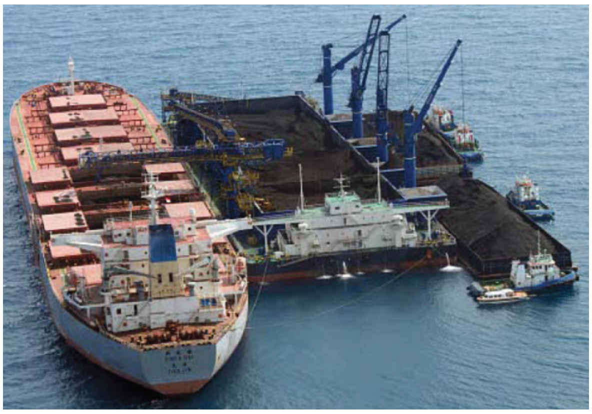


Figure 6.2: First example of indirect floating transshipment [105]

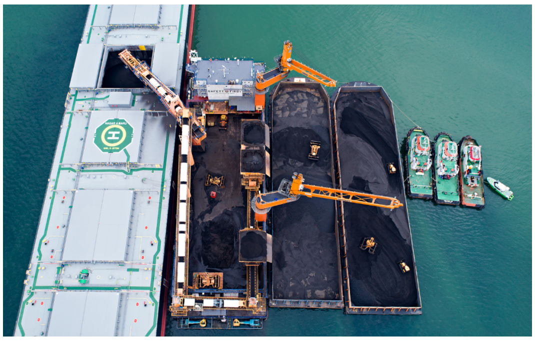


Figure 6.3: Second example of indirect floating transshipment [131]

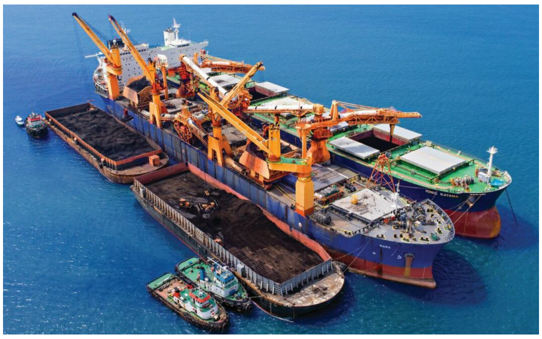


Figure 6.4: Third example of indirect floating transshipment [132]

6.2. Generalisation

The results of this study can partially be used for other case studies. For instance the results regarding the appropriate storage technique and recommended energy reduction strategies/techniques can be generalised for other case studies. This thesis also pointed out that the majority of the rules of thumb and practical experiences can be used as a rough estimate. Although, when things like the location determination and yearly production rate are completely different, some result cannot be generalised for other case studies. Another location and yearly production rate mean the bulk carrier configuration will be different and the throughput at the terminal will differ, resulting in other results for berths and handling rates. Other case studies might also use tandem offloading for STS, instead of a belt conveyor, resulting in a change of yearly weather downtime.

The results of this thesis are biased towards Allseas, since Allseas is the only stakeholder which is taken into account. The model can be adjusted in a way that other stakeholders can also use the model. For instance the owner of the terminal or owner of the bulk carriers (between the processing facility and the terminal) can use the model to get insights into despatch and demurrage costs.
The model can also be used to get insights within other deep-sea mining industries, such as cobalt crusts and sulphides. The location will be different, but the use of a production vessel is applicable.
Besides deep-sea mining industries, the model may also be used for the oil and gas industry. Where oil tankers are stationary loaded from oilfields at sea or floating production, storage, and offloading systems (FPSO).

7 Conclusion & Recommendations

7.1. Conclusion

There is currently no design guideline for a polymetallic nodule dry bulk (transshipment) terminal. In order to facilitate large-scale nodules collection in the not too distant future, the design of such a terminal should be investigated since the design and construction phase will take several years. This thesis is in collaboration with Allseas, and a case study has been executed around possible mining activities in the Pacific Ocean. The main research question of this thesis is as follows:

What should the design be for a dry bulk transshipment terminal to accommodate collected polymetallic nodules, considering logistics and location?

The simulation-based approach was used to answer the main research question. The simulation-based approach is able to integrate many stochastic variations, identify bottlenecks/constraints and allow sensitivity analysis or 'what if' scenarios. At the end of the study, the outcomes of the simulation-based approach are compared to another design method: rules of thumb and practical experiences.

Firstly, the appropriate storage technique was investigated and determined. A conventional longitudinal open stockpile has been selected. Open storage results in lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility. A drawback of open storage is that measures should be taken to prevent inhalation of dust and fines. The maximum handling rates for each type of equipment are also investigated, as well as comparable small-scale terminals. Mobile equipment proved to be conventional at small-scale terminals due to its cost-effectiveness, flexibility, and scalability. This information is used to make a recommendation regarding appropriate terminal equipment.

A simulation model is designed to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and the amount of machinery and their specifications. The majority of the supply chain is integrated within the model. Starting with the processes at the production vessel, where the collector and STS transfer with the belt conveyor unloader are simulated. A shuttle bulk carrier is used to sail between the production vessel and the transshipment terminal. The terminal processes such as unloading, transport and stacking are then simulated during the unloading phase of the shuttle bulk carrier. Besides the roundtrip of the shuttle bulk carrier between the transshipment terminal and production vessel, there is another roundtrip with bulk carriers between the transshipment terminal and the processing facility. For this roundtrip, the terminal processes such as loading, transport and reclaiming are simulated. Once the bulk carrier is filled, it sails towards the processing facility where the nodules are unloaded and processed to the desirable metals.

The location of the transshipment terminal was determined using a weighted criteria method, with Lazaro in Mexico emerging as the optimal location. On all the criteria (such as distance to production vessel and available quay space) it ended up with an excellent score.

Experiments were performed to simulate the in practice occurring scenarios, to evaluate terminal performance. A suggested terminal design is provided in figure 7.1 and will be explained below.

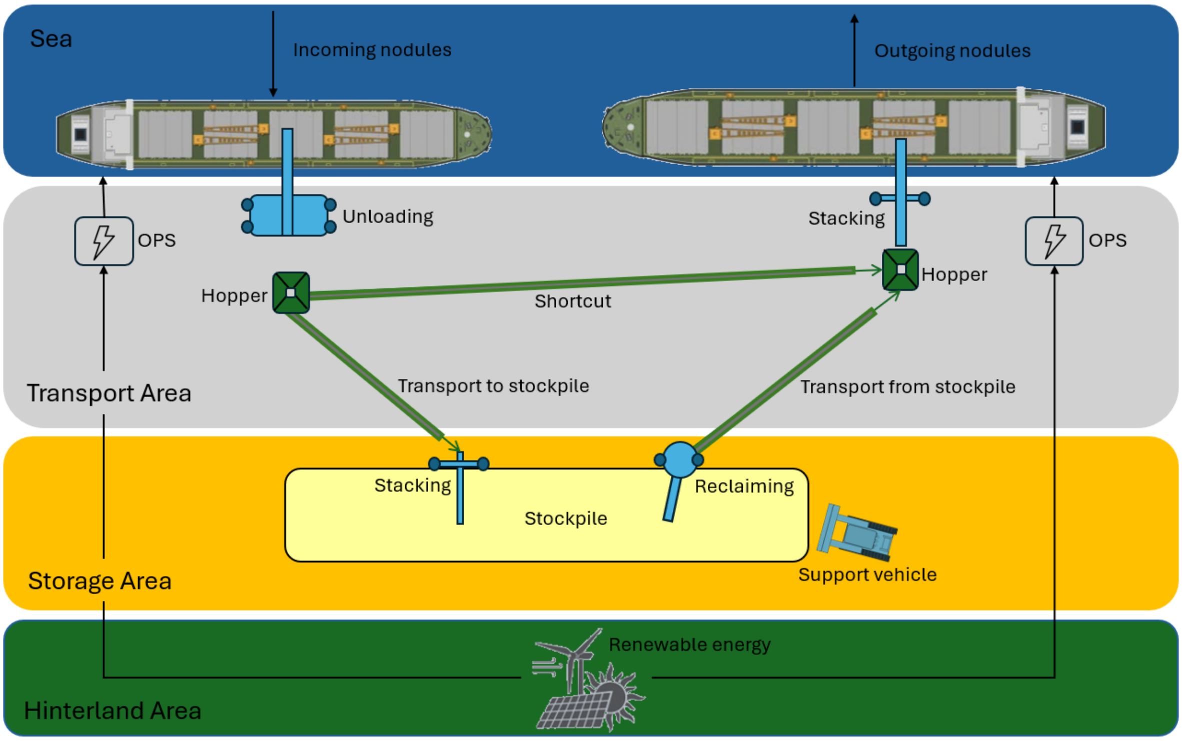


Figure 7.1: Schematic top view transshipment terminal design (dimensions not to scale)

First of all, the amount of bulk carriers and their capacities are determined. For the incoming nodules by shuttle bulk carriers between the transshipment terminal and the production vessel, more bulk carriers with a smaller capacity are preferred over less bulk carriers with a big capacity. The latter scenario resulted in lower waiting queue percentages but resulted in a higher terminal capacity and most importantly more lost collection days. The bulk carrier configuration and terminal should be designed to ensure that mining operations at the production vessel remain uninterrupted, so bulk carriers with a smaller capacity are desired. Having a slight overcapacity of shuttle bulk carriers is also desired to reduce the chances of interrupting the mining operations due to a full hold of the production vessel. Concerning the outgoing stream of nodules by bulk carriers between the transshipment terminal and processing facility, experiments indicated that the processing facility for a yearly production rate of 3 Mt/year is a bottleneck due to a single berth and 8 working hours a day. This has been solved by using self-unloaders (which reduce port times) for the roundtrip between the transshipment terminal and the processing facility.
Regarding the number of berths (and corresponding quay length), it is important to know the final yearly production rate. For the case study the yearly production rate will be gradually increased from 1 to 3 Mt/year. To avoid costly retrofittings/expansions, one berth for unloading and one berth strictly for loading operations is recommended (see figure 7.1). Separating the loading and unloading operations is also recommended because it results in a less complicated planning, less movement of equipment and no need for double equipment. The use of a floating crane is not attractive for the case study due to the smaller incoming bulk carriers (Handysize - 35 kDWT) in comparison to the bigger bulk carriers (Handymax - 55 kDWT) for the outgoing stream of nodules.
The appropriate terminal equipment can be selected by determining the required handling rate. Increasing the handling rates at the unloading berth of the terminal to have one shuttle bulk carrier less is not recommended, due to the increase in lost collection days. The handling rates are selected to have acceptable results regarding the kpi's, while not being over-classified (resulting in unnecessary expensive equipment).

The impact of redundancy in terminal equipment is also examined. This proved to have a minor impact since the waiting times at the production vessel increased, which shows that the production vessel besides the processing facility is also a bottleneck. This means that it does not make sense to speed up the terminal operations without improving the operations at the production vessel, since this is the weakest link in the chain.
Regarding the storage capacity (and corresponding storage area), the lower the terminal capacity, the worse it scores on the key performance indicators. Therefore, a trade-off was chosen to maintain a limited storage capacity while achieving acceptable values for the key performance indicators.
For the terminal design, knowing the development of the yearly production rate is thus important. For instance to prevent costly retrofittings or expansions for berths in the future, the highest yearly production rate should already be taken into account. The highest yearly production rate was also taken into consideration during the determination of the required handling rates and storage capacity.

Due to the rising energy costs and climate change targets, the energy efficiency within the transshipment terminal is also investigated. The use of LED lamps and a stockpile position as close as possible to the berths are recommended and speak for itself. Belt conveyor speed control is also highly recommended at the unloading berth, since the material flow is 50% of the time lower than the peak handling capacity (due to the intermediate and trimming stage during unloading). Belt conveyor speed control is not recommended for the loading berth, since the loading berth will have a constant material flow of 1000 tph, which means that belt conveyor speed control will likely have a small impact. The other energy reduction strategies and technologies, such as onshore power supply (OPS), alternative power supply (belt conveyor versus diesel trucks) and a shortcut at the terminal all resulted in a significant reduction in energy consumption. Besides the energy reduction, local pollution is also diminished, so these strategies and techniques are recommended as well. The use of OPS, belt conveyors and a shortcut are all integrated into the suggested terminal design in figure 7.1.

By combining the information of the selected handling rates, investigation of existing small-scale terminals and the recommended energy reduction strategies & technologies, the recommended equipment options for each terminal function were selected (visualized in table 5.5 in section 5.5). The use of mobile equipment is recommended due to cost-effectiveness, flexibility and scalability.

The results obtained with the simulation-based approach are compared with the other design method: established rules of thumb and practical experiences in the dry bulk terminal domain. The established rules of thumb and practical experiences are in most cases representative. Factors like the equipment installation factor, stacking and reclaiming capacities, (un)loading ship capacities and quay length factor are all within the boundaries of the rules of thumb or practical experience. Other factors like the storage factor and utilization rate of equipment were on the low side. Solely the berth utilization was high in comparison to practical experiences, but this has to do with the predictable and constant flow of bulk carriers within the supply chain of the case study. The equipment installation factor for low yearly production rates was also divergent, since the handling rates of the equipment are selected for 3 Mt/year. For 3 Mt/year, the equipment installation factor was indeed in line with the existing terminals.

Ultimately, a design for a dry bulk transshipment terminal to accommodate collected polymetallic nodules has been provided. The location determination and logistics are taken into consideration as well. This means, a start has been made with the design of such a dry bulk terminal which will be required to facilitate large-scale mining activities in the future.

7.2. Recommendations

This section addresses the recommendations for the various stakeholders. Recommendations for further research are also provided.

7.2.1. Recommendations for Allseas

The following recommendations for Allseas are formulated:

- Investigate the the supply chain without the use of a transshipment terminal:
  As discussed in chapter 6, the relatively low storage capacity of 60.000 tons for a yearly production rate of 3 Mt/year opens up opportunities for floating transshipment options. Further research is required to see whether the floating transshipment is even possible and whether it would beneficial in comparison to the use of a transshipment terminal.
- Investigate energy reduction during transport:
  As briefly discussed in section 5.4, energy reduction strategies during transport should also be further investigated. A speed reduction of 10%, 20%, and 30% reduce fuel consumption by 27.1%, 48.8%, and 60.3% and CO_2 emissions by 19%, 36%, and 51% respectively. The bigger the ship, the more impact the speed reduction has [118]. Also a speed reduction near the transshipment terminal and processing facility can be very interesting when a bulk carrier is likely to end up in a waiting queue at the terminal. The energy savings by reducing the speed near ports can reach up to 25.4% [119]. Although the waiting queue percentages are not that big, this could still have a positive impact.
- Weather downtime investigation:
  With the help of weather data and the workable weather window, the waiting-on-weather occasions can be simulated more into detail. The waiting-on-weather could be an issue in specific months, which makes it attractive to execute extensive planned maintenance in these periods. Further research will also help to see the impact on the STS transfer and yearly production rate more into detail.
- Coordination between stakeholders:
  In order to have an efficient supply chain, coordination between all the stakeholders is recommended. For instance, Allseas will have to look into the interests of the terminal owner and processing facility. By having coordination between these stakeholders, initiatives like reducing the moisture content as much as possible (to reduce drying and energy costs during the final processing step) can be realized.

7.2.2. Recommendations for Processing Facility

The following recommendations for the processing facility are formulated:

- Investigate impact of limiting moisture content:
  Further research concerning the stockpile is recommended. Increasing the stockpile capacity leads to longer residence times (thus more time for drainage) and decreasing the height results in faster drainage [40]. It could occur that these measures have very little influence since the transportation and storage at the processing facility nullify the measures taken at the transshipment terminal, so the impact of the measures should be further investigated.
- Working hours at processing facility:
  It is recommended for Allseas to look into the working hours at the processing facility. Now a comparison has been made between the use of self-unloading vessels versus 12 hour shifts at the processing facility in Japan. The costs were not taken into account during this comparison. Further research has to investigate whether 12 hour shifts are more attractive from a financial point of view, since self-unloading bulk carriers are more expensive than normal bulk carriers.

7.2.3. Recommendations for Further Research

The following recommendations for further research are formulated:

- Starting position bulk carriers:
  The following recommendation is focused on the model development. In the current model, the

bulk carriers start either at the production vessel (vessels for roundtrip between terminal and production vessel) or at the transshipment terminal (vessels for roundtrip between terminal and processing facility). The advice is to let all the bulk carriers start at a random position. This would decrease the duration of the warm-up period.

- Leaving of almost full bulk carriers:
  Another recommendation regarding the model itself, is the modelling of early departure of bulk carriers. When the hold of a bulk carrier at the production vessel or terminal is almost full (let's say the last 5%), it could reward to let the bulk carrier leave while it is not completely full instead of letting it wait for a long time because of an empty terminal or unexpected downtime. The pre- and post-operations before the next vessel arrives will usually provide sufficient time to solve the issue (e.g. downtime). Although this situation will not occur very often, further research is required to see the impact of this.
- Increase hold capacity of production vessel:
  More research is recommended about increasing the hold capacity of the production vessel. During this thesis, the hold capacity of the production vessel was not varied. However, it could potentially decrease the 'lost collector days due to a full hold'. Further research will have to point out the effects of a bigger hold capacity for the production vessel.
- Terminal equipment investigation:
  More research is required regarding the terminal handling equipment interaction with nodules. During this thesis, most of the existing terminal equipment is taken into account. However, it is unknown whether the use of a screw or bucket wheel unloader is appropriate. The nodules are very brittle which might result in powder after handling the nodules with the wrong equipment.
  Furthermore, when belt conveyors will be selected for the transshipment terminal, further research is required regarding the exact impact of speed control. The belt conveyors at the terminal are likely to be relatively short and will have a relatively low occupancy rate. The impact of speed control will then be limited [115], but further research is required to investigate whether speed control is worth it.

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A

Research Paper

A Simulation-Based Approach to Design a Dry Bulk Transshipment Terminal for Polymetallic Nodule Collection

A Discrete Event Simulation Study

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Abstract

There is a growing demand of various metals originating from the sustainable energy transition. The current supply and investments plans for these critical minerals are insufficient to enable this green energy transition. Other problems are the dependency of third countries and multiple drawbacks of land-mining. Deep-sea mining could be a great outcome, by collection of nodules on the seabed in the CCZ area. Different mining trials have been executed, but large-scale mining has not started yet. So far, there is no design guideline for a polymetallic nodule dry bulk (transshipment) terminal. The design and construction phase for a dry bulk terminal takes several years, therefore, the design of such a terminal should be investigated.

This research will focus on the design of a transshipment terminal to accommodate these large-scale mining activities in the future. The logistics and location determination of this terminal are also taken into account. The study contains a case-study which is formed in collaboration with Allseas. For this case-study, the simulation-based approach is chosen to design the transshipment terminal. This approach integrates many stochastic variations, identifies bottlenecks, and allows for sensitivity analysis or 'what if' scenarios. This method was compared to traditional design methods that rely on rules of thumb and practical experiences.

First of all, the appropriate storage technique has been investigated and determined. A conventional longitudinal open stockpile is selected. This option has lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility, although it requires measures to control dust.

A simulation model, containing the majority of the DSM supply chain, was designed to determine the sizing of the stockyard and seaside areas, the number of bulk carriers and their capacity, and the amount of machinery and their specifications.

The location of the transshipment terminal was determined using a weighted criteria method, with Lazaro in Mexico emerging as the most optimal location.

Experiments were performed to simulate the in practice occurring scenarios, to evaluate terminal performance. It was found that smaller capacity bulk carriers were preferred between the production vessel and terminal to have less interruption of mining operations. Experiments also indicated that the processing facility's single berth and limited working hours were bottlenecks, which are mitigated by using self-unloaders to reduce port times at the processing facility.

For berth configuration, it was recommended to have one berth strictly for unloading and one strictly for loading to avoid complex planning, equipment movements and the need for double equipment.

The appropriate handling rates were selected to balance efficiency and cost. Several options are recommended based on the maximum handling rates and knowledge of existing comparable small-scale terminals. Mobile equipment is recommended for its cost-effectiveness, flexibility, and scalability. Redundancy in terminal equipment had a minor impact, as the production vessel, besides the processing facility, proved to be a bottleneck. Speeding up the terminal operations without improving the operations at the production vessel, will only result in longer waiting queues at the production vessel.

Regarding the storage capacity, the lower the terminal capacity, the worse it scores on the key performance indicators. Therefore, a trade-off was chosen to maintain a limited storage capacity while achieving acceptable values for the key performance indicators.
Due to rising energy costs and climate change targets, the energy efficiency within the terminal is also investigated. Experiments have shown that energy reduction strategies and technologies, such as onshore power supply (OPS), alternative power supply (belt conveyor versus diesel trucks) and a shortcut at the terminal can significantly reduce energy consumption and are therefore recommended.
The results of the simulation-based approach were compared with traditional methods, which generally supported the simulation results. However, some differences were noted which have to do with the constant and predictable flow of bulk carriers in the case study.

Ultimately, a design for a dry bulk transshipment terminal that considers logistics and location has been provided. Although, several recommendations for further research can be made. For instance, investigating alternative transshipment methods, such as floating transshipment at sea due to the relatively low required storage capacity. However, challenges such as workable weather windows and the potential need for expensive equipment need further research to assess feasibility and benefits.
Weather influence during STS transfer should also be further investigated and integrated in the model. Furthermore, additional research is needed to determine the best handling equipment for nodules, as screw or bucket wheel unloaders might cause brittleness and turn nodules into powder.
Finally, coordination among all stakeholders is recommended, including the terminal owner and the processing facility, to implement initiatives like reducing moisture content to lower drying and energy costs during processing.

1 Introduction

Because of the green energy transition, there will be a growing demand for various metals to for example accommodate the building of electric cars. The current supply and investments plans for these critical minerals are insufficient to enable this green energy transition. Another problem is the dependency of China, which stimulates Europe to look for new mining opportunities. Land-mining also has large environmental impacts and convincing local residents is difficult. Deep-sea mining could be a great outcome, where this research focuses only on the polymetallic nodules within deep-sea mining. Billions of nodules lie on the seabed, in for example the Clarion-Clipperton Zone (in the Pacific Ocean between Mexico and Hawaii). Different mining trials have been executed, but large-scale mining has not started yet. The literature assignment of Ree, Chris van der (2023) in which the supply chain has been investigated, pointed out an important knowledge gap regarding the terminal storage. The design and construction phase for a dry bulk terminal takes several years. The construction for a dry bulk terminal for example is estimated to take 24 till 30 months [1]. The design and regulatory phase also require a significant amount of time. This highlights the importance to start with the design of a dry bulk (transshipment) terminal as soon as possible. This research will focus on the design of a transshipment terminal to accommodate these large-scale mining activities in the future. The paper will contain a case-study which is formed in collaboration with Allseas.
Design of dry-bulk terminals is currently partly based on rules of thumb and practical experiences. Besides rules of thumb and practical experience, results obtained with simulation tools can be used to design a dry bulk terminal [2]. This simulation-based approach will be used to design the transshipment terminal in this research. There is currently no design guideline for a polymetallic nodule dry bulk (transshipment) terminal and these simulations have not been executed yet. The dry bulk terminal enables fluctuations between the incoming and outgoing flow of material [3]. These fluctuations will undoubtedly occur when large-scale nodule collection activities take place in the future. A fluctuation could occur in the case of for example maintenance for the production vessel or delay in transport due to weather circumstances. Aspects like equipment, location, equipment capacities, storage method and sizing are undiscovered [4]. The main research question is formulated as follows: What should the design be for a dry bulk transshipment terminal to accommodate collected polymetallic nodules?
There are available studies which address the design of dry bulk terminals, however these studies are focused on an import or export terminal. The polymetallic nodule terminal will be a transshipment terminal. At a transshipment terminal, the commodity is unloaded from a feeder vessel to the shore. Later on, the commodity is loaded to a main line vessel. At a transshipment terminal, the commodity moves over the quay twice, for unloading and loading to another ship [5].
Energy consumption is the final aspect which is not taken into account in these studies. Nowadays, ports and terminals strive to improve energy efficiency, driven by rising energy costs over the past years. Climate change mitigation is also a key target for the port industry [6]. This illustrates why the energy consumption should also be taken into account for the design of a dry bulk terminal.

2 Terminal Storage

First of all, the appropriate storage technique will be selected. The choice for open or closed storage depends on the handling capacity, land use, construction and operating costs [7]. For the storage of nodules, the alpha radiation and moisture permeability should also be taken into account. Especially alpha radiation is very important since the inhalation of dust or fines should be prevented. Also inhalation of radon gas should be prevented, which becomes a problem in unventilated or enclosed spaces [8].
The moisture permeability has to do with the processing method of the nodules. For the case study, a rotary kiln will be used, where the kiln is operated at high uniform temperatures, which is required for drying, heating, reaction and soaking. A lot of energy is required to dry and heat the nodules. The moisture content of the nodules should be as low as possible to reduce drying energy and costs [9]. The initial moisture content of the nodules will likely be above the threshold moisture content when

the nodules arrive at the terminal. The threshold moisture content is the average moisture content in a stockpile below which no drainage occurs in the residence time. For materials with an initial moisture content below the the threshold moisture content, closed storage is advised to prevent absorption (for instance of rain water). This does not hold for materials with an initial moisture content above the threshold moisture content. A final measure is to increase the capacity and decrease the height of the stockpile. Increasing the stockpile capacity leads to longer residence times (thus more time for drainage) and decreasing the height results in faster drainage. Although, more research is required to quantify the impact of these measures, regarding the drying energy and costs at the processing facility. Taking all these aspects into account, longitudinal open storage has been chosen. Open storage has lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility. A drawback of open storage is that additional measures should be taken to prevent inhalation of dust and fines. A combination of measures like wind screens, covered storage areas (for instance cellulose crust, water sprinklers or use of tarpaulin), closed belt conveyors, water sprinklers and minimizing stockpile heights should be considered.

3 Model Development

To develop the desired model, a literature research have been executed about the design of dry bulk terminals using the simulation-based approach. Discrete event simulation (DES) is used in the majority of the simulations. DES offers many advantages, such as low computational costs, flexibility in adjusting, high accuracy, identifying utilization of equipment and finally the ability to identify bottlenecks and constraints [10]. Python in combination with the free add on SimPy will be used as a programming language.
The simulation model will be used to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and the amount of machinery and their specifications. Figure 3.1 shows the supply chain of the nodules which will be used to explain the model. The red dot in the ocean represents the mining location. The production vessel to collect the nodules can be seen on the bottom right. The production vessel will use the principle of a self-unloader to transfer the nodules to the shuttle bulk carrier which sails between the transshipment terminal and the production vessel. The principle of a self-unloader can be seen on the picture besides the production vessel, where a large belt conveyor is used to unload the ship.
The yellow dots represent the possible transshipment terminal locations. A decision for the transshipment terminal location will be made in the next chapter. At the transshipment terminal, the operations to handle the nodules, like unloading, loading, transport, stacking and reclaiming are modelled. Important to mention is that the unloading rate decreases as the hold capacity of the bulk carrier decreases. This is shown in figure 3.2. This is not the case for the unloading of the production vessel, since a self-unloader is able to maintain a constant unloading rate. For now the blue dot is assumed as the location of the terminal. The terminal will operate according the SSHINC principle: saturdays, sundays and holidays included. Practical experience points out that 360 working days at the terminal is feasible (minus the weather downtime which will be addressed that later on).
The yellow dot represents the location of the processing facility in the north of Japan. Bulk carriers will be filled at the terminal and are unloaded at the processing facility, after which the bulk carriers will sail with an empty hold back towards the terminal. The processing facility is operated 8 hours a day.

Figure 3.1: Supply chain of the nodules

Within the supply chain described above, there are many stochastic influences. For instance planned maintenance and mechanical downtime for the bulk carriers, vertical transport system, unloader, collector and the terminal equipment. Furthermore pre- and post-loading and unloading operations at the production vessel and the terminal, due to waiting for tugs and/or pilots, (de)berthing operations, sailing from anchorage to berth, procedures time like authorities and a shipping agent and finally the start-up operations of equipment to handle the material. The varying density of nodules at the seabed has also been taken into account. Log-normal distributions are suited to generate failure times [11], so log-normal distributions are used to determine the duration of mechanical downtime and planned maintenance. Normal distributions are used for the remaining distributions, like the duration of pre- and post-loading operations. Waiting-on-weather is also taken into account. The wave conditions play an important role during ship-to-ship transfer [12]. For the case study, a total weather downtime of 5% per year is expected by experts within Allseas. This includes weather where the collector is unable to collect nodules, terminal operations have to stop and where the production vessel is unable to transfer nodules to the shuttle bulk carrier.

Multiple key performance indicators are used to assess the outcomes of the experiments. The obvious ones are the waiting times at the terminal, processing facility, and production vessel. The port time and waiting-time/service-time ratio are also used. As well as the utilization rate of equipment and berth occupancy at the terminal and processing facility. Finally the 'collector days lost due to full hold of production vessel' and linked yearly production rate are used. The 'collector days lost due to full hold of production vessel' is a very important key performance indicator. When the hold of the production vessel has reached its limit, the collector has to stop. The stream of shuttle bulk carriers at the production vessel should be sufficient to restrict the lost collection days, otherwise the yearly production rate targets will not be met.

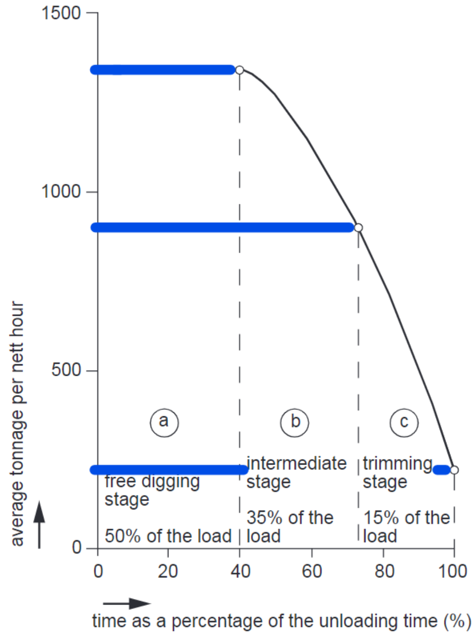


Figure 3.2: Unloading stages - blue bars indicate the 100%, 66% and 15% mark of the rated unloading rate (reworked from Ligteringen, 2017, by TU Delft - Ports and Terminals)

4 Location Determination Transshipment Terminal

Before heading towards the experimental phase, the location of the transshipment terminal for the case study needs to be selected first. The mining location and processing facility are pre-determined and will play a role in the decision-making for the transshipment terminal location due to the sailing duration. The mining location will be within the NORI D area, which is situated within the The Clarion-Clipperton Zone (CCZ) in the Pacific Ocean between Hawaii and Mexico. The processing facility location will be in the north of Japan. The existing berth of the processing facility is shown in figure 4.1. This terminal is operated 7 days a week for 8 hours per day. Geared or self-unloading bulk carriers will be required at this terminal since the berth is equipped with only one mobile crane which can do one hold at the time. The maximum unloading rate at the processing facility equals 1800 tons per hour and will not be exceeded during the experiments since the remaining equipment at the processing facility is likely not designed for higher unloading rates. For this research, the assumption has been made that other operations at the current processing facility quay will not exert influence on the experiments.

Figure 4.1: Processing facility location Japan

In order to determine an appropriate transshipment terminal location, the weighted criteria method has been used. The following factors are evaluated (ranked from least to most important): infrastructure costs, environmental impact, land access, labour availability, water access, land availability, available quay space, distance from terminal towards processing facility, distance from terminal to mining location.
19 possible locations are assessed, ranging from locations in Mexico, America, Canada and (small) islands in the Pacific Ocean. Lazaro in Mexico proved to be the optimal terminal location for now. On all the criteria it ended up with an excellent score. The only disadvantage is the distance towards the processing facility in Japan, in comparison to especially island locations such as Hawaii. On the other hand, the presence of an existing coal terminal is an important upside. Besides existing infrastructure and berths, it takes away some uncertainties about certain environmental regulations, draft restrictions and tide influence. Since the existing coal terminal is also able to deal with these criteria. Lazaro also offers sufficient space for expansion of the terminal in the future.

5 Experiments and Results

5.1 Bulk Carriers

First of all a final decision has been made about the number of bulk carriers and their capacity. Five different types of bulk carriers are taken into account: Handysize, Handymax, Panamax, Post-Panamax and Capesize, each with a deadweight tonnage (how much weight a ship can carry) of 35.000, 55.000, 80.000, 110.000 and 180.000 respectively. Also five different yearly production rate scenarios are taken into account (1, 1.5, 2, 2.5, 3 Mt/year), since Allseas will gradually increase the yearly production rate scenario from 1 million ton per year to 3 million ton per year. The number of required bulk carriers for the different yearly production rates is provided in figure 5.1 below.

For the final choice of the bulk carriers between the terminal and the production vessel, the bulk carrier capacity had a large influence on the 'lost collector days'. Smaller capacities and more vessels results in less lost collector days in comparison to big capacities and less vessels. Although, the waiting queue percentage increases with more bulk carriers with a smaller capacity. The use of smaller capacities also resulted in a lower required terminal capacity. Furthermore the benefit of a small vessel is the maneuverability, which is useful during ship-to-ship transfer at the production vessel. Taken all the aspects into account, the Handysize bulk carrier is selected with a kDWT of 35.

The decision-making for the bulk carriers between the processing facility and the terminal is more complex due to the large influence of the processing facility. Figure 4.1 shows the quay of the processing facility. Geared bulk carriers or self-unloaders will be required at this terminal since the berth is equipped with only one mobile crane which can do one hold at the time. The maximum unloading rate at this terminal is 1800 tph. Another aspect is the fact of 8 working hours a day. This meant that the processing facility could not keep up with the incoming rate of nodules for the 3 Mt/year yearly production rate scenario. Several options have been investigated, such as increasing the number of berths from one to two, increasing the working hours per day to 12 hours or the use of self-unloaders. A self-unloader is able to continuously unload at a constant rate and will thus decrease the port time significantly. The unloading stages (previously showed in figure 3.2) take up a lot of time. Especially at the final trimming stage, the unloading rate is much lower. The use of self-unloaders proved to be the most feasible option and scored better on the key performance indicators.
So from now on, a self-unloading vessel will be used for the roundtrip between the terminal and the processing facility. The use of a self-unloader results in the fact that the use of Post-Panamax and Capesize vessels is impossible, since there are no existing self-unloaders of that size. The draft restrictions at the processing facility also mean that a Panamax vessel is impossible, which means a decision has to be made between a Handysize and Handymax bulk carrier. The bigger the capacity of the ship, the higher the loading berth occupancy is at the transshipment terminal. On the other hand, the waiting queue percentage was still acceptable and a Handymax vessel resulted in a significant lower average and maximum terminal capacity.

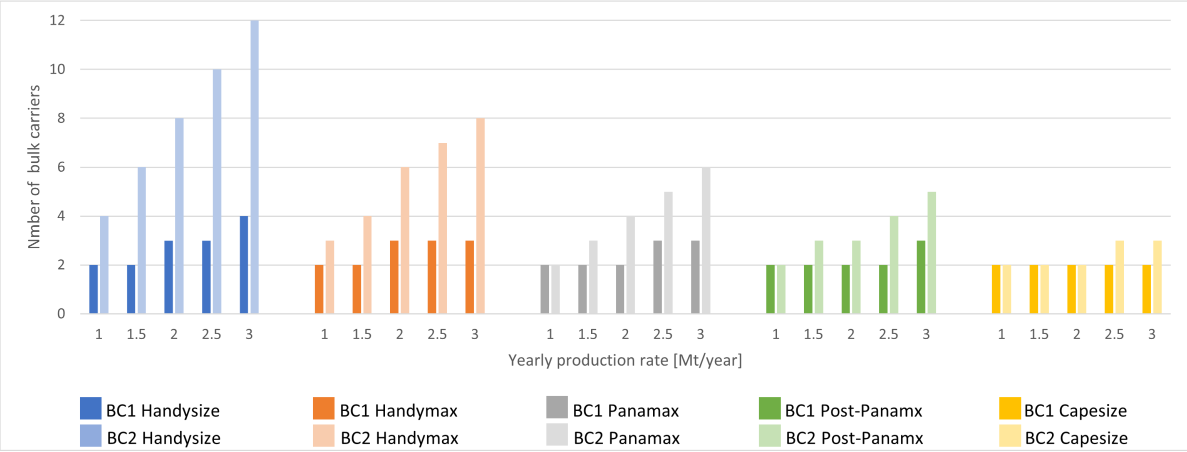


Figure 5.1: Number of required BC1 and BC2 bulk carriers for different yearly production rates and different vessel types

5.2 Berths

Then the amount of berths will be selected, after which the quay length is determined. Two options are considered: 1 versatile berth (where both loading and unloading can take place) or 2 dedicated berths (there is one berth for loading operations and one for unloading operations). The two berths already indicated berth occupancies of over 70%. According to literature, berth occupancies should typically be below 65% for a terminal with five or less berths [13]. So one versatile berth will likely result in long waiting queues and higher demurrage costs. Furthermore for this paper, a maximum yearly production rate of 3 Mt/year is picked. This yearly production rate might be even higher in the future, which indicates that 1 versatile berth will definitely not be sufficient. To avoid costly retrofitting or expansions, at least two berths will be assumed. While having two berths might seem excessive for lower annual production rates, such as 1 Mt/year, it provides valuable flexibility for familiarizing with all the operations. During the first year, maximum efficiency is unlikely as there will be a learning curve involved. With two berths available, the supply chain can better accommodate initial inefficiencies, ensuring smoother operations.
The choice for two dedicated berths instead of two versatile berths has to do with several reasons. Two versatile berths results in a more complicated planning and the need to constantly move equipment. But the main reason for two dedicated berths is that there will be not double loading and unloading equipment required.

The use of a floating crane has also been investigated, but will not be recommended for the case study. The bulk carrier configuration is not appropriate for the use of a floating crane, since a floating crane is usually used to unload the load of large bulk carriers into multiple smaller barges. This is not applicable to the case study since the bulk carriers used for the roundtrip between the terminal and the processing facility will be bigger.

By knowing the number of berths and vessel specifications, the quay length can be calculated by using the following formula (developed by Ligteringen (1999):

$$\mathbf{Quay\ length} = \mathbf{1.1}\ \times \boldsymbol{n_b} \times (\mathbf{LOA}_{\boldsymbol{average}} + \mathbf{15}) + \mathbf{15})$$

where n_b *is equal to the number of berths and* $\mathrm{LOA}_{average}$ *is the average calculated vessel length*

The vessel dimensions for a Handysize and Handymax are respectively 140 and 175 meter. An important remark is that the Handymax vessels are self-unloaders and generally have a bigger length, so 190 meter instead of 175 meter is chosen. This resulted in a required quay length of 411 meter.

5.3 Handling Rates

The next step is selecting the handling rates for the terminal equipment. Various handling rates ranging between 500 and 4500 tons per hour have been tested to see their impact. The maximum handling rate which shall be tested is 4500 tons per hour, since 4500 tons per hour is the maximum stacking and reclaiming capacity for a longitudinal stockpile [7]. For the chosen bulk carrier configuration it was not possible to have one bulk carrier less by increasing the handling rates. However, for the shuttle bulk carriers between the production vessel and the terminal, one bulk carrier less possible when the handling rate is increased and kept constant (for instance by using a self-unloader, bucket or screw type unloader). A drawback of one bulk carrier less is a significant increase in lost collection days. So increasing the handling rates at the unloading berth of the terminal to have one shuttle bulk carrier less is not recommended. In the end, the handling rates are selected to have acceptable results regarding the kpi's, while not being over-classified. Over-classification of equipment would result in unnecessary costs because of more expensive equipment. After the selection of the right handling rates, the appropriate terminal equipment is selected, which is primarily based on their maximum handling rates. Because the required handling rates are 1000 and 1500 tph, many terminal equipment options remain since these handling rates are not extremely high. A final recommendation regarding handling equipment will be made in section 5.7.

5.4 Storage Capacity

Then the maximum terminal capacity is varied to see the impact of different variations. According to A.J.A. Kleinheerenbrink (2012), the storage capacity is determined by trial and error, so this method has also been used in this research. For the 3 Mt/year scenario, storage capacities ranging between 5000 and 100.000 are tested. The lower the storage capacity, the higher the loading and unloading berth occupancies. The terminal percentage of a full and empty terminal also increased. Because of this increase, the port time increased, which then also resulted in higher waiting queue percentages for both ships. So a trade-off has to be found between on the one hand a low storage capacity, and on the other hand acceptable values for the key performance indicators. The most important key performance indicator was the 'lost collector days due to a full hold of the production vessel'. Where a relatively small difference in maximum storage capacity, could result in a significant increase of lost collection days. A storage capacity of 30.000 tons will be used for the yearly production rates of 1, 1.5 and 2 Mt/year. For 2.5 and 3 Mt/year, 60.000 tons will be used as a maximum storage capacity.

With the known required maximum storage capacity, the required storage area can be determined. This will be down with the formula provided below [14] (with clarification of the variables in figure 5.2):

$$m = hl\,\rho\left(w - \frac{h}{\tan(\alpha)}\right) + \frac{1}{3}\rho\pi\left(\frac{h^3}{\tan^2(\alpha)}\right) + \rho h\left(w - \frac{2h}{\tan(\alpha)}\right)\frac{h}{\tan(\alpha)}$$

$$h_{\max} = \tfrac{1}{2}\, w \tan(\alpha)$$

Where m is the pile's mass [ton], h is the pile's height [m], l is the length of the trapezoidal part [m], ρ is the dry bulk's density [t/m3], w is the pile's width [m] and α is the material's angle of repose [°].

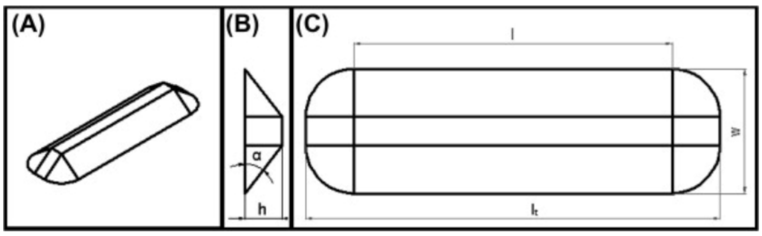


Figure 5.2: Variables used in the formula to calculate the mass of a pile [14]

With the formula above, the length of the stockpile can be determined. The other variables can be determined by investigating literature. The pile width usually varies between 40 and 100 meter. A common lane's width is 50 meter [2], which will also be used in the formula above. The height of the pile is normally limited by the stacking height of the stacker and/or reclaimer. Most stacking machines are able to stack up to a maximum of 23 meters [15]. The formula above indicated a maximum height of 18.8 meter so a height of 18 meter will be used to be on the safe side. A lower height is also beneficial in terms of dust control. A slightly lower height helps to reduce dust forming [16]. The final advantage of a lower height has to do with the moisture permeability described in chapter 2. Decreasing the height results in faster drainage [9]. This in the end will likely result in less energy consumption during the processing of the nodules.

For the calculations, an apparent density is taken of 1200 kg/m3 and an angle of repose of 37 degrees, which has been researched in the literature assignment of Ree, Chris van der (2023). The stockpile length for a storage capacity of 30.000 tons equals 65 meter. The stockpile length for a storage capacity of 60.000 tons equals 120 meter. A pile is often limited to a certain weight. This is 105 kton for coal piles and 175 kton for iron ore piles [2]. The 30 and 60 kton of the stockpiles above are below these limits, so one continuous stockpile will be used.

5.5 Redundancy of Equipment

Finally, the influence of redundancy for terminal equipment has also been investigated. The unloading side of the terminal did show some positive effects, but this resulted in a higher waiting queue at the production vessel. Till this point, the terminal has been simulated with one piece of equipment for every terminal operation. This could result in undesired extra port time for a bulk carrier when certain terminal equipment experiences downtime. With spare equipment, the result of unexpected downtime is minimized to one hour. This is because there is still time required to make a diagnose for what is wrong. After the diagnose, there is additional time needed for start-up operations and for the new equipment to get into the right position. So the influence of mechanical downtime will not be zero, but will be limited to one hour for all the terminal equipment.

An experiment has been performed for the 3 Mt/year scenario. This scenario has the highest berth occupancies and utilization rates of terminal equipment. The redundancy of equipment resulted in a lower average port time for BC1 bulk carriers (64.5 hours with redundancy versus 72 hours without redundancy). The unloading berth occupancy also decreased with roughly 5% to 70% with redundancy. Furthermore, the waiting queue at the unloading berth decreased from 3.1% to 1.7%, resulting in a lower waiting-time/service-time ratio (7.8% versus 5.9%). These are all significant decreases, although it did not influence the lost collector days due to a full hold. This is due to the fact that the waiting queue at the production vessel increased from 29.2% (without redundancy) to 33.6% (with redundancy). This means that the unloading at the production vessel is the main bottleneck. It does not make sense to improve the terminal operations on the unloading berth side, because this highlights the bottleneck at the production vessel even more.

For the loading berth, no significant changes were discovered regarding waiting queue times and loading berth occupancy. The gained up-time of the equipment has been nullified by waiting for an empty terminal.

5.6 Energy Reduction Strategies & Technologies

Ports and terminals strive to improve energy efficiency, driven by rising energy costs over the past years. Climate change mitigation is also a key target for the port industry [6]. This section will address energy reduction strategies and technologies to mitigate energy usage at the transshipment terminal.

Multiple energy reduction strategies and technologies were found. Firstly the use of LED lamps at the terminal, since lighting consumes 3-5% of the total energy in ports. Another strategy is the positioning of the stockpile, which should be as close as possible to the berths to minimize terminal transport. Belt conveyor speed control is also highly recommended at the unloading berth, since the material flow is 50% of the time lower than the peak handling capacity (due to the intermediate and trimming stage during unloading). As a result, the belt conveyor is not optimally filled during normal use. The throughput capacity can be adjusted to the current material flow by reducing the belt speed (speed variation). This increases the load of the belt optimally at the lowest possible belt speed [17]. Belt conveyor speed control is not recommended for the loading berth, since the loading berth will have a constant material flow of 1000 tph, which means that belt conveyor speed control will likely have a small impact.

The use of onshore power supply however is simulated to quantify the reduction in energy. When renewable energy sources are used (and the efficiency is set to 100% for renewable energy), almost 43% of energy can be saved in the case of a yearly production rate of 3 Mt/year, in comparison to idling diesel engines (with an efficiency of 45%). Besides the energy reduction, local pollution is also avoided.
The second energy reduction strategy is the use of alternative power supply, such as electrification of equipment or energy storage devices. An experiment has been performed to quantify the electrification of terminal transport, by replacing diesel trucks by belt conveyors. The use of belt conveyors resulted in a 39% lower energy consumption (solely terminal equipment taken into account) of 0.82 GW per 5 years. Although that is not the only reason to opt for belt conveyors. Other factors like the need for a road infrastructure, future expansions, local pollution and the need for handling stations for trucks and drivers are a drawback regarding the use of diesel trucks.
The final energy reduction strategy is the use of a shortcut at the terminal. The experiments with the floating crane already showed that a form of direct ship to ship transshipment could be interesting. The shortcut can be seen in figure 5.3. When both the unloading and loading berth are occupied, the nodules can be directly transported from the unloading berth to the loading berth. This reduces the terminal transport and the need for stacking and reclaiming operations. At the loading berth, the stream of nodules coming from the unloading berth will be combined with the 'conventional' stream of nodules (otherwise the loading rate would be too low in the case of the trimming stage of the unloaded bulk carrier). This means that the loading rate of the BC2 bulk carrier varies between 1000 and 2500 tph (depending on the hold capacity and thus unloading rate of the BC1 bulk carrier). The use of the shortcut resulted in a total energy reduction of 13.4%. Besides the decreased utilization rate of equipment, the lower loading berth occupancy also contributed to the energy reduction.

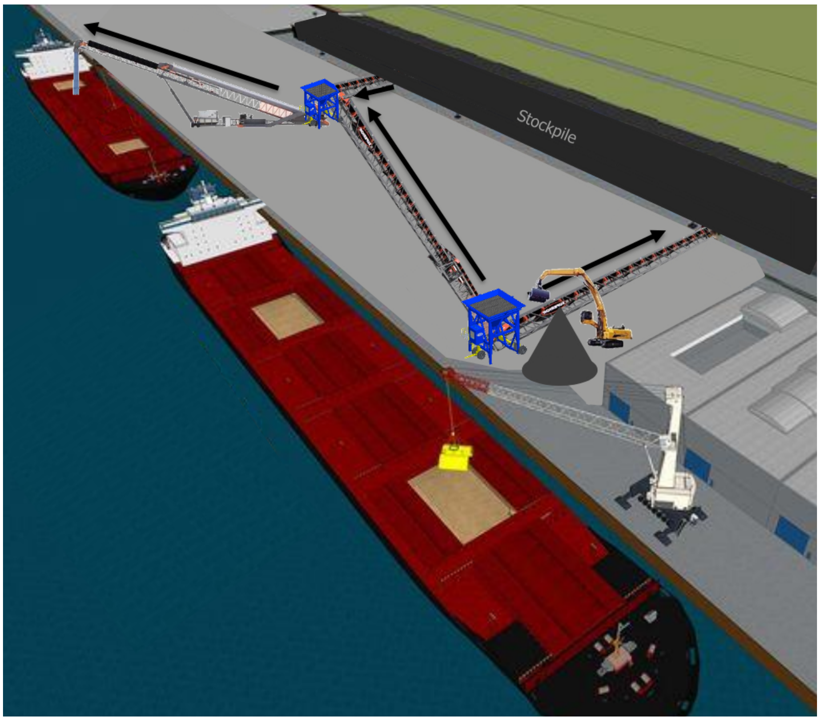


Figure 5.3: Shortcut at terminal

5.7 Handling Equipment

The handling equipment has been investigated to provide a recommendation for equipment selection. Multiple options for each terminal function, like stacking or loading are investigated. Also the maximum handling rates for each type of equipment are analyzed. Comparable small-scale terminals (with a relatively low yearly production rate < 3 Mt/year) are also shortly investigated to get a feeling for the used equipment in practice (see an example depicted in figure 4.1). Minor dry bulk terminals make use of floating and/or mobile cranes. Furthermore, cargo handling operations are supported by yard

vehicles such as bobcats, trailers and shovels/wheel loaders. Equipment like stacker-reclaimers are missing since they are typically used for dry bulk terminals with a higher yearly production rate [18].
By combining the information of the desired handling rates in section **??**, investigation of existing small-scale terminals and the results of the energy reduction strategies & technologies, the appropriate equipment can be selected for the transshipment terminal. Since the use of a shortcut is recommended, the loading equipment needs to be able to handle occasionally 2500 tph. This means that the possible loading equipment options decrease, since a material handling excavator, mobile harbour crane and screw type loaders are not sufficient concerning their handling capacity.
Furthermore, mobile equipment is mainly recommended due to the several advantages such as cost-effectiveness, flexibility and scalability. For the unloading equipment, five options remain. It us unknown whether the use of a screw or bucket wheel unloader is appropriate. The nodules are very brittle which might result in powder after handling the nodules with the wrong equipment. So more research will be required to make a final decision regarding the unloading systems. The equipment recommendations for each function are provided in table 5.1 below.

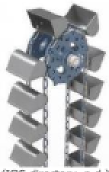
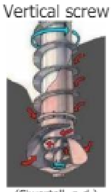
Function	Option 1	Option 2	Option 3	Option 4	Option 5
Storage types	Longitudinal open storage  (M. Droetteboom, 2020)				
Unloading systems	Mobile harbour crane  (Liebherr, 2024)	Material handling excavator  (PortCraneOperator, 2023)	Bucket elevator  (IQS directory, n.d.)	Bucket wheel  (PLM specials, n.d.)	Vertical screw  (Siwertell, n.d.)
Loading systems	Mobile shiploader (linear)  (Superior Industries, 2024)	Mobile shiploader (radial)  (Telestack, 2017)			
Terminal transport	Belt conveyor  (J. Williams, 2020)	Mobile belt conveyor  (Superior Industries, 2024)			
Stacking	Mobile stacker  (Metso, 2024)				
Reclaiming	Material handling excavator  (PortCraneOperator, 2023)	Wheel loader  (Indiamart, 2023)			
Support vehicle	Wheel loader  (Indiamart, 2023)	Bulldozer  (Driven by Battat, 2024)			

Table 5.1: Equipment recommendations

5.8 Comparison with Rules of Thumb & Practical Experiences

In the final section of this research, the two design methods to design a dry bulk terminal are compared to each other. The simulation-based approach has been used in this research and these results will now be compared to the rules of thumb and practical experiences.
Overall the results indicate to align with the rules of thumb and practical experiences. Factors like the equipment installation factor, stacking and reclaiming capacities, (un)loading ship capacities and quay length factor are all within the boundaries of the rules of thumb or practical experience. Figure 5.4 shows the data of 49 investigated dry bulk terminals [2]. The loading and unloading ship capacities, respectively 1000 and 1500 tph, are well within the boundaries.
The storage capacity of the transshipment terminal proved to be on the low side. The low storage capacities has to do with the fact that the inter-arrival times are relatively constant. There are a lot of random influences but in general the flow within the supply chain is constant and predictable. The storage capacity of the investigated terminals will also lead to oversized stockyards [2], so the lower storage capacity for the transshipment terminal seems acceptable.
The berth utilization was high in comparison to practical experiences, but this again has to do with the predictable and constant flow of bulk carriers within the supply chain of the case study. Since a high berth utilization did not result in high waiting queues. The equipment installation factor for low yearly production rates was also divergent, since the handling rates of the equipment are selected for 3 Mt/year, and thus over-classified for lower yearly production rates. For 3 Mt/year, the equipment installation factor was indeed in line with the existing terminals.

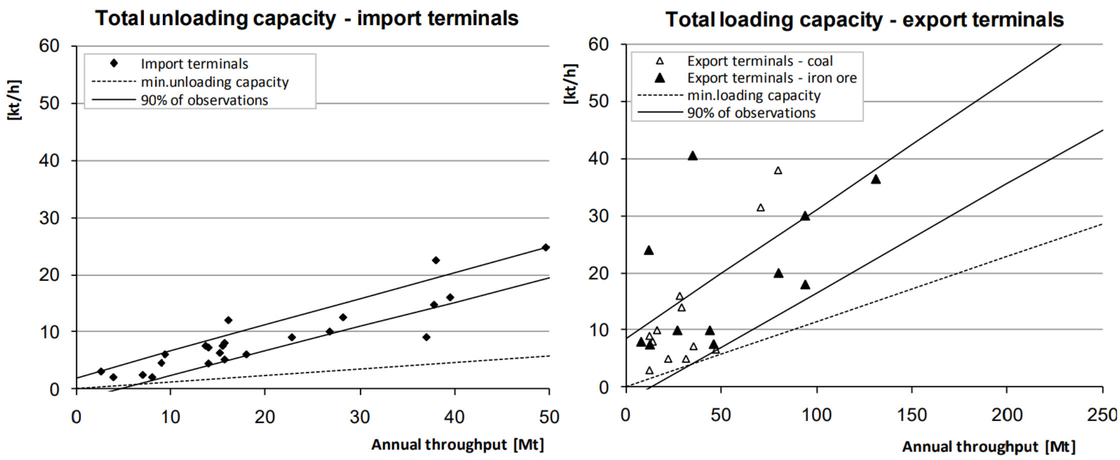


Figure 5.4: (Un)loading capacity of an import and export terminal [3]

6 Discussion

In this chapter, the limitations of this study and the generalisation of the results are discussed.

6.1 Limitations

The first limitation of this study is that the financial aspect is hardly considered. Regarding the bulk carrier configuration, bigger bulk carriers are more cost-effective regarding transport costs per ton [19]. Furthermore, the use of self-unloaders between the terminal and processing facility is not desired from a financial point of view.
The costs for the terminal equipment is also not taken into account. The costs are of course very important for Allseas and it might be helpful to use the following rule of thumb used by several experts within the dry bulk terminal field to estimate stockyard machine's investment cost: a machine fully installed at the stockyard has 6-8 times more costs than the machine's weight in kilograms [2].
Another point where financial considerations are overlooked is in the decision to opt for two berths. Return on investment is not considered when two berths are chosen for all annual production rates.

Using a single versatile berth for low annual production rates might offer a better return on investment. The final limitation regarding the financial aspect has to do with the option to use floating transshipment. The relatively low storage capacity of 60.000 tons for a yearly production rate of 3 Mt/year opens up opportunities for other transshipment options. For instance floating transshipment at sea, since this would decrease the total sailing distance significantly. Which is beneficial from a cost and environmental point of view. There are several options when it comes to floating transshipment at sea. The first option is direct floating transshipment (see figure 6.1) or self-unloading transshipment. The bulk carriers will be loaded by the production vessel (self-unloading transshipment) and sail directly towards the processing facility. Because of the large sailing distance and processing facility, the production vessel is likely to be more vulnerable to 'lost collector days due to a full hold'. This can be solved by having an over-capacity in bulk carriers but this would result in longer waiting queues at the production vessel and processing facility. Another option is the use of indirect floating transshipment (see figure 6.2). Then there is still a storage capacity to account for fluctuations in the flow of nodules. The main drawback of the solutions above is the workable weather window. Experts within Allseas mentioned it could be very difficult to use these types of transshipment in the case of rough sea conditions.
Another limitation is the use of a total weather downtime of 5% per year. Research shows that the influence of waiting-on-weather can have a significant impact on the yearly production rate [12]. With the help of weather data and the workable weather window, the waiting-on-weather occasions can be simulated more into detail, instead of using an annual weather downtime percentage.
The final limitation has to do with the movement of equipment during hold changes. The loading and unloading operations temporarily have to stop when the equipment has move to another hold of the bulk carrier. This phenomenon is not taken into account within the model.

Figure 6.1: Direct floating transshipment [20]

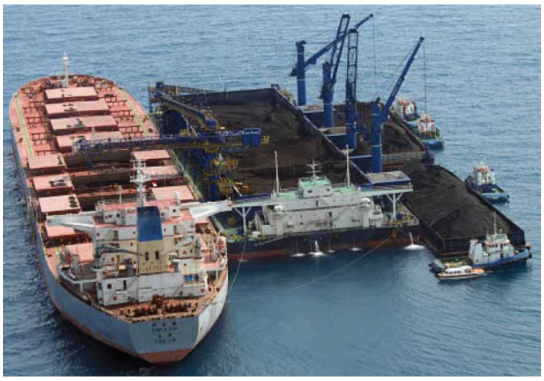


Figure 6.2: First example of indirect floating transshipment [20]

6.2 Generalisation

The results of this study can partially be used for other case studies. For instance the results regarding the appropriate storage technique and recommended energy reduction strategies/techniques can be generalised for other case studies. This study also pointed out that the majority of the rules of thumb and practical experiences can be used as an estimate. Although, when things like the location determination and yearly production rate are completely different, some result cannot be generalised for other case studies. Another location and yearly production rate mean the bulk carrier configuration will be different and the throughput at the terminal will differ, resulting in other results for berths and handling rates. Other case studies might also use tandem offloading for STS, instead of a belt conveyor, resulting in a change of yearly weather downtime.
The results of this study are biased towards Allseas, since Allseas is the only stakeholder which is taken into account. The model can be adjusted in a way that other stakeholders can also use the model. For instance the owner of the terminal or owner of the bulk carriers (between the processing facility and the terminal) can use the model to get insights into despatch and demurrage costs.
The model can also be used to get insights within other deep-sea mining industries, such as cobalt crusts and sulphides. The location will be different, but the use of a production vessel is applicable.
Besides deep-sea mining industries, the model may also be used for the oil and gas industry. Where oil tankers are loaded from oilfields at sea or floating production, storage, and offloading systems (FPSO).

7 Conclusion & Recommendations

7.1 Conclusion

There is currently no design guideline for a polymetallic nodule dry bulk (transshipment) terminal. In order to facilitate large-scale nodules collection in the not too distant future, the design of such a terminal should be investigated since the design and construction phase will take several years. This research is in collaboration with Allseas, and a case study has been executed around possible mining activities in the Pacific Ocean. The main research question of this paper is as follows:

What should the design be for a dry bulk transshipment terminal to accommodate collected polymetallic nodules, considering logistics and location?

The simulation-based approach was used to answer the main research question. The simulation-based approach is able to integrate many stochastic variations, identify bottlenecks/constraints and allow sensitivity analysis or 'what if' scenarios. At the end of the study, the outcomes of the simulation-based approach are compared to another design method: rules of thumb and practical experiences.

Firstly, the appropriate storage technique was investigated and determined. A conventional longitudinal open stockpile has been selected. Open storage results in lower investment costs, prevents inhalations of radon gas in an enclosed space and results in less drying energy required at the processing facility. A drawback of open storage is that measures should be taken to prevent inhalation of dust and fines. The maximum handling rates for each type of equipment are also investigated, as well as comparable small-scale terminals. Mobile equipment proved to be conventional at small-scale terminals due to its cost-effectiveness, flexibility, and scalability. This information is used to make a recommendation regarding appropriate terminal equipment.

A simulation model is designed to determine the sizing of the stockyard and seaside areas, amount of bulk carriers and their capacity and the amount of machinery and their specifications. The majority of the supply chain is integrated within the model. Starting with the processes at the production vessel, where the collector and STS transfer with the belt conveyor unloader are simulated. A shuttle bulk carrier is used to sail between the production vessel and the transshipment terminal. The terminal processes such as unloading, transport and stacking are then simulated during the unloading phase of the shuttle bulk carrier. Besides the roundtrip of the shuttle bulk carrier between the transshipment terminal and production vessel, there is another roundtrip with bulk carriers between the transshipment terminal and the processing facility. For this roundtrip, the terminal processes such as loading, transport and reclaiming are simulated. Once the bulk carrier is filled, it sails towards the processing facility where the nodules are unloaded and processed to the desirable metals.

The location of the transshipment terminal was determined using a weighted criteria method, with Lazaro in Mexico emerging as the optimal location. On all the criteria (such as distance to production vessel and available quay space) it ended up with an excellent score.

Experiments were performed to simulate the in practice occurring scenarios, to evaluate terminal performance. A suggested terminal design is provided in figure 7.1 and will be explained below.

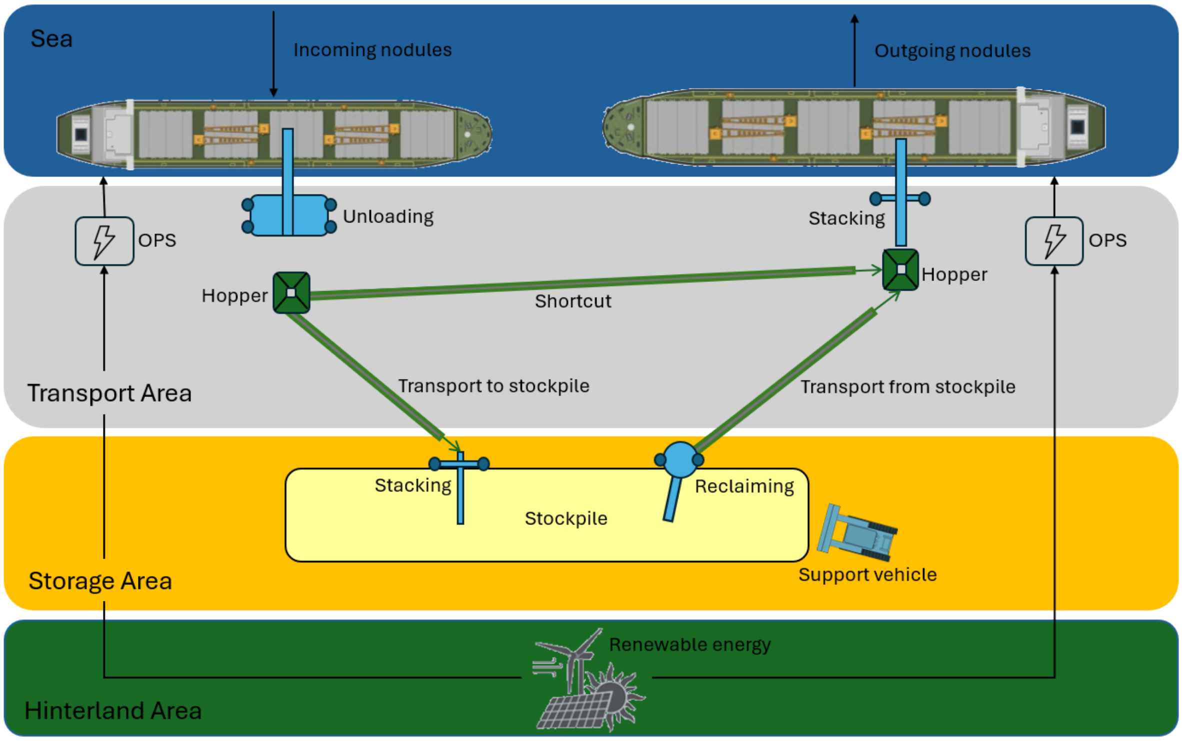


Figure 7.1: Schematic top view transshipment terminal design (dimensions not to scale)

First of all, the amount of bulk carriers and their capacities are determined. For the incoming nodules by shuttle bulk carriers between the transshipment terminal and the production vessel, more bulk carriers with a smaller capacity are preferred over less bulk carriers with a big capacity. The latter scenario resulted in lower waiting queue percentages but resulted in a higher terminal capacity and most importantly more lost collection days. The bulk carrier configuration and terminal should be designed to ensure that mining operations at the production vessel remain uninterrupted, so bulk carriers with a smaller capacity are desired. Having a slight overcapacity of shuttle bulk carriers is also desired to reduce the chances of interrupting the mining operations due to a full hold of the production vessel. Concerning the outgoing stream of nodules by bulk carriers between the transshipment terminal and processing facility, experiments indicated that the processing facility for a yearly production rate of 3 Mt/year is a bottleneck due to a single berth and 8 working hours a day. This has been solved by using self-unloaders (which reduce port times) for the roundtrip between the transshipment terminal and the processing facility.

Regarding the number of berths (and corresponding quay length), it is important to know the final yearly production rate. For the case study the yearly production rate will be gradually increased from 1 to 3 Mt/year. To avoid costly retrofittings/expansions, one berth for unloading and one berth strictly for loading operations is recommended (see figure 7.1). Separating the loading and unloading operations is also recommended because it results in a less complicated planning, less movement of equipment and no need for double equipment. The use of a floating crane is not attractive for the case study due to the smaller incoming bulk carriers (Handysize - 35 kDWT) in comparison to the bigger bulk carriers (Handymax - 55 kDWT) for the outgoing stream of nodules.

The appropriate terminal equipment can be selected by determining the required handling rate. Increasing the handling rates at the unloading berth of the terminal to have one shuttle bulk carrier less is not recommended, due to the increase in lost collection days. The handling rates are selected to have acceptable results regarding the kpi's, while not being over-classified (resulting in unnecessary expensive equipment).

The impact of redundancy in terminal equipment is also examined. This proved to have a minor impact since the waiting times at the production vessel increased, which shows that the production vessel besides the processing facility is also a bottleneck. This means that it does not make sense to speed up the terminal operations without improving the operations at the production vessel, since this is the

weakest link in the chain.
Regarding the storage capacity (and corresponding storage area), the lower the terminal capacity, the worse it scores on the key performance indicators. Therefore, a trade-off was chosen to maintain a limited storage capacity while achieving acceptable values for the key performance indicators.
For the terminal design, knowing the development of the yearly production rate is thus important. For instance to prevent costly retrofittings or expansions for berths in the future, the highest yearly production rate should already be taken into account. The highest yearly production rate was also taken into consideration for the determination of the required handling rates and storage capacity.

Due to the rising energy costs and climate change targets, the energy efficiency within the transshipment terminal is also investigated. The use of LED lamps and a stockpile position as close as possible to the berths are recommended and speak for itself. Belt conveyor speed control is also highly recommended at the unloading berth, since the material flow is 50% of the time lower than the peak handling capacity (due to the intermediate and trimming stage during unloading). Belt conveyor speed control is not recommended for the loading berth, since the loading berth will have a constant material flow of 1000 tph, which means that belt conveyor speed control will likely have a small impact. The other energy reduction strategies and technologies, such as onshore power supply (OPS), alternative power supply (belt conveyor versus diesel trucks) and a shortcut at the terminal all resulted in a significant reduction in energy consumption. Besides the energy reduction, local pollution is also diminished, so these strategies and techniques are recommended as well. The use of OPS, belt conveyors and a shortcut are all integrated into the suggested terminal design in figure 7.1.

By combining the information of the selected handling rates, investigation of existing small-scale terminals and the recommended energy reduction strategies & technologies, the recommended equipment options for each terminal function were selected (visualized in table 5.1 in section **??**). The use of mobile equipment is recommended due to cost-effectiveness, flexibility and scalability.

The results obtained with the simulation-based approach are compared with the other design method: established rules of thumb and practical experiences in the dry bulk terminal domain. The established rules of thumb and practical experiences are in most cases representative. Factors like the equipment installation factor, stacking and reclaiming capacities, (un)loading ship capacities and quay length factor are all within the boundaries of the rules of thumb or practical experience. Other factors like the storage factor and utilization rate of equipment were on the low side. Solely the berth utilization was high in comparison to practical experiences, but this has to do with the predictable and constant flow of bulk carriers within the supply chain of the case study. The equipment installation factor for low yearly production rates was also divergent, since the handling rates of the equipment are selected for 3 Mt/year. For 3 Mt/year, the equipment installation factor was indeed in line with the existing terminals.

Ultimately, a design for a dry bulk transshipment terminal to accommodate collected polymetallic nodules has been provided. The location determination and logistics are taken into consideration as well. This means, a start has been made with the design of such a dry bulk terminal which will be required to facilitate large-scale mining activities in the future.

7.2 Recommendations

The following recommendations for further research are formulated:

- Investigate energy reduction during transport:
  Energy reduction strategies during transport should also be further investigated. A speed reduction of 10%, 20%, and 30% reduce fuel consumption by 27.1%, 48.8%, and 60.3% and CO_2 emissions by 19%, 36%, and 51% respectively. The bigger the ship, the more impact the speed reduction has [21]. Also a speed reduction near the transshipment terminal and processing facility can be very interesting when a bulk carrier is likely to end up in a waiting queue at the terminal. The energy savings by reducing the speed near ports can reach up to 25.4% [22]. Although the waiting queue percentages are not that big, this could still have a positive impact.
- Weather downtime investigation:
  The weather conditions during STS transfer should be further investigated for the production

vessel location in the CCZ. A total weather downtime of 5% per year is assumed for this study. However, research shows that the influence of waiting-on-weather can have a significant impact on the yearly production rate [12]. With the help of weather data and the workable weather window, the waiting-on-weather occasions can be simulated more into detail (maybe the waiting-on-weather is only an issue in certain months).

- Investigate the the supply chain without the use of a transshipment terminal:
  As discussed in chapter 6, the relatively low storage capacity of 60.000 tons for a yearly production rate of 3 Mt/year opens up opportunities for floating transshipment options. Further research is required to see whether the floating transshipment is even possible and whether it would beneficial in comparison to the use of a transshipment terminal.
- Terminal equipment investigation:
  More research is required regarding the terminal handling equipment interaction with nodules. During this paper, most of the existing terminal equipment is taken into account. However, it is unknown whether the use of a screw or bucket wheel unloader is appropriate. The nodules are very brittle which might result in powder after handling the nodules with the wrong equipment.
  The costs for the terminal equipment is also not taken into account. The costs are of course very important for Allseas and it might be helpful to use the following rule of thumb used by several experts within the dry bulk terminal field to estimate stockyard machine's investment cost: a machine fully installed at the stockyard has 6-8 times more costs than the machine's weight in kilograms [2].

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B

Overview Dry Bulk Terminal Equipment

An overview of the equipment used at dry bulk terminals is given on the next page. The maximum handling rates of these equipment is provided in the page thereafter.

Table Overview Equipment

Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11	Option 12	Option 13
Storage types	Longitudinal (M. Droetteboom, 2020)	Radial (M. Droetteboom, 2020)	Conical (D. Roberts, 2018)	Circular dome storage (Geometrica, 2019)	Mammoth silo (M. Droetteboom, 2020)	Longitudinal covered (Geometrica, 2019)							
Unloading systems	Gantry crane (discontinuous) (Material Handling Consultants, n.d.)	Luffing crane (discontinuous) (S. Roker, 2018)	Bucket elevator (IQS directory, n.d.)	Bucket wheel (PLM specials, n.d.)	Vertical screw (Siwertell, n.d.)	Pneumatic conveyor (FLSmidth, n.d.)	Geared bulk carrier (discontinuous) (iStock, 2024)	Chain conveyor (Indiamart, 2014)	Self-unloader (Oldendorff, 2019)	Mobile harbour crane (discontinuous) (Liebherr, 2024)	Slurry system (Fox Venturi, 2020)	Material handling excavator (discontinuous) (PortCraneOperator, 2023)	Floating crane (discontinuous) (Control Techniques, 2009)
Loading systems	Gantry crane (discontinuous) (Material Handling Consultants, n.d.)	Luffing crane (discontinuous) (S. Roker, 2018)	Fixed shiploader (K. Sektani, 2008)	Polar/Radial shiploader (Tenova, n.d.)	Linear shiploader (Iskar, 2016)	Mobile harbour crane (discontinuous) (Liebherr, 2024)	Geared bulk carrier (discontinuous) (iStock, 2024)	Material handling excavator (discontinuous) (PortCraneOperator, 2023)	Floating crane (discontinuous) (Control Techniques, 2009)	Mobile linear shiploader (Superior Industries, 2024)	Truck mobile shiploader (Samson, 2024)		Mobile radial shiploader (Telestack, 2017)
Terminal transport	Belt conveyor (J. Williams, 2020)	Dumper truck (S. Wordsworth, 2020)	Slurry transport (Fox Venturi, 2020)	Pneumatic conveying (Inpak systems, 2021)	Truck (Rimo, 2021)	Bulldozer (Driven by Battat, 2024)	Mobile belt conveyor (Superior Industries, 2024)						
Transfer	Chute (ASGCO, 2023)	Hopper (M. Hefferman, 2022)											
Stacking	Radial stacker (Ameco, 2021)	Mobile stacker (Metso, 2024)	Long boom slewing stacker (N.M. Heilig, 2023)	Rail-mounted stacker (A. Mayers, 2022)	Bucket-wheel stacker-reclaimer (Thyssenkrupp, 2018)	Screw auger (Bruks Siwertell, 2023)	Tripper conveyor (SKE machinery, 2020)						
Reclaiming	Drum/barrel reclaimer (NOEN, 2023)	Material handling excavator (PortCraneOperator, 2023)	Portal scraper reclaimer (Ameco, 2019)	Screw auger (Bruks Siwertell, 2023)	Bucket-wheel stacker-reclaimer (Thyssenkrupp, 2018)	Bridge bucket wheel reclaimer (Fusionbmh, 2018)	Side scraper reclaimer (Ameco, 2024)	Wheel loader (Indiamart, 2023)					
Dust control stockpile	Tarpaulin (S Nair, 2017)	Cellulose crust (Den Bakker, 2023)	Water sprinklers (HBA-chemical, 2023)										

Table Handling Rates Equipment

Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11	Option 12	Option 13
Storage types	**Longitudinal** Stacking/Reclaiming rate: 4500 t/h (Schott, Lodewijks, 2006)	**Radial** Stacking: 6000 t/h (Siwertell Group, 2023) Reclaiming: 2500 t/h (Schade, 2019)	**Conical** Not taken into account	**Circular dome storage** Closed storage < 8000 t/h Stacking/reclaiming rate: 2000 t/h or 2300 t/h (Schott, Lodewijks, 2006)	**Mammoth silo** Closed storage < 8000 t/h Stacking rate: 1500 t/h Reclaiming rate: 2500 t/h (Schott, Lodewijks, 2006)	**Longitudinal covered** Closed storage < 8000 t/h (Schott, Lodewijks, 2006)							
Unloading systems	**Gantry crane (discontinuous)** 150 - 8000 t/h (Control Techniques, 2009)	**Luffing crane (discontinuous)** Up to 2300 t/h (Liebherr, 2024)	**Bucket elevator** 200 – 13000 t/h (Control Techniques, 2009)	**Bucket wheel** 1000 – 5000 t/h (PLM specials, 2023)	**Vertical screw** 2000 t/h (Bruks Siwertell Group, 2023)	**Pneumatic conveyor** 200-1000 t/h (Ligteringen, 2017) 100 – 800 t/h (Dry Bulk Number 4, 2017)	**Geared bulk carrier** 2000 t/h : Large grabs deck crane: 40 tons (GeneralCargoShip, 2014) Grab weight: 20 tons (DNV, 2024) (40 – 20) x 50 cycles/hour = 1000 tph. So 2000 tph for 2 deck cranes	**Chain conveyor** 200 t/h (Ligteringen, 2017)	**Self-unloader** Discharge capacity: 6000 t/h for biggest self-unloader of nearly 100 kDWT (Marine Accident Investigation Branch, 2011)	**Mobile harbour crane** Up to 2300 t/h (Liebherr, 2024)	**Slurry system** 7000 t/h (Srivastave et al., 2018)	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Floating crane** 3500 t/h (Jiangsu Tonghui Lifting Equipment, 2020)
Loading systems	**Gantry crane (discontinuous)** 150 - 8000 t/h (Control Techniques, 2009)	**Luffing crane (discontinuous)** Up to 2300 t/h (Liebherr, 2024)	**Fixed shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Polar/Radial shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Linear (traveling) shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Mobile harbour crane** Up to 2300 t/h (Liebherr, 2024)	**Geared bulk carrier** 2000 t/h : Large grabs deck crane: 40 tons (GeneralCargoShip, 2014) Grab weight: 20 tons (DNV, 2024) (40 – 20) x 50 cycles/hour = 1000 tph. So 2000 tph for 2 deck cranes	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Mobile linear shiploader** 3000 t/h (SKE Industries, 2024)	**Truck mobile shiploader** 1250 – 1500 t/h (Samson, 2014)	**Floating crane** 3500 t/h (Jiangsu Tonghui Lifting Equipment, 2020)	**Mobile radial shiploader** 3000 t/h (SKE Industries, 2024)	
Terminal transport	**Belt conveyor** Max 40000 t/h (Phoenix Belt conveyor Systems, 2012)	**Dumper truck** Max 500 t/h for a single truck (Llurba, 2021)	**Slurry transport** 7000 t/h (Srivastave et al., 2018)	**Pneumatic conveying** 600 t/h (Van Aalst Bulk Handling, 2024)	**Mobile belt conveyor** 8000 t/h (SKE Industries, 2024)	**Bulldozer** Maximum of 500 t/h over a distance of 15 meter (Ismail, 2012)	**Truck** 60 – 80 tons as a maximum (Sinotrukhowo, 2024) 30 tons is conventional (Hiltermann, 2024)						
Stacking	**Radial stacker** 8000 t/h (Vianen, 2015)	**Mobile stacker** 8000 t/h (SKE Industries, 2024)	**Tripper conveyor** 200-1000 t/h (Ku Qiao Equipment, 2024)	**Rail-mounted stacker** 10000 t/h (Vianen, 2015)	**Bucket-wheel cum stacker-reclaimer** 10000 t/h (Vianen, 2015)	**Screw auger** 2200 t/h (Napoleon, 2016)	**Long boom slewing stacker** 150 – 20000 t/h (Control Techniques, 2009)						
Reclaiming	**Drum/barrel reclaimer** 4500 t/h (Vianen, 2015)	**Wheel loader** 10 tons per bucket (Volve Construction, 2024)	**Side scraper reclaimer** 1000 t/h (Vianen, 2015)	**Screw auger** 1100 t/h (Napoleon, 2016)	**Bucket-wheel stacker-reclaimer** 500 – 20000 t/h (Control Techniques, 2009)	**Bridge bucket wheel reclaimer** 10000 t/h (Vianen, 2015)	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Portal scraper reclaimer** Single boom: 2200 t/h Double boom: 4400 t/h (Vianen, 2015)					

Table Appropriate Handling Equipment

Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11	Option 12	Option 13
Storage types	**Longitudinal** Stacking/Reclaiming rate: 4500 t/h (Schott, Lodewijks, 2006)	**Radial** Stacking: 6000 t/h (Siwertell Group, 2023) Reclaiming: 2500 t/h (Schade, 2019)	**Conical** Not taken into account	**Circular dome storage** Closed storage < 8000 t/h Stacking/reclaiming rate: 2000 t/h or 2300 t/h (Schott, Lodewijks, 2006)	**Mammoth silo** Closed storage < 8000 t/h Stacking rate: 1500 t/h Reclaiming rate: 2500 t/h (Schott, Lodewijks, 2006)	**Longitudinal covered** Closed storage < 8000 t/h (Schott, Lodewijks, 2006)							
Unloading systems	**Gantry crane (discontinuous)** 150 - 8000 t/h (Control Techniques, 2009)	**Luffing crane (discontinuous)** Up to 2300 t/h (Liebherr, 2024)	**Bucket elevator** 200 – 13000 t/h (Control Techniques, 2009)	**Bucket wheel** 1000 – 5000 t/h (PLM specials, 2023)	**Vertical screw** 2000 t/h (Bruks Siwertell Group, 2023)	**Pneumatic conveyor** 200-1000 t/h (Ligteringen, 2017) 100 – 800 t/h (Dry Bulk Number 4, 2017)	**Geared bulk carrier** 2000 t/h : Large grabs deck crane: 40 tons (GeneralCargoShip, 2014) Grab weight: 20 tons (DNV, 2024) (40 – 20) x 50 cycles/hour = 1000 tph. So 2000 tph for 2 deck cranes	**Chain conveyor** 200 t/h (Ligteringen, 2017)	**Self-unloader** Discharge capacity: 6000 t/h for biggest self-unloader of nearly 100 kDWT (Marine Accident Investigation Branch, 2011)	**Mobile harbour crane** Up to 2300 t/h (Liebherr, 2024)	**Slurry system** 7000 t/h (Srivastave et al., 2018)	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Floating crane** 3500 t/h (Jiangsu Tonghui Lifting Equipment, 2020)
Loading systems	**Gantry crane (discontinuous)** 150 - 8000 t/h (Control Techniques, 2009)	**Luffing crane (discontinuous)** Up to 2300 t/h (Liebherr, 2024)	**Fixed shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Polar/Radial shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Linear (traveling) shiploader** Screw: 2000 t/h (Dry Bulk Number 4, 2017) Conveyor: 2000+ t/h (Vu Minh, 2019)	**Mobile harbour crane** Up to 2300 t/h (Liebherr, 2024)	**Geared bulk carrier** 2000 t/h : Large grabs deck crane: 40 tons (GeneralCargoShip, 2014) Grab weight: 20 tons (DNV, 2024) (40 – 20) x 50 cycles/hour = 1000 tph. So 2000 tph for 2 deck cranes	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Mobile linear shiploader** 3000 t/h (SKE Industries, 2024)	**Truck mobile shiploader** 1250 – 1500 t/h (Samson, 2014)	**Floating crane** 3500 t/h (Jiangsu Tonghui Lifting Equipment, 2020)	**Truck radial shiploader** 1250 – 1500 t/h (Samson, 2014)	
Terminal transport	**Belt conveyor** Max 40000 t/h (Phoenix Belt conveyor Systems, 2012)	**Dumper truck** Max 500 t/h for a single truck (Llurba, 2021)	**Slurry transport** 7000 t/h (Srivastave et al., 2018)	**Pneumatic conveying** 600 t/h (Van Aalst Bulk Handling, 2024)	**Mobile belt conveyor** 8000 t/h (SKE Industries, 2024)	**Bulldozer** Maximum of 500 t/h over a distance of 15 meter (Ismail, 2012)	**Truck** 60 – 80 tons as a maximum (Sinotrukhowo, 2024) 30 tons is conventional (Hiltermann, 2024)						
Stacking	**Radial stacker** 8000 t/h (Vianen, 2015)	**Mobile stacker** 8000 t/h (SKE Industries, 2024)	**Tripper conveyor** 200-1000 t/h (Ku Qiao Equipment, 2024)	**Rail-mounted stacker** 10000 t/h (Vianen, 2015)	**Bucket-wheel cum stacker-reclaimer** 10000 t/h (Vianen, 2015)	**Screw auger** 2200 t/h (Napoleon, 2016)	**Long boom slewing stacker** 150 – 20000 t/h (Control Techniques, 2009)						
Reclaiming	**Drum/barrel reclaimer** 4500 t/h (Vianen, 2015)	**Wheel loader** 10 tons per bucket (Volve Construction, 2024)	**Side scraper reclaimer** 1000 t/h (Vianen, 2015)	**Screw auger** 1100 t/h (Napoleon, 2016)	**Bucket-wheel stacker-reclaimer** 500 – 20000 t/h (Control Techniques, 2009)	**Bridge bucket wheel reclaimer** 10000 t/h (Vianen, 2015)	**Material handling excavator** 2000 t/h Grab capacity up 25 tons (Mersinport, 2024). 80 cycles per hour (Hiltermann, 2024). 80 * 25 = 2000 tph	**Portal scraper reclaimer** Single boom: 2200 t/h Double boom: 4400 t/h (Vianen, 2015)					

C

Dry Bulk Vessel Categories

The dry bulk vessel categories are given in table C.1 below. Where DWT represents the deadweight tonnage, which is a measure of how much weight the ship is able to carry. Furthermore, the length, width and draft are provided in the table.

Category	**Limiting factor**	**Maximum dimensions (m)**			**kDWT**
		L_s	B_s	D_s	
Chinamax	large port access	375	65	24	400
Valemax	large port access	375	65	24	400
Malaccamax	Strait Malacca	400	59	20	300
Suezmax	Suez Canal	300	50	20	200
Capesize	large port access	330	42	19	200
Newcastlemax	Port of Newcastle	300	47	17	185
Dunkirkmax	Port of Dunkirk	289	45	16	175
Neo-Panamax	Panama Canal (new)	366	49	15.2	120
Panamax	Panama Canal (old)	295	32.3	12	80
Kamsarmax	Port of Kamsar	229	32.2	14.4	70
Seawaymax	St. Lawrence Seaway locks	226	23	7.92	25.5
Handymax	small port access	175	28	11	55
Handysize	small port access	140	21	9	35

Table C.1: Dry bulk vessel categories [91]

D

Environmental Impacts Supply Chain Deep-sea Nodule Collection

D.1. Environmental Impacts During Mining

The following environmental impacts could be a reason to stop commercial deep-sea mining. They are shortly investigated below.

- **Sediment plumes:**
  Sediment plumes occur in three different situations. The first one is the vertical discharge of SWOE. Another reason is the movement of the SMT with crawler tracks on the seabed. Finally, sediment plumes are caused by the SMT after discharging the seperated sediment at the rear of the SMT. The plume could cause burial of organisms or clog pores from small organisms, which has a negative influence on feeding. The recovery of the fauna is furthermore influenced by a change in characteristics of the sediment (e.g. large particles settle first). Another problem is the potential risk of toxic or oxygen-consuming substances which can lead to accumulation of contaminants. However, the occurrence and impact of these toxic metals is still under investigation. The last environmental impact by plumes is the very low organic carbon content in the redeposited sediment. All faunal classes will be influenced by the altered dispersal pattern of the nutrients. Besides the environmental issues, the plume also has a negative impact on the mining efficiency, since other nodules are buried by the plume [133].
- **Underwater noise pollution:**
  Several deep sea fish species communicate using low sound frequencies [134]. Underwater noise caused by the mining operation could have an impact on a number of fish species, regarding communication and hearing. Precise noise characteristics and the influence of them are still unknown [135].
- **Light pollution:**
  Organisms that have adapted to very low or no light emission could be influenced by light from deep-sea mining activities. In the search for polymetallic sulphides there is an example of shrimps being effected by lights. However, this does not hold for polymetallic nodule collection, since no manned submersibles with high-intensity lights are used there [136]. Besides the underwater light pollution, seabirds could be disorientated by artificial lighting on the support vessel. Further research is required to which extent this phenomenon happens [135].
- **Temperature increase seawater:**
  The SWOE discharge is warmer than the normal temperature at a large depth. There could be an increase of 5.8 to 11.4 degrees Celsius [137]. The impact is unknown but it could influence the metabolism, growth, reproductive success and survival of several deep-sea species [138].

Biodiversity loss:
The environmental impacts above could all contribute to a loss in biodiversity. Again, it is difficult to quantify this loss, because no large-scale mining has taken place yet [135]. An evaluation was

performed to investigate the disturbances from deep-sea nodule collection, combining 11 test-studies [139]. Immediately after the mining took place, major changes in density and diversity of groups occurred. The duration of this recovery differs. At seven different sites, the recovery of the fauna took up to 26 years. A small group returned to baseline conditions within two decades. However, almost all studies recognized some recovery within one year. Although there is a large variation in sensitivity amongst species of different sizes and groups . The conclusion of this research pointed out the limitations and mentioned the need for further research [139]. Multiple other investigations point out the plow marks of the SMT on the seabed, which are still visible after 20 years [140].

D.2. Comparison with Terrestrial Mining

An extensive study has been performed, looking at climate impact for producing batteries, following the polymetallic nodules route versus the conventional land ores path. Transportation, process type, infrastructure and prices are all included in the model. Figure D.1 shows the CO_2 emissions from land ores versus the nodules on the seabed. The nodules appear to be far more sustainable. This is due to the relatively low-energy-intensity during the collection phase. The ship-based transportation to an onshore plant is also beneficial. The nodules furthermore have a huge advantage of having four high-grade materials within one nodule without toxic heavy metals. Land ores would need three different ores of lower grades and a much larger overall mass to come to the same output (while managing toxic waste).

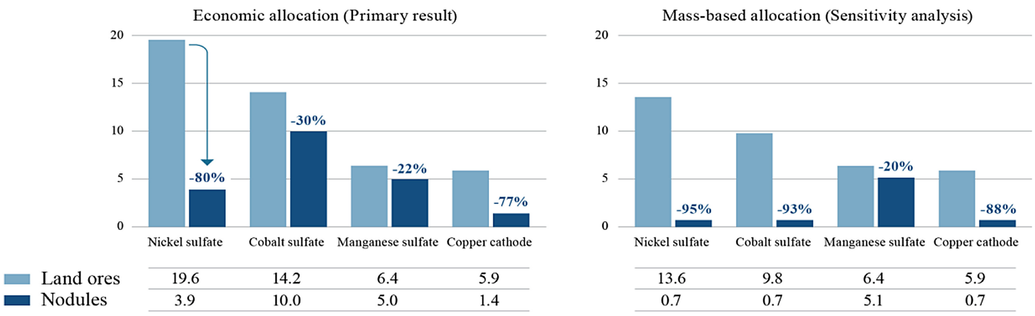

Figure D.1: Kg CO_2 per kg metal [18]

The scenario of 'green land-ores' is also taken into account. Where in this scenario for example 0% coal is used to produce electricity (versus 41% which it is nowadays). Even with the use of green land-ores, the nodules have 88% less emissions (mass-based allocation) to make 1 billion electric vehicles (EVs). The results are shown in figure D.2.

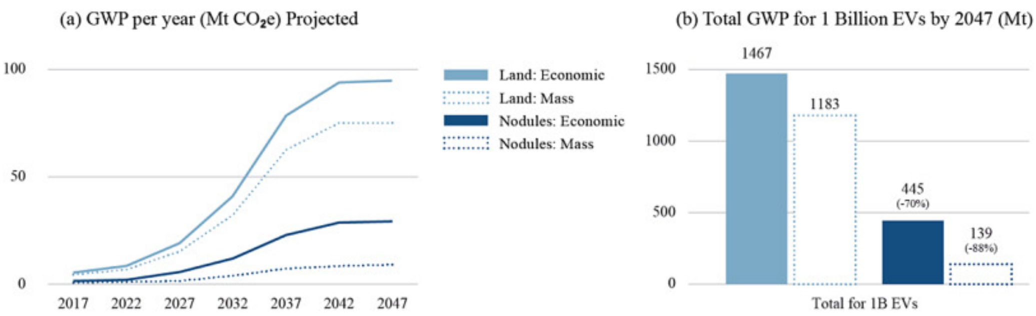

Figure D.2: Green land-ores versus nodules [18]

Of course, there are several uncertainties in the model for example uncertainties in the production path, but it shows the huge potential of manganese nodules [18]. Furthermore other downsides of land mining are not taken into account. Such as child labor in mining all over the world [141]. And the problems to open new mines, where the population in Portugal for example is protesting against mines in their region [142].

D.2.1. Environmental Impacts Processing

The CO_2 emissions of the nodules can be broken down to give more insight into the emissions of producing metals from 1 kg of nodules (figure D.3). This figure shows that the majority of emissions comes from pyro processing and refining. This is due to 'reduction smelting', where a reduction of oxides in the nodules is accomplished by reactions at high temperatures (above 1400 °C) [143]. Techniques to replace the coal could have a big positive influence on the emissions [18].

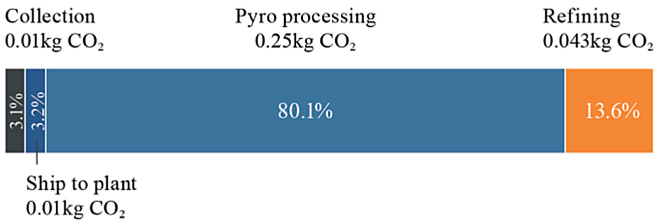

Figure D.3: Total CO_2 emissions from 1 kg of nodules [18]

D.3. Environmental Impacts Supply Chain

In this section, the environmental impacts are assessed. The environmental impacts during collection (like sediment plumes) are discussed in appendix D. The comparison between land-based mining and deep-sea nodule collection is also made in appendix D.

The scope of this literature review focuses on the supply chain between collecting the nodules and refining the nodules. In this subsection, the environmental impacts will be addressed during transshipment, transport and storage. The impacts are shortly listed below, since the environmental impacts are not the main focus of the literature assignment, but still important to consider.

- Material spillage with transshipment. In case of transshipment with a conveyor belt, material can be spilled into the ocean, for example due to waves. This should have a small impact, since the majority of the nodules will slowly sink towards the bottom again. However, in a harbour the spillage could be undesired [144].
- Emissions of the dry bulk carrier and the mining support vessel.
- Noise pollution of the dry bulk carrier and the mining support vessel [144]. And from the installed equipment in the dry bulk terminal.
- Fine dust emissions from (un)loading and storage in the terminal [145].
- Discharging cargo residues after washing of cargo holds. These residues may only be discharged 12 nautical miles offshore [144].
- During storage on land, potential toxic metal mixtures may be released. With potentially negative impacts on animal populations [146].

E

Background Supply Chain Steps

E.1. Seabed Harvesting & Vertical Transport

The concept for mining of the nodules occurs often with three main tools which are visualized in figure E.1. The first one is/are the Seafloor Mining Tool(s) (SMT), also called the nodule collector. This is a remotely operated underwater vehicle (ROV). The SMT has crawler tracks and is self-propelled. It collects the top-layer of the seafloor, consisting of nodules and sediment. The sediment is separated and discharged by the SMT at the back. This amount of re-suspended sediment is 2.5-5.5 ton for each ton of nodules [147], however this value is dependent on many factors and can thus vary. The sediment is discharged to minimize superfluous transport and prevent accumulation of sediment in the Vertical Transport System (VTS). This VTS is the second tool used for nodule collection. The nodules are transported from the SMT to the collection base station underwater via a flexible hose. The VTS enables the transport towards the vessel [148]. There are three main variations on the VTS:

- Air lift system: The air lift system injects compressed air halfway into the riser pipe to lift the nodules. The density of the slurry is reduced by the air and the flow is driven by a pressure difference [149]. Advantages of the air lift system are mainly maintenance focused. The compressors onboard the support vessel are relatively ease to maintain and there are no moving parts along the riser [150]. The operational costs are a disadvantage of the air lift system [151].
- Mechanical lift system: A mechanical lift system uses for example buckets to lift the nodules to sea-level. According to models it should be the most energy efficient transport of the three [149]. Buckets going down could even be used to discharge the superfluous sediment at the top, which will result in less energy required to lift the buckets kilometers up. However, a mechanical lift system has major disadvantages. For example, a winch which can achieve the production target does not exist. The weight of the cable system would furthermore be outrageous due to the large distance of 5000 meter for example [149].
- Pump lift system: The pump lift system uses submersible hydraulic pumps to lift the nodules (e.g. centrifugal or positive-displacement pumps). The advantage of pump lift systems is a higher efficiency of roughly 40% compared to air lift systems, with an efficiency of approximately 15% [152] [153]. A disadvantage of hydraulic transport is the extra amount of water which is pumped to the surface, which later on will have to be discharged [154].

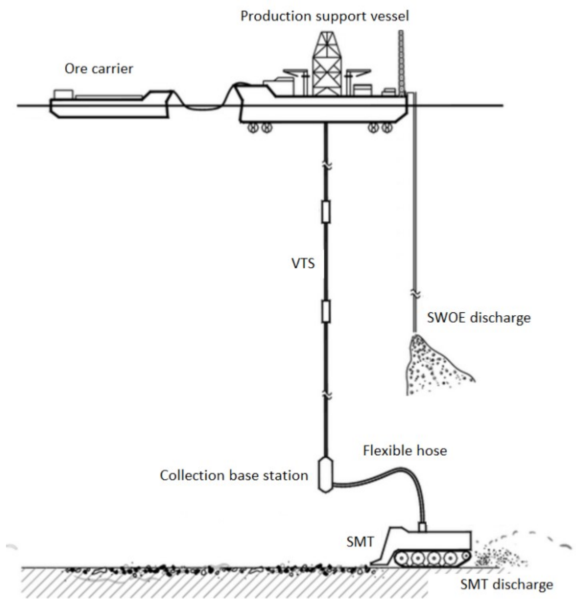

Figure E.1: Nodule collection system overview [148]

E.2. Processing & Handling

Once the stream of nodules arrives at the mining support vessel, the remaining sediment (approximately 10% [155]), waste and other effluents (SWOE) are poured out of the SWOE discharge. International Seabed Authority (ISA) draft regulations prescribed that this discharge should be at least 1000 meter below sea-level [156]. This is well below the sunlit zone (ocean layer where sunlight penetrates). Furthermore, this depth will also prevent the small particles to return to the surface. Discharging of the plume in the sunlit zone for example reduces photosynthesizing of plankton and visibility of predators [156]. The nodules are also dewatered at the production support vessel. This is to reduce the risk of liquefaction, which is described in section E.4.2. It also enables more efficient transport by preventing the transport of seawater in bulk carriers. So it increases the value of the material that is shipped to shore. The value of the material can be increased even more by concentrating at sea (removing superfluous sediment for example). Semi-submersible platforms can be used, which have been used for decades in the oil and gas industry. These platforms are stable and provide space for the required equipment. The metallurgical processing is very unlikely to occur on such a semi-submersible platform due to large energy and space requirements [157]. Crushing, to enable size reduction, might be an essential process prior to concentrating the nodules. This crushing could be another process performed at the production vessel.

E.3. Transshipment at Sea

Once the nodules are handled and processed at the production support vessel, the nodules are temporary stored in the production vessel or immediately transferred to a bulk carrier [148]. There are several ways to enable transshipment of the nodules from the support vessel to the bulk carrier. These techniques are summarized below:

- **Hydraulic (slurry) transport**: The nodules are re-watered and transported by a flexible pipeline to a bulk carrier. This decreases the chance of collisions between the bulk carrier and production vessel, since the ships remain at a certain distance from each other because the pipeline is able to stretch over a longer distance. A drawback of this option is the need for a de-watering station at the bulk carrier [154]. The excess water needs to be collected to avoid water pollution. This is technically challenging and expensive [26].
- **Self-unloader / Conveyor belt**: The production support vessel can be transformed to a self-unloading vessel. The nodules are temporary stored in the support vessel and are then unloaded via a series of conveyor belts (often consisting of a conventional troughed belt conveyor and a sandwich conveyor). A self-unloading bulk carrier is depicted in figure E.2. Both ships require

dynamic positioning to ensure safe operation during this transport. Another option is ship-to-ship mooring at sea. A possible advantage of dynamic positioning could be the ability to continue the nodule collection. Both ships have to travel at the speed of the SMT (0.3 - 0.5 m/s) while maintaining a predetermined vessel heading [156].

- **Floating terminal**: A less conventional solution is to use a floating terminal between the production vessel and the bulk carrier. A gantry crane or luffing crane for example is then used to transship the nodules. The use of the these cranes in combination with a grab makes the unloading discontinuous [46].
- **Bucket elevator**: The nodules are in this case vertically transported in a bucket attached to a belt or chain. These buckets act as 'digging scoops'. The buckets discharge the material onto a conveyor belt. Because of the ability to continuously unload, the bucket elevator has an advantage over crane grabs. Another advantage is that the bucket elevator is wear-resistant, suited for abrasive products, watery products and cohesive products (which the nodules are, although cohesion is unknown). Furthermore, the bucket elevator is also able to carefully handle sensitive materials, which might be required in case of the brittle nodules. [46]. On the other hand, the weight and need for relatively much maintenance are a disadvantage [158].
- **Bucket wheel**: A bucket wheel is very similar to a bucket elevator, but the material is not vertically transported in the buckets. Instead, the material is directly fed onto some sort of belt conveyor. The advantages named at the bucket elevator are also applicable for the bucket wheel. The bucket wheel however has less ability for reaching the corners in comparison with the bucket elevator [46].
- **Deck crane**: Deck cranes onboard the support vessel also enable transshipment to a bulk carrier. The deck cranes are equipped with grabs.

Chain, pneumatic and (vertical) screw conveyors were not taken into account since these techniques are unsuitable for bigger grain sizes or abrasive material [46].

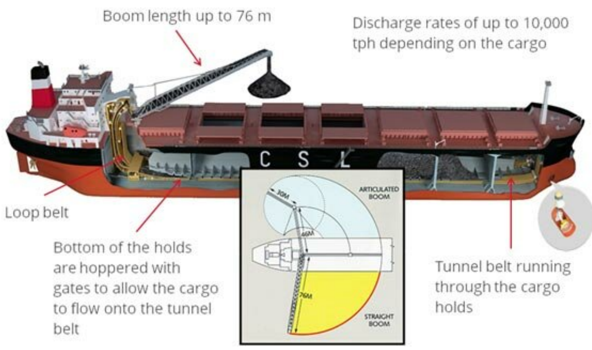

Figure E.2: Self-unloading bulk carrier [159]

E.4. Transport at Sea

Transport at sea might look very straightforward by just using a bulk carrier. Although there are multiple types of bulk carriers, as well as different categories. Furthermore there is the risk of liquefaction and dynamic separation during transport. All these aspects are addressed in this section.

E.4.1. Dry Bulk Vessel Types

There are several types of dry bulk carriers, which are listed below [46]:

- Basic bulk carrier (top left in figure E.3): a basic bulk carrier has several holds which are covered by hatch covers. A basic bulk carrier is also equipped with cranes to discharge material in small ports without appropriate equipment.
- Gearless carrier (top right in figure E.3): a gearless carrier is a dry bulk carrier without cranes or conveyors. They rely entirely on shore-based equipment for (un)loading operations.
- Laker (bottom left in figure E.3): a laker is especially made to operate in fresh water lakes. They can often be identified by having a forward house which helps in locks.

- Self-discharger (bottom right in figure E.3): a self-discharger uses a conveyor belt to discharge material very quick and efficient. More information was given in section E.3.
- Combined carrier: a combined carrier is able to carry different dry bulk materials at the same time, as well as oil in the wing tanks.
- BIBO (Bulk in, Bags out): BIBO bulkers are able to pack cargo in bags onboard and unload these bags at a later stage.

Figure E.3: Basic, gearless, lake and self-unloading bulk carrier respectively [160], [161], [162], [163]

There are also vessel categories besides the vessel types. These categories provide insight in the limiting factor, maximum dimensions and deadweight tonnage (DWT). The dry bulk vessel categories are given in table C.1 in appendix B.

E.4.2. Liquefaction & Dynamic Separation

Liquefaction and dynamic separation are important to take into account during transport at sea. During the overseas transport of the nodules, both phenomena might occur. Below a description is given:

- Liquefaction:
  The manganese nodules consist (like every other solid bulk cargo) of three main components: solid, moisture and void space (air). During overseas transport, vibrations and motion of the ship can compact the solid component to such an extent that there is no more void space (air) in between the solid and water. This water may become separated and start to force the solids apart. The cargo is then a viscous fluid instead of a solid state, which can be seen in figure E.4. This viscous fluid may flow to one side of the ship without moving back. This could lead to capsizing [164].
- Dynamic separation:
  Dynamic separation occurs with a considerable amount of fines particles, enough vessel motions and a high moisture content. Due to vessel motions, the solid particles compacts underneath and the moisture in the cargo migrates to the top. The fine particles prevent the water from draining towards the bottom [165]. The water accumulated at the top could again results in a worst-case scenario of capsizing.

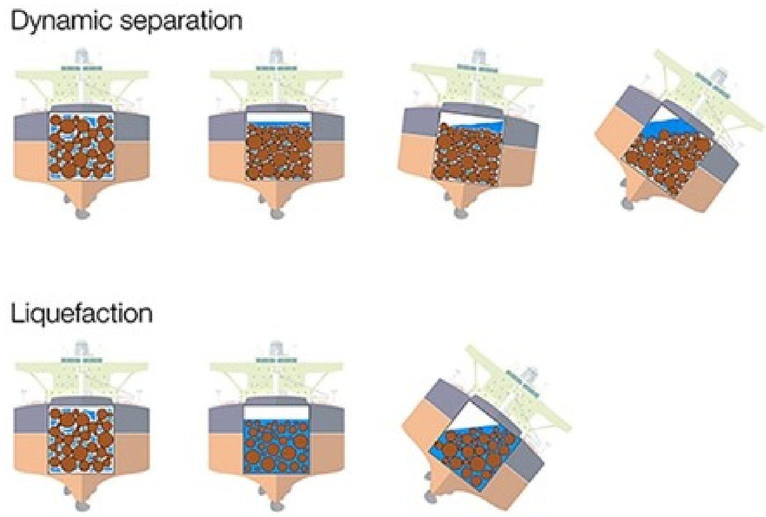

Figure E.4: Dynamic separation & liquefaction [164]

To prevent these cargo instabilities, the fines or the moisture content needs to be reduced. To reduce the moisture content, the Transportable Moisture Limit (TML) is of great importance. The TML represents the maximum moisture content of a cargo to ensure safe transportation. The TML is equal to 90 % of the Flow Moisture Point (FMP). There are different manners to get to the TML. For example the Proctor Fagerberg Test, Flow Table Test or Penetration Test [166]. Several experiments are conducted, but no hard conclusion can be drawn yet. That has for example to do with the particle size distribution, which differs depending on the type of vertical transport which is used. But the rule of thumb is, the larger the nodules, the less chance there is for cargo instabilities [167].
To conclude, more research is required to determine whether dynamic separation and liquefaction are indeed a concern. If liquefaction is indeed a threat, then the installation of longitudinal bulkheads can provide an outcome [168].

E.5. Processing of the Nodules

Once the nodules are collected and brought to a processing plant, further processing of the nodules is executed to extract the valuable metals. The extraction of the metals is mainly focused on copper, nickel, cobalt and manganese. Nodule processing can be divided into two categories [169]:

- Hydrometallurgical: in such a process, acid and alkali leaching are applied with or without further reduction. Leaching is a process where chemicals are used to convert a certain metal into a soluble salt, while the impurity stays insoluble.
- Pyrometallurgical: this process uses pretreatments (typically above 300 °C) such as sulfaction, chlorination and melting. The pretreatments are usually followed by hydrometallurgical processes, which makes it a pyro-hydrometallurgical process.

There are many different variations to both processes with its up- and downsides. Factors that play a roll are [169]:

- Cost of energy
- Demand of specific metal: e.g. some process variations are better at extraction of manganese.
- Environmental impact: e.g. pyrometallurgical techniques require a lot of energy for pre-drying the nodules to remove large quantities of moisture.
- Costs of plant set-up
- Ease of operation: amount of process steps
- Reagent costs

For the treatment of polymetallic nodules, several processes have been investigated. The Cuprion process, sulphuric leaching or smelting (with the use of a rotary kiln and calcination) are promising options to extract nickel, copper, cobalt and manganese [39]. The metals company have been doing tests with smelting, calcination and a rotary kiln, but no conclusions were made whether that is the best proccesing technology [170].

An example of a pyro-hydrometallurgical process can be seen in figure E.5. It starts with crushing and grinding of the nodules. The crushing and grinding is applied in many metallurgical processes [171]. This is performed to unlock (liberate) the valuable minerals [172]. This step does require little energy, since nodules are very fragile because of their high porosity [169]. Then the pretreatments and leaching occurs. The end result is extracted cobalt, nickel, copper and an iron-silicon-manganese alloy residue.

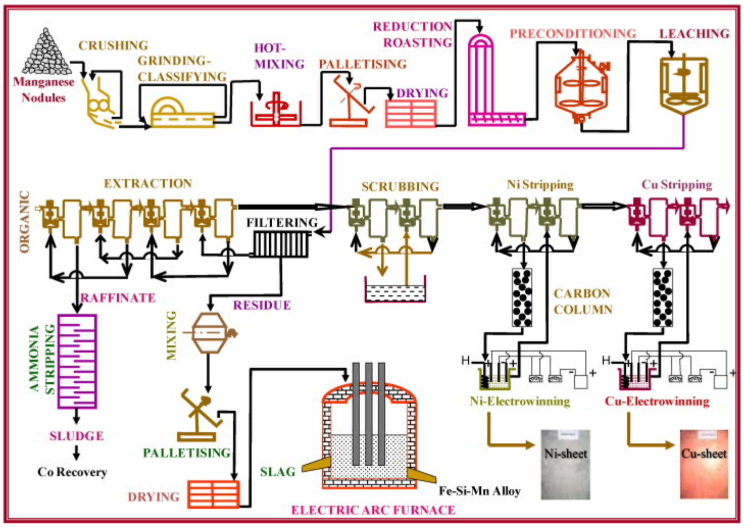

Figure E.5: Schematic flow sheet of a pyro-hydrometallurgical NML process [169]

After the extraction of metals from the nodules, the metals still have impurities (ores for example). Refining is then used to remove these impurities for effective usage. The metals are as pure as possible produced and precious by-products are also recovered. The purity is based on the usage of the metal [173]. In figure E.6, the refining process is visualized after the pyro-processes for nodules.

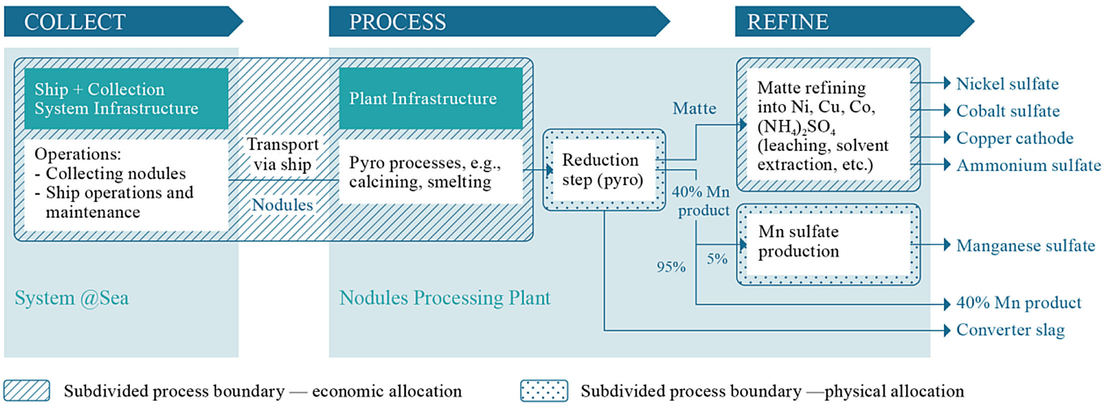

Figure E.6: Schematic flow sheet of a pyro-hydrometallurgical NML process [18]

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Table of Relevant Studies

Reference	Excel	Programming language	Simulation program	Discrete-event	Process Interaction Approach	Characteristics
Baunach et al. (1985)				X		This paper compared different berth and equipment configurations for a real-world coal terminal in Indonesia.
El Sheikh et al (1987)		X (UCSD Pascal)				The use of a simulation model to aid in the planning of future berth requirements.
Park, Noh (1987)		X (Fortran)	X (SLAM)	X		The planning of port capacity, considering both physical and economic impacts of the port system. Furthermore a case-study performed on terminals in the USA.
Dahal et al. (2003)			X (Simple ++)	X		In this paper, a genetic algorithm metaheuristic approach (including discrete event simulation) is used to solve design and operational problems in bulk handling port facilities. Two case studies are performed to show a significant improvement.
Sanchez et al (2005)		X	X (ProModel)	X		A case-study for Mexican Coal terminal. A model is built to simulate ship arrivals. The goal is to determine the optimum number and sizes of piers needed. Key factors for indicating port congestion and system capacity are: length of queues, berth utilization factor/berth commitment, port empty/proportion of time system is idling, average turnaround time (waiting + service + other delays), average queueing time.
Ottjes et al. (2007)			X (Tomas)	X	X	This paper discussed a simulation model to design and improve operational control of large bulk terminals. Things like material flow patterns, stock lay-out, equipment used, equipment reliability and number of operational control methods are configurable. Break down behaviour is also modelled at an individual equipment level. The key performance indicator of such a system is the waiting time of bulk carriers. The model is developed according the process interaction method.
Cigolini, Rossi (2010)	X	X (Visual Basic)	X (Arena)	X		This paper addresses the sizing of transshipment systems in dry-bulk. A metamodel is used, which is made up from three parts. One part focusses on route topology and traffic. The second part addresses offshore transshipment systems. The last part focuses on a simulation model with the help of a software application.
Bot (2012)		X (Delphi)	X (Tomas)	X	X	This paper is used for determination of the required storage capacity of an import dry bulk terminal. Bot, P.C. (2012) stated that in order to minimize the payment of demurrage costs, the stockyard needs to be sufficiently large to eliminate bottlenecks. The largest effects on the required storage capacity of an import dry bulk terminal are annual throughput and the storage time in the stockyard.
Kleinheerenbrink (2012)	X					Kleinheerenbrink comes up with a design support tool which can be used during the conceptual design of a dry bulk terminal. The characteristics and common performances of all these components, processes and means of transport are investigated, which has led to empirical values and capacity ratios (EV&CR) which are used in the design support tool. Experiments are performed to investigate the influence of the following four seaside parameters separately on the required storage capacity: annual throughput, average vessels' tonnage, vessels inter-arrival time distribution and the vessels' tonnage distribution.
Vianen et al. (2012)		X (Delphi)	X (Tomas)	X	X	Paper about route selection to transport materials. A dynamic planner can be useful tool to present alternative routes if conveyors or machines break down. Delays of ships and disturbances of terminal equipment are stochastic variations which are considered.
Vianen et al (2014)		X (Delphi)	X (Tomas)	X	X	This paper provides a methodology to determine the required stockyard size for dry bulk terminals. The storage factor (ratio between annual throughput and stockyard size) is an important factor. Stochastic variations in the ship inter-arrival times, ship sizes and bulk material storage times are taken into account.
Vianen et al (2015)		X (Delphi)	X (Tomas)	X	X	In this paper, a simulation is applied for the scheduling of stacker-reclaimers to increase performance by reducing waiting times. Decisions need to be taken to determine whether a stacker-reclaimer should interrupt ship servicing in favour of train loading for example.
Vianen (2015)		X (Delphi)	X (Tomas)		X	The main research question of this PhD thesis was: how to design dry bulk terminals? The terminal is once again decomposed into subsystems: seaside, landside and stockyard. This is done due to the dependencies between the terminal functions. It is stated that simulation is a must to take stochastic variations into account.
Vianen et al (2015)		X (Delphi)	X (Tomas)	X	X	This paper addresses the conveyor belt network design at dry bulk terminals. Stochastic variations in ship interarrival times, shiploads and equipment availabilities enlarge the need for a simulation model. The conveyor belt network connectivity, storage policy and stochastic distributions are addressed in the paper. Redundancy of piles showed to be more effective rather than installing the maximum number of connections.
Ernst et al (2017)			X (CPLEX)	X		This paper addresses the question of how to allocate vessels to a location on a berth and the sequence in which the vessels should be processed in order to minimize delays for dry bulk terminals. An important aspect in berth allocation is the influence of tidal times. Fully loaded vessels might not be able to departure. Mixed integer linear programming is used.
Zhu et al (2018)		X	X (Witness)			A simulation model was built to calculate the throughput capacity of a coal export terminal. Furthermore, the model is able to analyse capacity changes for varying storage times, shiploads, and ship inter-arrival times.
J. Xin et al (2018)		X (MATLAB)	X (CPLEX)	X		This paper describes stockpile scheduling. Both discrete-event and continuous-time dynamics are used. A model predictive controller is proposed to maximize the terminal operation profit. Monte Carlo simulations were also used.
Unsal, Oguz (2019)				X		This problem consists of three important operations: (i) berth allocation, (ii) reclaimer scheduling, and (iii) stockyard allocation. Tidal time windows, multiple stacking pads and non-crossing of reclaimers are taken into account. Mixed-integer programming is used to address the main problems. Constraint programming on the other hand is used for the subproblems.
van den Heuvel (2019)		X (Python)	X (Trafalquar)			Heuvel, S. van den (2019) addressed the stochastic distributions, like arrival times of vessels and their load sizes. These variables make it difficult to predict the maximum required storage level. The paper aims to investigate the required storage level of a dry bulk terminal. Queueing models are used in the process. The most important conclusions are listed below: • A smaller storage area results in an increase of the waiting times of the vessels. • Dry bulk terminals have a lot of downtimes because of the weather. In rain or strong wind the processes are usually paused, which can affect the storage requirement. • A terminal with more commodities needs more storage capacity. A case study showed that the storage level limits for five commodities were almost twice as high compared to one commodity. • When the delay times of the vessels increase, the storage level limits and waiting times of the vessels increase as well.
Benfei, Tian (2019)		X	X (Witness)	X		This paper is a scarce one, since it focuses on a transshipment terminal instead of an import or export terminal. A simulation model is developed, including different subsystems for: seagoing ship-arrival, yard operation and barge arrival. Fluctuations in (un)loading efficiency were considered. Three different layouts were established and analysed using the simulation model.
Ouhaman et al (2020)			X (CPLEX)			In this paper, a real-world storage space allocation problem is considered at an export bulk terminal. The problem is mixed integer linear and a heuristic method is used to solve large data sets.
Patel (2021)	X					A conceptual design tool is developed to account for a range of throughputs, shiploader configurations, stockyard machinery configurations and landside equipment configurations. The tool provides outputs for each major infrastructure element of a dry bulk terminal. The conceptual design tool provides a range of options and considers a number of inputs including varied vessel sizes and varied annual throughput capacities.
Junglas, Schmedes (2022)		X (Matlab)	X (SimEvents)	X		This paper addresses the problem of different velocities between conveyors, which can lead to modelling difficulties in discrete-event simulation.