S.A.J. Kox

A Tool for Estimating Marine Terminal Dimensions and Costs in a Project's Feasibility Phase

Taking into account uncertainties

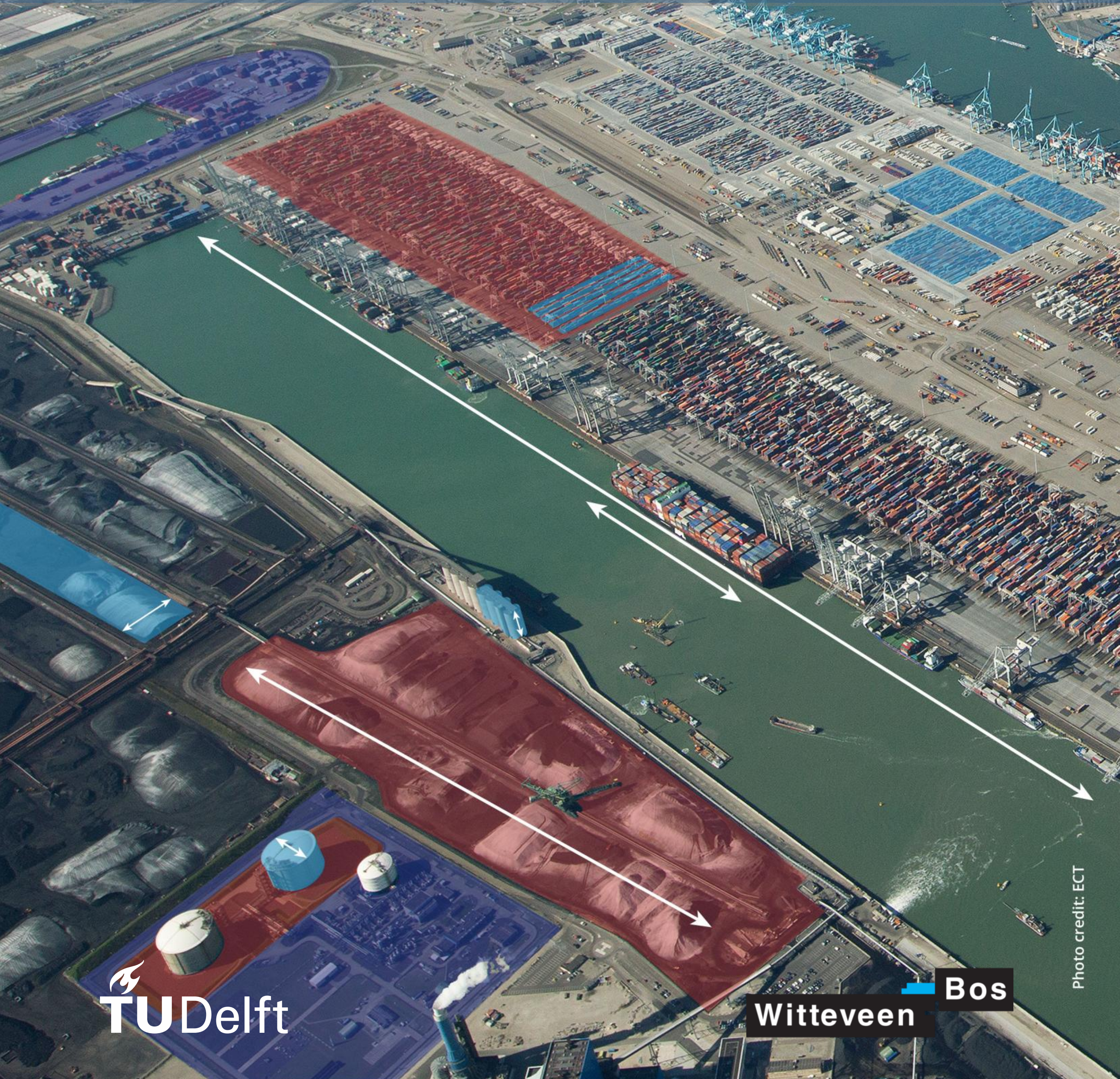


Photo credit: ECT

TU Delft

Witteveen Bos

A Tool for Estimating Marine Terminal Dimensions and Costs in a Project's Feasibility Phase

Taking into account uncertainties

by

S.A.J. Kox

in partial for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology,
to be defended publicly on Wednesday January 25, 2017 at 9:30 AM.

Supervisor:	Prof. ir. T. Vellinga	TU Delft
Thesis committee:	Dr. ir. B.A. Pielage	Witteveen+Bos
	Ir. P. Quist	TU Delft
	Dr. ir. O. Morales-Nápoles	TU Delft

Keywords

Marine terminal design, containers, dry bulk, liquid bulk, design rules, construction costs, unit costs, probabilistic tool, Monte Carlo simulation, Expert Judgement Elicitation, uncertainty, dependence, Cooke's Classical model, conditional probability technique, EMO terminal.

Abstract

The main objective of this study is the realisation of a computer tool. The function of the tool is to estimate the required dimensions and quantities of essential container, dry and liquid bulk terminal elements, in an early design phase. As well as to give an estimate of the construction costs of these marine terminals. Terminal element dimensions are for instance the quay length and storage area. Examples of terminal element quantities are the number of berths and the number of ship-unloading equipment. The spear point of the tool is the probabilistic approach, in which uncertainties -concerning design rule variables- are taken into account. This approach results in probability distributions for the dimensions and quantities. The aim of the tool is to aid terminal or port designers by allowing them to easily consider a vast amount of input combinations. The designer therefore does not have to make exact assumptions that could lead to certain important combinations not being considered. The computations that the tool performs are based on research in this study. This research concerns terminal design rules and guidelines, common values of design rule variables and unit costs. For two variables -of which no common values could be found- Expert Judgement Elicitation (EJE) on uncertainty is applied. The results are weighted combinations of uncertainty distributions elicited from the experts. A different EJE on dependence is applied to estimate the relationships between average import, export and transhipment container dwell times. Finally, the tool is applied to the EMO terminal in Rotterdam. The EMO terminal is the largest dry bulk terminal in Europe. This application makes it possible to compare the tool's results to the actual terminal properties. For the same terminal a sensitivity analysis is performed on the estimated total construction costs, to certain variables.

Preface

Hereby I would like to present my master thesis. This thesis forms the conclusion of my education at the faculty of Civil Engineering at Delft University of Technology. There, I followed the Rivers, Ports, Waterways and Dredging Engineering track as part of the master Hydraulic Engineering. In this track I specialised in the field of Ports.

I conducted my research at the consultancy firm Witteveen+Bos. Their workplace meant being surrounded by a group of likable and inspirational people in an excellent environment and -not unimportantly- provided an outstanding cup of coffee.

First of all, I would like to thank my supervisor Ben-Jaap Pielage from Witteveen+Bos for his input and constructive feedback during the entire length of my research. I would also like to thank the other members of my thesis committee: chairman Tiedo Vellinga, Peter Quist and Oswaldo Morales-Nápoles. I am grateful for their time, trust and understanding during both the highs and the lows. A special thanks goes out to Oswaldo for his enthusiasm, fast e-mail replies and all the short-notice meetings.

Furthermore, I would like to thank Sip Meijer from Witteveen+Bos and Han Ligteringen from TU Delft for their contributions to this study regarding marine terminals in general. Likewise, I want to thank Robert Jan Smits van Oyen from Tebodin for his input concerning dry bulk terminals. Another person I would like to express my gratitude to is Erik Schulte Fischedick, who helped me a great deal with the part of my study concerning the subject of costs. And of course I cannot refrain from thanking my fellow students at Witteveen+Bos for the regular chats, the occasional drinks and their humour which surely have helped me along the way.

Last but not least I want to thank my parents and my sisters for their interest, constant support and belief in me.

Steven Kox,

Delft, January 2017

Summary

In the feasibility phase of a marine terminal design project dimension estimates are made. Ordinarily they are based on few calculations, with many assumptions and therefore risk a high level of uncertainty. This leads to the consideration of only a small number of possible input combinations. Furthermore marine terminal design rules and guidelines are scattered over a large number of publications. Specific information about when to use a particular value of a design rule variable cannot easily be found. For the previously mentioned reasons *Witteveen+Bos* requires an easy-to-use tool that can compute the main required terminal dimensions[1]. As well as a construction costs estimate of container, dry bulk and liquid bulk terminal types. In this way many input combinations can be computed in a timely fashion. Moreover they can be compared by looking at the resulting dimensions, quantities and/or the costs. An instant cost estimate is in this case very useful since the economic and financial feasibility are often of main concern for a client. Realising such a tool is the main objective of this study. A distinctive feature of the tool is the probabilistic approach. This approach allows the terminal designer/planner to easily consider a great amount of input combinations. The designer therefore does not have to assume single, fixed values for variables, which could lead to certain important input combinations not being considered. The consideration of many input combinations can result in a more accurate and realistic design. Moreover, when -in a project- certain necessary information is missing, not all required values of the parameters may be known. Common values of these variables -researched in the literature study- can be called upon when desired. The tool is applicable to modern greenfield terminals -that are used for the handling and short-term storage of cargo- in developed countries. The tool's output is purely numerical. Consequently neither the position of the terminal in a port nor the layout of the terminal are considered.

An extensive literature study covers information about the essential elements of the three terminal types. As well as the available design guidelines and rules, common values of variables and unit costs. The foremost goal of the literature study is to obtain information that can be used for the development of the tool. A second intention of the literature study is to function as a manual for terminal designers. For all main terminal elements design rules are found that are used for dimensioning and quantification. For most variables common -or realistic- values are gathered from literature. Unit costs for all essential terminal elements are researched as well. For some variables common values could not be identified. Two of these variables, namely the *total terminal factor*[2] and the *average storage occupancy*[3], are factors that can significantly influence the required storage and terminal areas. Due to the importance of these variables common values are determined by using the opinions of experts. Values for the remaining variables are determined by analysing the properties of existing terminals.

A method to combine the opinions of experts is *Expert Judgement Elicitation* (EJE). With this method experts are assessed in a structured way, allowing for the results to be treated as scientific data. Four experts in the field of marine terminal design and/or port master planning have been assessed. They have been asked to quantify their uncertainty of the total terminal factor and average storage occupancy for the three terminal types. The assessments and the aggregation of the experts' estimates have been performed in accordance with *Cooke's Classical model*. With

[1] The main terminal dimensions being the quay length, total terminal area and dredging depth. Other dimensions and quantities such as the storage yard area, number of (un)loading cranes, number of storage yard equipment, etc. are determined as well.

[2] The total terminal factor is the percentage of the storage area (including internal infrastructure) with respect to the total terminal area.

[3] The average storage occupancy is the percentage of the design storage capacity that is actually used, averaged over a year.

this method the experts are weighted based on their estimates of seed variables, of which the answers are known to the researcher. The two, previously mentioned, target variables are quantified by using the obtained weights to combine the individual experts' uncertainty distributions of these variables. The resulting cumulative probability distributions are depicted in Figure 1.

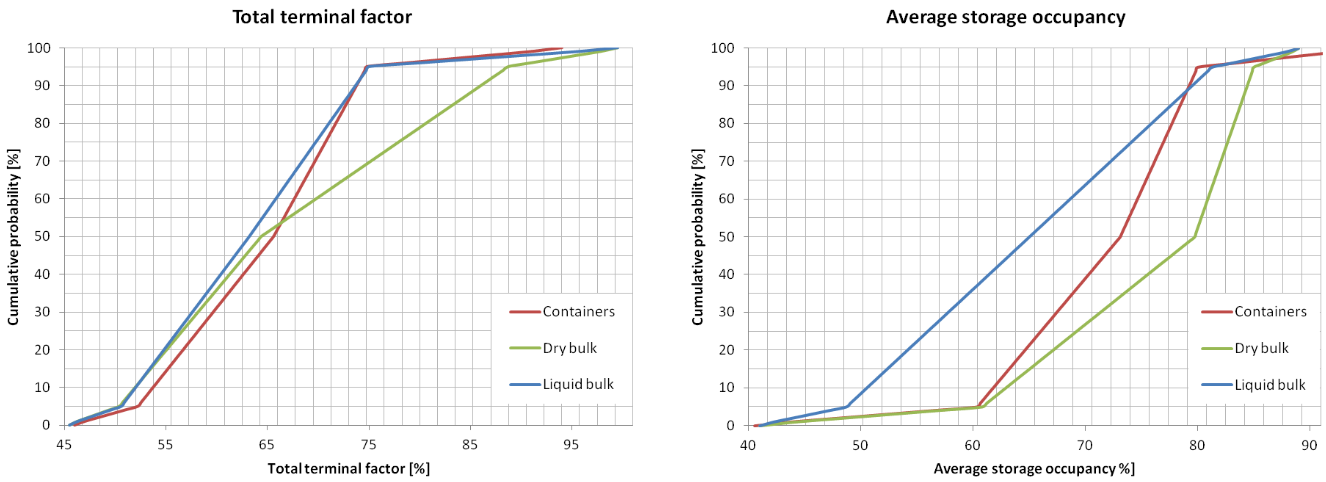


Figure 1: Cumulative probability distributions resulting from the EJE on uncertainty

Since the tool uses random variables dependence between certain variables is of importance. Dependence between the average dwell times of import, export and transhipment containers is expected. The same four experts have been asked for their estimates of these dependencies using the *conditional probability technique*. This elicitation method also uses seed variables to be able to weight the experts' estimates of the dependencies between target variables. The dependence between random variables can be expressed by means of the rank correlation. The experts think that there are moderately positive relationships between import & transhipment and export & transhipment container dwell times. They think the relationship between import & export container dwell times is weakly positive. A positive rank correlation, ranging from zero to one, quantifies how well two random variables are described by a function that is entirely increasing. The resulting rank correlations are depicted in Figure 2. The EJE method for dependence is a new technique and is currently being researched at *Delft University of Technology*. A second aim of the application of EJE on uncertainty and dependence in this study is to introduce these methods to this field of expertise. These methods are therefore elaborated on in this study.

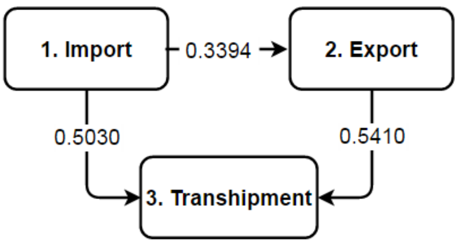


Figure 2: Rank correlations between the average container dwell times from the EJE on dependence

The tool is realised in *Microsoft Excel* using the programming language *Visual Basic for Applications*. Users select the desired terminal type, where after uncertainty distributions can be specified for all required variables. The tool then performs a *Monte Carlo simulation* in which random values are drawn from the uncertainty distributions. A computation results in probability distributions that are derived from the estimates of the terminal elements' dimensions, quantities and costs. The final exact dimensions, quantities and costs estimates are obtained when the designer/planner or client specifies a desired quantile. The 70% quantile is recommended. The aim of the tool is to be easy-to-use, this reflects onto the design of the tool itself. The tool is positively received by Witteveen+Bos and the Port of Rotterdam has shown interest as well.

The tool is applied to the actual coal and iron ore handling terminal *EMO* (*Europees Massagoed Overslag*), which is the largest dry bulk terminal in Europe. The input for the tool is partly based on terminal information and information about operations originating from EMO. Not of all required variables information is available. For these remaining variables uncertainty distributions, that are based on the studied common values, are used. The tool gives realistic results, of which the 70% quantiles match the actual dimensions and quantities of the terminal. When the assumption is made that the terminal was well designed in the past, it can be concluded that the tool can be trusted. Nevertheless it is advised -based on experience from the case study- to not use large uncertainties for variables. As these variables will dominate the resulting dimensions and costs. As a rule-of-thumb for uniform and triangular distributions the upper limit should not be more than twice the lower limit. The estimated total construction costs of the terminal amount to € 358,853,000.[4] To this sum the quay wall for sea-going vessels is the highest contributor, as is depicted in Figure 3. From a sensitivity analysis of the variables with an uncertainty it can be concluded that the average vessel length, and hence the quay wall, as well as the stockpile height have the highest influence on the estimated total costs. These results are for the EMO case with its specific input. The conclusions are therefore not per definition true for other terminals. They may however be of assistance in other terminal design projects.

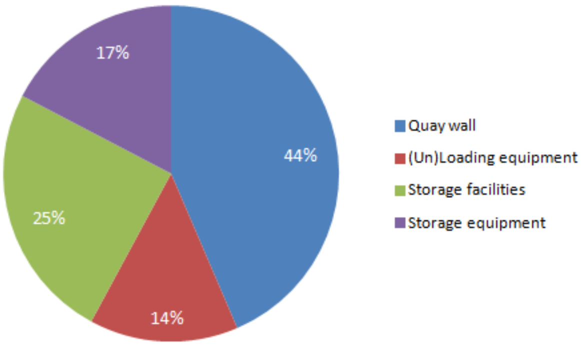


Figure 3: The contribution of the 70% quantiles of the cost elements to the total costs

[4] Besides the quay wall for sea-going vessels this costs estimate considers gantry grab cranes for unloading, loading equipment, stockpile pavement and stacking-reclaiming equipment. Terminal elements that are not taken into account are roads, buildings, train and crane rails, belt conveyors, the quay wall for barges and corresponding loading equipment.

List of abbreviations

AGV	Automated Guided Vehicle
ASC	Automated Stacking Crane
BN	Bayesian Network
CFS	Container Freight Station
DM	Decision Maker
DWT	Deadweight Tonnage
EJE	Expert Judgement Elicitation
FEU	Forty foot Equivalent Unit
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MHC	Mobile Harbour Crane
RMG	Rail Mounted Gantry
RTG	Rubber Tyred Gantry
SC	Straddle Carrier
SSK	Standaard Systematiek voor Kostenramingen (Dutch)
STS	Ship To Shore
TEU	Twenty foot Equivalent Unit
TTU	Tractor Trailer Unit
ULCC	Ultra Large Crude Carrier
VBA	Visual Basic for Applications
VLBC	Very Large Bulk Carrier
VLCC	Very Large Crude Carrier

List of symbols

Latin symbols	Description	Unit
d_d	Required dredging depth	m
f_b	Bulking factor of CFS	-
f_{area}	Ratio gross over net storage area	-
f_s	Storage factor	TEU/year/m^2 or tonne/year/m^2
f_{TEU}	TEU factor	-
h_{dt}	Dredging tolerance	m
h_{guc}	Gross underkeel clearance	m
h_{pile}	Stockpile height	m
$h_{pile,max}$	Maximum stockpile height	m
$\overline{h}_s$	Average stacking height	m
l_{lane}	Required stockpile lane length	m
m_b	Estimated berth occupancy factor	-
m_s	Estimated storage occupancy factor	-
n_b	Number of berths	-
n_c	Total required number of cranes	-
n_{cb}	Number of cranes per berth	-
n_{hy}	Number of operational hours per year	hour/year
n_{lanes}	Number of stockpile lanes	-
r	Spearman's rank correlation	-
r_c	Capacity ratio	-
r_{st}	Ratio of average stacking height over maximum stacking height	-
$\overline{t}_d$	Average dwell time of cargo	days
w_{lane}	Stockpile lane width	m
A_{CFS}	Required area for the container freight station	m^2
A_{gr}	Gross required storage area	m^2
A_t	Required total terminal area	m^2
A_{TEU}	Gross storage density for maximum stacking height	m^2/TEU
C	Throughput over the quay	TEU/year or tonne/year
C_b	Berth productivity	TEU/year or tonne/year
C_{equip}	Combined loading/stacking and unloading/reclaiming capacity of terminal equipment	tonne/hour
C_{in}	Number of incoming containers from the waterside per year	TEU/year
C_{out}	Number of outgoing containers to the waterside per year	TEU/year
C_{trans}	Number of transhipment containers per year	TEU/year
C_y	Number of container movements over the yard per year	TEU/year
D	Silo or tank diameter	m
D_s	Draught of design vessel	m
H	Silo or tank height	m
H_{retain}	Retaining height of a sheet pile quay wall	m
I	Entropy	-
L_{ml}	Additional quay length to account for mooring lines	m
$\overline{L}_s$	Average vessel length	m

$L_{s,max}$	Length of the largest vessel frequently calling at the terminal	m
L_q	Quay length	m
N_{20}	Number of TEU’s	-
N_{40}	Number of FEU’s	-
$\overline{P}_{berth}$	Average combined pump productivity per berth.	tonne/hour
$\overline{P}_{gross}$	Average gross productivity per (un)loading crane	moves/hour or tonne/hour
T_s	Service time of a vessel	hour
V_c	Volume of a TEU container	m^3
$V_{storage}$	Required total storage volume	m^3
W	Terminal equipment weight	tonne

Greek symbols

α	Total terminal factor	-
θ	Angle of repose of cargo	degrees
ρ	Pearson’s product moment correlation	-
$\overline{\rho}_c$	Average cargo density	tonne/m^3
μ	Ratio of transhipped containers	-

List of figures

Appendices

List of tables

Appendices

Table of contents

1 INTRODUCTION

In the introduction the reader is presented with the motivation for this study. Hereafter the main research objective and research questions are specified. The chapter concludes with the limits that are posed to this research.

1.1 Problem description

Marine port terminals form the interface between different modes of transport of cargo. The design of ports and port terminals occurs in multiple phases. During the early design phase of a terminal a basic design is made. This is done by analysing different scenarios of trade and traffic for the port's master plan period.

For the design of port terminals no official international regulations are available. Due to this lack of regulation various guidelines or design rules for determining the required dimensions of port terminals exist. Most design rules are in the form of equations, consisting of parameters. These design rules are based on miscellaneous studies concerning a wide range of situations. As a consequence it may become unclear when to use particular rules and especially which values for the parameters. This leads to the demand for an elaboration on the main existing terminal design rules in combination with a clear overview of the common values of the parameters.

Calculating the required main terminal dimensions by hand for the various scenarios is a time consuming effort. For this process computer tools can be very helpful. Presently several tools[5] exist that use simulation for the design of terminals. These tools however require extensive input and are thus more suited for later design phases. In the early design phase less data is available and multiple scenarios have to be analysed. Therefore a tool is needed that can be used to compute terminal designs with few data in a timely fashion.

Predictions for future situations usually have an increasing uncertainty over time. Port master plans are designed for large periods of time and some variables that -among others- determine the terminal dimensions may therefore be subject to uncertainty. In the present situation calculations are made by assuming certain values for parameters that are uncertain, this can lead to under or over dimensioning of terminals. In order to account for uncertainty we can incorporate a probability distribution for specific variables. This way many input combinations are included in one single calculation resulting in a more complete and realistic analysis.

Among the main concerns for parties that order the design of a terminal are the economic and financial feasibility. In order to make a project feasible costs are an important aspect. It would therefore be useful to be able to give a rough construction cost estimate for a terminal design in the feasibility phase of a project. Similarly to the design rule parameter values uncertainties about the prices or costs of terminal elements are common. This of course lends itself for a similar probabilistic calculation approach.

[5] For example the simulation software TIMESQUARE of TBA (2016) or Port Simulation Software of Simio (2016) or results from studies like Vianen, T. van (2015).

According to PIANC (2014b) liquid-, dry bulk and containers are the main commodities in waterborne transport. The worldwide container transport has an average forecasted annual increase in cargo of 6% (from 2012 to 2017). This can mostly be attributed to the increase of manufactured goods and the shift from bulk and general cargo to container cargo; PIANC (2014b), Quist & Wijdeven (2014). Due to the increase in global energy and steel demand the demand for coal and iron ore also increases according to Vianen, T. van (2015). This has as an effect that the bulk transport volumes of these goods increase as well. Because of the importance of these commodities in worldwide sea trade the focus in this research will be on these types of cargo and their corresponding terminal designs.

1.2 Research objective

In this section the main objective of this research is defined. To fulfil this objective research questions and sub-objectives are defined that each partly contribute to reaching the main objective. Each research question/objective is individually elaborated on. This section can be seen as an outline of the current report.

Main research objective

"The development and application of a tool for estimating the main required marine terminal dimensions and corresponding construction costs with a limited available amount of data and including uncertainties for the variables and costs."

At Witteveen+Bos the demand for a tool that can be used to quickly determine marine terminal dimensions exists. This thesis fulfils this demand by the realisation of a program written in Microsoft Excel. With the tool the main terminal dimensions (quay length, terminal area and water depth) can be calculated as well as the required amount of terminal equipment and storage utilities and their dimensions. Also the direct costs are calculated for most of the main terminal elements individually and in total. The tool is applied in a case study.

Research question I

"What are the main terminal elements and the existing terminal design guidelines and design rules?"

Information about the different terminal types and their main elements is gathered, this supports the more theoretical design guidelines and rules. These guidelines and rules are described in literature and come in the form of equations, rules-of-thumb and recommendations. With these rules the required terminal dimensions can be determined for a specific situation. These rules are primarily studied so that they can be implemented in the tool. Another goal is to create a clear overview of these rules so that terminal designers can consult it when needed. This research question is treated in Chapter 2.

Research question II

"What are common values for the design rule parameters and what are common unit costs of terminal elements?"

Since during the early design phases specific information is often missing assumptions have to be made. It would therefore be useful to have an overview of parameter values[6] that are commonly used. These common -or standard- parameter values are studied in literature. Often

[6] Parameter values are the values that are required as input for the terminal dimensioning equations.

literature proposes ranges of values, these can be seen as probability distributions. These distributions function as standard input for the tool in case no project information is available to the tool user. In Chapter 2 a clear overview is created by presenting the common values in a table per terminal type. This way terminal designers can easily consult the considered information. In order to be able to give a cost estimate of a terminal, terminal element prices are required. These prices are treated in Section 2.4.

Research question III

"*What are the uncertainty distributions of the total terminal factor*[7] *and the average storage occupancy factor*[8] *and what are the correlations between average import, export and transhipment container dwell times?*"

The research in literature on common values of parameters did not result in values or distributions for two important variables; the total terminal factor and average storage occupancy. In this study experts are asked for their estimates of these common values by means of a scientific method called Expert Judgement Elicitation. Expert Judgement Elicitation is a statistical method to objectively combine the opinions of experts. Furthermore the presumption existed by the writer that between the random average dwell times of import, export and transhipment containers dependencies exist. This could however not be confirmed in literature. Therefore another Expert Judgement Elicitation method is used to ask these dependencies from experts and to scientifically combine them. A dependence between random variables can be expressed by the rank correlation. This research question is treated in Chapter 3.

Chapter 4 concerns the creation of the tool. The tool computes the main required dimensions of a container, dry or liquid bulk terminal. The input variable values can be chosen to be deterministic or a probability distribution. The tool performs a number of iterations, as specified by the user, in which realisations are drawn from the distributions. The tool uses the design rules from the literature study for the calculations. The outputs are probability distributions for the resulting terminal dimensions and for the other intermediate results. Construction costs are calculated in the same way.

Research question IV

"*What terminal elements contribute the most to, and what input parameters have the largest influence on, the total construction costs of one specific terminal?*"

In a case study an existing terminal is considered. Actual terminal data is used as much as possible for the input parameters, for the unknown parameters common values are used. The terminal elements that contribute the most to the construction costs are identified. Furthermore an analysis is performed in order to determine the variables to which the total costs are sensitive. This research question is treated in Chapter 5.

[7] The gross storage area (net storage area incl. internal infrastructure) divided by the total terminal area.
[8] Average volume of cargo in the storage yard divided by the design capacity of the yard.

1.3 Research scope

The limits of the study are discussed in this section.

- Marine terminals for greenfield port development are considered as requested by Witteveen+Bos.
- Only modern terminals for developed countries are taken into account. This choice is made since most parameter values in literature of the terminal design rules are for these kind of terminals.
- Functions of the considered terminals are the handling and short-term storage of cargo. Therefore terminals that are used as strategic buffer for cargo or that include or only serve local industry (e.g. refineries) are not included in the research.
- The research and the tool include the level of detail that is required for the early design phases of a project, as requested by Witteveen+Bos.
- The output of the tool is purely numerical. The layout of a terminal or port is not considered, the tool's results can be used as a help in determining these.
- The main terminal dimensions are considered, intermediate results are presented as well. The most important results are:
    - Quay wall length or jetty length and the amount of jetties
    - Water depth
    - Total terminal area
    - Gross storage areas
    - Number of (un)loading equipment
    - Number of equipment in between waterside and storage yard, and/or on the yard itself.
    - Storage utility (stockpiles, silos, tanks, etc.) dimensions and amounts.
- The main cost items are considered. The individual and total direct costs are presented as well as the estimated construction costs. The main cost items are:
    - Quay wall or jetties
    - Storage utilities (pavement, storage sheds, silos, tanks, etc.)
    - Ship (un)loading equipment
    - Equipment in between waterside and storage yard, and/or on the yard itself
    - Bunds for liquid bulk terminals
- The commodities and cargo types that are considered in this research are depicted in Figure 4. The choice for coal, iron ore and grains is made since these are the three most transported dry bulk goods according to PIANC (2014b). The choice for crude oil is made since it is one of the most transported liquids according to Agerschou (2004) and rules-of-thumb can be found in literature. Liquefied Natural Gas (LNG) is included as well since it is more environmentally friendly compared to other fossil fuels and some parties therefore expect a growth, according to Het Financieele Dagblad (2016).

  The tool includes the option to determine the terminal dimensions for other kinds of liquids as well by changing material properties. This also holds for dry bulk cargoes, however not all dry bulk cargoes are handled by the equipment types and stored in the storage utilities that are included in the tool.

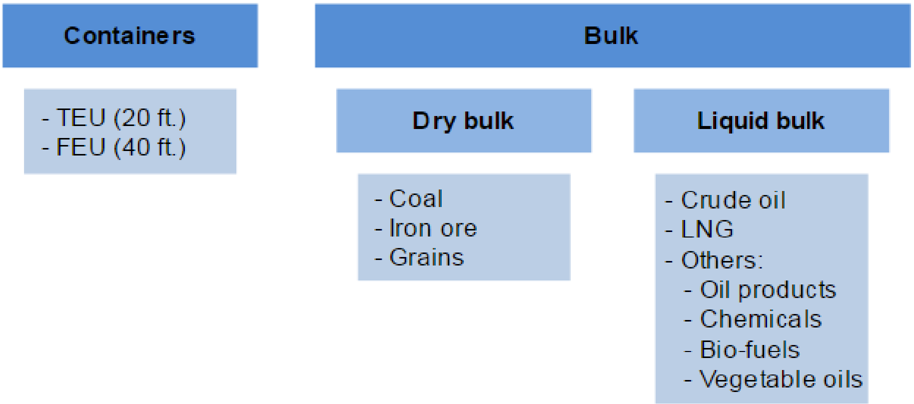


Figure 4: Commodities with cargo types that are considered in this research. Source: Own work

In the course of this study some smaller limitations are made in view of the limited duration of a MSc thesis. When this is the case a reference is made to this chapter.

2 LITERATURE STUDY

The literature study focuses on available design guidelines, rules, common values of parameters and unit costs. The aforementioned related to the design of a marine terminal in the early phases of a greenfield project. For each terminal type[9] this information is provided in this chapter. In order to assist in explaining the treated terminal specifics; background information for each terminal type is provided as well. In this study only modern terminals in developed countries are considered. This narrowing of the scope is done since common values of parameters for terminals in developing countries are not sufficiently treated in literature.

Goal of the literature study: To provide a clear overview of terminal dimension design rules, common values of parameters and terminal element unit costs for the reader and as input for the computer tool.

2.1 Container terminals

For container terminals first general background information is presented in order to give the reader more insight in the most important aspects of a terminal. Then the relevant equipment properties that are needed as input for the design rules are given. In the last section the design guidelines, rules and common values of parameters are treated.

2.1.1 Background information

This section considers container terminals and is based on Agerschou (2004), PIANC (2014b), PIANC (2014b), Quist & Wijdeven (2014) and Mohseni (2011). Information is provided about container types, vessels and terminal elements.

2.1.1.1 Containers

Containers are a standardised form of cargo and exist in various types and sizes. In Figure 5 some examples of container types are given that are all 40 ft except the Tank Container which is 20 ft. However all these containers come in both sizes; PIANC (2014a).

[9] The considered terminal types are container, dry bulk and liquid bulk terminals.

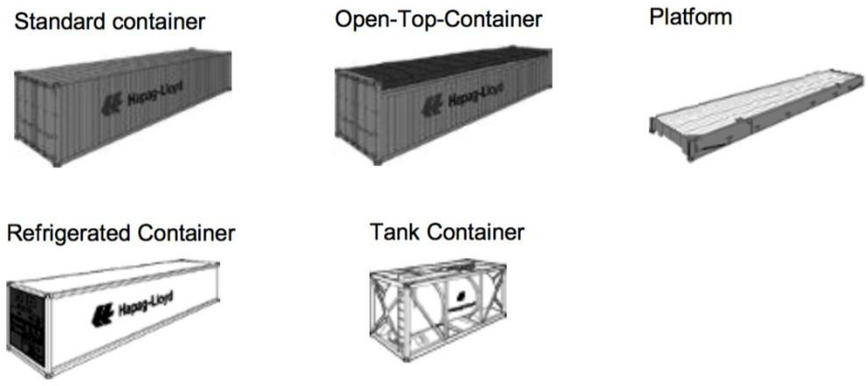


Figure 5: Some examples of container types. Source: PIANC (2014a)

For this research only the following container sizes are considered:

- Twenty foot Equivalent Unit or TEU (l = 6.10 m, b = 2.44 m, h = 2.60 m)
- Forty foot Equivalent Unit or FEU or 2 TEU (l = 12.20 m, b = 2.44 m, h = 2.60 m)

2.1.1.2 Vessels

Container vessels are categorised in different classes depending on the vessel size. Shipping lines continuously increase the size of their vessels to make use of the economy of scale principle according to Quist & Wijdeven (2014). In Figure 6 the development of container vessel capacities (vertical axis) from 1981 to 2013 (horizontal axis) is depicted, in which the light blue line represents the largest ship size and the dark blue line the average ship size.

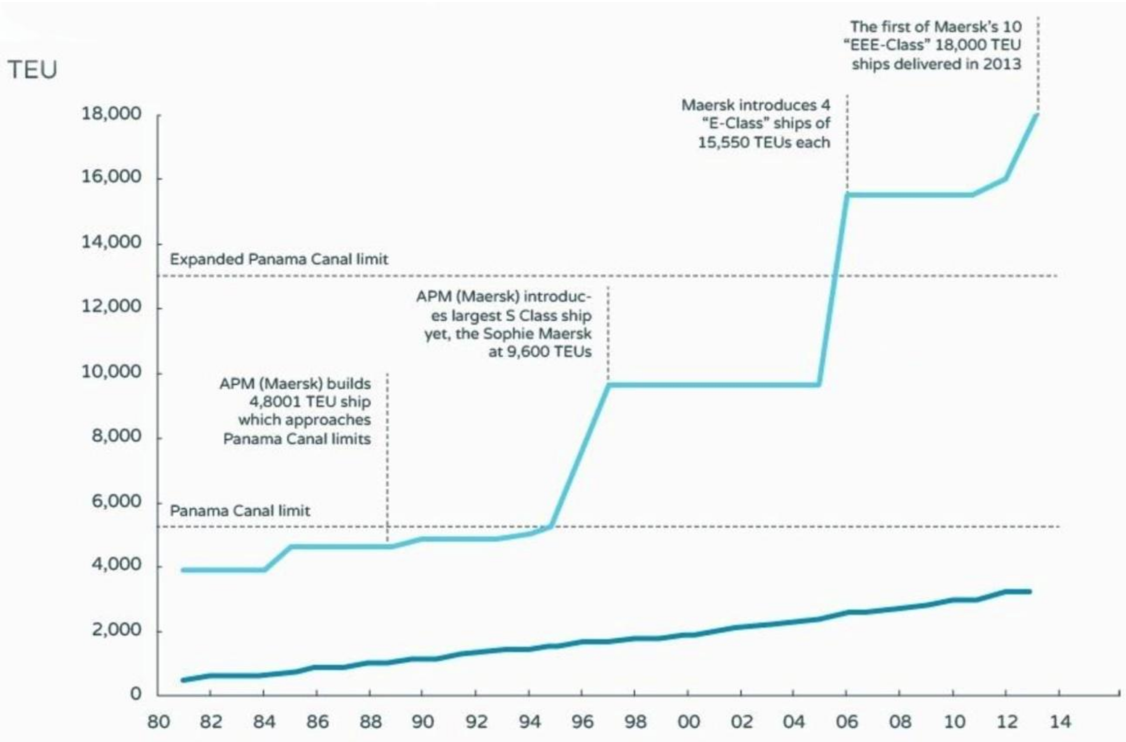


Figure 6: Development of the container vessel capacity with milestones of container shipping company Maersk. Source: Clarkson Research Services, 2013

In Table 1 an overview of the most important classes with corresponding vessel sizes is presented. The Deadweight Tonnage (DWT) is the mass of the cargo, fuel, crew, passengers, fresh water and provisions on a ship. The draught is the maximum distance in meters between the waterline and the keel of the ship and the beam is the maximum width of the ship; Ligteringen & Velsink (2012).

Table 1: Container vessel classes and dimensions

Class	Capacity [TEU]	DWT average [tonne]	Length [m]	Draught [m]	Beam [m]
1st generation	750 - 1100	14,000	180 - 200	9	27
2nd generation	1500 - 1800	30,000	225 - 240	11.5	30
3rd generation	2400 - 3000	45,000	275 - 300	12.5	32
4th generation	4000 - 4500	57,000	290 - 310	12.5	32.3
Post Panamax	4300 - 5000	54,000	270 - 300	12	38 - 40
Jumbo	6000 - 9000	90,000	310 - 350	14	43
New Panamax	13,000	151,000	366	15.2	49
Super-Post Panamax	14,000 - 18,000	157,000 - 194,000	400	14.5 - 15.5	56 - 59

Source: Quist & Wijdeven (2014)

2.1.1.3 Terminal elements

Typical elements of a container terminal are (see Figure 7):

- Quay
- Apron
- Storage yard
- Landside area

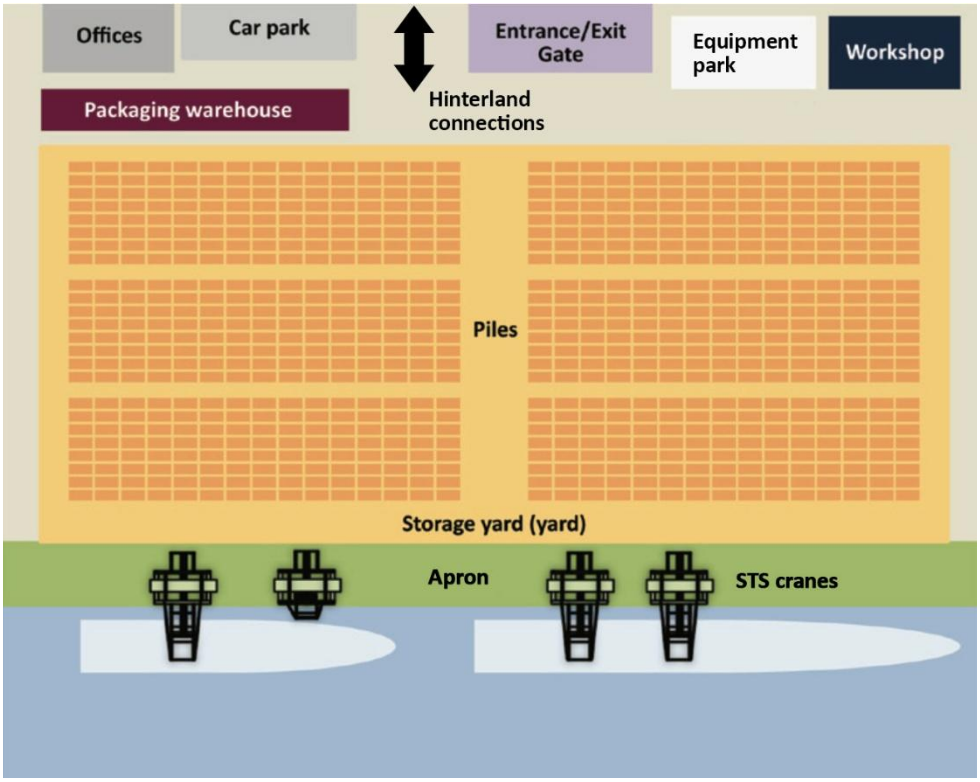


Figure 7: Schematic representation of typical container terminal elements. Based on: Monfort et al. (2011)

2.1.1.4 Quay

For container terminals a vertical quay wall that is directly connected to the land is used. Jetties are not commonly used since ship-to-shore cranes need much space and the storage yard is preferably as close to the berth as possible. Quay walls exist in many forms with the main types being sheet pile walls and gravity walls. For quay walls with large retaining heights often combined sheet pile walls are used; these consist of heavy primary elements (such as tubular piles) with intermediate sheet piles, as depicted in Figure 8 and Figure 9. Combinations between and variants of these types exist as well, for more information reference is made to de Gijt & Broeken (2005). Often containers are transported to and from barges from the quay for sea-going vessel. This has as disadvantage that the capacity of the large STS-cranes designed for sea-going vessels is not met. Also barges regularly collect containers at multiple terminals, this is time consuming; Quist & Wijdeven (2014). To tackle these problems a separate quay for barges can be implemented in a terminal. This is however not implemented as explained in the introduction.

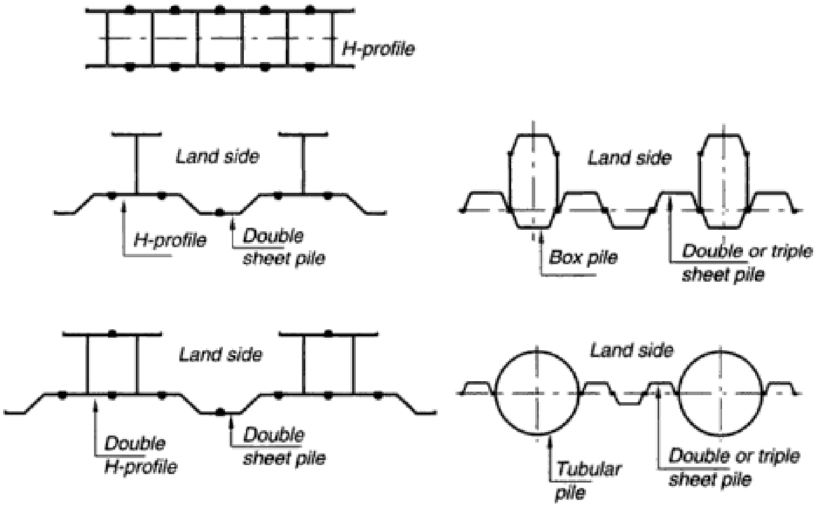


Figure 8: Horizontal cross-sections of various combined sheet pile quay walls. Source: de Gijt & Broeken (2005)

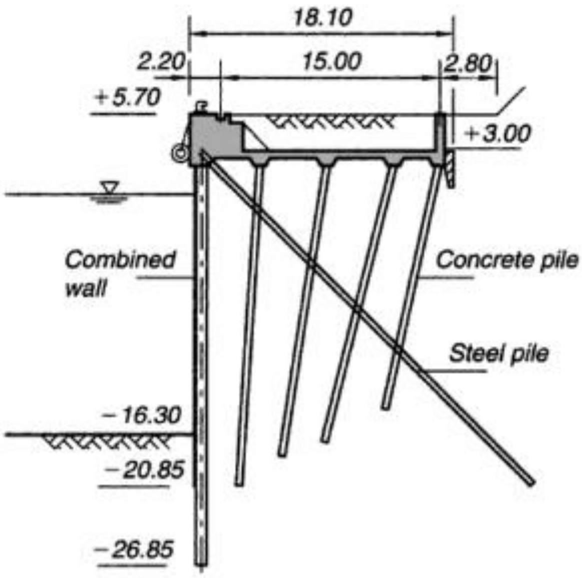


Figure 9: Example of a combined sheet pile quay wall with concrete capping beam in Hansaport, Hamburg. Source: de Gijt & Broeken (2005)

2.1.1.5 Apron

The apron area typically consists of the following elements with their specific functions and equipment:

- Section between quay wall and crane rail
- Crane
    - Crane rail gauge: area between the crane rails.
    - Outreach: extending part of the boom on the backside of the crane.
- Access roadway
- Zone between roadway and storage yard

The choice of equipment usually depends on vessel sizes, economics and the desired density and productivity.

Cranes

To load and unload containers between vessel and quay large cranes are used. There are two different types of cranes that are used to transport containers from ship to shore and vice versa:

- Ship-to-Shore (STS) gantry crane: Consists of a frame that is mounted on rails running parallel to the quay and of a boom that extents horizontally over the ship. Containers are hoisted between the legs or at the outreach of the crane. Cranes usually are described by the length of the boom (in number of containers) and the rail gauge.
- Mobile Harbour Crane (MHC): A crane that is mounted on rubber tyres and supported by outriggers. The crane can be moved to any location, given that the terminal foundation can withstand the pressure, and it can be used for multiple sorts of cargo. MHC cranes have a lower capacity than STS cranes but have increased flexibility.

STS gantry cranes are the most used cranes on container terminals. These cranes have to adapt to the increasing container vessels sizes, which is depicted in Figure 10.

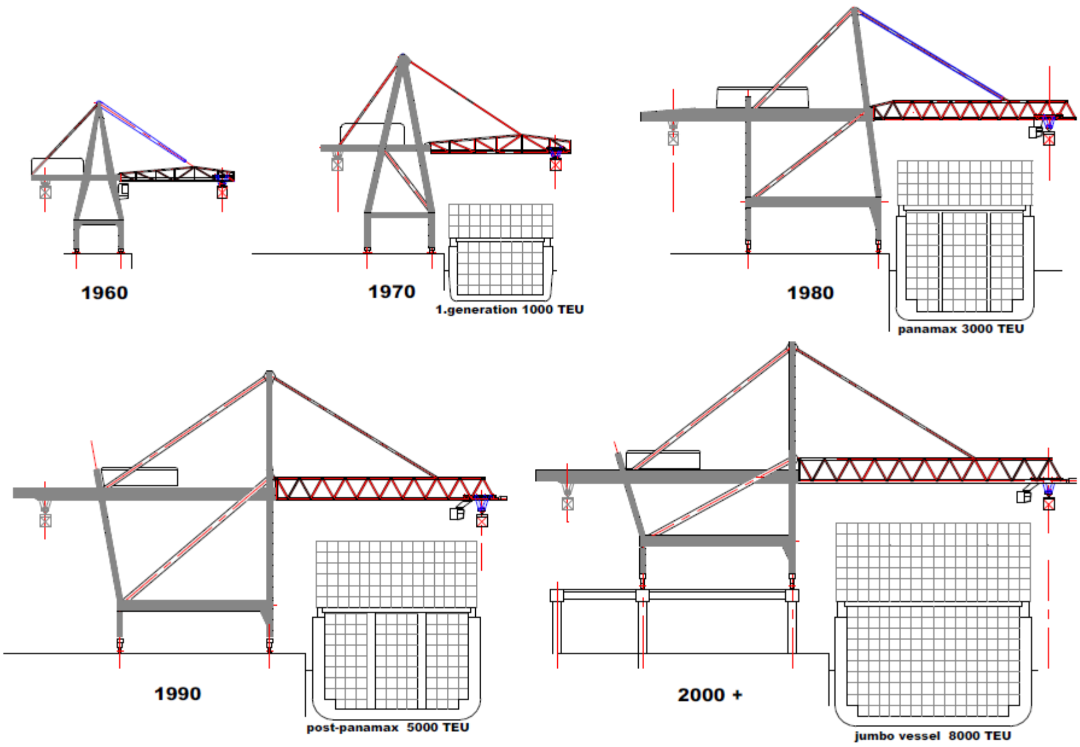


Figure 10: Development of ship-to-shore cranes. Source: Presentation Prof. ir. J.C. Rijsenbrij. TU Delft course "wb3410 Large Scale Transportation Systems"

Improvements to gantry cranes exist that increase the capacity of the cranes. Some examples of such improvements are listed below; from PIANC (2014b) and Lind et al. (2007):

- Tandem forties spreader: can hoist two FEU's side by side at the same time (see Figure 11):
  - Single hoist: Both spreaders are lifted only together.
  - Dual hoist: Spreaders can be lifted separately, horizontal motion is combined. Doubles the productivity according to Saanen (2004).
- Dual trolley: Two independent trolleys. One trolley moves containers between ship and a platform, the second trolley moves containers between platform and landside. Can improve productivity with about 15 to 20% according to Saanen (2004).
- Remote controlled cranes.

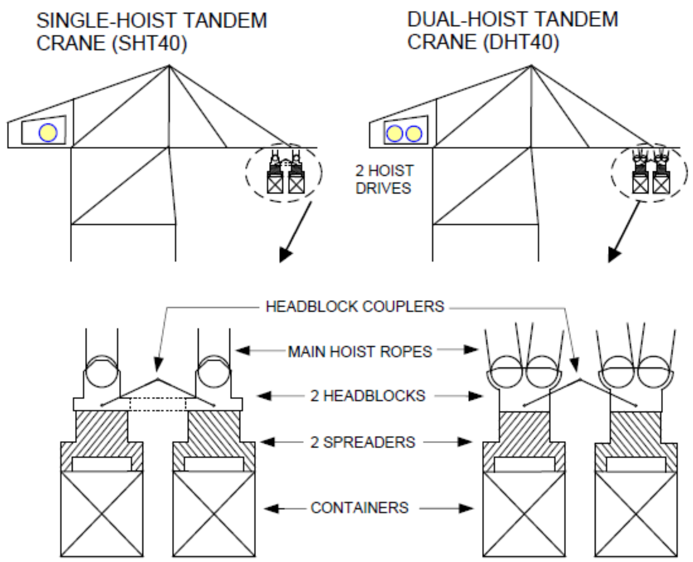


Figure 11: Single and Dual Hoisting systems of an STS crane. Source: Lind et al. (2007)

These improvements are not implicitly included in this research in order to not further complicate the input. To still be able to take these improvements into account the user can manually change the STS crane productivity in the tool.

Transport between crane and storage yard

Equipment types for the handling of containers from the apron to the storage yard are (Figure 12):

- Tractor Trailer Units (TTU) or chassis system: Using trailers specifically designed for container transport. The containers are loaded to/from the trailer/chassis at the crane. The container can then be (un)loaded by a crane located at the storage yard, or the chassis with the container can be parked in the storage area. It is also possible to immediately transport the container over the road network to its destination. The trailers/chassis are moved by means of tractors or trucks.
- Reach stackers: Comparable with top loader but with a telescopic boom. It can therefore reach further then one row so that stacks can be four containers wide, with access on both sides.
- Straddle carriers: Can lift containers between its wheels. A straddle carrier is able to lift a container 1 over 2 or 1 over 3. The straddle carrier is quite space efficient but can be difficult to operate.
- Automated Guided Vehicle (AGV): Vehicles that transport containers automatically on the terminal. Results in an efficient terminal but investment costs are high. This equipment type is not included in the computer tool since no capacity properties are known.

Figure 12: Clockwise starting from the left: TTU, reach stacker, straddle carrier, AGV. Source: Google

Some of these equipment types do not need other machines to do the (un)loading. Others can only transport the container and need cranes to be (un)loaded. These cranes are described in the following section. In PIANC (2014a) more extensive information can be found about all container terminal equipment.

2.1.1.6 Storage yard

The storage yard has to be able to accommodate different sorts of containers, in this research regular and empty containers are considered. The storage yard itself can be divided into the following main elements:

- Import
- Export: Positioned as close to the quay wall as possible will facilitate efficient loading of vessels.
- Empties: Can have a dedicated storage area and can be stacked up to nine containers high by means of Empty Container Handlers that are similar to Top loaders. All empty containers do not have to be reachable by the equipment and can therefore be very densely stacked. May be positioned outside of the terminal area.
- Container Freight Station (CFS): A covered area (building) that is used to strip and stuff containers. The CFS may also be positioned outside of the terminal area.

An additional container terminal element can be a leaking container pit. This may be positioned outside of the storage yard but inside the terminal area.

Equipment used only at the container yard is (see Figure 13):

- Rubber Tyred Gantry (RTG) crane: A portal crane mounted on rubber tyres. The most common dimensions are a width of 6 + 1 or 7 + 1 (number of containers + driving lane) and an ability to lift 1 over 5 or 6. These cranes are used in combination with tractor-trailers. The optimum layout has the tracks parallel to quay.
- Rail Mounted Gantry (RMG) crane: Similar to RTG but mounted on rails. Can be used in combination with tractor-trailers or AGV’s. Most used forms are perpendicular rails with end loaded stacks or parallel rails with side loaded stacks. An RMG can be (partly) automated and is then called Automated Stacking Crane (ASC).

Figure 13: Rubber tyred gantry crane (left), Rail mounted gantry crane (right). Source: Google

Container stacks have different forms depending on the terminal equipment. The space in between the containers and the maximum stacking height depends on the equipment type. As an example RMG cranes have a much higher maximum yard density than reach stackers because of the large differences in space needed between containers and the maximum stacking height. Some container yard layouts corresponding to a certain equipment type are displayed in Figure 14.

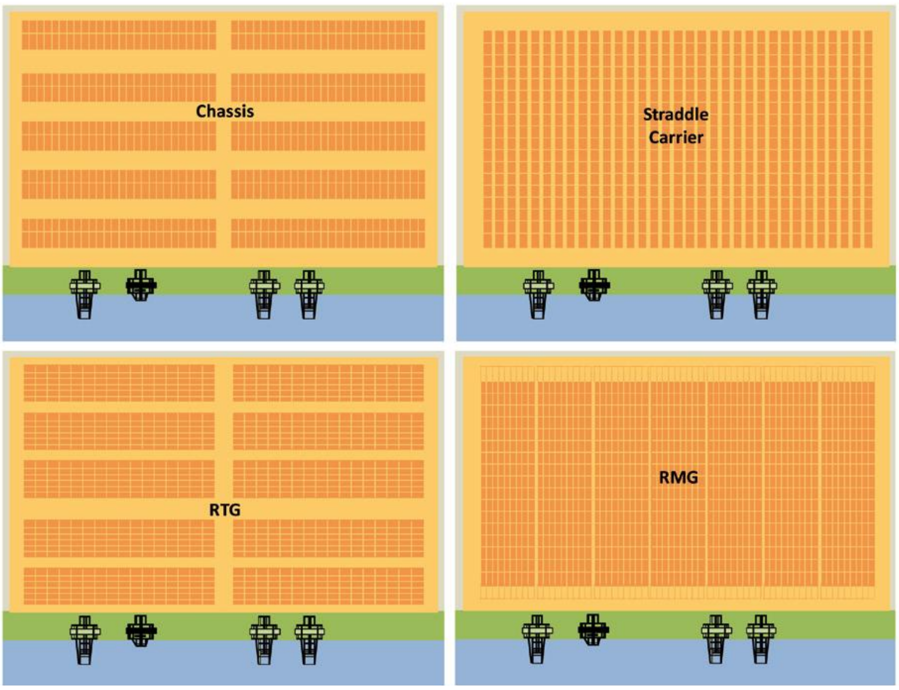


Figure 14: Container storage yard layout per equipment type. Source: Monfort et al. (2011)

Gateway terminals are terminals that mainly import and export cargo. For terminals with a large transhipment to gateway ratio parallel stacks have been found to be more efficient. For a larger proportion of gateway transport perpendicular stacks are more efficient according to simulations; PIANC (2014a).

The pavement and foundation of the apron and storage yard are also important factors for a terminal design. The requirements depend on the type of terminal equipment.

2.1.1.7 Landside area

The landside area consists of:

- Landside traffic circulation system
  - Gate
  - Loading space
  - Queuing space
  - Equipment parking
- Buildings
  - Offices
  - Terminal equipment maintenance/repair facility
  - Fuel station

Additional elements that may be required are:

- Rail terminal
- Container repair facility
- Container inspection facility

2.1.2 Equipment properties

The properties of the terminal equipment that are required for the dimensioning of a container terminal are given in this section. A division is made between quay cranes and equipment used between quay and storage yard and on the yard itself.

2.1.2.1 Quay cranes

The quay cranes that are mentioned in Section 2.1.1.4 are STS Gantry cranes and MHC cranes. The average gross productivity is defined as the average number of moves per hour including unproductive intervals such as crane repositioning, moving hatches to/from quay and time between shifts; PIANC (2014b). These productivities are listed per crane type in Table 2.

Table 2: Quay crane productivity

Crane	Average gross productivity
Ship-to-shore gantry crane	Low 20 - 25 moves/hour Medium 25 - 30 moves/hour High 30 - 35 moves/hour
Mobile harbour crane	15 - 20 moves/hour

Source: PIANC (2014b)

The required apron width per crane with a certain rail span is listed in Table 3.

Table 3: Apron widths per quay crane type

Crane	Rail span [m]	Apron width [m]
Ship-to-shore gantry crane	15 - 20	40 - 55
	30.48	55 - 75[1]
Mobile harbour crane	-	25 - 30

Note 1: When a perpendicular RMG is used on the storage yard or an AGV system in between; the apron width ranges between 100 - 120 meter.

Sources: Agerschou (2004), PIANC (2014a) and Quist & Wijdeven (2014)

2.1.2.2 Storage yard equipment

The equipment properties for transport between quay and storage yard and storage yard cranes are given in Table 4. All these equipment types can place containers on the yard, only the RTG and RMG need other equipment for the transport between quay and storage yard.

The gross storage density takes into account the internal roads and the stacking height.

Table 4: Properties for equipment between quay and storage yard and on the yard itself

Equipment	Average stacking height [-]	Maximum stacking height [-]	Gross storage density [m^2/TEU]	Average over maximum stacking height [-]
Chassis system	1	1	40 - 66.7	1.00
Empty handler	6 - 9	9	6 - 11	0.67 - 1.00
Reach stacker	2 - 4	7	20 - 30	0.29 - 0.57
Straddle carrier[1]	1 - 2	4	10 - 13	0.25 - 0.50
RTG	3 - 4	6	7.5 - 16	0.50 - 0.67
RMG	3 - 4	7	7.5 - 11	0.50 - 0.57

Note 1: Maximum from Monfort et al. (2011) unrealistically high with respect to the other literature so an alternate maximum is used.

Based on Böse (2011), Ligteringen & Velsink (2012), Monfort et al. (2011), PIANC (2014b) and PIANC (2014a).

The required number of yard equipment per quay crane depends on the (combination of) used equipment types on the terminal. The number of equipment per combination is presented in Table 5.

Table 5: Required number of equipment per quay crane

Required number of equipm. per STS crane		Equipment between quay and yard		
		TTU	SC	AGV
Equipment at yard	RS	3 - 6 TTU 3 - 4 RS		
	SC		3 - 5 SC	
	RTG	3 - 6 TTU 2 - 3 RTG		
	RMG	3 - 6 TTU 2 - 3 RMG		3 - 6 AGV 2 - 3 RMG

Notes: TTU = Tractor Trailer Unit, SC = Straddle Carrier, RS = Reach Stacker, RTG = Rubber Tyred Gantry, RMG = Rail Mounted Gantry, AGV = Automated Guided Vehicle, STS = Ship-To-Shore crane.

Based on Böse (2011) and PIANC (2014a)

2.1.3 Design guidelines, rules and parameters

First the concept of transhipment is described. Then design guidelines, rules and parameters are provided for determining the quay length, storage yard area and water depth. Values used in practice of the parameters are listed in Section 2.1.3.5.

2.1.3.1 Transhipment

The terminal throughput is the sum of the incoming and outgoing number of containers over the quay per year. Incoming and outgoing containers cannot be confused with import and export containers, if there is transhipment of containers. Transhipment containers are containers that enter the terminal via deep-sea or feeder vessels and leave the terminal via those same modes of transport. Other containers are counted as import/export containers. When containers are -after being imported- exported again to barges this does not count as transhipment according to Saanen (2004). The ratio between the number of transhipment containers and incoming/outgoing containers is denoted by μ. The ratio can be calculated with the following equation, based on Saanen (2004) and adjusted for TEU's instead of container moves:

$$\mu = \frac{C_{trans}}{C_{in} + C_{out}} = \frac{C_{trans}}{C} \tag{1}$$

Where,

μ Ratio of transhipped containers [-].
C_{trans} Number of transhipment containers per year [TEU/year].
C_{in} Number of incoming containers from the waterside per year [TEU/year].
C_{out} Number of outgoing containers to the waterside per year [TEU/year].
C Throughput. Number of container movements over the quay per year [TEU/year].

When the terminal throughput is used to calculate the required storage yard area, transhipment containers are counted twice. The number of containers over the yard (stack visits), that determines the required yard area, is the number of containers over the quay (terminal throughput) corrected for transhipment containers. This is defined by the following equation, based on Saanen (2004):

$$C_y = C - C_{trans} = C \cdot (1 - \mu) \tag{2}$$

Where,

C_y Number of container movements over the yard per year [TEU/year].
C Throughput. Number of container movements over the quay per year [TEU/year].
C_{trans} Number of transhipment containers per year [TEU/year].
μ Ratio of transhipped containers [-].

The previously mentioned cargo flows over the quay and over the storage yard are depicted in Figure 15. To help clarify this; a 100% transhipment terminal requires half the storage yard capacity of a 100% import/export terminal while the throughputs (movements over the quay) are the same, from Saanen (2004).

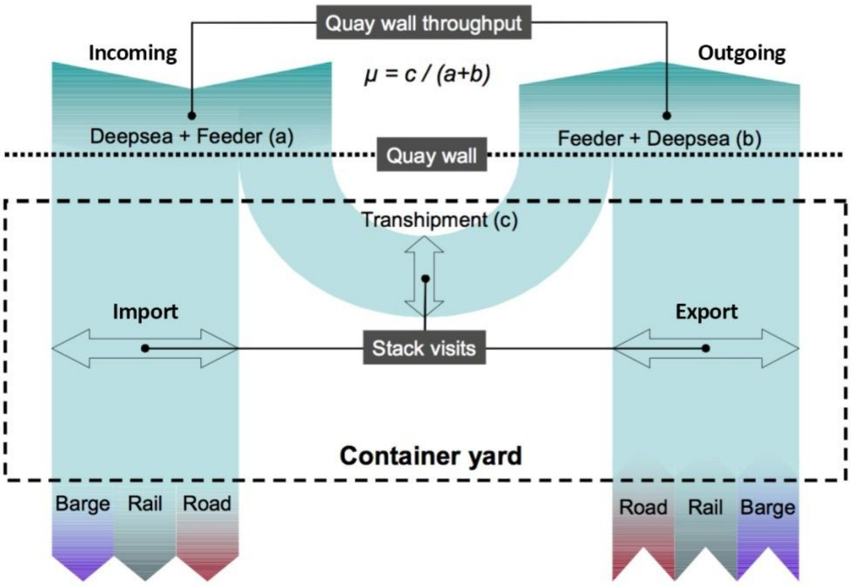


Figure 15: Container flow over the quay and yard. Based on: Saanen (2004)

2.1.3.2 Quay length

Two quick estimation methods exist for determining the required quay length. Also empirical rules-of-thumb exist that can be used as a check for calculated quay lengths. The methods are:

1. Berth productivity
2. Maximum service time
3. Empirical rules-of-thumb

Berth productivity

This method uses the annual throughput, crane productivity and number of cranes to determine the required quay wall length. First the berth productivity is calculated with the following equation from PIANC (2014b):

$$C_b = \overline{P}_{gross} \cdot f_{TEU} \cdot n_{cb} \cdot n_{hy} \cdot m_b \tag{3}$$

Where,

C_b Berth productivity [TEU/year].

$\overline{P}_{gross}$ Average gross productivity per crane [moves/hour]. Average number of containers moved between berthing completed and de-berthing started. This variable therefore includes unproductive intervals such as crane repositioning, moving hatches to/from quay and time between shifts.

f_{TEU} TEU factor; the ratio between 40 ft. and 20 ft. containers [-]. Defined in Equation (5), from Böse (2011).

n_{cb} Number of cranes per berth [-].

n_{hy} The number of operational hours per year [hour/year]. Very much dependent on the local situation.

m_b Estimated berth occupancy factor [-]. The acceptable occupancy factor depends on the allowable waiting time in terms of service time, the number of berths and the sort of terminal (e.g. dedicated shipping line). The factor can be calculated with the following equation, based on Saanen (2004):

$$m_b = \frac{\sum_{i=1}^{n}\left(L_{s,i} \cdot T_{s,i}\right)}{L_q \cdot n_{hy}} \tag{4}$$

Where,

$L_{s,i}$ Length of vessel i of total of n vessels berthed in measurement period n_{hy} [m]. This length should include twice the L_{ml} (see Equation (7)). Only vessel $i = n$ should include this additional length once.

$T_{s,i}$ Service time (or effective berthing time) of vessel i of total of n vessels berthed in measurement period n_{hy} [hour]. Time the vessel is berthed outside of the operational hours does not count.

L_q Quay length [m].

$$f_{TEU} = \frac{N_{20} + 2 \cdot N_{40}}{N_{20} + N_{40}} \tag{5}$$

Where,

f_{TEU} TEU factor; the ratio between 40 ft. and 20 ft. containers [-]. A value of 1.60 means 60% of the containers are FEU's.

N_{20} Number of TEU's [-].

N_{40} Number of FEU's [-]. A factor of two is used in the equation since two TEU's equal one FEU.

The required number of berths is then calculated by the equation from PIANC (2014b):

$$n_b = \frac{C}{C_b} \tag{6}$$

Where,

n_b Number of required berths [-].

C Number of container movements over the quay per year [TEU/year].

C_b Berth productivity [TEU/year].

Then with the determined number of berths the required quay wall length is calculated by means of the following equations from PIANC (2014b):

$$L_q = \begin{cases} L_{s,max} + 2 \cdot L_{ml} & for\ n_b = 1 \\ 1.1 \cdot n_b \cdot \left(\overline{L}_s + L_{ml}\right) + L_{ml} & for\ n_b > 1 \end{cases} \tag{7}$$

Where,

L_q Required quay wall length [m].

$L_{s,max}$ The length of the largest vessel frequently calling at the terminal [m].

$\overline{L}_s$ The average vessel length [m].

L_{ml} The additional quay length required for and aft of the vessel to account for the mooring lines [m].

n_b Number of berths [-].

The factor 1.1 accounts for variability in the vessel length since an average value is used, results from a study done by UNCTAD (1984).

Maximum service time

Another method to determine the required number of STS cranes, the respective crane productivity and the number of berths is to pose a maximum allowable service time for a vessel. A common maximum of 24 hours of time-in-port is used since the service time has a large influence on a vessel's operating costs; from Saanen (2004) and Quist & Wijdeven (2014). The required quay length can then be calculated with the equations in the previous section.

Empirical rules-of-thumb

A few empirical rules exist that are mostly used for a quick check of the calculated quay length.

The first rule-of-thumb gives empirically determined benchmarks for the berth capacity in TEU per metre of quay per year that are given in Table 6. The table originates from Drewry (2010). The values are based on actual, non-estimated, throughput data of the year 2009 of 201 container terminals with a throughput of more than 200,000 TEU. The quay length can be calculated by dividing the annual container throughput by the berth capacity.

Table 6: Berth capacity benchmarks

Region	North America	Europe	Latin America	Far East	Southeast Asia
TEU per metre quay	526	712	742	1,224	1,578
Region	**Middle East**	**South Asia**	**Others**	**World**	
TEU per metre quay	1,341	1,216	743	933	

Notes: Container terminals with throughput > 200,000 TEU in 2009.
Only terminals with STS cranes are considered.
Others includes Africa and Oceania.

Source: Drewry (2010)

Another berth capacity is proposed by Ligteringen & Velsink (2012) and is 300 to 1000 TEU per year. A remark is made that the large uncertainty is due to the many types of equipment and the number and type of ships.

The second rule-of-thumb is based on an average quay length per STS crane. According to PIANC (2014b) on average one crane per 100 metre of quay is common on container terminals. This can however increase to one crane per 75 metre for high capacity terminals. To calculate the quay length the average metres per crane should be multiplied with the required number of cranes (n_c), that can be calculated with the following equation that is derived from Equation (3):

$$n_c = \frac{C}{n_{hy} \cdot \overline{P}_{gross} \cdot f_{TEU} \cdot m_b} \tag{8}$$

Where,

n_c	Required number of cranes [-].
C	Number of container movements over the quay per year [TEU/year].
n_{hy}	The number of operational hours per year [hour/year].
$\overline{P}_{gross}$	Average gross productivity per crane [moves/hour]. Average number of containers moved between berthing completed and de-berthing started. This variable therefore includes unproductive intervals such as crane repositioning, moving hatches to/from quay, time between shifts and simple repairs.
f_{TEU}	TEU factor; the ratio between 40 ft. and 20 ft. containers [-]. Defined in Equation (5).
m_b	Estimated berth occupancy factor [-]. This factor depends on the allowable waiting time in terms of service time, the number of berths and the sort of terminal (e.g. dedicated shipping line).

2.1.3.3 Terminal area

The terminal area can be calculated with:

1. General approach
2. Empirical rule-of-thumb

General approach

The total terminal area can be determined by a summation of the gross required storage areas for the different flow directions (import, export and transhipment; see Figure 15) plus the required area for empties and the container freight station, see Figure 16. The equations needed for these elements are given in this section. The desirable total depth (from quay wall to landside terminal boundary) of a container terminal lies between 400 and 500 metres depending on local conditions.

Figure 16: Container terminal with total terminal area (blue) and gross storage areas (red). S.L. Port of Barcelona (Spain). Source: Google Earth

The general equation for determining the gross required storage area per container flow direction is based on the version of Quist & Wijdeven (2014) of an equation originating from UNCTAD (1985), and is as follows:

$$A_{gr,i} = \frac{C_{y,i} \cdot \bar{t}_d \cdot A_{TEU}}{r_{st} \cdot m_s \cdot 365} \tag{9}$$

Where,

- $A_{gr,i}$ Gross required storage area per flow direction and/or stack type (including internal roads)[10] [m^2]. For import, export and transhipment cargo flows and empties stack.
- $C_{y,i}$ Number of container movements over the yard per year per flow direction [TEU].
- $\bar{t}_d$ Average dwell time of containers in the stack [days]. Average time a container spends in the yard.
- A_{TEU} Gross storage density for maximum stacking height [m^2/TEU]. The required area per container in a fully utilised stack including roads in between the stacks.
- r_{st} Ratio of average stacking height over maximum stacking height [-]. In order to limit the amount of repositioning of containers in the stack, which is larger for higher stacks.
- m_s Estimated storage occupancy [-]. Average number of containers in yard divided by the design capacity of the yard (taking into account re-positioning, so r_{st}). To account for the random arrivals and departures of cargo.

The gross required storage area plus additional area for infrastructure and buildings on the terminal (see Section 2.1.1) is the required total terminal area, calculated by the following equation (own work):

$$A_t = \frac{\sum A_{gr,i} + A_{CFS}}{\alpha} \tag{10}$$

[10] The gross required storage area includes the net storage area (purely container stacks) and internal roads in between the stacks. The apron, other roads and buildings on the terminal are included in the required total terminal area (A_t).

Where,

A_t Required total terminal area [m^2]. Area including the stacks, storage yard, apron, infrastructure and buildings.

$A_{gr,i}$ Gross required storage area per flow direction and/or stack type (including internal roads) [m^2]. For import, export and transhipment cargo flows and empties stack.

A_{CFS} Required area for the container freight station [m^2]. See Equation (11).

α Total terminal factor; the percentage of storage area and internal roads in the stack with respect to the total terminal area [-].

<u>Container freight station</u>

To determine the required area for the container freight station the following equation is used, based on a version of Quist & Wijdeven (2014) of an originating equation from PIANC (2014b), and is as follows:

$$A_{CFS} = \frac{C_{CFS} \cdot V_c \cdot \bar{t}_d \cdot f_{area} \cdot f_b}{\bar{h}_s \cdot m_s \cdot 365} \tag{11}$$

Where,

A_{CFS} Required area for the container freight station [m^2].

C_{CFS} Number of container movements per year through the CFS [TEU].

V_c Volume of 1 TEU container [m^3].

$\bar{t}_d$ Average dwell time of containers in the CFS [days]. Time between arrival of vessel and departure of container from the terminal for import containers, for export vice versa according to Monday Nyema (2014).

f_{area} Ratio gross over net area of CFS [-]. To account for containers being stored around the CFS during transfer of cargo.

f_b Bulking factor of CFS [-]. To account for cargo that needs special treatment or repairs.

$\bar{h}_s$ Average stacking height in the CFS [m].

m_s Estimated storage occupancy [-]. Average number of containers in yard divided by the design capacity of the yard. To account for the random arrivals and departures of cargo.

Empirical rule-of-thumb

According to Saanen (2004) the required total terminal area can be determined by the annual number of containers over the quay divided by the maximum annual container handling capability per total area of the terminal (or container storage factor f_s). The container storage factors according to Saanen (2004) can be used as a check for a calculation, the factors are:

- 2.3 TEU/year/m^2 for gateway terminals (import/export terminals).
- 5.0 TEU/year/m^2 for hub terminals (transhipment terminals).

A terminal can be classified as a gateway terminal if the ratio of transhipped containers $\mu \leq 0.5$. A terminal can be classified as a hub terminal if $\mu > 0.5$.

In Table 7 average container storage factors are listed, based on Drewry (2010). The values are based on actual, non-estimated, throughput data of the year 2009 of 201 container terminals with a throughput of more than 200,000 TEU. The figures are averages, therefore variation because of terminal types (gateway or hub) is not taken into account. The higher values for the regions in Asia are due to the large amount of hub terminals, based on Heymann (2006).

Table 7: Storage factor benchmarks

Region	North America	Europe	Latin America	Far East	Southeast Asia
TEU/year/m^2	0.74	2.09	1.74	3.37	5.66
Region	**Middle East**	**South Asia**	**Others**	**World**	
TEU/year/m^2	2.84	3.34	2.18	2.25	

Notes: Container terminals with throughput > 200,000 TEU in 2009.
Only terminals with STS cranes are considered.
Others includes Africa and Oceania.

Based on Drewry (2010)

Ligteringen & Velsink (2012) proposes 0.6 to 1.0 TEU per year per terminal surface.

2.1.3.4 Water depth

When few data is available a quick estimation of the required depth to be dredged can be made. The required depth is dependent on the static draught of the fully loaded design vessel, the gross underkeel clearance and a dredging tolerance. The gross underkeel clearance consists of the net underkeel clearance and vertical ship motions (due to swell, waves, squat and trim). The required depth can be calculated with the following equation, based on PIANC (1995):

$$d_d = D_s + h_{guc} + h_{dt} \tag{12}$$

d_d Required dredging depth [m].
D_s Draught of design vessel [m].
h_{guc} Gross underkeel clearance [m].
h_{dt} Dredging tolerance [m].

In PIANC (1995) a minimum gross underkeel clearance (h_{guc}) is specified as a percentage of the ship's draught (D_s). Values are presented in Table 8 for various wave conditions. For container vessel dimensions see Table 1.

Table 8: Minimum gross underkeel clearance for certain wave conditions

Wave conditions	h_{guc}/D_s
Sheltered waters	10 %
Wave height ≤ 1.0 m	30 %
Higher waves with unfavourable periods and directions	50 %

These values apply to large ships (≥ 200,000 DWT), it is an overestimation for smaller vessels.

Source: PIANC (1995)

2.1.3.5 Common values of parameters

Values that are proposed in literature of the input parameters used in the design rules are listed in Table 9. For various parameters minimum and maximum values are proposed, resulting in a range of possible values. This can be represented by a uniform random distribution. When this is the case the reader should make an estimate of which part of the distribution to use. The sources of the values are numbered in square brackets.

Table 9: Parameter values of container terminal design rules

Symbol	Unit	Description and values
f_{area}	-	*Ratio gross over net area of CFS.* A value of 1.40 is proposed by [2].
f_b	-	*Bulking factor of CFS.* Ranges between 1.10 and 1.20 [2].
f_s	TEU/year/m^2	*Storage factor.* Value of 2.3 for gateway terminals and 5.0 for transhipment terminals [9]. Global average of 2.2 regardless of terminal classification. Between 0.6 and 1.0 [12]. For values per global location see Table 7 (p.41) [10].
f_{TEU}	-	*Ratio between 40 ft. and 20 ft. containers.* Typical value for a modern terminal is 1.50 [5] or 1.60 [1]. Can be as high as 1.9 for developed countries or smaller than 1.5 for underdeveloped countries [5].
h_{dt}	m	*Dredging tolerance.* A value of 0.60 is proposed by [13].
h_{guc}	m	*Minimum gross underkeel clearance.* For values see Table 8 (p.41).
$\overline{h}_s$	m	*Average stacking height in CFS.* Height of 1 container is 2.60 m.
m_b	-	*Estimated berth occupancy.* For values see Table 10 (p.44).
m_s	-	*Estimated storage occupancy.* Determined in Expert Judgement Elicitation, see Section 0. Literature: Typical values around 70% [5]. Between 65% and 70% [2]. For CFS between 60% and 70% [2].
n_{cb}	-	*Number of cranes per berth.* On average 3 cranes per berth [2]. Maximum of 7 [7].
n_{hy}	hour/year	*Number of operational hours per year.* Very much dependent on local situation. A typical modern terminal operates 24 hours a day for 360 days a year; this is 8640 hours per year [5].
r_{st}	-	*Ratio average stacking height over maximum stacking height.* For values see Table 4 (p.33).
$\overline{t}_d$	days	*Average dwell time of containers in stack.* Typical values for full containers are 4 - 10 days [8]. They should not exceed 5 days [11]. Imported containers 6 - 7 days [8], export containers 4 - 5 days [8]. Empty containers have dwell times from 7 - 20 days [5 & 8]. CFS's have typical dwell times of 5 days [4].
A_{TEU}	m^2/TEU	*Gross storage density.* For values see Table 4 (p.33).
D_s	m	*Draught of the design vessel.* For values see Table 1 (p.25).
L_{ml}	m	*Additional quay length required for and aft of vessel to account*

Symbol	Unit	Description and values
		for mooring lines. Normally 15 metres [2] or 30 metres [5] is used.
$\overline{L}_s$	m	*Average vessel length.* For regular vessel lengths see Table 1 (p.25).
$L_{s,max}$	m	*Length of largest vessel frequently calling at terminal.* For regular vessel lengths see Table 1 (p.25).
$\overline{P}_{gross}$	moves/hour	*Average gross productivity per crane.* For values see Table 2 (p.32).
V_c	m^3	*Volume of 1 TEU container.* The volume is 29 m^3.
a	-	*Total terminal factor.* Determined in Expert Judgement Elicitation, see Section 0. Literature: Ranges between 55% and 80% [3], or between 60% and 70% [8]. A typical value is 75% [1]. Between 50% and 70% when CFS within terminal boundaries, between 60% and 80% without CFS in terminal [9].

Sources:
[1] Personal communication with S. Meijer (19-04-2016)
[2] Quist & Wijdeven (2014)
[3] Monfort et al. (2011)
[4] Kersten (2010)
[5] PIANC (2014b)
[6] Agerschou (2004)
[7] Personal communication with B.A. Pielage.
[8] PIANC (2014a)
[9] Saanen (2004)
[10] Drewry (2010)
[11] Fourgeaud (2000)
[12] Ligteringen & Velsink (2012)
[13] PIANC (1995)

Berth occupancy factor

The acceptable berth occupancy factor depends on the number of berths and the allowable average waiting time in terms of average service time of vessels (T_w/T_s). Based on various economic feasibility studies a reasonable value for T_w/T_s for container terminals is found to be 0.10; according to Agerschou (2004). The probabilistic Queuing Theory is used to determine the occupancy ratios. This theory is not treated in this research since it is outside its scope, for a better understanding of the general Queuing Theory reference is made to Sztrik (2012). An application of the theory on terminal design can be found in Agerschou (2004).

The queuing system can be denoted by the Kendall notation: "inter arrival time distribution"/"service time distribution"/"number of berths". Arrivals of vessels can be random for common user terminals, a negative exponential inter arrival time (denoted by M) is then assumed. When arrivals are less random an Erlang-K distribution (denoted by E_K) with K = 2 is assumed. Service time distributions are also taken as an Erlang-K distribution with a value of K = 4 (the higher the K-value the more constant the inter arrival or service times are). Realistic queues are $M/E_4/n$ for common user container terminals and $E_2/E_4/n$ for dedicated shipping line container terminals, according to Monfort et al. (2011) and Terblanche & Moes (2009). Acceptable berth occupancy factors corresponding to these queues for T_w/T_s = 0.10 are given in Table 10.

Table 10: Acceptable berth occupancy factor for container terminals for T_w/T_s = 0.10

Number of berths n_b [-]	Acceptable berth occupancy factor m_b [%]	
	Common-user $M/E_4/n$	Dedicated $E_2/E_4/n$
1	14	31
2	36	53
3	49	63
4	57	70
5	63	73
6 or more	67	77

Source: Monfort et al. (2011)

To use this table an iteration must be performed. First a value for the occupancy has to be assumed, then the number of required berths is calculated with Equations (3) and (6). The occupancy corresponding to this calculated number of berths must then be checked with the assumed occupancy. If they do not correspond the same steps have to be taken again. The berth occupancy factor tables are not used in the tool since in some cases this iteration proves to be divergent. A manual iteration by the user of the tool by using the information in the table is of course still possible. Saanen (2004) states that most terminals try to keep the berth occupancy below 60 to 65%.

2.2 Dry bulk terminals

For dry bulk terminals first general background information is presented in order to give the reader more insight in the most important aspects of a terminal. Then the relevant equipment properties that are needed as input for the design rules are given. In the last section the design guidelines, rules and common values of parameters are treated.

2.2.1 Background information

This section considers dry bulk terminals and is based on Agerschou (2004), Ligteringen & Velsink (2012), PIANC (2014b), UNCTAD (1985) and GreenPort (2016). Information is provided about dry bulk commodities, vessels and terminal elements.

Dry bulk is characterised as cargo that is loaded or discharged in a loose form. In 2010 over one third of the international seaborne trade consisted of dry bulk. The most transported commodities are coal, iron ore, grain, phosphate rock, bauxite/alumina forming respectively 30.75%, 28.25%, 10.72%, 0.72% and 2% for bauxite of the total annual worldwide shipment of dry bulk in 2010 according to PIANC (2014b).

Only the three most important commodities (coal, iron ore and grains in general) are included in the computer tool, this to make it less complex. In this section however more commodities are treated in order to give the reader an overview of the different possibilities.

2.2.1.1 Commodities

Various properties of the cargoes should be taken into account when designing dry bulk terminals. These properties of the cargoes are:

- Cargo density
- Angle of repose: maximum angle with respect to the horizontal to which a material can be piled without slumping.
- Dust generation
- Hazardous properties
    - Susceptibility to fire/explosion
    - Spontaneous combustion
- Resistance to degradation by mechanical handling
- Handling properties
    - Corrosiveness
    - Abrasiveness

For this research however only the main dimensions of the terminal are analysed. Resistance to degradation and the handling properties of the cargoes do not directly influence these dimensions, therefore these properties are not taken into account. The commodity types that are included in the research are listed below including some examples of cargoes:

- Minerals
    - Iron ore
    - Bauxite
    - Phosphate rock
- Coal
    - Thermal coal
    - Anthracite coal

        - Metallurgical coal
- Wood products
    - Wood chips
    - Wood pellets
- Agricultural products
    - Grain
        - Wheat
        - Rye
    - Maize
    - Sugar
    - Soybeans
- Others
    - Alumina
    - Cement

Properties of the mentioned goods are listed in Table 11.

Table 11: Material properties

Commodity	Cargo density [tonne/m^3]	Angle of repose [°]	Common storage location	Dust generation	Hazardous properties: Susceptibility to fire/dust explosion	Hazardous properties: Spontaneous combustion[1]
Iron ore	*2.13 - 3.03*	*30 -50*	*Outdoors*	*Yes*	*No*	*No*
Bauxite	1.09 - 1.19	28 – 49	Outdoors	Yes	No / yes	No
Phosphate rock	1.02 - 1.09	30 -35	Both	Yes	No	No
Coal	*0.52 - 0.93*	*30 - 45*	*Outdoors*	*Yes*	*Yes / yes*	*Yes*
Wood chips	0.15 - 0.40	42 - 50	Outdoors	Yes	Yes / yes	Yes
Wood pellets	0.60 - 0.70	32 - 39	Indoors	Yes	Yes	Yes
Wheat	*0.75 - 0.85*	*25 - 30*	*Indoors*	*Yes*	*Yes / yes*	*No*
Rye	*0.71*	*30*	*Indoors*	*Yes*	*Yes / yes*	*No*
Maize	0.71 - 0.80	30 -40	Indoors	Yes	Yes / yes	No
Sugar	0.80 - 0.90	40	Indoors	Yes	Yes / yes	No
Soybeans	0.78 - 0.81	30	Indoors	Yes	Yes / yes	Yes
Alumina	1.19 - 1.43	35	Indoors	Yes	No	No
Cement	1.56 - 1.64	35	Indoors	Yes	No / yes	No

Note 1: Sensitivity to spontaneous ignition requires maximum stockpile heights

Based on Agerschou (2004), Ligteringen & Velsink (2012), PCA Consultants (n.d.), Wu (2012) and material safety data sheets.

2.2.1.2 Vessels

In Table 12 an overview of the most important vessel classes with corresponding vessel sizes is presented.

Table 12: Dry bulk vessel classes and dimensions

Class	DWT [tonne]	Length [m]	Draught [m]	Beam [m]	Number of holds [-]
Handysize	10,000 - 35,000	115 - 170	7 - 10	14 - 27	3 - 5
Handymax	35,000 - 55,000	180 - 190	10 - 12	27 - 32	5 - 7
Panamax	55,000 - 80,000	200 - 290	12 - 15	32.2	7
Capesize	80,000 - 150,000	230 - 280	14 - 18	35 - 45	8 - 9
VLBC	> 150,000	280 - 362	18 - 24	45 - 65	9 - 11

Source: Kleinheerenbrink (2012)

Handysize and Handymax vessels are used for the transport of different types of cargoes between smaller ports. Capesize and VLBC (Very Large Bulk Carrier) vessels are used for the transport of coal and iron ore and are too big to pass the Panama and Suez canals. For a comparison between the Handymax and VLBC vessel classes see Figure 17.

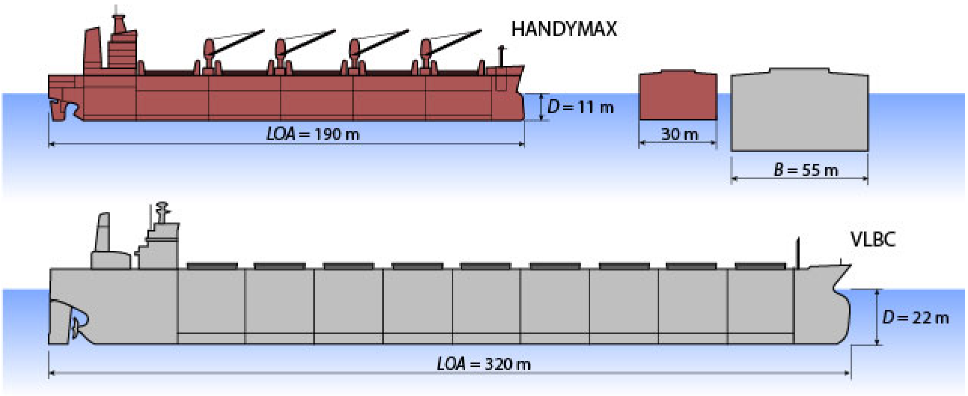


Figure 17: Example of dimensions of a Handymax and VLBC vessel. Source: Kleinheerenbrink (2012)

2.2.1.3 Dry bulk terminal elements

Dry bulk terminals consist of the following elements (see Figure 18):

- Quay or jetty
- Loading/unloading equipment
- Horizontal transportation equipment
- Storage equipment
- Storage facilities

Differences exist between for example large-scale export terminals and import terminals. The basic elements are similar but particulars are dependent on local conditions and the transported commodities.

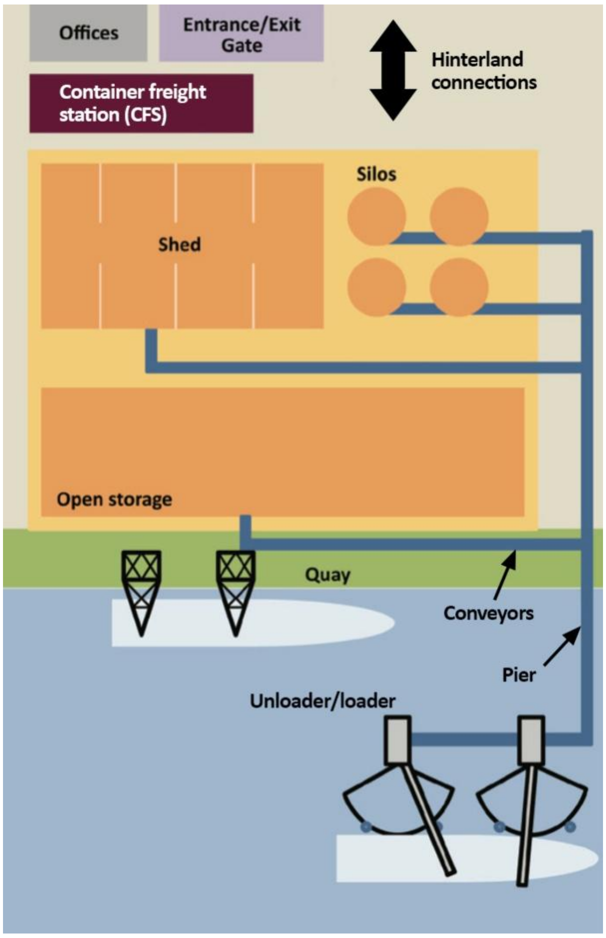


Figure 18: Schematic representation of typical dry bulk terminal elements. Based on: Monfort et al. (2011)

2.2.1.4 Quay/jetty

Dry bulk vessels can have large draughts. Especially vessels that transport ores can have draughts of up to 24 metres because of the large cargo density and thus large DWT. For these kind of vessels it can be more economical to realise a jetty (pier) instead of a quay wall.

Quay walls exist in many forms with the main types being sheet pile walls and gravity walls. Combinations between and variants of these types exist as well, for more information reference is made to de Gijt (2010).

Jetties can be positioned parallel or perpendicular to the terminal. Perpendicular placed jetties are called finger piers. Parallel positioned jetties are called T-shaped or L-shaped jetties, see Figure 19. These types of jetties can have separate mooring dolphins on one or both ends, connected to the main structure with a catwalk.

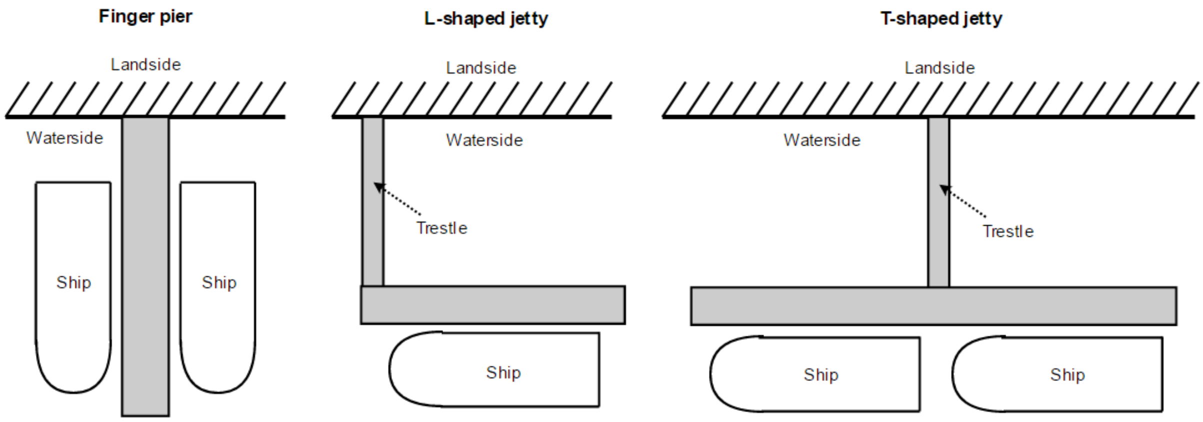


Figure 19: Schematic overview of three different jetty types. Source: Own work

On the quay and on a pier loading and/or unloading equipment is positioned. The transport of bulk to and from the jetty is done with conveyor belts or pipelines.

2.2.1.5 Loading/unloading equipment

In contrast to container STS cranes the equipment needed for the loading and unloading of dry bulk differs per transport direction. The selection of equipment depends on the type and quantity of the bulk material, space and environmental conditions and the intensity of operations. The available equipment types are listed in this section.

Loading equipment

Loading equipment are often relatively simple machines since most bulk can be dropped in the cargo holds making use of gravity. Basically the loader consists of a feed conveyor and a chute. Typical loading equipment types are (see Figure 20):

- Quadrant loaders: Consist of a bridge that is supported by a pivot point landwards and a circular track seawards and has a telescopic boom. A shuttle system provides full hatch coverage. One or two quadrant loaders can be used on one vessel.
- Linear loaders: Consists of a bridge that is supported by a pivot point landwards and a seawards track parallel to the ship. The bridge moves along its length over the pivot causing the front side of the bridge to move parallel to the ship. A loading boom is connected to the bridge.
- Travelling loaders: Boom moving parallel to the ship, bulk material is fed to the boom via a conveyor.

For very dusty materials like cement pneumatic loader/unloaders are used. For small terminals with low capacity requirements wheel mounted mobile installations can be used. Another option is a fixed loading point where the ship has to move to distribute the cargo.

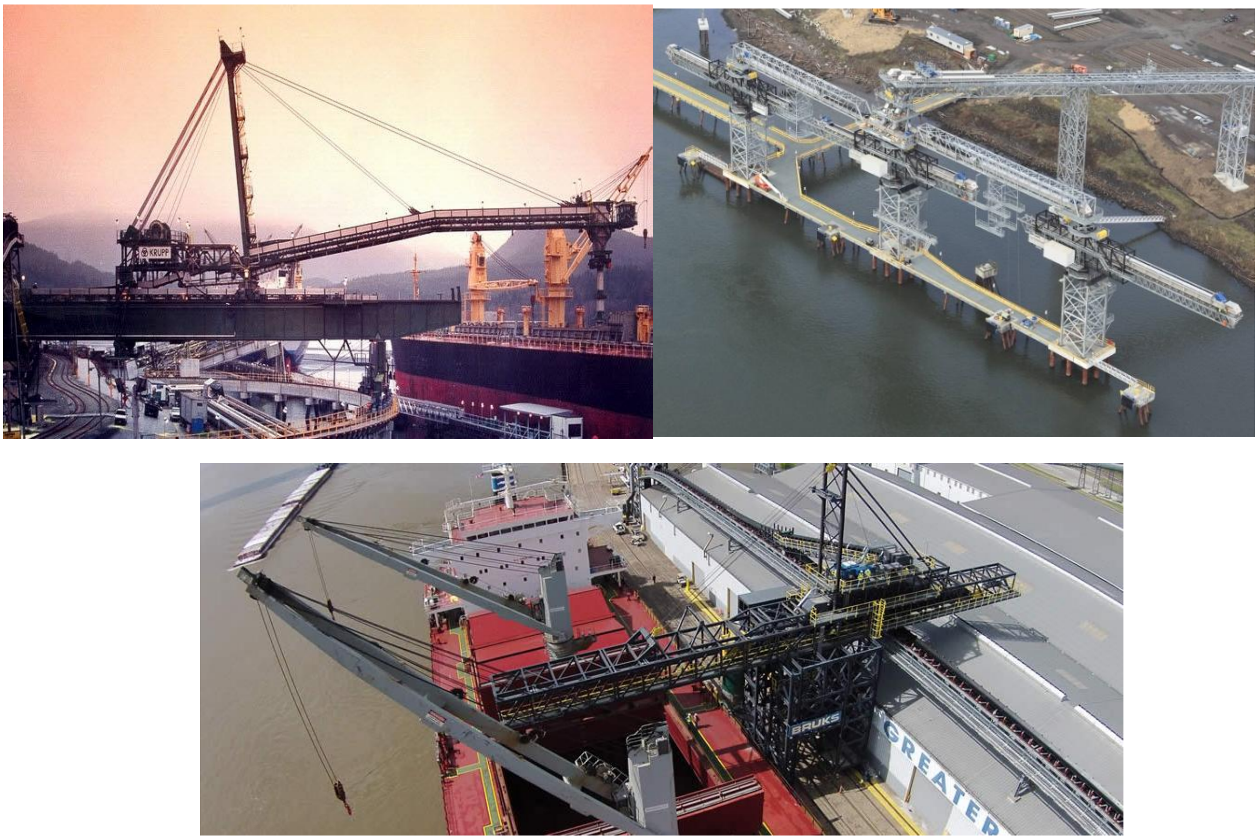


Figure 20: Clockwise starting from the left: Quadrant loader, linear loader and travelling loader. Source: Google

Unloading equipment

Unloading of bulk carriers requires more activities and therefore the installations are more complex. There are five main unloading systems (see Figure 21):

- Gantry grab unloaders: Rail mounted with a cantilever boom and grab that can move perpendicular to the berth. Discharges through a hopper onto a conveyor.
- Grab rigged harbour cranes
    - Level luffing cranes: Moves on rails and discharges into a hopper in front of the crane avoiding the need the rotate during discharging.
    - Mobile harbour crane: Moves on wheels. The movement takes longer than for rail mounted cranes since the outriggers have to be moved every time.
- Continues unloaders: Rail mounted with a rotating boom of fixed length and a vertical conveyor system with a steerable digging foot. The vertical conveyor system can be a bucket elevator, a screw or a spiral conveyor. They can discharge onto belt conveyors, trucks or rail wagons.
- Pneumatic unloaders: Exists in the form of suction or pressure types. They can be wheel or rail mounted and are used to handle dry, low density bulk material (e.g. cement or grain). They discharge into pipeline systems or silos on shore.

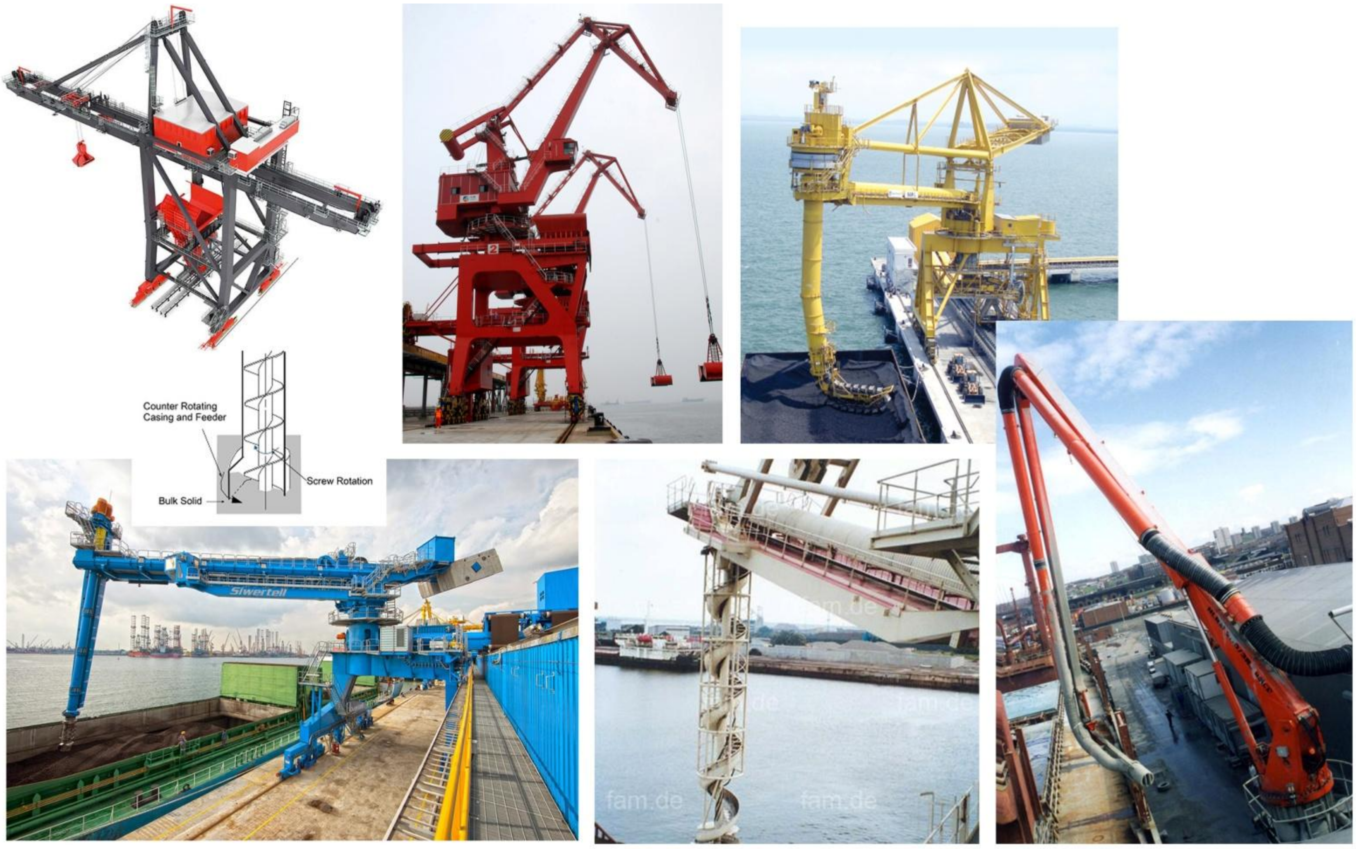


Figure 21: Clockwise starting from the top left: Gantry grab, level luffing cranes, bucket elevator, pneumatic, spiral and screw conveyors (with screw detail). Source: Google

2.2.1.6 Horizontal transport equipment

Transport within the terminal from ship to stacker or from reclaimer to ship is generally done by belt conveyors. For dusty materials conveyor belts are covered over the full length, also water can be used to reduce the creation of dust. Covered conveyer belts are also used for cargoes that can suffer from the weather, such as grains. Transport by means of water and pneumatic transport is done through pipelines.

For smaller terminals another option is bulldozers that move the cargo between storage and ship. This is much cheaper but also dramatically reduces the throughput capacity.

For export terminals often a rail connection is used. At the terminal the wagons are emptied to a belt conveyor or pneumatic discharge system. For import terminals the transport out of the terminal is done by barges, road or rail. This can be done directly from the bulk carrier or via the stockpile. For road and rail transport often loading silos are used.

Recommended are shared routes (a belt conveyer and corresponding equipment that can transport cargo in both directions), unless for a specific reason a dedicated route is applied.

Figure 22: Belt conveyor. Source: Google

2.2.1.7 Storage equipment

The handling of material in the storage yard is generally done by bulldozers or by stackers, reclaimers or a combination of both systems; a stacker-reclaimer.

Stackers are machines that move on rails parallel to a stockpile with a perpendicular boom containing a belt conveyor. A stacker generally can make piles on either side of the rails. A belt conveyor is positioned under the stacker along the stockpile length and is used to transport the material from the stockpile to the (un)loading equipment or the inland transport loading system.

Reclaimers are similar machines but equipped with for example a bucket wheel in order to reclaim the material. Both functions are combined in a stacker-reclaimer, only one function can be performed at a time however. Other means of reclaiming are scraper reclaimers or underground belt conveyors that transport material that is pushed on it with bulldozers. The mentioned machines are depicted in Figure 23.

Figure 23: Loader (top left), scraper reclaimer (bottom left) and stacker-reclaimer (right). Source: Google

2.2.1.8 Storage facilities

There are three kinds of storage facilities for dry bulk:

- Open storage
- Covered storage
- Silos

A general observation is that the more different products a terminal handles the more storage area is required.

Open storage

The main type of storage is open storage in stockpiles. The dimensions of the stockpile are dependent on the angle of repose of the material and the discharge of the storage equipment. Open storage can be used for materials that do not impact the environment and do not suffer from serious degradation by exposure to the elements. The height of a stack is determined by the bearing capacity of the soil and the reach of the stacker/reclaimer. The most common way to store bulk material is the wind-row arrangement where long stacks are formed. Another way is to make circular piles with a stacker/reclaimer in the centre. This form is used at smaller terminals, it is not included in the computer tool because of time limitations.

For dusty materials that cause pollution or dust explosions a protective foam layer can be used or the stockpile can be sprayed with water.

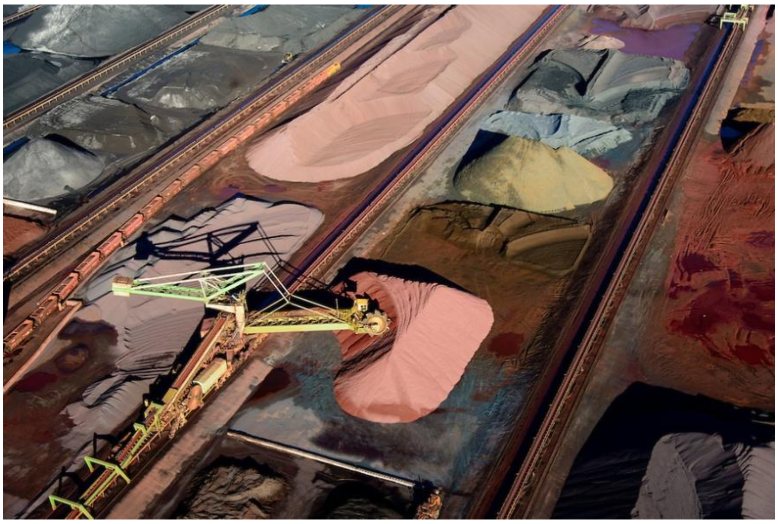


Figure 24: Dry bulk wind-row stockpiles with stacker-reclaimer. Source: Google

Covered storage

Materials that can suffer from the weather or that impact the environment require covered storage. The main types of covered storage are portal framed structures (horizontal storage or sheds) and domes. Discharge into the horizontal storage usually takes place via a belt conveyor positioned in the top of the structure. Reclaiming is done by a scraper reclaimer, an underground conveyor or bulldozers. For an example of a covered structure see Figure 25. In a dome circular stackers and scraper reclaimers or bulldozers are used. The use of covered storage increases over the years because of the increasing attention at the environmental impact of dry bulk terminals. Domes are not further treated in this study for they are not included in the computer tool because of time limitations.

Figure 25: Covered storage with a belt conveyor for stacking. Source: Google

Silos

Vertical circular silos are a specific form of covered storage and are typically used for the storage of free flowing dusty materials such as grains or cement. Moreover silos exist that can be used to store non-free flowing materials; Eurosilo (2016). The silos are filled with covered conveyors from the top and are emptied at the bottom to conveyors or pipes, or directly to trucks or train wagons. An example of a terminal with silos is depicted in Figure 26. For non-free flowing materials a central vertical screw conveyer is used to realise the outflow. Advantages of silos are that no reclaiming equipment is needed (gravity is used) and a limited space is needed. Disadvantages are the higher costs and the limitation to a specific commodity.

Figure 26: Artist impression of silos on a terminal. Source: Google

2.2.2 Equipment properties

The properties of the terminal equipment that are required for the dimensioning of a dry bulk terminal are given in this section. A division is made between ship (un)loading equipment on the quay and stackers and reclaimers in the storage area.

2.2.2.1 Ship loading and unloading equipment

Productivity rates of unloaders and loaders are dissimilar. Typical rated capacities for unloaders are listed in Table 13. The rated capacity (or free digging rate) is the unloading rate based on the cycle time of a full bucket or grab from the digging point in the ship to the hopper and back. Some of these values are common minimum and maximum values, although lower or higher capacities may exist. The reader should make an estimate of values that are appropriate to be used in a specific case. For the coal and iron ore unloading process grab cranes or bucket elevators are used. Grain can be unloaded by all listed unloaders.

Table 13: Typical rated capacities for unloaders

Unloader type	Typical rated capacity [tonne/hour]
Gantry grab unloader	500 - 3000
Grab rigged harbour crane	200 - 1500
Continues unloader	
Bucket elevator	1000 - 5000
Chain conveyor	200
Vertical screw conveyor	900
Spiral conveyor	75
Pneumatic unloader	200 - 500

Based on Ligteringen & Velsink (2012), UNCTAD (1985) and PIANC (2014b).

Normal load capacities vary between 500 and 7,000 tonne/hour according to Kleinheerenbrink (2012) and Vianen, T. van (2015). Kleinheerenbrink even reports capacities as high as 20,000 tonne/hour.

The effective capacity of (un)loaders is the typical rated capacity including interruptions for e.g. cleaning, moving between holds and small repairs. The ratio between the effective capacity and the typical rated capacity is called the 'through ship efficiency', these factors are given in Table 14.

Table 14: Through-ship efficiency factors

	Unloading	Loading
Through-ship efficiency	0.5	0.7

Source: UNCTAD (1985)

Lodewijks et al. (2009) states that in reality the gross productivity of loaders and unloaders is much less than the effective capacity. This is due to operational availability of the equipment, which is around the 80%. The downtime of equipment can have a significant influence on the berth productivity. According to Vianen et al. (2014) the installed unloading capacity of coal and/or iron ore import terminals is 3 to 4.5 times the minimum required unloading capacity. For export terminals, and thus loading equipment this factor is 1.5 to 2.5. In the tool this factor is not taken into account since it is no specific design rule used in early phase terminal planning, according to the studied literature.

2.2.2.2 Stackers and reclaimers

According to UNCTAD (1985) typical reclaim capacities for a stacker-reclaimer are between 1000 and 3000 tonne/hour while stacking capacities of 6000 tonne/hour and more are reached. Scraper-reclaimers can achieve reclaim capacities of up to 1000 tonne/hour.

Vianen et al. (2014) assumes for coal and iron ore terminals as common gross hourly capacity of stackers 2000 tonne/hour, for reclaimers 1500 tonne/hour, for stacking of a bucket-wheel stacker-reclaimer 2000 tonne/hour and for reclaiming of the same machine 1500 tonne/hour.

Kleinheerenbrink (2012) gives the capacities for coal and iron ore terminals as listed in Table 15.

Table 15: Stacking and reclaiming capacities

[tonne/hour]	Coal		Iron ore	
	Average	Maximum	Average	Maximum
Stacking	3000	10,000	3500	10,000
Reclaiming	2000	6000	2500	15,000

Source: Kleinheerenbrink (2012)

2.2.3 Design guidelines, rules and parameters

The design guidelines, rules and parameters are provided for determining the number of berths and storage yard area. The required dredging depth can be determined as in Section 2.1.3.4. Values used in practice for the parameters are listed in Section 2.2.3.3.

2.2.3.1 Number of berths

First a method is treated with which the required number of berths can be determined. Also a method is considered that can function as a check. The methods are:

- Berth productivity
- Empirical rule-of-thumb

Berth productivity

The method to calculate the required number of berths is similar to the berth productivity method explained in Section 2.1.3.2. However the cargo is not expressed in TEU but in metric tonnes. The berth productivity is therefore calculated by the following equation, based on PIANC (2014b):

$$C_b = \overline{P}_{gross} \cdot n_{cb} \cdot n_{hy} \cdot m_b \tag{13}$$

Where,

C_b Berth productivity [tonne/year].

$\overline{P}_{gross}$ Average gross productivity per ship (un)loading equipment [tonne/hour]. Average number of tonnes moved between berthing completed and de-berthing started. This variable therefore includes unproductive intervals such as crane repositioning, moving hatches to/from quay, time between shifts and simple repairs.

n_{cb} Number of (un)loaders per berth [-].

n_{hy} The number of operational hours per year [hour/year].

m_b Berth occupancy factor [-]. The acceptable occupancy factor depends on the allowable waiting time in terms of service time, the number of berths and the sort of terminal (e.g. dedicated shipping line). For berthing at a quay wall the factor can be calculated with the following equation, based on Saanen (2004):

$$m_b = \frac{\sum_{i=1}^{n}\left(L_{s,i} \cdot T_{s,i}\right)}{L_q \cdot n_{hy}} \tag{14}$$

For berthing at a jetty the berth is treated as a binary object; the berth is either free or occupied. Lengths are therefore not taken into account. For this situation the factor can be calculated with the following equation, based on Saanen (2004):

$$m_b = \frac{\sum_{i=1}^{n} T_{s,i}}{n_{hy}} \tag{15}$$

Where,

$L_{s,i}$ Length of vessel i in [m] of total of n vessels berthed in measurement period n_{hy}. This length should include twice the L_{ml} (see Equation (7)). Only vessel $i = n$ should include this additional length once.

$T_{s,i}$ Service time (or effective berthing time) in [hour] of vessel i of total of n vessels berthed in measurement period n_{hy}. Time the vessel is berthed outside of the operational hours does not count.

L_q Quay length [m].

The required number of berths is then calculated by the following equation from PIANC (2014b):

$$n_b = \frac{C}{C_b} \tag{16}$$

Where,

n_b Number of required berths [-].

C Mass of handled cargo per year [tonne/year].

C_b Berth productivity [tonne/year].

Then with the determined number of berths the required quay wall length can be calculated according to the following equation from PIANC (2014b):

$$L_q = \begin{cases} L_{s,max} + 2 \cdot L_{ml} & for\ n_b = 1 \\ 1.1 \cdot n_b \cdot \left(\overline{L}_s + L_{ml}\right) + L_{ml} & for\ n_b > 1 \end{cases} \tag{17}$$

Where,

L_q Required quay wall length [m].

$L_{s,max}$ The length of the largest vessel frequently calling at the terminal [m].

$\overline{L}_s$ The average vessel length [m].

L_{ml} The additional quay length required for and aft of the vessel to account for the mooring lines [m].

n_b Number of berths [-].

The factor 1.1 accounts for variability in the vessel length since an average value is used, results from a study done by UNCTAD (1984).

Instead of a quay wall a jetty can be used as well, the specific form has to be determined. The dimensions are among other things dependent on the design ship length, required length for the mooring lines and the required water depth. In the tool jetty dimensions are approximated in order to be able to derive the costs of this terminal element. The method that is used is described in Section 2.4.2.

Empirical rule-of-thumb

Vianen et al. (2014) gives empirically determined quay capacity characteristics in tonne per metre of quay per year for coal and iron ore terminals, both for import and export. These figures are based on his study of 49 dry bulk terminals. The resulting values are given in Table 16. The quay length can be calculated by dividing the annual throughput by the quay capacity factor, this can be used as a check for calculated quay lengths.

Table 16: Quay capacity factors for coal and iron ore terminals

Commodity	**Quay capacity factor [x10³ tonne/year/m¹]** Import terminals	Export terminals
Coal	10 - 30	10 - 30
Iron ore	25 - 75	50 - 150

Source: Vianen et al. (2014)

2.2.3.2 Storage area

To determine the required storage area for a dry bulk terminal a few methods exist. First there is a conventional equation that uses the annual throughput and average dwell time of the cargo. Secondly two rules-of-thumb exist that can be used to estimate the required storage area; these rules are based on a capacity ratio and a storage factor.

General approach

This method makes use of the conventional equation to calculate the required gross storage area for general cargo/multi-purpose terminals, based on PIANC (2014b):

$$A_{gr,i} = \frac{C_i \cdot \bar{t}_d \cdot f_{area}}{\bar{\rho}_c \cdot \bar{h}_s \cdot 365 \cdot m_s} \tag{18}$$

Where,
$A_{gr,i}$ Gross required storage area per commodity type[11] [m²].
C_i Mass of handled cargo per year per commodity type [tonne/year].
$\bar{t}_d$ Average dwell time of cargo in the stockpile [days].
f_{area} Ratio between gross and net storage area [-].
$\bar{\rho}_c$ Average cargo density [tonne/m³].
$\bar{h}_s$ Average stacking height [m].
m_s Estimated storage occupancy [-]. Average mass of cargo in stockpile divided by the design capacity of the stockpile. To account for the random arrivals and departures of cargo.

Instead of calculating the required area with Equation (18), the equation is rewritten in order to calculate the required volume of the storage at a certain moment. In order to calculate a volume both sides of the equation are multiplied by the average stacking height $\bar{h}_s$. The ratio between gross and net storage area is used in a later calculation step. This results in the following equation:

$$V_{storage,i} = \frac{C_i \cdot \bar{t}_d}{\bar{\rho}_c \cdot 365 \cdot m_s} \tag{19}$$

Where,
$V_{storage,i}$ Required total storage volume per commodity type [m³].
C_i Mass of handled cargo per year per commodity type [tonne/year].
$\bar{t}_d$ Average dwell time of cargo in the stockpile [days].

[11] The gross storage area includes the net storage area and internal roads, pipelines and/or conveyor belts and equipment rails at the storage yard. Other buildings and infrastructure in between quay and yard on the terminal are included in the required total terminal area (A_t).

$\overline{\rho}_c$ Average cargo density [tonne/m^3].
m_s Estimated storage occupancy [-]. Average mass of cargo in stockpile divided by the design capacity of the stockpile. To account for the random arrivals and departures of cargo.

In this study wind-row stockpiles, covered storage sheds and silos are considered. Wind-row and covered storage use the same methods of calculating the required stockpile length and storage area. For storage in silos the required number of silos must be determined, the required storage area can then be calculated with a method that is described in Appendix VI . More information about common dimensions of the three different storage types can be found under the heading 'Storage types' in this subsection. The calculation method of wind-row and covered stockpiles is presented in this subsection.

Wind-row stockpiles are lanes consisting of a trapezoidal cross-section of a certain length. A lane only consists of the pile of cargo, the adjacent infrastructure is not included. The area occupied by internal infrastructure is taken into account by f_{area} in Equation (22). This lane length can be calculated with the following equation, derived from Vianen et al. (2012) and including the number of lanes in the stockpile (assuming equal lane lengths for all lanes):

$$l_{lane} = \frac{V_{storage}}{\left[\frac{h_{pile}}{h_{pile,max}} \cdot \left(2 - \frac{h_{pile}}{h_{pile,max}}\right) \cdot \left({}^{1}/_{4}\, w_{lane}{}^{2} \cdot \tan\theta\right)\right] \cdot n_{lanes}} \tag{20}$$

Where,
l_{lane} Required lane length [m].
$V_{storage}$ Required total storage volume [m^3].
h_{pile} Height of the pile [m].
w_{lane} Width of a lane [m].
θ Angle of repose [degrees].
n_{lanes} Number of lanes in stockpile [-]. The lanes are assumed to have equal length.
$h_{pile,max}$ Maximum height the pile can attain [m], defined in Vianen et al. (2012) as:

$$h_{pile,max} = {}^{1}/_{2}\, w_{lane} \cdot \tan\theta \tag{21}$$

Where,
w_{lane} Width of a lane [m].
θ Angle of repose [°].

The gross required storage area per commodity type can then be calculated with the following equation (own work):

$$A_{gr,i} = n_{lanes} \cdot l_{lane} \cdot w_{lane} \cdot f_{area} \tag{22}$$

Where,
$A_{gr,i}$ Gross required storage area per commodity type [m^2].
n_{lanes} Number of lanes in stockpile [-].
l_{lane} Required lane length [m].
w_{lane} Width of a lane [m].
f_{area} Ratio between gross and net storage area [-].

The gross required storage area plus additional area for other infrastructure and buildings on the terminal is the required total terminal area (own work):

$$A_t = \frac{\sum A_{gr,i}}{\alpha} \tag{23}$$

Where,

A_t Required total terminal area [m^2]. Area including the stockpiles, terminal infrastructure and buildings.

$A_{gr,i}$ Gross required storage area per commodity type [m^2].

α Total terminal factor; the percentage of storage area and internal roads in the stockpile with respect to the total terminal area [-].

Common in modern terminals is a bypass which makes it possible to transport cargo between ship and hinterland without using the storage area. Typically less than 5% of the annual throughput is bypassed while terminals want to reach about 20% according to Lodewijks et al. (2009).

Capacity ratio

The capacity ratio (r_c) indicates the percentage of the annual throughput that must be able to be stored on the terminal at a certain time. In the literature several ratios are proposed. Kraaijveld & van Hemert (1984) gives a rough assumption of the required storage capacity of 2 months of the annual throughput, for coal only. For a steady annual throughput this gives a capacity ratio of 16%. Lodewijks et al. (2009) proposes a value of 10% of the annual throughput. UNCTAD (1985) proposes a capacity ratio of 16%. Vianen et al. (2014) distinguishes between import with capacity ratios between 5% and 22% and export with ratios between 3% and 10%. These values are however for coal and iron ore terminals. PIANC (2014b) proposes a ratio between 10% and 25% for coal import terminals.

Vianen et al. (2012) notes that a dry bulk terminal should at least be able to store one full shipload of a cargo type. So if a terminal can handle multiple cargo types the storage area should be dimensioned accordingly.

The required storage volume per commodity type can be calculated with the following equation that is rewritten from Equation (18) and is adjusted to fit the descriptions of the capacity ratio in the literature:

$$V_{sp,i} = \frac{C_i \cdot r_c}{\overline{\rho}_c} \tag{24}$$

Where,

$V_{sp,i}$ Required storage volume of the stockpile per commodity type [m^3].

C_i Mass of handled cargo per year per commodity type [tonne/year].

r_c Capacity ratio [-]. Percentage of annual throughput that must be able to be stored on the terminal at a certain time.

$\overline{\rho}_c$ Average cargo density [tonne/m^3].

The total gross storage area can again be calculated by means of Equations (20) to (23).

Storage factor

The storage factor (f_s) relates the annual throughput with the total terminal area. Ligteringen & Velsink (2012) proposes storage factors for coal, iron ore and crude oil (liquid bulk) for import terminals and states that export terminals have higher factors. According to Vianen et al. (2014) these factors are too low, more material can be stored per square meter of storage area accordingly. Vianen's observations are based on a study of 49 dry bulk terminals. The information from both sources has been combined in Table 17.

Table 17: Storage factors

Commodity	Storage factor f_s [tonne/year/m^2]	
	Import terminals	Export terminals
Coal	15 - 75	60 - 185
Iron ore	30 - 80	70 - 210
Crude oil (liquid bulk)	40 - 50	-

Sources: Vianen et al. (2014) and Ligteringen & Velsink (2012)

Storage types

The considered storage types are the open wind-row storage, covered horizontal storage and silos (see Section 2.1.1.6).

Coal and iron ore are usually stored in an open storage. Wind-row storage typically consists of one or multiple trapezoidal or triangular shaped rows of cargo. Common widths are between 40 and 100 meters according to Vianen et al. (2014). Dimensions found in practice of coal and iron ore lanes (or stockpiles) according to Kleinheerenbrink (2012) are given in Table 18. EMO terminals use a maximum stacking height of 18 metres according to Kleinheerenbrink (2012).

Table 18: Pile dimensions of coal and iron ore wind-row stockpiles

Dimensions [m]	Import terminals	Export terminals
Lane length limits	300 - 1200	300 - 1300
Lane length average	665	800
Lane width limits	30 - 75	30 - 85
Lane width average	45	50

Source: Kleinheerenbrink (2012)

Ratios between the lane length and width, according to Vianen et al. (2014), are given in Table 19.

Table 19: Ratios between length and width of stockpiles for coal and iron ore

	Import terminals	Export terminals
Length-width ratio limits	1.2 – 4.6	1.3 – 4.5
Length-width ratio average	2.5	2.6

Source: Vianen et al. (2014)

Covered horizontal storage in the form of a portal structure consists of the same trapezoidal or triangular shaped row but is protected by an outer shell. It can be assumed that more area is required with respect to wind-row storage, also depending on the type of stacking/reclaiming equipment inside the shed. Extra space next to the stockpile on all sides can be assumed to be between 5 and 10 metres approximately; personal communication with Smits van Oyen, R. J. (12-05-2016).

Silos come in many different types and sizes. For free flowing materials, such as grains, a flat bottom silo is a suitable storage facility. GSI manufactures these silos, that come in different sizes. An example is shown in Figure 27.

Figure 27: GSI grain silo. Source: GSI (2016)

The unrelated minimum and maximum dimensions are listed in Table 20 to give a rough indication.

Table 20: Minimum and maximum values of characteristics of GSI silos for free flowing materials

	Minimum	Maximum
Capacity [m^3]	940	41,165
Diameter D [m]	7.3	41.2
Height H [m]	9.8	30.1

Data source: GSI (2016)

Eurosilo manufactures silos for non-free flowing materials ranging from 500 to 100,000 cubic metres. Eurosilo states that a silo requires only one third of the area[12] required when using a horizontal stockyard (open or covered storage), see Figure 28.

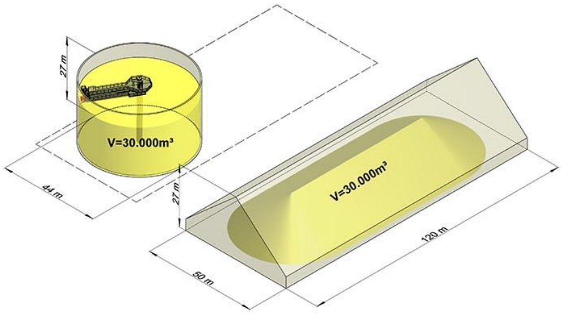


Figure 28: Eurosilo in comparison to storage shed. Source: Eurosilo (2016)

In order to give a rough indication of Eurosilo silo dimensions unrelated minima, maxima and average values of silo characteristics data[13] are given in Table 21.

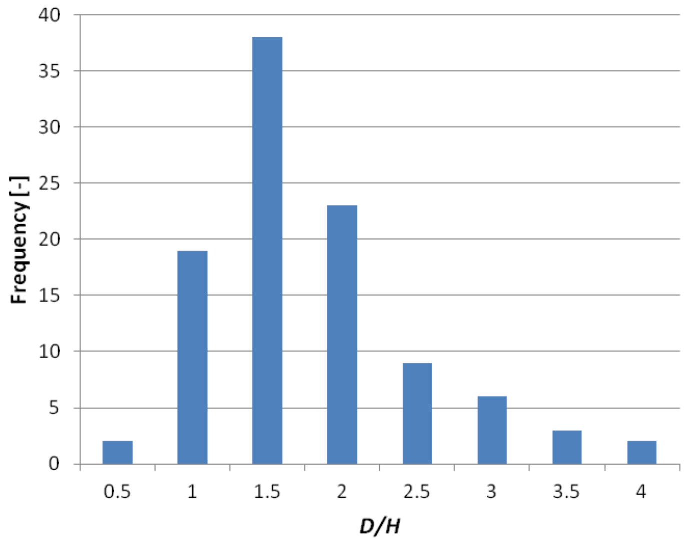
[12] The suggested area is the net required storage area; thus not including internal roads.
[13] Silo characteristic data only from Eurosilo, regardless of cargo type, volume and continent.

Table 21: Minimum, maximum and average values of characteristics of Eurosilo silos for non-free flowing materials

	Minimum	Maximum	Average
Capacity [m^3]	144	100,000	13,305
Diameter *D* [m]	4.6	56.6	24.9
Height *H* [m]	4.7	50.0	17.5
D/*H* [-]	0.4	4.0	1.6

Data source: Eurosilo (2016)

The ratios between silo diameter and height are depicted in a histogram in Figure 29.



Data source: Eurosilo (2016)

Figure 29: Histogram of the ratio of silo diameter and height

2.2.3.3 Common values of parameters

Values that are proposed in literature of the input parameters used in the design rules are listed in Table 22. For various parameters minimum and maximum values are proposed, resulting in a range of possible values. This can be represented by a uniform random distribution. When this is the case the reader should make an estimate of which part of the distribution to use. The sources of the values are numbered in square brackets.

Table 22: Parameter values of dry bulk terminal design rules

Symbol	Unit	Description and values
f_{area}	-	*Ratio gross over net storage area.* No common values found. Often a stroke with a width of 5 to 25 metres is used around the net storage area [5].
f_s	tonne/year/m^2	*Storage factor.* For values see Table 17 (p.61).
h_{dt}	m	*Dredging tolerance.* A value of 0.60 is proposed by [13].
h_{guc}	m	*Minimum gross underkeel clearance.* For values see Table 8 (p.41).
$h_{pile,max}$	m	*Maximum height of the stockpile.* A common maximum stacking height for a stacker-reclaimer is

Symbol	Unit	Description and values
		23 metres [1].
l_{lane}	m	*Required lane length.* For values see Table 18 (p.61).
m_b	-	*Estimated berth occupancy.* For values see Table 23 (p.65).
m_s	-	*Estimated storage occupancy.* Determined in Expert Judgement Elicitation, see Section 0. Literature: Common value is 80% [6].
n_{cb}	-	*Number of (un)loaders per berth.* Differs per equipment type. Usually 1 or 2 cranes per berth, with a maximum of 4 [5].
n_{hy}	hour/year	*Number of operational hours per year.* Very much dependent on local situation. EMO terminal operates 24 hours a day for 365 days a year; this is 8760 hours per year [7].
r_c	%	*Capacity ratio.* Ratios in general or for certain cargo types can be found at the end of Section 2.2.3.2.
$\overline{t}_d$	days	*Average dwell time of cargo in the stockpile.* The average dwell time of dry bulk cargo should not exceed 2 weeks [2], this value seems idealistic. Dwell time can also be approximated by: $\overline{t}_d = r_c \cdot n_{hy}/24$.
w_{lane}	m	*Width of a lane.* For values see Table 18 (p.61).
D	m	*Silo diameter.* For values see Table 20 and in Table 21. Table 21 (p.62).
D_s	m	*Draught of the design vessel.* For values see Table 12 (p.47).
H	m	*Silo height.* For values see Table 20 and in Table 21. Table 21 (p.62).
L_{ml}	m	*Additional quay length required for and aft of vessel to account for mooring lines.* Normally 15 metres [4] or 30 metres [3] is used.
$\overline{L}_s$	m	*Average vessel length.* For normal vessel lengths see Table 12 (p.47).
$L_{s,max}$	m	*Length of largest vessel frequently calling at terminal.* For normal vessel lengths see Table 12 (p.47).
$\overline{P}_{gross}$	tonne/hour	*Average gross productivity per ship (un)loading equipment.* For values see Section 2.2.2.1.
a	-	*Total terminal factor.* Determined in Expert Judgement Elicitation, see Section 0.
θ	°	*Angle of repose of material.* For values see Table 11 (p.46).
$\overline{\rho}_c$	tonne/m^3	*Average cargo density.* For values see Table 11 (p.46).

Sources:

[1] Vianen et al. (2014)

[2] Fourgeaud (2000)

[3] PIANC (2014b)
[4] Quist & Wijdeven (2014)
[5] Various bulk terminals in Google Earth
[6] Kleinheerenbrink (2012)
[7] EMO (2016)
[8] PIANC (1995)

Berth occupancy factor

The acceptable berth occupancy factor depends on the number of berths and the allowable average waiting time in terms of average service time of vessels (T_w/T_s). According to Monfort et al. (2011) a reasonable value for T_w/T_s for dry bulk terminals is 0.50. The probabilistic Queuing Theory is used to determine the occupancy ratios. This theory is not treated in this research since it is outside its scope, for a better understanding of the general Queuing Theory reference is made to Sztrik (2012). An application of the theory on terminal design can be found in Agerschou (2004).

The queuing system can be denoted by the Kendall notation: "inter arrival time distribution"/"service time distribution"/"number of berths". Arrivals of vessels can be random for common user terminals, a negative exponential inter arrival time (denoted by M) is then assumed. When arrivals are less random an Erlang-K distribution (denoted by E_K) with K = 2 is assumed. Service time distributions are also taken as an Erlang-K distribution with a value of K = 2 (the higher the K-value the more constant the inter arrival or service times are). A realistic queue is $M/E_2/n$ for common user dry bulk terminals according to Monfort et al. (2011) and Terblanche & Moes (2009). For dedicated shipping line dry bulk terminals $E_2/E_2/n$ is proposed by Monfort et al. (2011) and Vianen, T. van (2015). Acceptable berth occupancy factors corresponding to these queues for T_w/T_s = 0.50 are given in Table 23.

Table 23: Acceptable berth occupancy factor for dry bulk terminals for T_w/T_s = 0.50

Number of berths n_b [-]	Acceptable berth occupancy factor m_b [%] Common-user $M/E_2/n$	Dedicated $E_2/E_2/n$
1	41	55
2	64	73
3	73	81
4	78	84
5	82	87
6 or more	84	89

Source: Monfort et al. (2011)

To use this table an iteration must be performed. First a value for the occupancy has to be assumed, then the number of required berths is calculated with Equations (13) and (16). The occupancy corresponding to this calculated number of berths must then be checked with the assumed occupancy. If they do not correspond the same steps have to be taken again. The berth occupancy factor tables are not used in the tool since in some cases this iteration proves to be divergent. A manual iteration by the user of the tool by using the information in the table is of course still possible.

2.3 Liquid bulk terminals

For liquid bulk terminals first general background information is presented in order to give the reader more insight in the most important aspects of a terminal. Then the relevant equipment properties that are needed as input for the design rules are given. In the last section the design guidelines, rules and common values of variables are treated.

2.3.1 Background information

This section considers liquid bulk terminals and is based on Agerschou (2004), Ligteringen & Velsink (2012), PIANC (2014b) and UNCTAD (1985). Information is provided about liquid bulk commodities, vessels and terminal elements.

2.3.1.1 Commodities

The vast majority of liquid bulk trade is in crude oil and petroleum products. Other product groups like chemicals or vegetable liquids form a smaller part of the world trade in liquid bulk; Agerschou (2004).

Liquid bulk commodity types are:

- Crude oil
- Oil products
- Chemicals
- Liquefied gas
- Vegetable oils
- Bio-fuels

Liquid bulk materials often are hazardous substances. They can be flammable, explosive, toxic or corrosive. Therefore safety measures are required in and around the port terminal. Liquid bulk cargo can also be polluting which asks for protective measures.

Liquefied gasses are the most dangerous kind of liquid bulk. Examples are Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG). These gasses reach a liquid state when cooled and/or pressurised. When the liquid reaches its boiling point gasses form that are highly flammable and thus potentially very dangerous.

In the tool only crude oil and LNG are specifically implemented. This since crude oil is het most transported cargo type and in literature rules-of-thumb can be found; Agerschou (2004). LNG is a fossil fuel but it is cleaner than for example diesel, due to lower emission levels. Therefore - although it still has a long way to go- LNG is a promising fuel; Het Financieele Dagblad (2016). Because of this and in order to inform the reader about the very different requirements for these kind of terminals LNG is included in this study. The tool also allows the user to define other types of liquids, for these liquids some material properties have to be specified.

2.3.1.2 Vessels

Liquid bulk vessels are divided in different types, depending on the transported commodity. Crude oil is typically transported in large tankers; Very Large Crude Carriers (VLCC) or Ultra Large Crude Carriers (ULCC), of 200,000 DWT and greater. Refined oil products, chemicals and vegetable oils are transported in product tankers up to 100,000 DWT. Typical dimensions are given in Table 24.

Table 24: Liquid bulk oil/product vessel classes and dimensions

Class	DWT [tonne]	L [m]	Draught [m]	Beam [m]
Product/chemical tankers	3000 - 50,000	90 - 210	6.0 - 12.6	13.0 - 32.2
Tankers	60,000 - 175,000	217 - 300	13.0 - 17.7	36.0 - 52.5
VLCC	200,000 - 300,000	310 - 350	18.5 - 21.0	55.0 - 63.0
ULCC	350,000 - 500,000	365 - 415	22.0 - 24.0	65.5 - 73.0

Source: PIANC (2014b)

Liquid bulk carriers with typical transported cargo type and DWTs are depicted in Figure 30.

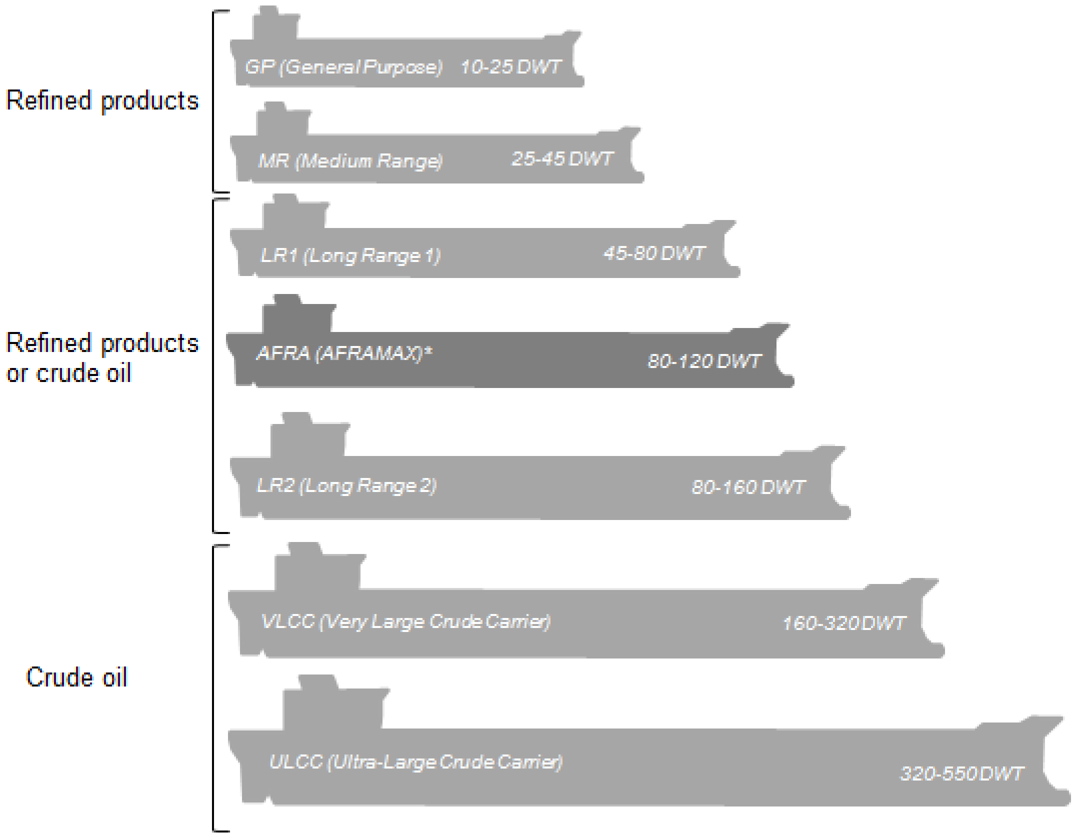


Figure 30: Liquid bulk vessel types with the typical cargo types and DWTs. Source: U.S. Energy Information Administration

LNG is transported in liquefied gas carriers. LNG carriers are divided in Membrane or Prismatic and Sphere or Moss type vessels. Typical dimensions are given in Table 25.

Table 25: Liquid bulk LPG/LNG vessel classes and dimensions

Class	DWT [tonne]	L [m]	Draught [m]	Beam [m]	Approx. Capacity [m^3]
LNG Carriers (Membrane)	51,000 - 75,000	249.5 - 288.0	10.6 - 11.5	40.0 - 49.0	90,000 - 145,000
LNG Carriers (Spherical, Moss)	27,000 - 125,000	207.8 - 345.0	9.2 - 12.0	29.3 - 55.0	40,000 - 267,000

Source: PIANC (2014b)

Figure 31: Spherical LNG carrier (upper), Membrane LNG carrier (lower). Source: PIANC (2012)

2.3.1.3 Liquid bulk terminal elements

Liquid bulk terminals consist of the following elements (see Figure 32):

- Jetty
- Pipelines
- Storage tanks

Liquid bulk terminals are often linked to local industry, long term storage is therefore not needed. However also stockholding terminals (that function as a long term storage), gateway terminals (that import and export cargo), or transhipment terminals for liquid bulk exist. These different types of liquid bulk terminals largely dictate the required capacity of the terminals.

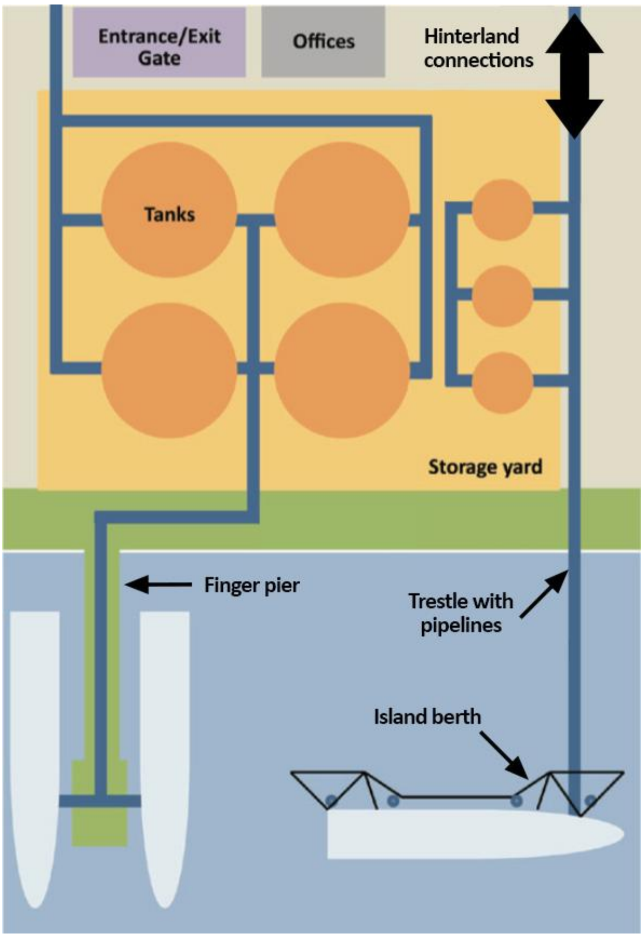


Figure 32: Schematic representation of typical liquid bulk terminal elements. Based on: Monfort et al. (2011)

2.3.1.4 Jetty

At marine liquid bulk terminals jetties are often of the island berth type. These consist of an approach bridge (trestle) from the shore to the loading platform with access roadway and pipeway. The loading platform houses a loading arm, pipelines, service building, fire fighting equipment, spillage tank and possibly a jetty crane (depends if resupplying of the vessel is accommodated). Furthermore separate mooring and breasting dolphins are used, since vessel access is only required at the centre of the vessel. The dolphins are connected to the loading platform by catwalks. An overview of an island berth type jetty is depicted in Figure 33.

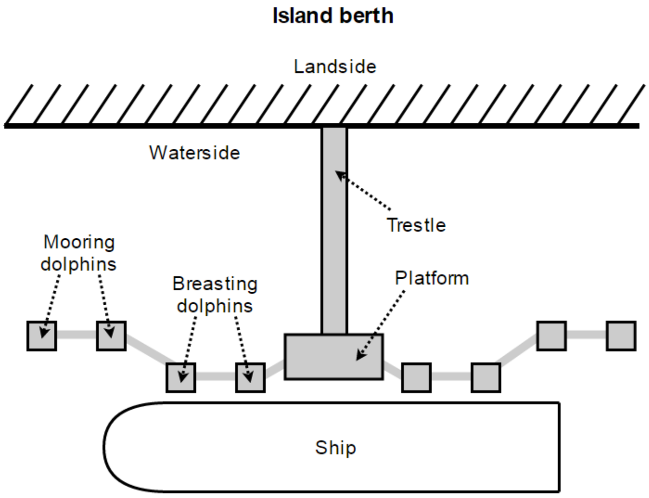


Figure 33: Schematic overview of an island berth type jetty. Source: Own work

The loading arm can be in the form of rigid pipes connected to the vessel and allowing for ship motion by means of swivel joins. Or in the form of a more flexible rubber or fabric hose.

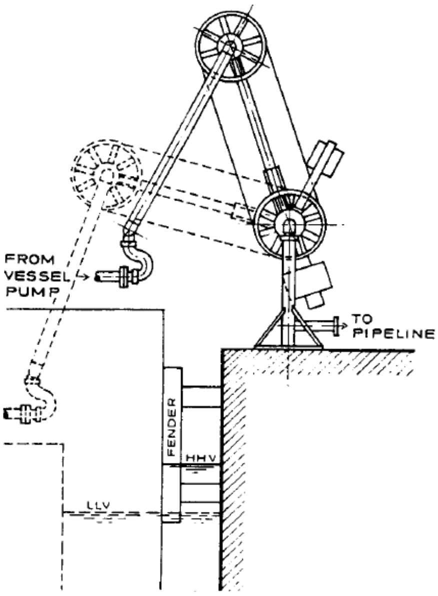


Figure 34: Liquid bulk loading arm. Source: Agerschou (2004)

2.3.1.5 Pipelines

At import terminals the liquid cargo is pumped with ship pumps through the unloading arm into pipelines positioned on the pier. The unloading capacity is therefore determined by the ships pumps and not by the terminal equipment. The pipelines go to the storage tanks on the terminal.

When pipelines will be used for different commodities or when the liquid is likely to solidify during transport; equipment is needed for cleaning the pipes. This equipment is normally located at the (un)loading platform and near the storage tanks.

For some materials heating (e.g. some vegetable oils) or cooling (e.g. LNG or ammonia gas) has to be applied in order to keep the material in a liquid form. This affects the pipeline design; for example insulation and expansion loops have to be applied. Pipelines are usually combined in large pipeways that run through the terminal area.

Cooled or pressurised liquids require a vapour-return-system that transports vapour, that forms when boiling occurs while loading the ship, back to the shore.

Methods for the handling of liquefied gas are similar to those of oil and petroleum products. Exceptions are the cooling and/or pressurisation (including the loading arm) of the cargo. Strict regulations apply for positioning the tanks with respect to other buildings, this is discussed in Section 2.3.3. Also the position of ships with respect to other vessels is prone to regulations, these are however not in the scope of this study.

2.3.1.6 Storage tanks

The storage of liquid bulk happens in large cylindrical steel tanks. The (floating) roofs of the tanks prevent contamination from weather and prevent the evaporation of the liquid into the atmosphere. Crude oil and oil product tanks usually have a capacity between 500 and 20,000 cubic metres, however larger tanks exist. Examples of tanks are depicted in Figure 35. Vegetable oil tanks are generally smaller since shiploads are smaller, the tank capacity is normally about 1,000 tonnes or less.

Figure 35: Liquid bulk tanks with external floating roofs. Source: Google

Two options for storage exist; switch tanks or dedicated tanks. Switch tanks allow for different types of cargo to be stored, this requires however cleaning and degradation costs but has large impact on the size of the terminal. Dedicated tanks store one type of cargo only.

On liquid bulk terminals bunds are used to capture spills. These bunds can be concrete or earth walls surrounding a single tank or tank group and must be designed so that at least a full tank load can be captured within these walls.

Figure 36: Satellite picture of a liquid bulk terminal with various tank sizes and earth bunds (green squares). Source: Google

LNG

Gasses that are liquefied by cooling require tanks with insulation and a refrigeration plant. LNG is stored in cryogenic tanks that have to be manufactured from special alloys on account of the very low temperature (and consequently brittleness of steel). These tanks also consist of a double wall as a safety measure, see Figure 37.

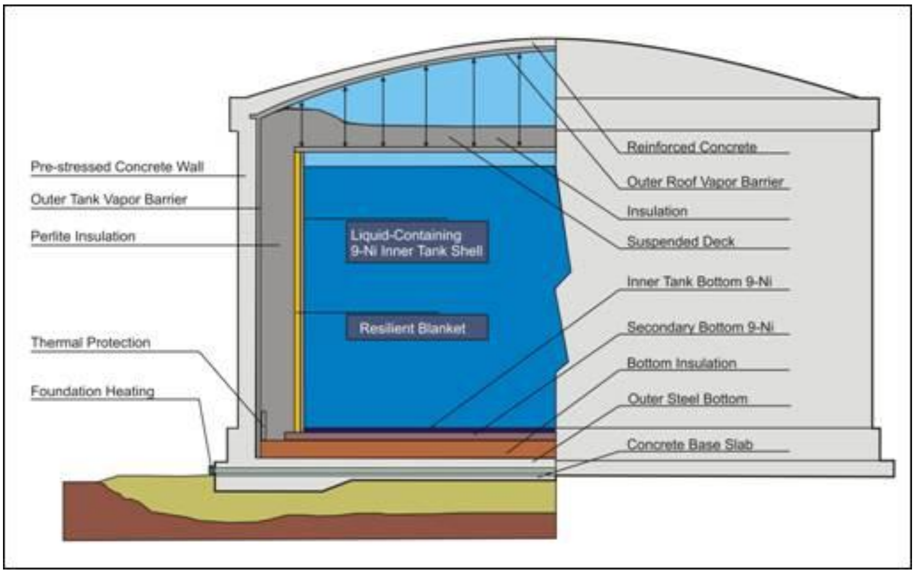


Figure 37: Full containment cryogenic LNG storage tank schematisation[14]

An LNG terminal requires additional components in order to convert the liquefied gas to a natural gas. As an indication these components are depicted in. They are however not a part of this research as explained in the introduction and because of the goal to maintain the general nature of this research.

[14]Source: http://www.epd.gov.hk

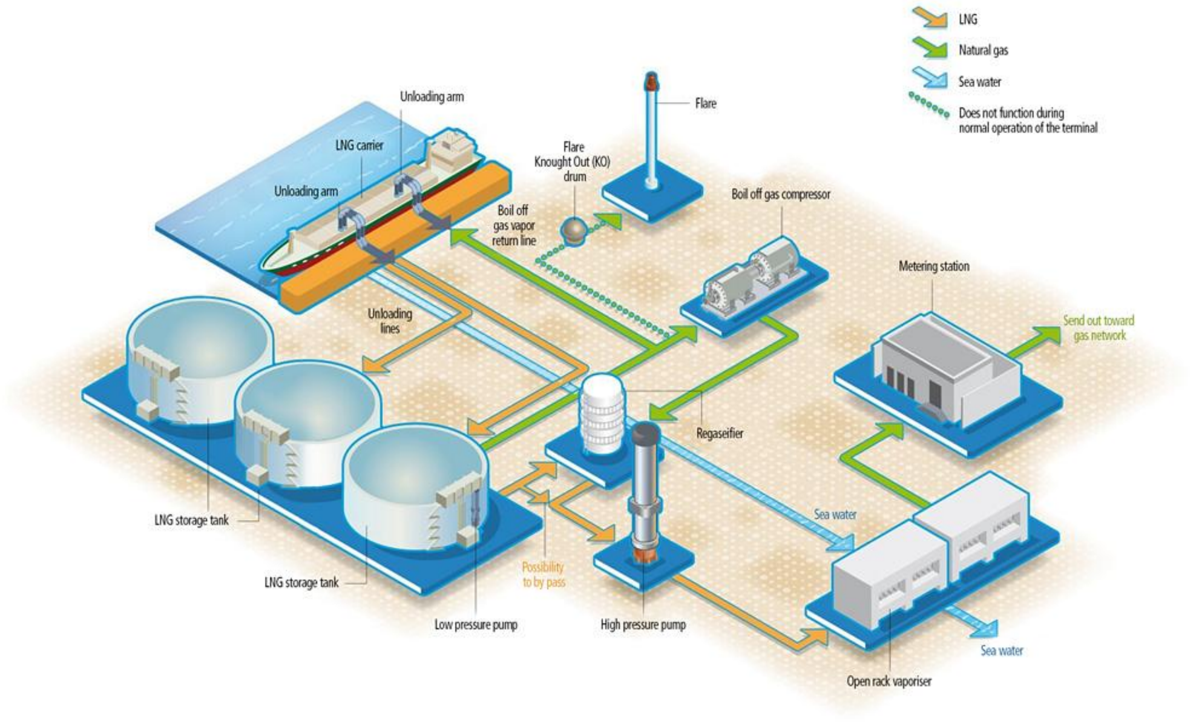


Figure 38: Indication of LNG terminal components[15]

2.3.2 Equipment properties

The only specific equipment on a liquid bulk terminal are the pumps and attachments. Important aspects are the pump capacity and pipeline length and diameter. The properties and the selection of pumps and pipelines is another field of expertise, this is therefore not included in this research. Liquid bulk unloading performance depends on the vessel size and the corresponding pump capacity of the vessel. It also depends on liquid properties such as viscosity, temperature and safety regulations; Fourgeaud (2000).

Ligteringen & Velsink (2012) states that tankers smaller than 250,000 DWT typically have a combined net pump capacity (from ship to shore) of about 10% of their DWT. And PIANC (2014b) states that for edible oil carriers the pump capacity from shore to ship is 100 - 150 tonne/hour.

Fourgeaud (2000) states that most liquid bulk carriers are operated within one day. Throughput varies from 300 to 1000 m^3/hour for small and regular sized vessels to 15,000 m^3/hour and higher for VLCC and ULCC.

2.3.3 Design guidelines, rules and parameters

The design guidelines, rules and parameters are provided for determining the number of berths and storage yard area. The required dredging depth can be determined as in Section 2.1.3.4. Values used in practice of the parameters are listed in Section 2.3.3.3.

[15] Source: https://www.edf.fr

2.3.3.1 Number of berths

The number of berths can be determined using the berth productivity and/or maximum service time method.

Berth productivity

This method is similar to the one for dry bulk terminals in Section 2.2.3.1, and is based on PIANC (2014b). It is however adjusted so that the average combined pump productivity per berth (or equivalently per vessel, since jetties are used) is used instead of the productivity per crane or pump.

$$C_b = \overline{P}_{berth} \cdot n_{hy} \cdot m_b \tag{25}$$

Where,

C_b Berth productivity [tonne/year].

$\overline{P}_{berth}$ Average combined pump productivity per berth [tonne/hour]. Average number of tonnes moved between berthing completed and de-berthing started by means of the combined pump capacity.

n_{hy} The number of operational hours per year [hour/year].

m_b Berth occupancy factor [-]. The acceptable occupancy factor depends on the allowable waiting time in terms of service time, the number of berths and the sort of terminal (e.g. dedicated shipping line). For berthing at a jetty the berth is treated as a binary object; the berth is either free or occupied. Lengths are therefore not taken into account. For this situation the factor can be calculated with the following equation, based on Saanen (2004):

$$m_b = \frac{\sum_{i=1}^{n} T_{s,i}}{n_{hy}} \tag{26}$$

Where,

$T_{s,i}$ Service time (or effective berthing time) of vessel i of total of n vessels berthed in measurement period n_{hy} [hour]. Time the vessel is berthed outside of the operational hours does not count.

The required number of berths is calculated with Equation (16).

Then with the determined number of berths the number and form of the jetties has to be determined. In this study only island berth type jetties for liquid bulk terminals are considered. The jetty can be divided into the trestle structure and the berthing structure, an island berth jetty only has one berth. The length of the trestle is purely dependent on the local situation. The berthing structure length is a summation of the design vessel length ($L_{s,max}$) and an additional length for and aft of the vessel (L_{ml}).

Maximum service time

Another method to determine the required number of pumps, the pump productivity and the number of berths is when a maximum allowable service time is posed. A common time-in-port is 1 to 1.5 days according to Ligteringen & Velsink (2012) and PIANC (2014b). The required number of berths can be calculated with the equations of the previous section.

2.3.3.2 Storage area

For the calculation of the storage area for liquid bulk terminals the same general approach can be used as for dry bulk terminals. Furthermore some rules-of-thumb for the storage capacity exist in literature. Safety requirements such as bunds and minimum distances are in order for some commodities. These are treated in this section.

General approach

The required storage volume per cargo type can be calculated with the following equation that is equal to Equation (19). It is rewritten from an equation in PIANC (2014b) in order to result in a storage volume instead of a storage area. The equation is as follows:

$$V_{storage,i} = \frac{C_i \cdot \bar{t}_d}{\bar{\rho}_c \cdot 365 \cdot m_s} \tag{27}$$

Where,

$V_{storage,i}$ Required storage volume of the tanks per commodity type [m^3].

C_i Mass of handled cargo per year per commodity type [tonne/year].

$\bar{t}_d$ Average dwell time of cargo in the tanks [days].

$\bar{\rho}_c$ Average cargo density [tonne/m^3].

m_s Estimated storage occupancy [-]. Average mass of cargo in tanks divided by the design capacity of the tanks. To account for the random arrivals and departures of cargo.

When the required storage volume is determined the number of required tanks can be calculated. The net storage area is the area covered by the storage tanks. The gross storage area consists of the net storage area, the area surrounded by bunds and the internal roads. The gross storage area for tank storage can be calculated with a method that is described in Appendix VI . When the gross storage area is calculated and the total terminal factor (α) is known the total terminal area can be calculated with Equation (23).

Rules-of-thumb

The rules-of-thumb consist of percentages that determine the required number of tonnes of cargo that should be stored at a certain point of time.

PIANC (2014b) proposes a storage capacity ratio (r_c) of 3 or 4 times the DWT of the largest vessel that calls at the terminal. They also propose a capacity of 3% to 5% of the annual terminal throughput. Agerschou (2004) complements this by stating that 3 or 4 times the largest shipload per cargo type must be able to be stored for dedicated storage tanks. For switch tanks this is 3 or 4 times the largest shipload regardless the cargo type.

Ligteringen & Velsink (2012) recommends the ability to store one month of consumption on the terminal. In other words the total output of one month should be able to be stored on the terminal at a certain point of time. Furthermore for crude oil they propose a storage factor that is given in Table 17.

Bunds

VROM (2008) gives as a guideline that the volume between bunds should have a minimum capacity of the volume of the largest tank surrounded by the bund plus 0.25 metres for wind waves plus an additional height for subsidence. If there are other tanks surrounded by the same bund then 10% of the volume of these tanks should be able to be contained too.

Minimum distances

For non-hazardous materials there are no rules for the distance between tanks. Using Google Earth a practical minimum is found of 5 metres, this is of course not a binding value.

In the Netherlands flammable products are categorised as listed in Table 26.

Table 26: Flammable liquid classes

	Flashpoint boundaries
Class 1	0 °C < flashpoint < 21 °C Boiling point > 35 °C
Class 2	21 °C < flashpoint < 55 °C
Class 3	55 °C < flashpoint < 100 °C

Source: VROM (2008)

For minimum distances between objects and tanks -for the storage of flammable products of classes 1, 2 or 3- see Table 27. The table is based on VROM (2008) which in turn is based on *Institute of Petroleum Code 19, Model Code of safe Practice.*

Table 27: Minimum distances between objects and tanks with flammable products

Tank type	**Object**	**Minimum distance**
Tanks with fixed roofs, including tanks with internal floating roofs.	Between groups of small tanks[1]	15 metres
	Between a group of small tanks[1] and a tank outside the group	Smallest distance of: 1. Half of largest diameter of the tanks 2. Diameter of the smallest tank 3. 15 m. But not smaller than 10 m or larger than 15 m.
	Between tanks that are not part of a group of small tanks	15 metres
	Between a tank and a filling point or building.	15 metres
Tanks with floating roofs.	Between two tanks with floating roofs.	10 m if tank diameter ≤ 45 m. 15 m if tank diameter > 45 m. For crude oil: 30% of tank diameter but larger than 10 m. *Tank with largest diameter determines distance.
	Between tank with floating roof and tank with fixed roof.	Smallest distance of: 1. Half of largest diameter of the tanks 2. Diameter of the smallest tank 3. 15 m. But not smaller than 10 m or larger than 15 m.
	Between a tank and a filling point or building.	10 metres

Tank type	Object	Minimum distance
	Between a tank and terminal border.	15 metres

Note 1: Small tanks are defined as tanks with a diameter < 10 m and a height < 14 m. A group of small tanks may be considered a single tank with respect to spacing or bunding. A small tank group can have a combined capacity of maximum 8000 m^3.
Note 2: For tanks with diameter larger than 18 m. it may be necessary to enlarge the distances.

Source: VROM (2008)

For minimum distances between objects and tanks -for the storage of flammable fuels of classes 1, 2 or 3- see Table 28. The table is based on VROM (2008) which in turn is based on *Institute of Petroleum Code 2, Marketing Safety Code.*

Table 28: Minimum distances between objects and tanks with flammable fuels

Object	Minimum distance
Between tanks with diameter > 10 m. or height > 14 m.	Smallest distance of: 4. Half of largest diameter of the tanks 5. Diameter of the smallest tank 6. 15 m. But not smaller than 10 m.
Between a tank and a filling point or building.	15 metres
Between a tank and terminal border.	15 metres

Note: For tanks with diameter larger than 18 m. it may be necessary to enlarge the distances.

Source: VROM (2008)

The failure of an LPG tank can lead to the evaporation of a large amount of LPG. With air an explosive mixture is formed that can cause a boiling liquid expanding vapour explosion when an ignition source is present. To avoid fires or explosions minimum distances to near objects are listed in Table 29. A threshold for the maximum permissible heat intensity is taken as 10 kW/m^2 in VROM (2013). The source does not mention specific international regulations.

Table 29: Minimum distances from object to LPG tank

Object	Minimum distance
Tank with flammable liquid (flashpoint < 60 °C)	Distance corresponding to 10 kW/m^2 in Figure 4.1 of VROM (2013)
Tank with flammable liquid (flashpoint > 60 °C)	3 metres
Flammable material or other objects inside the bund	Distance corresponding to 10 kW/m^2 in Figure 4.3a, 4.3b or 4.3c of VROM (2013)

Source: VROM (2013)

The Dutch guideline for the storage of cryogenic gasses (such as LNG) is VROM (2014), this however only applies to tanks from 0.125 to 100 m^3. The minimum distances to objects near the tank are listed in Table 30. The source does not mention specific international regulations.

Table 30: Minimum distances from object to cryogenic gas tanks

Object	Minimum distance
Tank with flammable liquid (flashpoint < 60 °C)	Distance corresponding to 10 kW/m^2 in Figure 3.1 of VROM (2014)
Tank with flammable liquid (flashpoint > 60 °C)	Half the tank diameter[1]
Tank with liquefied flammable gasses (volume > 150 m^3)	15 metres

Note 1: VROM (2014) proposes 3 metre for not-soil-covered tanks, the minimum distance for soil-covered tanks is used in the table.

Source: VROM (2014)

Tanks sizes

Liquid bulk tanks come in many different types and sizes. The DWT varies per cargo type. For example crudes are transported by large carriers while vegetable oils are transported by smaller vessels. The required storage space is therefore smaller for the latter, this results in smaller tanks. To be able to give a rough indication of tank dimensions the liquid bulk cargoes are divided into four groups:

1. Crude oil, petroleum products, diesel, fuels
2. Chemicals, bio fuels, mineral oils
3. Vegetable oils
4. LNG

The following liquid bulk terminals located in Rotterdam (unless indicated otherwise) are investigated:

Table 31: Investigated liquid bulk terminals divided into groups

Group	Terminals
1	Vopak Europoort, Maasvlakte Olie Terminal, Euro Tank Terminal, Nova Terminals
2	Vopak TTR, Koole Tank Storage, Odfjell Terminals, Rubis Terminals, Noord Natie Odfjell Terminals (Antwerp)
3	Koole Tank Storage, Nova Terminals, Noord Natie Odfjell Terminals (Antwerp)
4	Gate Terminal, Enagas (Barcelona), Sagas (Sagunto)

Per terminal on average the smallest, medium and largest tanks are measured. The tank diameter is approximated by means of Google Earth. The tank height is approximated by means of data from Actueel Hoogtebestand Nederland (2016). The tank capacity is approximated with the diameter and height. The resulting minimum, maximum and average characteristics per group are listed in Table 32.

Table 32: Minimum, maximum and average values of characteristics of liquid bulk tanks

	Group 1			Group 2		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Capacity [m^3]	1,154	118,236	58,252	142	45,696	8,997
Diameter D [m]	12.0	84.7	55.0	3.0	51.9	20.9
Height H [m]	10.2	33.7	20.2	12.5	25.0	17.3
D/H [-]	1.2	4.4	2.8	0.2	2.4	1.2
	Group 3			**Group 4**		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Capacity [m^3]	142	21,220	5,874	53,766	180,000	152,233
Diameter D [m]	3.0	42.3	18.9	75.8	88.0	82.0
Height H [m]	10.2	25.0	16.1	23.9	33.2	28.9
D/H [-]	0.2	2.8	1.3	2.3	3.4	2.9

2.3.3.3 Common values of parameters

Values that are proposed in literature of the input parameters used in the design rules are listed in Table 33. For various parameters minimum and maximum values are proposed, resulting in a range of possible values. This can be represented by a uniform random distribution. When this is the case the reader should make an estimate of which part of the distribution to use. The sources of the values are numbered in square brackets.

Table 33: Parameter values of liquid bulk terminal design rules

Symbol	Unit	Description and values
f_s	tonne/year/m^2	*Storage factor.* For values see Table 17 (p.61).
h_{dt}	m	*Dredging tolerance.* A value of 0.60 is proposed by [4].
h_{guc}	m	*Minimum gross underkeel clearance.* For values see Table 8 (p.41).
m_b	-	*Estimated berth occupancy.* For values see Table 34 (p.81) Optimal value is between 50% and 65% [1].
m_s	-	*Estimated storage occupancy.* Determined in Expert Judgement Elicitation, see Section 0.
n_{hy}	hour/year	*Number of operational hours per year.* No values in literature.
r_c	%	*Capacity ratio.* Ratios can be found in Section 2.3.3.2.
$\bar{t}_d$	days	*Average dwell time of cargo in the tanks.* No values in literature.
D	m	*Tank diameter.* For values see Table 32 (p.79).
D_s	m	*Draught of the design vessel.*

Symbol	Unit	Description and values
		For values see Table 24 and Table 25 (p.67).
H	m	*Tank height.* For values see Table 32 (p.79).
L_{ml}	m	*Additional quay length required for and aft of vessel to account for mooring lines.* Normally 15 metres [3] or 30 metres [2] is used.
$L_{s,max}$	m	*Length of largest vessel frequently calling at terminal.* For normal vessel lengths see Table 24 and Table 25 (p.67).
$\overline{P}_{berth}$	tonne/hour	*Average combined pump productivity per berth.* For general pump capacities see Section 2.3.2.
α	-	*Total terminal factor.* Determined in Expert Judgement Elicitation, see Section 0.
$\overline{\rho}_c$	tonne/m^3	*Average cargo density.* Crude oil: 0.790 and 0.973 and LNG: between 0.41 and 0.50.

Sources:
[1] Personal communication with R. J. Smits van Oyen (13-05-2016)
[2] PIANC (2014b)
[3] Quist & Wijdeven (2014)
[4] PIANC (1995)

Berth occupancy factor

The acceptable berth occupancy factor depends on the number of berths and the allowable average waiting time in terms of average service time of vessels (T_w/T_s). According to Monfort et al. (2011) a reasonable value for T_w/T_s for (liquid) bulk terminals is 0.50. The probabilistic Queuing Theory is used to determine the occupancy ratios. This theory is not treated in this research since it is outside its scope, for a better understanding of the general Queuing Theory reference is made to Sztrik (2012). An application of the theory on terminal design can be found in Agerschou (2004).

The queuing system can be denoted by the Kendall notation: “inter arrival time distribution”/”service time distribution“/”number of berths”. Arrivals of vessels can be random for common user terminals, a negative exponential inter arrival time (denoted by M) is then assumed. When arrivals are less random an Erlang-K distribution (denoted by E_K) with K = 2 is assumed. Service time distributions are also taken as an Erlang-K distribution with a value of K = 2 (the higher the K-value the more constant the inter arrival or service times are). A realistic queue is M/E_2/n for common user (liquid) bulk terminals according to Monfort et al. (2011) and Terblanche & Moes (2009). For dedicated shipping line bulk terminals E_2/E_2/n is proposed by Monfort et al. (2011). Acceptable berth occupancy factors corresponding to these queues for T_w/T_s = 0.50 are given in Table 34.

Table 34: Acceptable berth occupancy factor for liquid bulk terminals for T_w/T_s = 0.50

Number of berths n_b [-]	Acceptable berth occupancy factor m_b [%]	
	Common-user $M/E_2/n$	Dedicated $E_2/E_2/n$
1	41	55
2	64	73
3	73	81
4	78	84
5	82	87
6 or more	84	89

Source: Monfort et al. (2011)

To use this table an iteration must be performed. First a value for the occupancy has to be assumed, then the number of required berths is calculated with Equations (25) and (16). The occupancy corresponding to this calculated number of berths must then be checked with the assumed occupancy. If they do not correspond the same steps have to be taken again. The berth occupancy factor tables are not used in the tool since in some cases this iteration proves to be divergent. A manual iteration by the user of the tool by using the information in the table is of course still possible.

2.4 Costs determination

In order to give a rough estimation of the construction costs of a greenfield marine terminal prices for certain terminal elements are required, these are referred to as unit prices or unit costs. The prices of those elements are covered in this section and are based on literature review and interviews. First general prices, that can be used for multiple container types, are given. Then for each terminal type prices are given for the specific terminal elements. Prices are often not easily obtained since manufacturers see it as competition sensitive information.

2.4.1 Unit costs, construction costs and inflation

Direct costs are defined as costs directly related to the production or supply of a product or service; from the Dutch *Standaard Systematiek voor Kostenramingen* (SSK) definitions. A construction costs estimate consists of direct costs (labour, equipment and materials), indirect costs (e.g. site organisation, site management, general costs etc) and contingencies (unforeseen costs). An elaboration on how to calculate these costs can be found in Appendix I , since they are confidential.

The direct costs are calculated by using unit costs and quantities. Unit costs are a price per unit metrics. These unit costs are presented in this section.

Prices are adjusted for inflation in the tool itself, therefore prices in this section are given in their original price level. All prices are in Western European rates. Prices that were given in USD are converted to EUR with the conversion rate of 1 USD = 0.896 EUR, from Google on 30-08-2016. Prices of some elements go back to as far as 1998. In the period between then and now not only inflation plays a role but also technological improvements. These improvements may have an impact on the price, for this study this is however discarded due to time limitations.

2.4.2 General unit costs

Terminal elements that apply to more than one terminal type are quay wall and jetty structures.

2.4.2.1 Quay wall

In de Gijt (2010) quay walls from around the world are analysed. De Gijt looked at the quantities of material (concrete, steel) in the quays and the amount of man hours needed to build the quays. In his study direct costs for certain types of quay walls per metre of quay are presented. The studied quay wall type in the current research is limited to sheet pile walls, due to time limitations. De Gijt’s research led to the following direct cost formula for sheet pile quay walls per metre of quay:

$$C = 627.05 \cdot H_{retain}{}^{1.2878} \tag{28}$$

Where,
C Quay wall direct costs [EUR/m^1]. In 2008 price level.
H_{retain} Retaining height [m].

Obviously this is an approximation of real costs since the total costs are dependent on aspects like; soil conditions, crane loads, construction materials, wave climate, tidal variation and the country de Gijt (2010).

De Gijt's formula is checked by means of data of quay walls of different terminal types, from a port master plan project of Witteveen+Bos. This data is confidential, the results are therefore presented in Appendix I .

2.4.2.2 Jetty

In de Gijt (2010) many quay walls were analysed in order to derive a formula for the costs per metre of quay as a function of the water depth. No similar literature can be found concerning the costs of jetties. Also not enough data is available to determine a similar relation for jetty costs as part of this study. Therefore the decision is made to approximate the jetty costs per metre of jetty based on a few projects performed by Witteveen+Bos. For this analysis a distinction is made between jetties of the finger pier and liquid bulk type. An elaboration can be found in Appendix I .

2.4.3 Container terminal unit costs

Container terminal cost elements can be divided into civil works and equipment. Civil works consists of the quay wall, STS crane rails, apron and storage yard pavement and the construction of the container freight station (CFS). The equipment consists of STS cranes, tractor trailer units, straddle carriers, automated guided vehicles, reach stackers, rubber tyred and rail mounted gantry cranes.

2.4.3.1 Equipment

Saanen (2004) gives prices for these equipment types. The prices are among others based on Drewry (1998), it is assumed that these prices are according to the Dutch 1998 price level. In Saanen (2004) no prices are given for a rubber tyred gantry crane. In Böse (2011) however investment costs of both RMG and RTG cranes are qualitatively described. As a scale low, medium, high and very high investment costs is used. Costs of RMG cranes are described as high and RTG cranes as medium. Therefore it can be assumed that there is a 25% difference between the costs of both crane types.

Table 35: Unit costs container terminal equipment

Equipment	**Unit costs** (1998 price level) [EUR/pc]	**Unit costs** (2016 price level) [EUR/pc]
STS crane	5,000,000 - 7,500,000	7,140,000 - 10,710,000
Tractor trailer unit	90,000	130,000
Straddle carrier	500,000	715,000
Automated guided vehicle	350,000	500,000
Reach stacker	325,000	465,000
Rail mounted gantry crane	1,100,000 (6 wide) - 1,600,000 (9 wide)	1,570,000 - 2,285,000
Rubber tyred gantry crane	825,000 - 1,200,000 [1]	1,180,000 - 1,715,000

Note 1: No price given but determined by own calculation
Source: Saanen (2004)

2.4.3.2 Civil works

The quay wall costs are considered in Section 2.4.2. Apron and storage yard pavement is assumed to be the same sort of (paving stones) pavement. The CFS is assumed to be a warehouse structure. Unit prices for these last two elements are provided in Appendix I , since they are confidential. Crane rails are not included in the tool since the costs are minor compared to the costs of a quay wall per metre.

2.4.4 Dry bulk terminal unit costs

Dry bulk terminal cost elements can be divided into civil works and equipment. Civil works consists of the quay or jetty, open stockpile foundation, conveyors and pipelines, storage shed and silos. The equipment consists of gantry grab crane, bucket elevator, chain-, vertical screw-, spiral- and pneumatic conveyors, ship loader, bucket wheel stacker-reclaimer and scraper-reclaimer.

2.4.4.1 Equipment

In Vianen, T. van (2015) investment costs for bucket wheel stacker-reclaimers are determined by the weight of the machines. These weights are in turn related to the machines combined (sum of stacking and reclaiming) capacity. In order to derive an equation for the bucket wheel stacker-reclaimer weight as a function of the combined capacity data points from the research are used and a linear curve is fitted:

$$W = 0.0769 \cdot C_{equip} + 135.80 \quad (29)$$

Where,

W Stacker-reclaimer weight [tonne].

C_{equip} Combined stacker-reclaimer capacity [tonne/hour]. Sum of the stacking and reclaiming capacity.

No difference is made between the various boom lengths. According to the same study several experts use the rule-of-thumb that the machine's investment costs in Euros are 6 to 8 times the weight in kilograms. Since this is a rule-of-thumb no price level is known. The previous information is depicted in Figure 39.

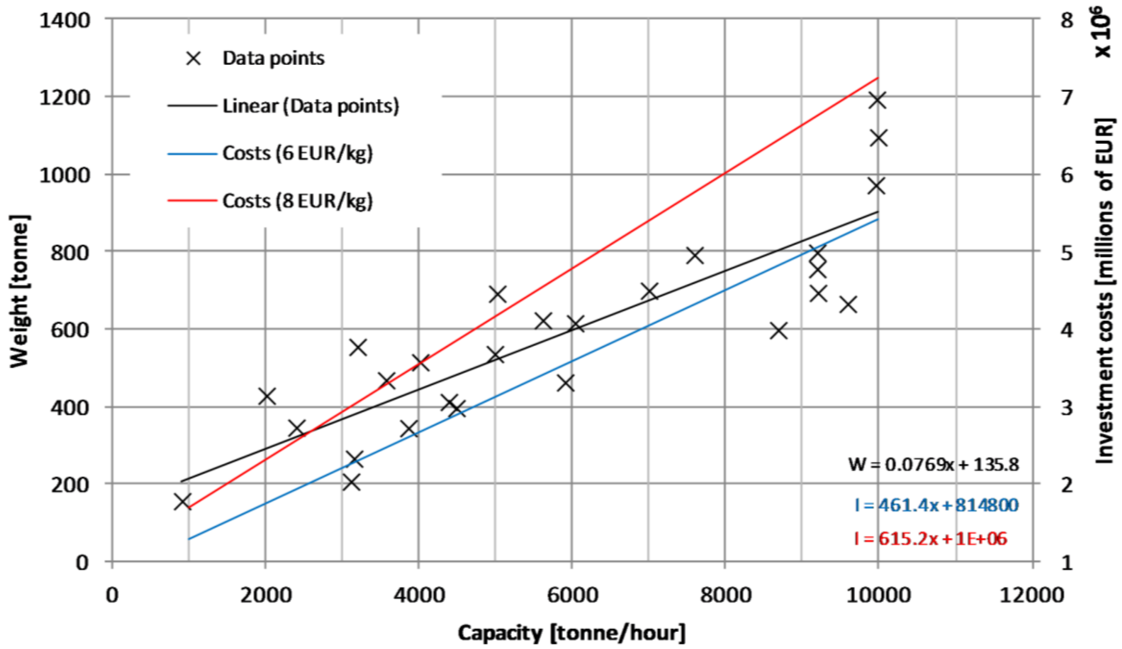


Figure 39: Bucket wheel stacker-reclaimer combined capacities versus machine weight (black). And high (red) and low (blue) boundaries for investment costs. Based on Vianen, T. van (2015)

In Chapter 2.2.2.2 the average combined capacity of this type of machine is 5,000 tonne/hour. This leads to costs ranging from € 3,121,800 to € 4,162,400 per piece of equipment.

Of the other dry bulk terminal equipment no price information can be found. The contacting of different equipment manufacturers in order to ask for price information would take up too much time and results would not be guaranteed. Therefore the choice is made to use the relationship between capacity and weight of stacker-reclaimers also for the other equipment types. Obviously the machines do not consist of exactly the same parts and do not come in the same sizes, but they are used for the same purpose executed in a different way. By means of Google pictures of different machines of the same type are inspected and compared to the base case; that is the stacker-reclaimer. The average difference in weight is then visually estimated with a percentage. This leads to a capacity-weight function for each equipment type. With the equipment capacities found in the literature study the corresponding weights can be determined. For the bucket wheel stacker-reclaimer the combined (un)loading capacity is used, the unloading machines however do not have a loading capacity. Unloading equipment capacities have to be multiplied by 2 in order to match the required combined capacity for the equation. The same method applied for a loader results in too high prices so the loading capacity is not doubled. The percentages and functions are listed in Table 36. Multiplying the weights with a factor of 6 to 8 EUR/Kg results in the equipment costs. It is stressed that this is a rough estimation of the investment costs of dry bulk terminal equipment.

Table 36: Weight as function of combined capacity for various dry bulk terminal equipment

Equipment type	Percentage of machine weight with respect to stacker-reclaimer [%]	Weight W [tonne] as a function of combined capacity C_{equip} [tonne/hour]
Bucket wheel stacker-reclaimer	*100*	$W = 0.07690\ C_{equip} + 135.80$
Gantry grab crane	95	$W = 0.07306\ C_{equip} + 129.01$
Bucket elevator	110	$W = 0.08459\ C_{equip} + 149.38$
Chain conveyor	95	$W = 0.07306\ C_{equip} + 129.01$

Equipment type	Percentage of machine weight with respect to stacker-reclaimer [%]	Weight *W* [tonne] as a function of combined capacity C_{equip} [tonne/hour]
Vertical screw	95	W = 0.07306 C_{equip} + 129.01
Spiral conveyor	95	W = 0.07306 C_{equip} + 129.01
Pneumatic conveyor	80	W = 0.06152 C_{equip} + 108.64
Loader	85	W = 0.06537 C_{equip} + 115.43
Scraper-reclaimer	5	W = 0.00385 C_{equip} + 6.79

Note: percentages based on visual comparison between photos.

According to Vianen, T. van (2015) continuous unloading equipment is more expensive than grab crane unloaders because of the higher technological complexity, this is however not considered when only looking at the machine weights. Therefore further research is recommended for increasing the reliability of these costs.

2.4.4.2 Civil works

The quay wall and jetty costs are considered in Section 2.4.2. The open stockpile foundation is assumed to be a pavement. Storage sheds are assumed to be warehouse structures and silos are assumed to have a conical or flat roof and conical bottom. Unit costs for these last two elements are provided in Appendix I , since they are confidential. Belt conveyors and pipelines that are used to transport dry bulk cargo across the terminal are not included in the cost estimates in the tool. The length of these elements depends on the layout of the terminal which is not determined by the tool.

2.4.5 Liquid bulk terminal unit costs

Liquid bulk terminal cost elements consists of jetty for (un)loading (see Section 2.4.2), pipelines, LNG tanks, regular tanks and bunds. This subsection also covers a rule-of-thumb for the total costs of the landside of the terminal.

2.4.5.1 Pipelines

The length of the pipelines that transport cargo across the terminal depend on the layout of the terminal. The terminal layout is not determined by the tool and pipelines are therefore not included in the cost estimates in the tool.

2.4.5.2 Tanks and bunds

LNG tank costs are much higher than regular steel tanks; Ligteringen & Velsink (2012). It turned out to be impossible to find decent cost information for LNG tanks. Only one price is found in an online version of a LNG market research report from The McIlvaine Company[16]. The report gives construction costs ranging from 49.3 mln to 67.2 mln EUR for an LNG tank of 160,000 m^3. From the text it can be derived that the price level is from around the year 2000. Obviously the downside is that the costs of only one specific tank volume are given. To still be able to calculate the costs of LNG tanks with other capacities the unit costs are determined by dividing the two cost limits by the tank volume and by subtracting the additional direct costs, indirect costs and contingency costs. This leads to direct unit costs between 181.1 EUR/m^3 and 246.9 EUR/m^3. In reality the unit costs will decrease for increasing tank volume (the economy of scale principle) but

[16] Information about the report (such as title or year) cannot be found.
URL: http://www.mcilvainecompany.com/industryforecast/LNG/overview/Otofc.htm

this cannot be quantified due to lack of data. The relations found for regular tanks also cannot be used since LNG tanks are very different than regular storage tanks.

Unit costs for regular tanks and bunds are provided in Appendix I , since they are confidential.

2.4.5.3 Rule-of-thumb total landside area

Robert Jan Smits van Oyen (Manager Logistics and Asset Management & Maintenance at Tebodin Consultants & Engineers) mentioned in an interview (12-05-2016) that as a rule of thumb for the total landside[17] the investment costs range between € 500 and € 1,000 per cubic metre of storage volume on the terminal. The subtraction of the additional direct costs, indirect costs and contingency costs results in the direct unit costs from € 295 to € 590 per cubic metre of storage volume. Terminals with large tanks are on the lower side of the range while terminals with multiple small tanks are on the higher side. Approximately 50% of the total costs can be attributed to the tanks according to Smits van Oyen.

[17] Landside includes: Storage tanks, pipelines, equipment and other infrastructure.

3 EXPERT JUDGEMENT ELICITATION

In Chapter 2 equations are provided that make it possible to determine the required container, dry and liquid bulk terminal dimensions. Common values for the variables, or parameters, in these equations are studied as well. Some parameters like for example the throughput are project specific and for which no useful standard values can be found. For other variables like for example cargo dwell time or crane capacities similar values or values -within certain ranges- occur at terminals globally. However not for all parameters -that are considered in this study- common values can be found. In order to be able to scientifically obtain values for these variables Expert Judgement Elicitation (EJE) is used. In this study EJE is used for the variables *total terminal factor*[18] (α) and *average storage occupancy*[19] (m_s). These variables are studied because they are expected to have a large influence on the dimensions, since they are both factors. By using this method the opinions of expert are combined with a structured performance-based approach which fills in the missing information from literature. The results of the expert assessment can be treated as scientific data. This data is an addition to the variable values in Sections 2.1.3.5, 2.2.3.3 and 2.3.3.3, and is used as input in the computer tool.

Furthermore another method using the same principle is used to estimate the dependence between the import, export and transhipment container dwell times when they are assumed to be random variables. The uncertainty distributions of these random variables are based on the common values of parameters found in the literature study (Section 2.1.3.5). Both methods are presented and applied in this chapter.

The use of Expert Judgement Elicitation in this chapter is to introduce this type of research to the port or terminal design sector as an excellent way to combine the opinion of experts. Aligning with this purpose the theory is explained in this chapter and in detail in Appendix III .

Goal of the application of Expert Judgement Elicitation: Obtaining the uncertainty distributions of the total terminal factor and average storage occupancy factor. As well as the dependence between the import, export and transhipment container dwell times, represented as random variables. And bridging the gap between practice and theory of Expert Judgement Eliciting in this field of expertise.

3.1 The method

Using the advice of experts for uncertainties is obviously not a new practice. However usually this happens in an informal way resulting in an unstructured decision making process. Expert Judgement Elicitation is a structured process with transparent rules that has the goal of treating the

[18] The total terminal factor is the percentage of the storage area (including internal infrastructure) with respect to the total terminal area.

[19] The average storage occupancy is the percentage of the design storage capacity that is actually used, averaged over a year

judgements as scientific data; Aspinall (2008). Currently at Delft University of Technology research is being performed on Expert Judgement Elicitation.

In this study expert opinions are asked for the uncertainty of six different parameters and the dependence between three other variables. Both these applications are elaborated on in Section 3.1.1 and Section 3.1.2.

3.1.1 Eliciting uncertainties

Various methods for eliciting expert uncertainties exist, for this study the *Classical model* from Cooke (1991) is used. Cooke's model applies a performance-based combination of expert's uncertainty distributions. Multiple experts[20] are assessed individually about their uncertainty of the value of a measurement or observation from within their field of expertise. They are asked to give their opinion about values of variables that are the target of the research (target variables) and about values of variables that are not of direct interest (seed variables). The uncertainty distributions given by the experts for these seed variables are scored since the exact actual values are known by the analyst. From these scores a weight is determined for each expert. These weights are attributed to the experts' uncertainty distributions for the target variables. Therefore resulting in a performance-based determination of uncertainty by experts. This method results in a cumulative probability distribution, according to the chosen weighting scheme, for each variable. This subsection is entirely based on Aspinall (2008), unless indicated otherwise.

Most common is to ask the expert for his/her opinion on the representation of the 5^{th}, 50^{th} and 95^{th} percentile of the expert's subjective uncertainty distribution. The calibration, or weighting, of the experts happens by means of two characteristics. On the one hand *calibration*, which measures the statistical likelihood that a set of actual values corresponds to the expert's assessments. In other words this tests to what extent the expert's estimates can be trusted to approximate the (uncertainty of the) variables. On the other hand *information* is used. Information measures the degree to which the uncertainty distribution of an expert is concentrated compared to other experts in the same group. In other words this tests how sure an expert is about his estimates.

A certain weighted combination of the experts' uncertainty distributions is often called a *Decision Maker* (DM). Usually ten seed variables are used for scoring the experts. The expert's weight is determined by the product of the calibration and information scores. Good expertise means good calibration and superior information, this is rewarded by a high weight and thus a larger influence on the DM. The decision making process is schematised in Figure 40.

In 2008 already 45 expert elicitations with the unequal weighting of experts had been performed and reviewed under contracts, and often the results were published. This experience shows that in the majority of the cases the individual weighting of experts results in more accurate and informative results then assigning equal weights to experts. Therefore the Classical Model approach is well established and an excellent method to assess the judgement of experts in a structured fashion. For the theory concerning Expert Judgement Elicitation on uncertainty reference is made to Section III.1 of the appendices.

[20] The minimum number of experts to assess is four according to Cooke & Goossens (2008).

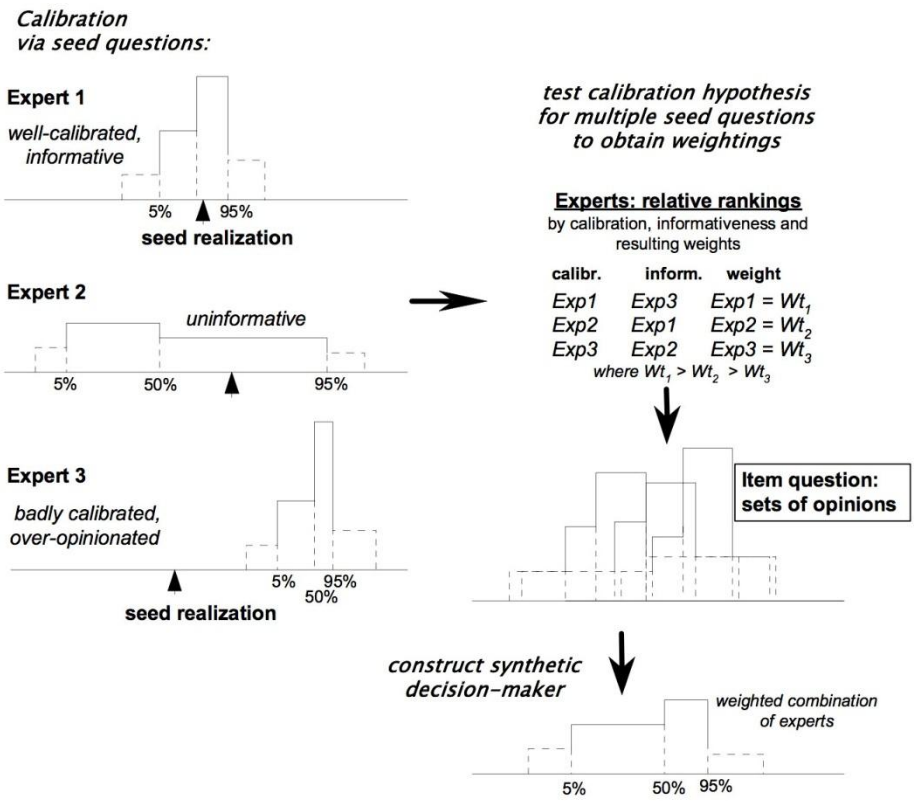


Figure 40: A schematic example of the determination of a DM with 1 seed and 1 target variable by 3 experts. Source: Aspinall (2008)

3.1.2 Eliciting dependence

In this study dependencies between random variables are quantified by means of correlations. Correlation is a measure of, on one hand, the strength; quantifying the degree to which two random variables are functionally related. And on the other hand the direction (positive or negative) of the relationship between two random variables. In this study both *Spearman's rank correlation coefficient* (r) as *Pearson's product moment correlation coefficient* (ρ) are used.

Ranking means the assignment of positions to the observations of a variable, in this case, in ascending order. When the rank correlation between two variables is wanted the rankings of the two are compared. The degree of similarity determines Spearman's rank correlation coefficient, which ranges between -1 and 1. A positive rank correlation quantifies how well two random variables are described by a function $f(x)$ that is increasing for increasing x. In other words, $f(x)$ is a positive monotonic function. The rank correlations $r = -1$ and $r = 1$ are assigned to two variables that are perfectly described by respectively a negative and positive monotonic function. A value of 0 means there is no monotonic relation, however this does not imply there is no relation at all. Pearson's product moment correlation coefficient assesses the positive or negative linear relationship between two variables and also ranges between -1 and 1. The previous is based on Udny Yule et al. (1950).

To visualise relationships between variables a *Bayesian Network* (BN) can be created, an example is depicted in Figure 41. The dependencies are represented by the rank correlation. Where $r_{4,3}$ stands for the unconditional rank correlation between random variables 4 and 3. $r_{4,2|3}$ represents the conditional rank correlation between random variables 4 and 2, given random variable 3. $r_{4,1|3,2}$ represents the conditional rank correlation between random variables 4 and 1, given random variables 2 and 3.

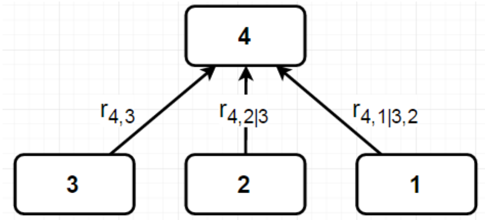


Figure 41: BN of four variables with conditional relations. Source: Morales-Napoles et al. (2007)

Multiple experts[21] are assessed individually about the dependency between different measurements or observations from within their field of expertise. For the dependence assessment at least one seed dependence must be used to be able to score the experts, here holds the more seeds the better.[22] For this study one seed variable is used due to reasons elaborated on in the introduction. The expert's estimates of the target correlations are weighted by means of these scores. Various methods for eliciting rank correlations exist, Kraan (2002) gives an overview. For this study the *conditional probability technique* is used. This method makes experts give an estimate of what they think is the probability that some variable X_1 is observed above its median when it is given that variable X_2 is observed above its median. From these probabilities the rank correlations can be determined. Combining the weighted correlation estimates of the experts results in a correlation matrix. This paragraph is based on Morales-Napoles et al. (2007). For the theory concerning Expert Judgement Elicitation on dependence reference is made to Section III.2 of the appendices.

3.2 The assessed variables

For two important variables no common values could be found during the literature study. These variables are the total terminal factor (α) and the storage occupancy (m_s). These parameters are both factors used to calculate the total terminal area. They can therefore have a large impact on the terminal dimensions. The dependence between average dwell times for different cargo flows is determined by the *conditional probability technique*.

3.2.1 Total terminal factor

The total terminal factor (α with unit %) is the percentage of all the gross storage areas with respect to the total terminal area; $\alpha = \frac{\sum A_{gr}}{A_t}$. For container terminals the gross storage area only includes the stacks and internal infrastructure inside the storage area (including import, export, transhipment, empties stacks and container freight station). The total terminal area includes the total landside (including the gross storage area, other buildings, other infrastructure on the terminal, terminal gates, etc.) and waterside area (the apron). The uncertainty of the total terminal factor is assessed for container, dry bulk and liquid bulk terminals. See Figure 42 for an example of a container terminal, with in red the gross storage areas and in blue the total terminal area.

[21] Dr. Morales-Nápoles stated in personal communication that the minimum number of experts to assess is 4.
[22] From personal communication with Dr. Morales-Nápoles.

Figure 42: TCB, S.L. Port of Barcelona (Spain). Source: Google Earth

For dry bulk terminals the gross storage area includes the area covered by stockpiles and stackers/reclaimers and conveyor belts in between the stockpiles. As well as the area covered by storage sheds and silos including the surrounding area that is kept clear of objects. The total terminal area also includes the quay or jetty area used for berthing. For an example see Figure 43.

Figure 43: Kinder Morgan, Norfolk (Virginia, USA). Source: Google Earth

For liquid bulk terminals the gross storage area includes the area covered by the storage tanks. Also the surrounding area that is kept clear of objects or the area that is surrounded by and including the bunds (earth walls) is included. The jetty area used for berthing is included in the total terminal area. For an example see Figure 44.

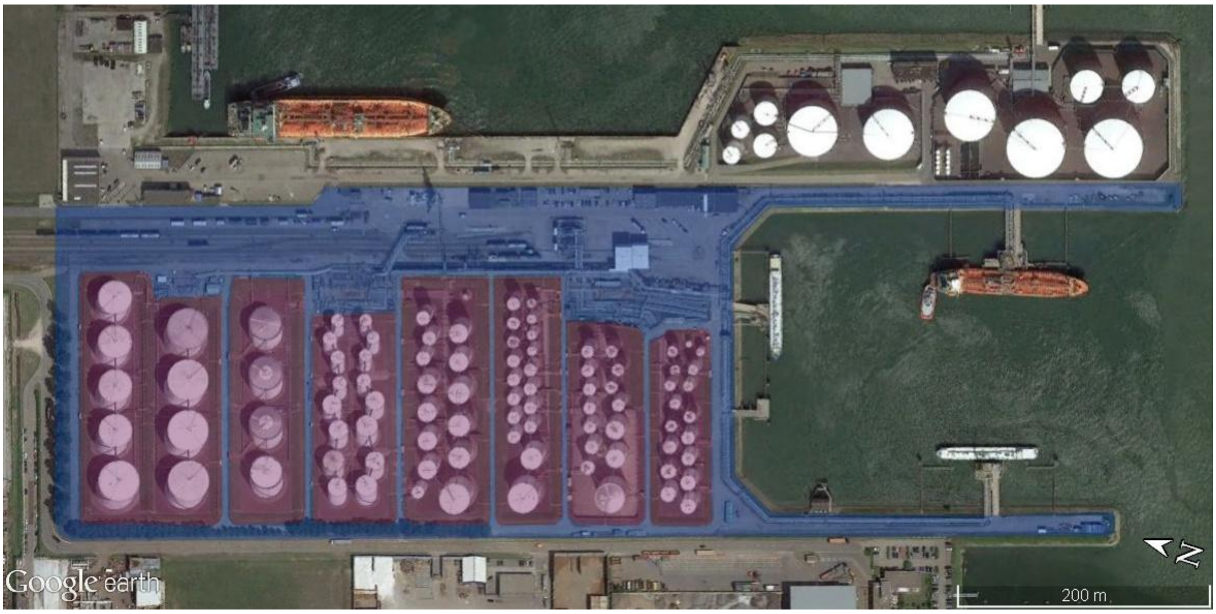


Figure 44: Vopak TTR, Port of Rotterdam. Source: Google Earth

3.2.2 Storage occupancy factor

The average annual storage occupancy (m_s with unit %) -or storage or yard utilisation- is defined as the number of occupied storage slots or occupied storage volume divided by the total number of storage slots or storage volume according to the design capacity. This factor takes into account the fluctuations in required storage capacity due to random arrivals and departures of cargo. The storage occupancy factor is assessed for container, dry bulk and liquid bulk terminals. The uncertainty is assessed by experts.

3.2.3 Average dwell time

The definition used for dwell time in this research is: the time between the moment that a container is unloaded from a vessel and the moment that same container leaves the terminal boundaries, and vice versa. The average dwell time is taken as the yearly average of dwell times of all containers within a certain cargo flow. The cargo flows that are taken into account in this research are import, export and transhipment. For these average dwell times common values are found in literature. However there might be a dependence (relationship) between them when they are considered as random variables. The dependencies, denoted by r, are depicted in Figure 45. Where $r_{2,1}$ stands for the unconditional rank correlation between random variables 2 and 1. $r_{3,1|2}$ means the conditional rank correlation between random variables 3 and 1, given variable 2. The three dependencies are assessed by the experts.

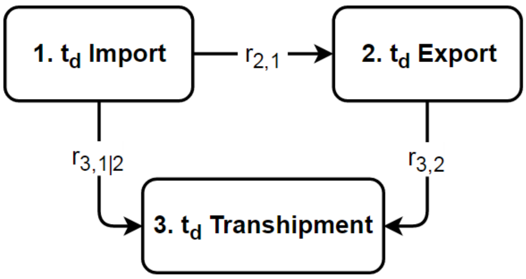


Figure 45: (Un)Conditional rank correlations between the random dwell times. Source: Own work

3.3 The elicitation

The uncertainty elicitation method the *Classical model* is applied to the total terminal factor and the average annual storage occupancy. The dependence elicitation method *conditional probability technique* is applied to the average container dwell times. For this study four experts have been elicited. These four experts all specialise in the field of terminal and port planning. The experts were personally assessed in approximately one hour. The assessments were face-to-face since the probabilistic approach is likely to raise questions. All experts completed two questionnaires; one regarding uncertainty and one dependence. The two questionnaires are included in Appendix IV .

The uncertainty questionnaire consists of ten seed variables (or calibration variables) and six target variables. These ten seeds consist of six questions concerning the total terminal factor and four concerning the average storage occupancy, and thus are related to the target variables. In these questions the expert is asked for his/her estimate of the variable in an actual situation, in this case a marine terminal. The seed variables are selected such that they resemble as much as possible the variables of interest, when also the required information is available. The dependence questionnaire consists of one seed dependency and three target dependencies. Only one seed is used because data -used to determine the dependence- is very hard to come by. As well as for the reasons stated in the introduction. The seed dependency variables are the quarterly container throughput and quarterly number of container vessels in the Port of Rotterdam in between January 1997 and December 2014. These seed variables do not match the target variables which are average container dwell times for import, export and transhipment containers. The experts are however expected to be knowledgeable about all these variables since they occur in the same field of expertise. The seed variable realisations (or actual values) can be found in Section IV.3 of the appendices. The assessment results are presented and discussed in Section 3.4.

3.4 Analysis of the results

This section provides an analysis of the elicitation results and presents the conclusions. These are again divided into uncertainty and dependence. The complete Expert Judgement Elicitation is performed as is described in Appendix III .

3.4.1 Uncertainty

This section first presents a summary of the elicitation results. Then observations of the performance of the experts are provided. Hereafter the uncertainties of the experts are combined by various Decision Makers. As explained earlier a Decision Maker (DM) is a certain weighted combination of experts' uncertainty distributions. The best DM is then chosen and the corresponding resulting probability distributions for the target variables are determined.

3.4.1.1 Elicitation results summary

This subsection presents general observations that can be made regarding the assessment results of the seed and target variables. The experts' uncertainty distributions are given in Section V.1 of the appendices. All experts' conclusions, and motivations for these conclusions, are summarised per questionnaire item in Section V.2 of the appendices.

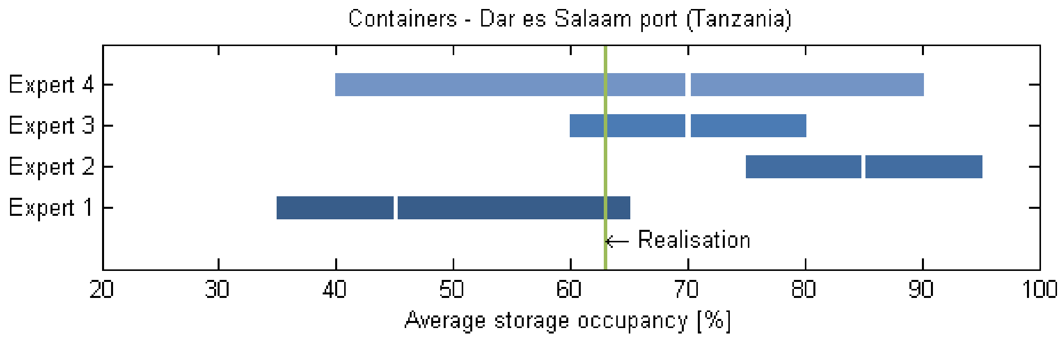
Seed variables

For most seed variables multiple experts tend to arrive at the same conclusions. However they do propose different distributions for all questions. Also their motivations for the conclusions are not always similar; they have their own angle from which they assess the problem. To show this, one of the ten seed question is elaborated on. The mentioned differences in conclusions and distributions is demonstrated by seed question eight, of which the results are depicted in Figure 46. The graph represents the experts' opinions about this single questionnaire seed variable. Each horizontal bar represents the uncertainty between the 5th and 95th percentiles provided by the corresponding expert. The white vertical bars represent their 50th percentile. The true value (or realisation) of the seed variable is depicted by a vertical green line.

The conclusions and motivations for this specific seed question are:

- Experts two and three (E2 and E3) have the same conclusions and motivations: they think that this terminal is near its maximum capacity since they know an expansion is planned (motivation), therefore utilisation will be high (conclusion).
- E3 also states that for container terminals an occupancy of 70% is high while for dry and liquid bulk terminals the percentages are lower. Eventhough E2 and E3 have similar conclusions their uncertainty distributions are not the same.
- E4 has the same conclusion but a different motivation; he thinks that dwell times in Africa are larger (motivation), so that probably leads to a higher yard utilisation (conclusion). He also thinks that in Africa strange situations can occur so the expert uses a large uncertainty.

For the seed questions in seven of the ten cases at least two experts give the same motivation for their shared conclusion. For only one question two experts (E2, E4) give contradicting conclusions. The concerning seed variable is the total terminal factor for the Vopak TTR liquid bulk terminal in Rotterdam. E1 provides a similar distribution as E4. The consequences are discussed in 3.4.1.3.



Notes: Bar limits are 5th and 95th quantiles, white stripes are medians and green line is the actual value.

Figure 46: Uncertainty distributions of the experts for seed question 8. Source: Own work

Target variables

This paragraph discusses the general observations that can be made from the elicitation results of the target variables.

- Expert one (E1) provides asymmetrical uncertainty distributions. The medians of his estimates for the total terminal factor target variables -for the three terminal types- are similar.
- E2 uses for his target variables similar medians as for his estimates of comparable seed variables. He chooses his uncertainty interval larger for the target questions.
- E3 chooses the target total terminal area distributions exactly the same as for the (first in the sets of two) corresponding seed variables. His estimated interval widths for all target variables are equal to his seed variable estimates.
- E4 uses for his target variables similar medians as for his estimates of comparable seed variables. His interval widths are much smaller for the target total terminal factor variables than for corresponding seed variables, this in contrast to E2. For the storage occupancy target variables his interval widths are similar to the those of the corresponding seed questions.

A demonstration of some of these observations is depicted in Figure 47. Here the upper plot shows the results of the experts for the seed variable concerning the Kinder Morgan dry bulk terminal in the USA. The lower plot shows corresponding target variable results for the total terminal factor of a dry bulk terminal in general.

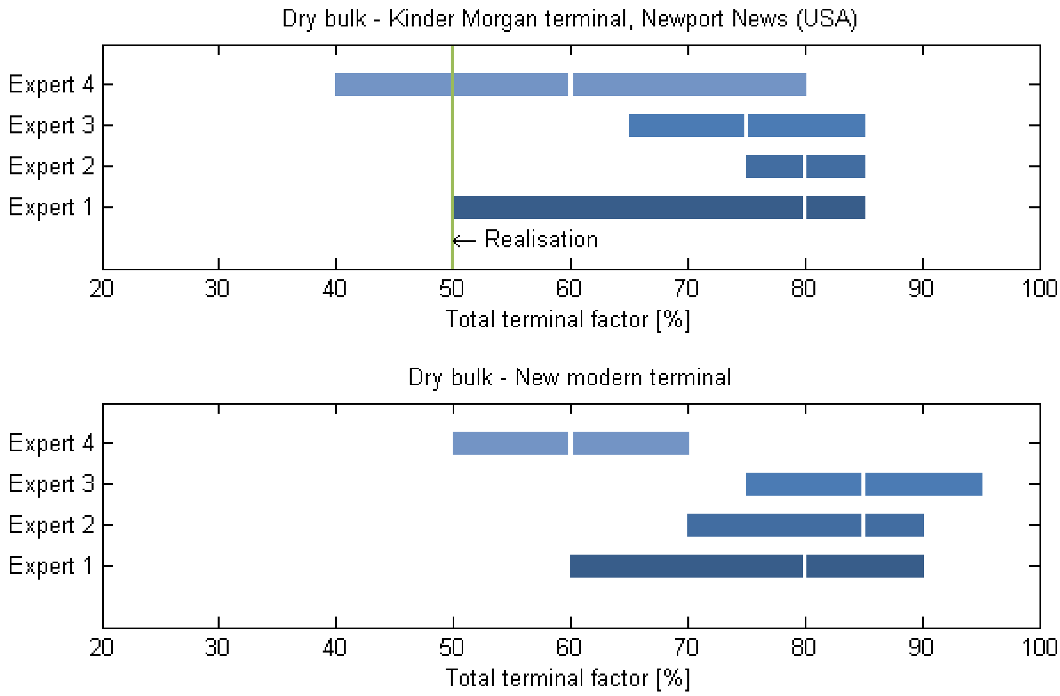


Figure 47: Uncertainty distributions of the experts for seed question 4 (upper) and target question 12 (lower). Source: Own work

3.4.1.2 Experts performances

As is explained in Section III.1 of the appendices, the uncertainties of the experts are judged by means of their calibration and information scores (considering seed variables only). Calibration quantifies the extent to which the estimates of the expert concur with the actual values (or realisations), in a statistical sense. The calibration score is an absolute score and lies in the interval (0, 1), in which 1 equals perfect calibration. Information quantifies the extent to which an expert is certain. The information score is determined relative to another distribution. This distribution is dependent on the uncertainty estimates of the other experts. The information score scale is therefore not absolute. Since information does not take realisations into account, information scores can be determined for only the seed or both seed and target questions.

The total score (or un-normalised weight) of an expert is the product of the calibration and information scores. Here holds the higher the weight the better. The calibration score has the most influence on the total score since the calibration score increases more rapidly. Table 37 presents the mentioned scores and the resulting total score per expert. Two different information scores are computed by considering only seed variables or both seed and target variables. Large differences between both information scores can indicate that an expert answers the seed and target questions differently. This is not desired in an elicitation. In this assessment this is however not the case, as can be observed.

Experts 2 and 3 both have low calibration scores. Expert 2 however has a high information score. Expert 3 is a little bit less certain and has slightly better calibration results. However the calibration score is still low compared to experts 1 and 4, therefore resulting in a low weight. This, as calibration has a larger effect on the un-normalised weight. Expert 1 and 4 both have good calibration scores as well as information scores, this results in good un-normalised weights (or total scores) for both. Very low calibration scores for the seed variables may originate from the expert not understanding the method or the meaning of the questions themselves. Even though the expert may have good estimates for the target variables, as a result of their calibration scores their opinions are only slightly or not used at all in the Decision Maker. This is further discussed in Section 3.5.

Table 37: Calibration and information scores and the total score of the four experts

	Calibration	Information seed variables	Information all variables	Total score
Expert 1	0.3136	0.5786	0.5604	0.18145
Expert 2	2.39E-08	1.016	0.8417	2.428E-08
Expert 3	5.60E-05	0.7015	0.6602	3.928E-05
Expert 4	0.2895	0.2807	0.3658	0.08126

3.4.1.3 Decision Makers

As is already explained the uncertainties of the experts are weighted on account of their calibration and information scores, this is done by means of the *Excalibur*[23] software. A Decision Maker combines the uncertainty distributions of the experts per item by using a certain weighting method. The considered weighting methods are:

- Global weights: Uses the un-normalised weights. Per expert the weights are the same for all items.
- Item weights: A variation of global weights where each item can have a different set of weights. Uses the individual information scores of the experts per item and the calibration scores to determine a different set of weights for each item.
- Equal weights: The weights are the same for all experts and for all items.

The global and item weights can be optimised. When optimising; an iteration is performed where the minimum allowable calibration score is increased. When experts do not meet the minimum score their uncertainties are not taken into account in the DM. The optimisation ultimately chooses the calibration score for which the un-normalised weight of the DM is maximum. The goal is to choose the DM with the best calibration and information scores. In Table 38 the calibration scores and information scores (considering only seed variables) are given per expert and Decision Maker (with given weighting method). A DM can be seen as a virtual expert.

Table 38: Calibration and information scores for experts and Decision Makers calculated with Excalibur.

	Calibration	Information seed variables
Expert 1	0.3136	0.5786
Expert 2	2.39E-08	1.016
Expert 3	5.60E-05	0.7015
Expert 4	0.2895	0.2807
DMgl	0.5503	0.2379
DMgl_op	0.3136	0.5786
DMit	0.6827	0.2658
DMit_op	0.6827	0.2660
DMeq	0.1135	0.1187

Notes: DM = Decision Maker, gl = global weights, it = item weights, eq = equal weights, op = optimised.

[23] Originally developed at TU Delft, now maintained by Lighttwist Software.
URL: http://www.lighttwist.net/wp/excalibur

The DM with the highest calibration and total information scores is desired. In principle all DM's are acceptable to be used since the calibration scores are higher than the 0.05 limit. However equal weights (DMeq) can be discarded since the scores are lower than those of the best experts. Global optimised weights (DMgl_op) does not combine distributions but only uses the distributions of expert 1, this is not preferable. Global weights (DMgl) scores a little bit lower on calibration and information than item weights (DMit) and item optimised weights (DMit_op). The latter two have almost identical scores, DMit_op is however a little bit better on estimating the distributions with more certainty (smaller intervals). It can be observed that DMit_op has more than twice the calibration score of the highest scoring expert. Using this Decision Maker therefore highly increases the accuracy of the resulting uncertainty distributions compared to for example using only the best scoring expert or taking the average of all the experts. Figure 48 demonstrates some of the mentioned observations for the total terminal factor seed variable; concerning a dry bulk terminal in Shanghai. The distributions of the various Decision Makers for the specific variable are depicted.

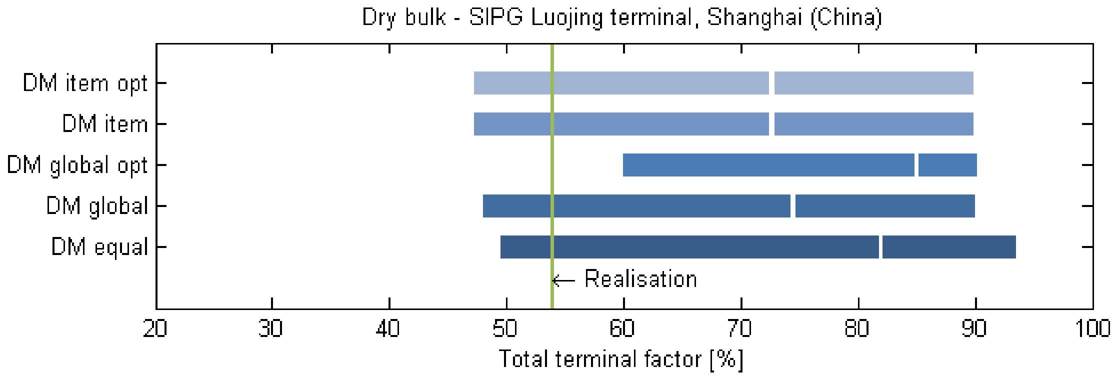


Figure 48: Uncertainty distributions of all DM's for seed question 3

As discussed in Section 3.4.1.1; E2 and E4 have contradicting conclusions for the question about the Vopak TTR liquid bulk terminal in Rotterdam. However due to the choice for DMit_op, E1 and E4 receive by far the highest weights so the DM is not affected by this disagreement. Which expert gives the right conclusion can of course not be determined in this study. The uncertainty distributions of the experts and the DMit_op are depicted in Figure 49. Similar graphical representations of the distributions for all questionnaire items are given in Section V.1 of the appendices.

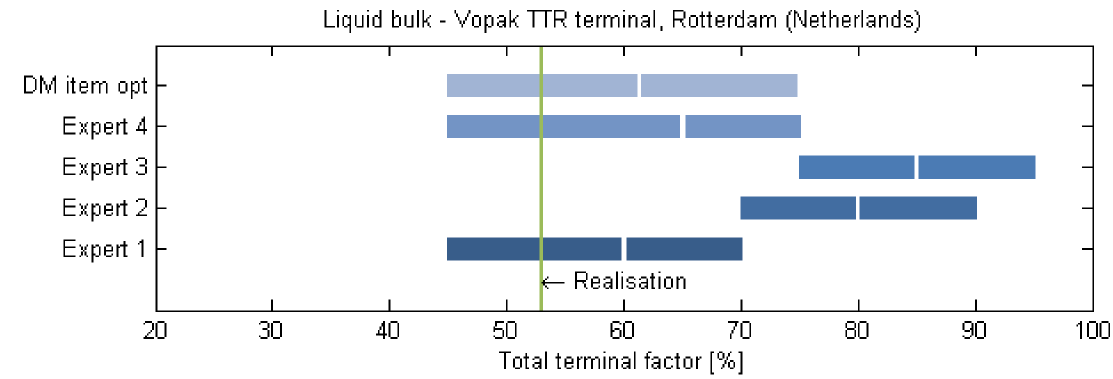


Figure 49: Uncertainty distributions of the experts and the chosen DM for seed question 6. Source: Own work

3.4.1.4 Resulting distributions

Using the Decision Maker with the optimised item weighting method (DMit_op) results in probability distributions for the six target variables. The 5th, 50th and 95th quantiles are calculated and the lower and upper 5% of the distributions can again be estimated by the *k% overshoot rule* with k = 10 (see Section III.1 of the appendices). This results in the quantiles presented in Table 39.

Table 39: Uncertainty distributions as a result of the Expert Judgement Elicitation

		Quantiles				
		q_0	q_5	q_{50}	q_{95}	q_{100}
Total terminal factor [%]	Containers	46.00	52.24	65.60	74.80	94.00
	Dry bulk	45.50	50.41	64.40	88.75	99.50
	Liquid bulk	45.50	50.62	63.22	75.00	99.50
Average storage occupancy [%]	Containers	40.50	60.34	73.09	80.00	94.50
	Dry bulk	41.00	60.80	79.73	85.00	89.00
	Liquid bulk	41.00	48.71	65.00	81.29	89.00

From these distributions cumulative probability distributions can be made by linear interpolation. The cumulative distributions are used for the common values of parameters in Chapter 2 and as standard values in the computer tool. Random values can be drawn from these cumulative distributions by using the *Random Sampling* method which is described in Section 4.3.1. The cumulative probability distributions are depicted in Figure 50.

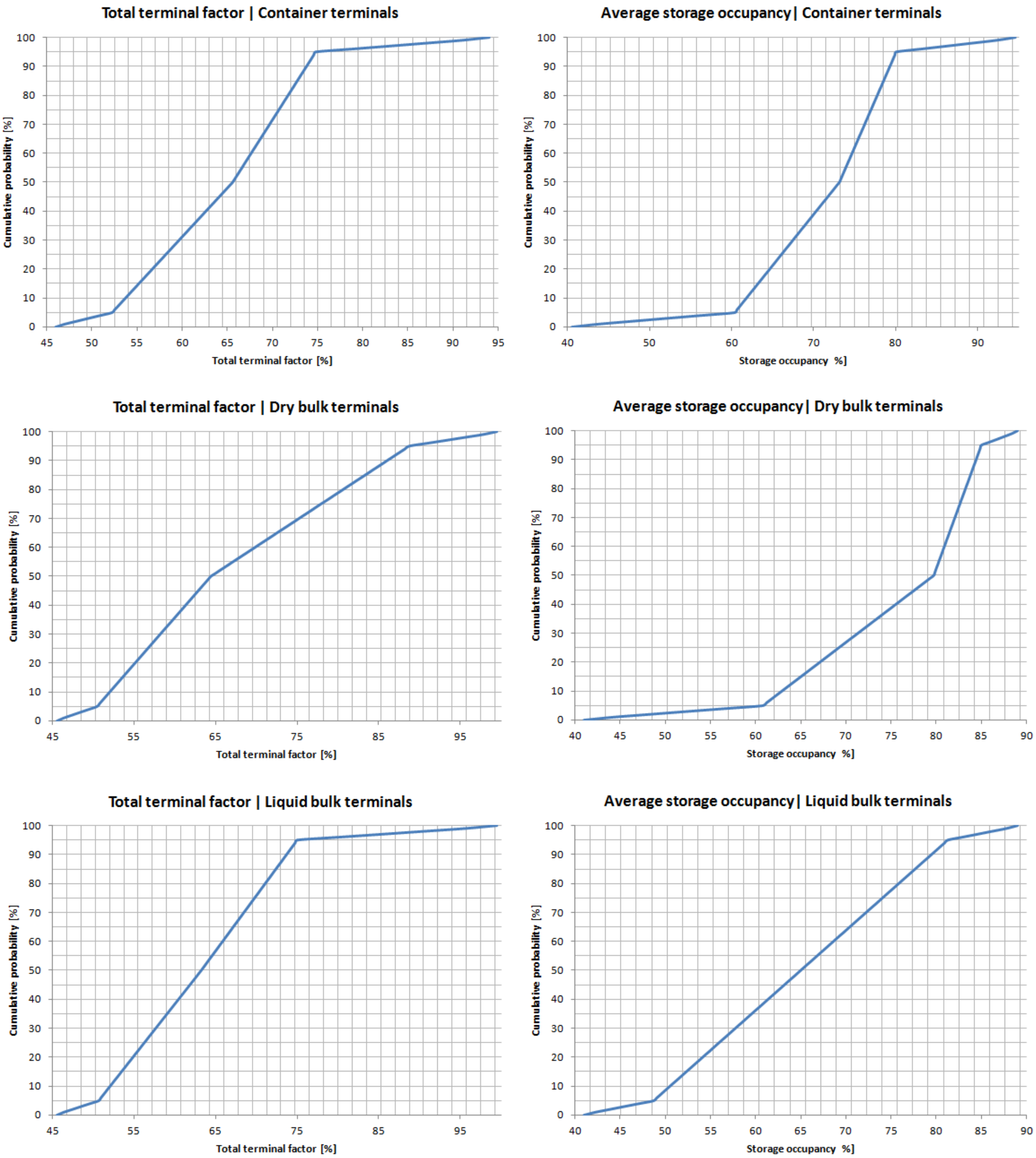


Figure 50: Cumulative probability distributions as a result of the EJE on uncertainty. Source: Own work

These distributions are constructed from the different opinions of experts. They give an indication of what the values of the variables can be. This study (especially Chapter 2) aims to provide a general overview of the different terminal types with their main elements, design rules and common values of variables. In some situations other values may be more adequate to be used.

The tool allows the user to specify custom distributions, this also holds for the total terminal factor and estimated storage occupancy. Even though the distributions are only based on the estimates of experts one and four they are valid results and can therefore be used.

3.4.2 Dependence

For the elicitation the four experts were asked the following target questions:

1. Suppose the dwell time of import containers is observed above its median value. What is the probability that the dwell time of export containers will also be observed above its median value?
2. Suppose the dwell time of export containers is observed above its median value. What is the probability that the dwell time of transhipment containers will also be observed above its median value?
3. Suppose the dwell time of import and export containers are observed above their median values. What is the probability that the dwell time of transhipment containers will also be observed above its median value?

This section first presents a summary of the elicitation results. Then observations of the performance of the experts are provided. The best pooling method is chosen and the corresponding resulting correlation matrix for the target variables is determined.

3.4.2.1 Elicitation results summary

The experts give quite similar probabilities for the seed question, only expert three thinks the two random variables are independent. In fact experts one and four exactly predict the actual correlation of the two random variables. In Figure 51 the true seed probability is depicted in green. Due to the fact that only one seed is used these two experts dominate when the experts' estimates are combined. Of course this does not mean that experts two and three are by definition wrong about the target questions.

For the target questions it cannot be concluded that certain experts give similar estimates. The most notable are the estimates of expert four since they seem to differ quite much compared to the other experts' estimates. In Figure 51 also the target estimates of the experts are depicted. A summary of the motivations of the experts is presented:

- Experts one and two (E1 and E2) think that import and export dwell times are both dependent on customs, while transhipment is not. They therefore choose a medium positive dependence. Their estimated probability for target question two is smaller, since they argued that transhipment is not influenced by customs. Therefore the correlation between export and transhipment dwell times is smaller. For the last target question the experts think that in this situation (when import and export dwell times are high) the terminal does not work efficiently. So the transhipment dwell time will also be higher, resulting in a larger probability. Despite having the same motivations they use different probabilities.
- E3 thinks that export and import dwell times are intertwined, he therefore chooses a large probability for target question one. He thinks that export and transhipment dwell times are not much related since export flows can be planned while for transhipment this is much more difficult. Despite this he chooses a small positive dependence for question two. The expert states that when the import dwell time is also taken into account -next to export and transhipment- there is no dependence any more. For target three he therefore chooses independence.

- E4 thinks that import and export dwell times are independent since they are two different modes of transport. For the second target question the expert argues that for example when an STS crane is impeded this will affect both export and transhipment dwell times. He therefore chooses a relatively high dependence. For the last question he uses the same motivation as E1 and E2, his chosen probability is however much larger.

For their full motivations reference is made to Section V.2 of the appendices.

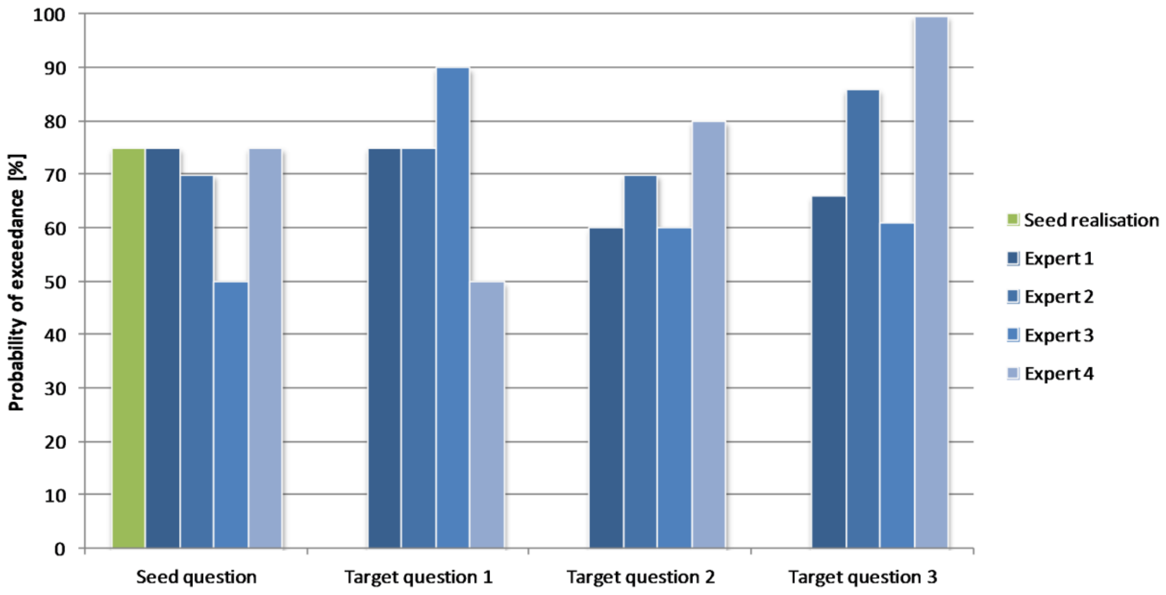


Figure 51: Probabilities estimated by the experts, as answers to the seed and target questions.

3.4.2.2 Experts performances

As described in Section III.2 of the appendices, the experts are scored by means of a dependence calibration score (d-calibration score with symbol D). This d-calibration score is introduced in Morales-Napoles & Worm (2013) and makes use of the *Hellinger distance*. The experts are scored on their estimate of a correlation between two seed variables; namely the quarterly container throughput (C_q) and quarterly number of container vessels (n_{ships}) in the Port of Rotterdam in between January 1997 and December 2014. The expert's estimates are in the form of a probability, this probability can be converted to a rank (r) or product moment correlation (ρ) for a normal *copula*[24] by using the theory provided in the appendix. The correlations are represented by a correlation matrix. In these matrices each item represents a dependence between two variables, the main diagonals are therefore one. Since for the seed question only one dependency between two variables is considered the matrices are 2 x 2. The seed correlation matrix therefore has the following form:

$$\begin{array}{cc} & \begin{array}{cc} C_q & n_{ships} \end{array} \\ \Sigma_C = & \begin{bmatrix} 1 & \rho \\ & 1 \end{bmatrix} \begin{array}{c} C_q \\ n_{ships} \end{array} \end{array}$$

The symmetrical product moment correlation matrix of the seed variable realisation (or actual value) is:

[24] A copula is a multivariate probability distribution of which the marginal probability distributions are uniform; Genest & Favre (2007).

$$\Sigma_C = \begin{bmatrix} 1 & 0.7078 \\ & 1 \end{bmatrix}$$

The symmetrical product moment correlation matrices of the experts (E1, ..., E4) are represented by $\sum_{E1}, \dots, \sum_{E4}$. Expert 3 thinks the two variables are independent, his correlation ρ is therefore zero.

$$\Sigma_{E1} = \begin{bmatrix} 1 & 0.7071 \\ & 1 \end{bmatrix}, \Sigma_{E2} = \begin{bmatrix} 1 & 0.5878 \\ & 1 \end{bmatrix}, \Sigma_{E3} = \begin{bmatrix} 1 & 0 \\ & 1 \end{bmatrix}, \Sigma_{E4} = \begin{bmatrix} 1 & 0.7071 \\ & 1 \end{bmatrix}$$

To pool the experts' estimates the equal and global weights methods are considered. For the equal weights method every expert gets the same weight. For the global weights method a calibration threshold is used that is increased in an iterative process. When the individual d-calibration score of an expert is below this threshold the weight of that expert is zero. The remaining experts their weights are based on the contribution of the individual calibration scores to the total. The weighted combination of each iteration step (each increase of the threshold) is treated as a virtual expert of which the d-calibration is determined as well. The weighted combination with the highest calibration score is selected. The resulting d-calibration scores for the two different weighting methods are listed in Table 40. It can be concluded that the use of global weights results in the best calibration of the pooled experts' estimates.

Table 40: d-calibration scores per weighting method (combination of experts)

	d-calibration score
Equal weights	0.8635
Global weights	0.9994

The optimum calibration threshold for the global weights is 0.9130 which leads to the use of experts one and four only, see Table 41 for the individual d-calibration scores. These two experts almost exactly predicted the true correlation, the d-calibration is therefore practically 1. It is therefore also quite obvious that the combined calibration score would be lower when expert two and three would be included. The d-calibration scores of experts two and three are good as well, this indicates that their target estimates are also valuable. Due to the near perfect seed estimates of experts one and four they are however not taken into account in the pooled dependencies. This situation is exceptional and can be prevented by using more complex seed variables; such as seeds with conditional dependencies (like the target dependencies in this study). The experts are less likely to perfectly predict the seed dependencies in that case.

Table 41: Dependence calibration score and weight per expert

	d-calibration score	**Weight**
Expert 1	0.9994	0.5
Expert 2	0.9125	0
Expert 3	0.6816	0
Expert 4	0.9994	0.5

Due to the global weights scheme, the average of the estimates is taken per dependency of experts one and four. As can be seen in Figure 51; E1 and E4 give the most opposing estimates for the target dependencies, while both perfectly agree on the seed variable. Only for the first target question E3 instead of E1 gives an opposing estimate to E4. E3 however has the lowest d-calibration score, so this is ignored for this matter. The global weights scheme, by taking the average of E1 and E4, therefore gives a good representation of all the individual experts' estimates.

3.4.2.3 Resulting correlation matrix

For combining the target dependency estimates of the experts, their correlation matrices ($\sum_T$) and weights are required. Since for the target questions three dependencies between three variables are considered the matrices are 3 x 3. The weights are calculated in Section 3.4.2.2, the symmetrical matrices are presented here:

$$\Sigma_T = \begin{array}{c} \begin{array}{ccc} t_{d,import} & t_{d,export} & t_{d,transh} \end{array} \\ \begin{bmatrix} 1 & r_{2,1} & r_{3,1} \\ & 1 & r_{3,2} \\ & & 1 \end{bmatrix} \end{array} \begin{array}{l} t_{d,import} \\ t_{d,export} \\ t_{d,transh} \end{array}$$

$$\Sigma_{T,E1} = \begin{bmatrix} 1 & 0.6902 & 0.4258 \\ & 1 & 0.2963 \\ & & 1 \end{bmatrix}, \Sigma_{T,E2} = \begin{bmatrix} 1 & 0.6902 & 0.8763 \\ & 1 & 0.5697 \\ & & 1 \end{bmatrix}$$

$$\Sigma_{T,E3} = \begin{bmatrix} 1 & 0.9464 & 0.3030 \\ & 1 & 0.2963 \\ & & 1 \end{bmatrix}, \Sigma_{T,E4} = \begin{bmatrix} 1 & 0 & 0.5802 \\ & 1 & 0.7953 \\ & & 1 \end{bmatrix}$$

Pooling the experts' opinions by means of the global weights method results in the target correlation matrix $\sum_R$. This matrix is used in the tool when drawing random numbers for the import, export and transhipment dwell times. As already explained the correlations are a measure of strength and direction of the relationship between two variables, ranging from -1 to 1. The target rank correlation matrix and product moment correlation matrix are:

$$\Sigma_R = \begin{bmatrix} 1 & 0.3394 & 0.5030 \\ & 1 & 0.5410 \\ & & 1 \end{bmatrix}_{rank} : \begin{bmatrix} 1 & 0.3536 & 0.5207 \\ & 1 & 0.5590 \\ & & 1 \end{bmatrix}_{product\ moment}$$

These matrices are equivalent since the normal copula is used. The relation between the rank correlation (r) and product moment correlation (ρ) is: $\rho = 2 \cdot \sin(r \cdot \pi/6)$, reference is made to Equation (36). The product moment correlation matrix is used in the tool, as the *RiskAMP* add-in requires this. The rank correlations are depicted in Figure 52.

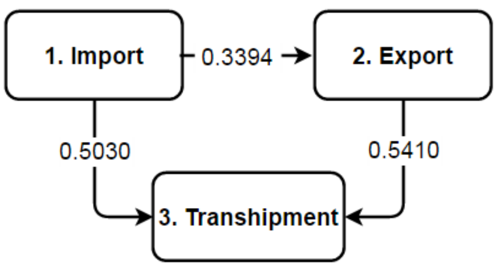


Figure 52: BN with unconditional rank correlations between the average container dwell times. Source: Own work

It can be concluded that there are dependencies between the dwell times of the three different container flows. There are moderate positive relationships between import & transhipment and export & transhipment container dwell times. As well as a weakly positive relationship between import and export container dwell times.

3.5 Discussion

Some of the four elicited experts know each other. This could raise doubt about the results being biased. This is however not the case since the experts did not know the questionnaire questions beforehand and the elicitation documents were collected afterwards.

EJE on uncertainty

For the EJE four experts are assessed. Including more experts may lead to a more complete Decision Maker, since more motivations are taken into account. Most of the assessed experts claim to have more knowledge about container terminals than about dry and liquid bulk terminals.

Even though the calibration and information scores of the DMit_op of all the questionnaire items are quite good, ultimately they are only based on the opinions of two experts. It can be observed from the assessment data that on average the information and calibration scores are the best for the dry bulk terminal variables, the scores for the container and liquid bulk terminal variables are similar but lower. Creating three separate questionnaires, for the three terminal types in combination with a sufficient number of experts only on those specific terminals, may improve the results. This way experts are scored only on their own field of expertise, which can improve their weights for the corresponding target variables. Then the chance that 'good' knowledge is lost, because of low weights, is smaller. The number of seed variables in this elicitation is sufficient.

EJE on dependence

For the dependence assessment only one seed is used. This choice is made since suitable data is very hard to come by. One goal of the EJE on dependence is finding the correlations between the average container dwell times of the different cargo flows. Another goal is to introduce this method in this field of expertise. For the latter goal the importance is that the technique is presented, regardless the number of seed variables. Moreover in this study two experts perfectly estimated the seed correlation and therefore have dominating weights. This is an exceptional situation and can be prevented by asking the experts about conditional dependencies. Accordingly it is recommended to use seed variables with a similar number of (conditional) dependencies as for the target variables. Nevertheless the results in this study are a good representation of the individual experts' opinions.

In the study Morales-Napoles et al. (2016) it was concluded that experts who perform well in an uncertainty assessment do not necessarily show good performance in a dependence assessment with similar variables. Calibration scores therefore have to be determined separately. The results of the current study show that experts one and four score best in both the uncertainty and dependence assessments. This highlights that the same experts scoring well in an uncertainty and dependence assessment is possible but is not a certainty, according to Morales-Napoles.

4 THE TOOL

This chapter is dedicated to the computer tool that is created from the ground up as part of this study. The tool is used to compute terminal dimension and costs, this is elaborated on in the first section. Hereafter the structure of the tool is considered. By the structure is meant: information about the programming language and the framework of the main elements of the front-end and back-end of the tool.[25] The tool is the property of Witteveen+Bos and is therefore not included in this report.

Chapter goal: Providing information about the application, assumptions & restrictions, computations and software structure of the tool.

4.1 Tool function

The tool determines the required dimensions, quantities and construction costs of a marine terminal, which are listed in Section 4.2.2. It can function as a quick help in estimating the main terminal dimensions as well as for more detailed aspects like the number of vessel (un)loading equipment or yard handling equipment. An estimate of the direct costs is made by using the calculated dimensions and quantities in combination with unit prices (Section 2.4).

When certain information is missing in the early design phases of a project not all required parameter values may be known. Therefore standard (or common) values for these input parameters are presented in the literature study (Sections 2.1-2.3) and by means of Expert Judgement Elicitation (Chapter 3). Thus when not all required input parameters are obtained for the project of the terminal designer, the standard values can be used to give a proper estimate of the terminal dimensions and costs. The tool helps the terminal planner by making it possible to insert the uncertainties (in the form of uncertainty distributions) into the tool instead of having the planner assume a single value. Consequently the tool performs a probabilistic calculation which results in probabilities of occurrence for the terminal dimensions and costs.

Growth scenarios of for example the estimated throughput over a certain number of years cannot specifically be inserted in the tool. However, it is possible to perform separate computations with input corresponding to certain moments in the growth path. The results of the different computations can then be used to develop a phased master plan for the terminal.

4.2 Tool structure

This section covers the choice of the programming language used for the tool and it defines the main elements of the tool and their relations.

[25] By front-end the user interface is meant. By back-end the underlying software code is meant.

4.2.1 Software

The tool is realised in Microsoft Excel. Excel is chosen since it is a widely used program; at Witteveen+Bos similar modelling tools are often made in Excel. The tool makes use of a lot of user input and standard values of parameters, the cells in an Excel worksheet can function perfectly as a way to input and output values. Moreover when insights change or minor errors are discovered it is quite easy to adjust the tool by people with minor programming skills.

The input and output of information takes place in the worksheets that are directly accessible to the user. The calculations and logics however take place in coded modules; the code is written in Visual Basic for Applications[26] (VBA). VBA is based on the object oriented standalone programming language Visual Basic. VBA however is not standalone and requires a host application like Excel. By separating the input and output from the operations the tool in itself is more transparent. The choice to implement the calculations and logics in VBA is made because using the cells in Excel for this purpose would lead to a chaotic collection of code of which the overview is easily lost and which is very hard to debug.

For the probabilistic calculations that are performed in the tool the Monte Carlo method is used, this method is elaborated on in Section 4.3. To be able to perform a Monte Carlo simulation in Excel the tool uses a paid Excel add-in called RiskAMP[27]. The tool only uses RiskAMP's functions to generate random numbers from given random distributions and its functionality to include dependence between random variables. For the writer it is possible to create these functions himself however due to time limitations the choice is made to use RiskAMP.

4.2.2 Worksheets

The Excel tool consists of nine worksheets, each with its own function. In general the sheets are the input/output, standard data, unit costs and calculation sheets. These worksheets interact by means of the VBA code, elaborated on in Section 4.2.3. This is depicted in Figure 53. A summary of the most important aspects of the different sheets is given in this subsection.

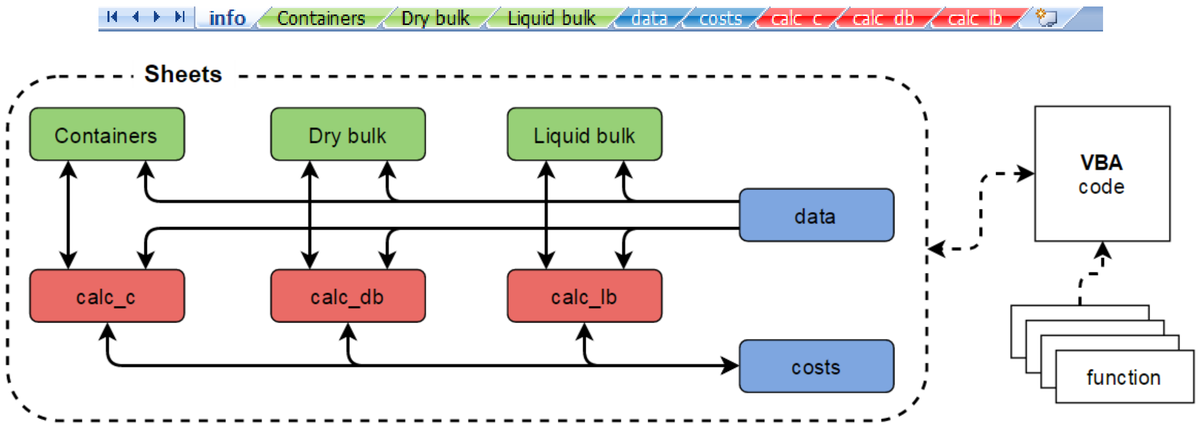


Figure 53: The nine worksheets in Excel (upper). The relations between worksheets and VBA code (lower). Source: Own work

[26] For more information about VBA, URL: https://msdn.microsoft.com/en-us/library/office/gg264383.aspx

[27] For more information about RiskAMP, URL: https://riskamp.com/

4.2.2.1 *Input/output sheets*

The *Containers*, *Dry bulk* and *Liquid bulk* sheets form the input/output sheets. These sheets consist of separate input and output parts.

Input

The input section of these sheets consists of all the calculation variables that are divided into categories; general, cargo flows, quay, storage yard and vessels/basin. A small part of the Containers input sheet is depicted in Figure 54 (upper). For each variable one of four uncertainty distributions can be chosen via a dropdown menu, examples of these distribution types are depicted in Figure 55. For the chosen distribution the corresponding parameters have to be specified, this is done with a separate window that can is opened by clicking the '...' button. The uniform distribution input window is displayed in Figure 54 (lower left). Right from the '...' button the values that are used for the computation are displayed. A small red triangle notifies the user that more information about the corresponding variable or option is available, this information is shown when the mouse is hovered above the triangle, see Figure 54 (lower right).

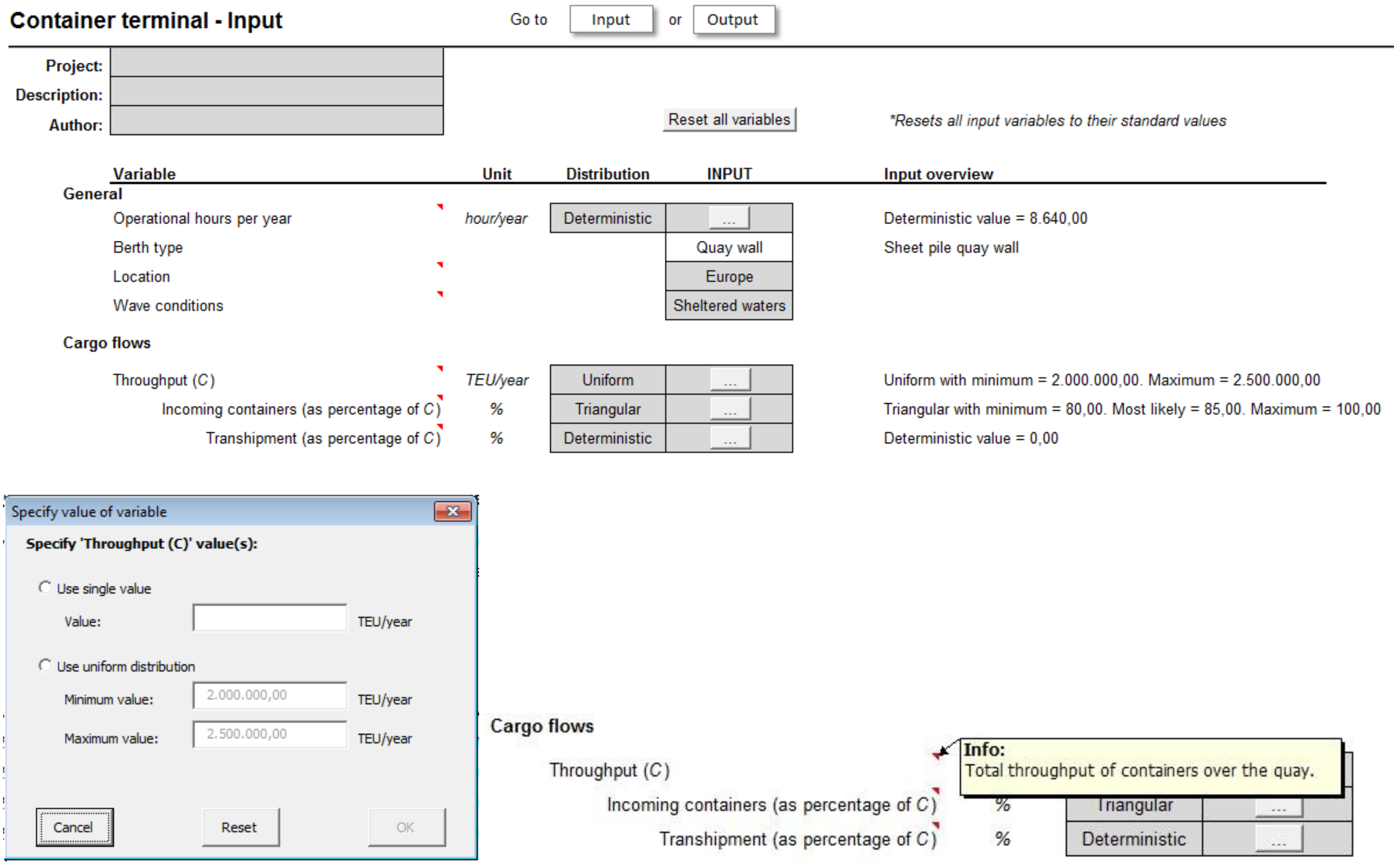


Figure 54: Part of container terminal input sheet (upper), uniform distribution input window (lower left), information label of the throughput variable (lower right). Source: Own work

As mentioned in the previous paragraph the four distribution types that can be used for the input parameters are depicted in Figure 55.

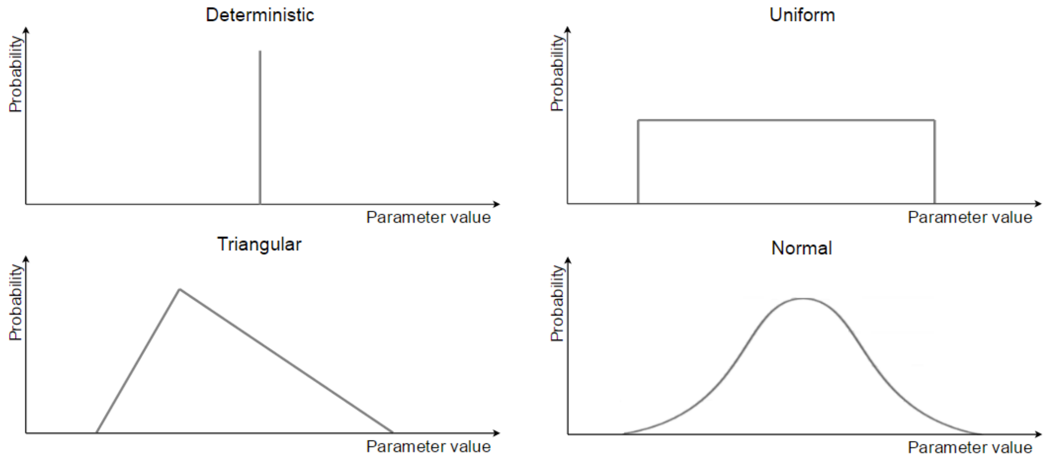


Figure 55: Examples of the four possible uncertainty distribution types. Source: Own work

For many variables common values of parameters are included in the tool. These values can be used for a specific variable by using the 'Reset' button in the uncertainty window. If the user wants to reset all variables in the selected input sheet the 'Reset all variables' button can be used. Some non-numerical variables (e.g. yard equipment type) are also required, these can be chosen via a dropdown menu. For dry bulk en liquid bulk terminals the cargo type(s) have to be selected. Most of the input parameters have to be provided for each cargo type separately. The tool performs the calculations for each cargo type separately and finally sums them up. For container terminals the standard berthing object is a quay wall since jetties are almost never used at container terminals. For dry bulk terminals a choice can be made between a quay wall or jetty because both are used in practice. For liquid bulk terminals the standard berthing object is a jetty, since quay walls are not common. These limitations are made to reduce the tool's complexity.

The number of iterations of the Monte Carlo simulation must be specified in the input section as well. The inflation parameters must be specified as well. These parameters are the year until which the inflation has to be calculated and the average annual inflation rate. These options are depicted in Figure 56. A recommended number of iterations -based on the case study- is a 1000. Too quickly see the effect on the results, of changes to the input, a smaller number of iterations (e.g. 250) can be used.

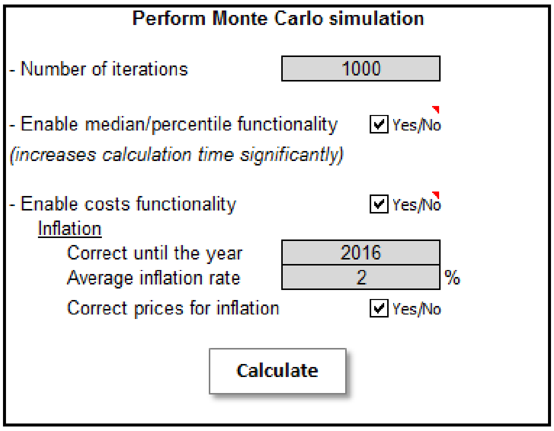


Figure 56: Calculation properties. Source: Own work

Output

The output section displays the results of the calculations. Since probabilistic calculations are performed the results are probability density distributions (in the form of histograms). These histograms are in other words relative frequency plots, an example is depicted in Figure 57. The relative frequency (or probability of occurrence) that a result falls in a certain range (or bin) of results is represented on the vertical axis. Each value on the horizontal axis represents the upper boundary of a bin, the previous value represents the lower boundary of the same bin. The lower limit of the very first bin is not given, but this bin has the same width as the others. All the computation results are given below, for dry and liquid bulk terminals the other results are shown for each cargo type that is selected.

- Main results:
  - Quay length (zero when a finger pier jetty is selected. For an island berth jetty this length is the required berthing structure length).
  - Total terminal area
  - Dredging depth
- Other results for a container terminal:
  - Number of berths
  - Annual berth productivity
  - Number of STS cranes
  - Number of equipment between quay and yard
  - Quay length from berth capacity check
  - Quay length from crane spacing check
  - Total gross storage area
  - Gross storage areas for import, export, transhipment, empties and CFS
  - Number of storage yard equipment
  - Total terminal area from storage factor check
- Other results for a dry bulk terminal, results are divided per cargo type:
  - Number of berths
  - Number of jetties
  - Berth productivity of unloading and loading equipment
  - Total number of unloading and loading equipment
  - Required capacity (in weight and volume) of storage
  - Total number of stacking and reclaiming equipment
  - Lane length of the stockpile or stockpile length in the storage shed or number of silos.
  - Terminal area
  - Terminal area from storage factor and capacity ratio and from a single shipload
- Other results for a liquid bulk terminal, results are divided per cargo type:
  - Number of jetties
  - Jetty trestle length
  - Berth productivity of unloading and loading equipment
  - Required capacity (in weight and volume) of storage
  - Number of tanks
  - Number of tank groups
  - Volume of sand required for the bunds
  - Terminal area
  - Terminal area from storage factor and capacity ratio and from a single shipload

For the ‘other results’ only the value of a user-specified quantile is provided. The probability distribution of these additional results can be called for individually. When for dry and/or liquid bulk terminals multiple cargo types are selected the main results show the sum of the individual results.

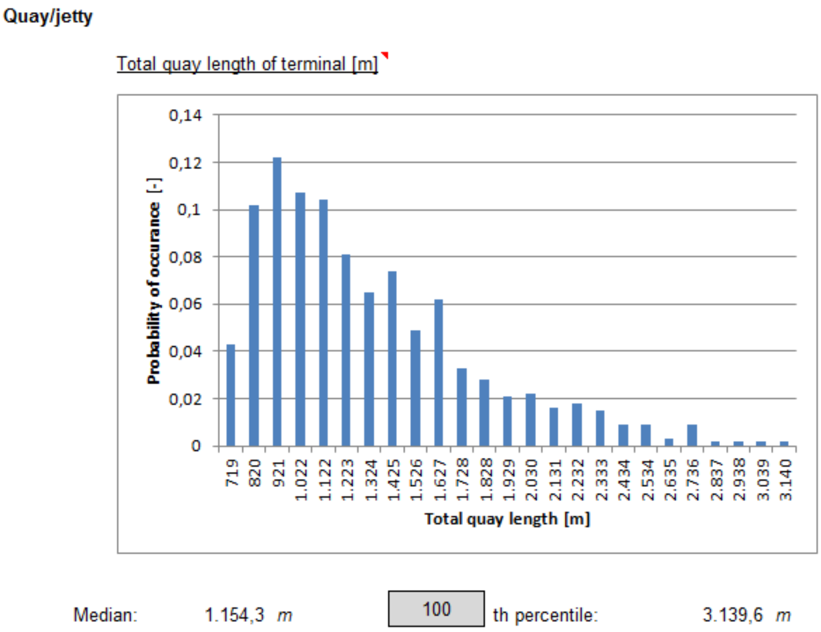


Figure 57: A main tool result; histogram of the required quay length of an example project. Source: Own work

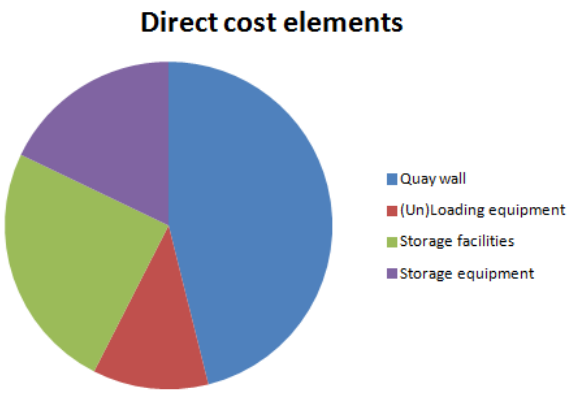
Another output are the estimated terminal construction costs that are computed by means of the unit costs presented in Section 2.4. The main cost items -per terminal type- are:

- Container terminal
  - Quay wall: Costs including the supply of material and the required man-hours.
  - Pavement: Costs for the supply and construction of the terminal pavement. This includes the stabilising sand layer underneath the pavement.
  - STS cranes: Investment costs, excluding crane rails. The foundation is not directly taken into account, however a quay wall partly bears the weight of the equipment. The foundation is therefore partly included in the unit costs of a quay wall; if the equation of de Gijt is used.
  - Terminal equipment: Investment costs of equipment between the quay and storage yard and on the yard itself.
  - CFS: Costs for the construction of a warehouse structure.
- Dry bulk terminal
  - Quay wall/jetties: Costs including the supply of material and the required man-hours.
  - (Un)Loading equipment: Investment costs of the loading and unloading equipment, excluding rails. Regarding the foundation, see STS cranes.
  - Storage facilities: Costs including the construction of:
    - Terminal pavement, for wind-row stockpiles.
    - Warehouse structure, for storage sheds.
    - Silos.
  - Storage equipment: Investment costs of the stacking and reclaiming equipment, excluding rails and foundation.
- Liquid bulk terminal
  - Jetties: Costs including the supply of material (concrete, steel, tubular steel piles, bollards, fenders, loading arms and quick release hooks) and the required man-hours.
  - Tanks: Costs including the supply and construction of the tanks.
  - Bunds: Costs including the supply and handling of the soil.

Cost elements that are not included are roads, buildings, train and crane rails, belt conveyors and pipelines. The main direct cost items, that can consist of multiple terminal elements, are listed and a *pie chart* displays this information graphically. The costs are given for the user-specified percentile; as the costs are also represented by a probability distribution. The total construction costs are computed from the total direct costs using the SSK definitions (reference is made to Section 2.4.1). When for dry or liquid bulk terminals multiple cargo types are selected the presented costs are a summation of the costs per cargo type. An example is depicted in Figure 58 in which the direct, indirect, contingency and resulting construction costs of a dry bulk terminal are shown. These costs correspond to the 80% quantile.

SSK cost estimate

Show results of: 80 th percentile



Direct costs items:				
Quay wall			€	65,532,800
(Un)Loading equipment			€	16,249,092
Storage facilities			€	34,969,970
Storage equipment			€	25,429,460
~~Conveyors/pipelines, roads, buildings~~				- +
Direct costs			**€**	**142,181,322**
Additional direct costs	15.0	%	€	21,327,198 +
Direct costs incl. allowance			**€**	**163,508,521**
Indirect costs	25.0	%	€	40,877,130 +
Costs foreseen			**€**	**204,385,651**
Contingency	20.0	%	€	40,877,130 +
Total construction costs			**€**	**245,262,781**

Figure 58: Overview of the direct and total construction costs of an example project. Source: Own work

4.2.2.2 Standard data and unit costs sheets

The standard *data* sheet contains literature study results (see Chapter 2) that can be used for calculations. The sheet contains tables with common values for the calculation variables per terminal type. Per variable the distribution with corresponding value is listed. The distribution parameters can all be changed by the user if desired, this is however not required. Parameters of multiple distribution types (deterministic, uniform, triangular and normal) can be inserted. Also a table with constants exists in this sheet, these constants are used for the computations and are all deterministic. The data sheet also contains equipment properties and benchmarks that are sorted in tables and that are used by the tool.

The unit *costs* sheet has the same function as the data sheet but it stores unit prices/costs. The unit costs that are used for the current calculation are stored in this sheet, these can be changed by the user -in the same way as the common values of variables in the data sheet- if desired. Also standard values for these costs are stored in this sheet, these standard costs are treated in Section 2.4. Per terminal type the costs used for calculations can be changed to the standard costs by using the 'Reset to standard' button. For each cost item the year of the corresponding price level is given. Over the period between that year and the year specified in the input sheet the inflation is calculated; but only if 'Yes' is selected in the table for the specific cost item. For some cost items the costs are determined with a formula. This can be selected -if applicable- at the same place the distribution type is specified. Additionally the tool requires the user to fill in the value -1 in the deterministic cell if the costs should be computed by an equation. An example of a unit costs table for a container terminal is depicted in Figure 59. The last column cannot be changed by the user, it holds all random values drawn from the specified distribution when a new calculation is performed.

calcCosts_C — Note: values in grey cells can be changed by user. Price levels for formulas are listed here only for indication, the year used for calculation is implemented in VBA.

Reset to standard

#	Unit	Cost element	Price level year	Adjust costs for inflation	Uncertainty *	Deterministic *	Min	MostLikely	Max	Mean	Standard deviation	Random distr
1	€/m	Quay wall	2008	Yes	Formula	-1						-1
2	€/m²	Pavement		No	Deterministic	50						0
3	€/pc	STS crane	2016	Yes	Uniform		5,000,000		7,000,000			6270050.13
4	€/pc	TTU	2016	Yes	Deterministic	90,000						0
5	€/pc	SC	2016	Yes	Deterministic	500,000						0
6	€/pc	AGV	2016	Yes	Deterministic	350,000						0
7	€/pc	Reach stacker	2016	Yes	Deterministic	325,000						0
8	€/pc	RTG	2016	Yes	Deterministic	1,000,000						0
9	€/pc	RMG	2016	Yes	Deterministic	1,300,000						0
10	€/m²	CFS	2016	Yes	Deterministic	255						0.000

* = when formula is selected as uncertainty the deterministic value must be set to -1.

Figure 59: Overview of a container terminal unit costs table. Source: Own work

4.2.2.3 Calculation sheets

A *calculation* sheet contains the values of the input variables (the parameters of the specified uncertainty distribution) of the specific terminal type. During a calculation randomly drawn instances of the distributions (both input variables and unit costs) are written to this sheet. The results (both dimensions and costs) of a calculation are written to the sheet as well. The calculation sheets are not meant to be adjusted by the user.

Since the drawn values and results are written to the sheet on the same row, the data can be used to create scatter plots. These plots can indicate dependence between two selected variables.

4.2.3 VBA code

The VBA code handles the 'communication' between Excel cells, it changes the layout of the input/output sheets, it makes logical decisions and it calculates the terminal dimensions and costs. The VBA code is written inside functions that are in turn positioned inside *Modules*, *Sheet Objects* and *Forms*. Forms (one for every uncertainty distribution type) are used by the user to insert the distributions. Also the standard values of parameters can be obtained from here. Sheet Objects (one for every worksheet) change the lay-out of the input/output sheets when certain events, triggered by the user, happen. The modules contain the remaining -and largest part- of the code. All these elements including their relations are depicted in Figure 60. The used modules are:

- *SheetCore*: Controls all the functions that have to do with the reading and writing of values/content. Passes values between cells of the different sheets. Also contains the function that starts a calculation.
- *CalcCore*: Contains the general calculation function, which in its turn delegates calculation functions in *calc_C*, *calc_Db* and *calc_Lb*. The Monte Carlo simulation is performed in this function. This module also draws and reads random values and creates histogram data.
- *calc_C, calc_Db, calc_Lb*: Contain the equations to calculate the terminal dimensions and costs per iteration per terminal type.
- *calc_Gen*: Contains general equations that can be used for multiple terminal types.

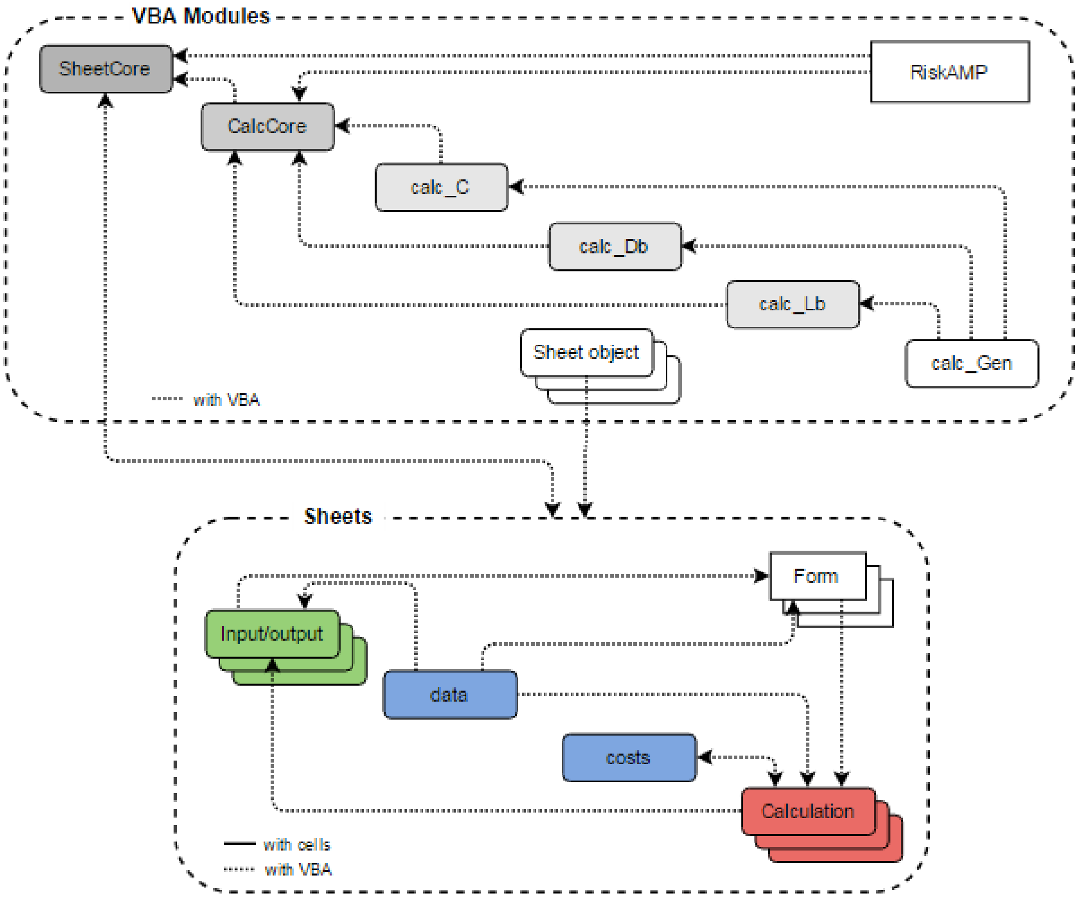


Figure 60: Relations between het Excel worksheets and the VBA modules. Source: Own work

4.3 Tool calculation methods and restrictions

This section covers equations not treated in the literature study (Chapter 2), choices and restrictions that are used for the terminal calculations in the tool. First the Monte Carlo simulation method is treated, then each terminal type is elaborated on individually.

4.3.1 Monte Carlo simulation

Monte Carlo calculations are used by many people for many applications and are a scientifically accepted method. Reasons for the use of Monte Carlo simulation are the convenience, ease and directness of the method; Whitlock & Kalos (2009).

In a Monte Carlo simulation a given number of N realisations of a given number of random variables I are sampled. In each simulation iteration one realisation for the I variables are sampled. These realisations are used as input for a deterministic calculation. Therefore each iteration has one calculation outcome. The total simulation then has N outcomes. In this study the probability density of the outcomes is determined by creating bins of possible outcome values and dividing the number of outcomes in each bin by the number of iterations N. The probability density can therefore also be called the relative frequency of the outcomes.

Sampling

For Monte Carlo simulations often *Random Sampling* is used. For each sample using this method a uniform random value is drawn. The sample's realisation is obtained by using the random value as input for the inverse of the cumulative distribution function of the variable. The previous is based on Whitlock & Kalos (2009).

The *Excel* add-in *RiskAMP* uses *Latin Hypercube Sampling*. In Latin hypercube Sampling the probability distribution range is divided into a number of bins K. The width of each bin is chosen such that the bin represent a probability of size $1/K$. Then per bin Random Sampling is used to obtain a specific number of realisations per bin. The previous is based on M. D. Mckay & Conover (2000). Using Latin Hypercube Sampling leads to every part of the distribution being equally represented during the sampling. This results in less required samples (Monte Carlo iterations) and thus less computing time according to RiskAMP (2016).

4.3.2 Container terminal calculation

For the container terminal design calculation all important equations and calculation methods are described in Section 2.1.3. The following clarifications can however be made.

Cargo flows

All cargo flow percentages (import, export, transhipment, empties and CFS) are with respect to the total throughput (containers over the quay).

Quay wall

When for the calculation of the quay wall costs the formula of de Gijt (2010) is used, the retaining height H is calculated. This is done by summing up the water depth (assumed to be equal to the required dredging depth, calculated by the tool) and a value for the freeboard resulting in L_{upper}. To calculate H ($H = L_{upper} + L_{lower}$) the sheet pile length under the sea bed L_{lower} needs to be determined. This is in this case done by defining the linear relation $L_{upper} : L_{lower}$. In the tool this is assumed to be 1 : *sheet pile length factor*. These dimensions are depicted in a simplified cross-section of a sheet pile quay wall in Figure 61. The freeboard and sheet pile length factor are given as a constant in Table 1 *Additional parameters (Constants)* of the *data* sheet in the tool.

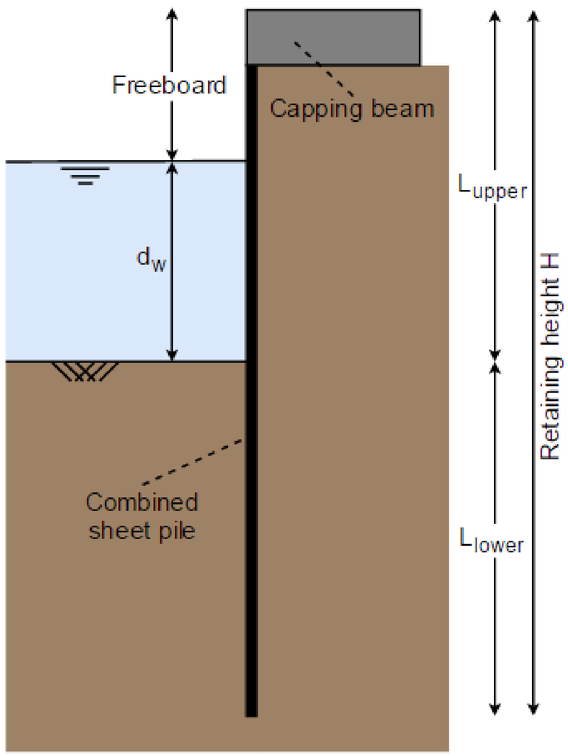


Figure 61: Schematic cross-section of sheet pile quay wall dimensions. Source: Own work

4.3.3 Dry bulk terminal calculation

The most important dry bulk terminal design equations and calculation methods are described in Section 2.2.3. The remaining dry bulk calculations are treated in this subsection and are divided into general aspects, quay or jetty and terminal area calculations.

4.3.3.1 General

- In order to limit the complexity of the tool the cargo type has to be selected. A choice can be made between: coal, iron ore, coal and iron ore, one or two grain types. For each selected cargo type a separate calculation is made. The results of these separate calculations are displayed in the output section of the worksheet. The main terminal dimensions are of course dependent on all cargo types and thus are a summation of the individual results.
- One type of berth can be chosen for all cargo types; quay wall or jetty. In the tool this basically only leads to differences in costs since the required number of berths is assumed to be independent of the type of berth. For dry bulk terminals the considered jetty type is a finger pier only; this to not further complicate the tool input and the realisation of the tool for that matter.
- For the costs calculation of the loading, unloading, stacking and reclaiming equipment the capacity is required of each machine. The tool however only uses the gross productivity as input. The capacity is computed by assuming it is equal to the typical rated capacity and using the factors presented in Section 2.2.2.1.

4.3.3.2 Quay/jetty calculation

- For a dry bulk quay wall the note in Section 4.3.2 also holds.
- For a terminal with jetties it must be selected if the jetties (finger piers) have berths on both sides.
- Finger piers often have an additional length (L_{add}) next to the required length for berthing ($L_{req} = L_s + 2 \cdot L_{ml}$). This length has to be specified. For an overview of these lengths see Figure 62.
- When jetties are selected the overall results include a summation of all the jetty lengths, this is to give an indication. The individual jetty lengths and the required number of jetties are listed per cargo type separately.
  When a quay wall is selected the required quay lengths are summed up, taking into account the additional lengths for mooring that are counted double.
- When in the input parameters the incoming cargo is not set to 100% of the total throughput there is also an outgoing cargo flow. Outgoing cargo flow requires loading equipment. The number of loading and unloading equipment is determined and the number of required berths is determined separately. The quay lengths or number of jetties corresponding to the summation of the number of required berths for both flow directions are given as results in the output.

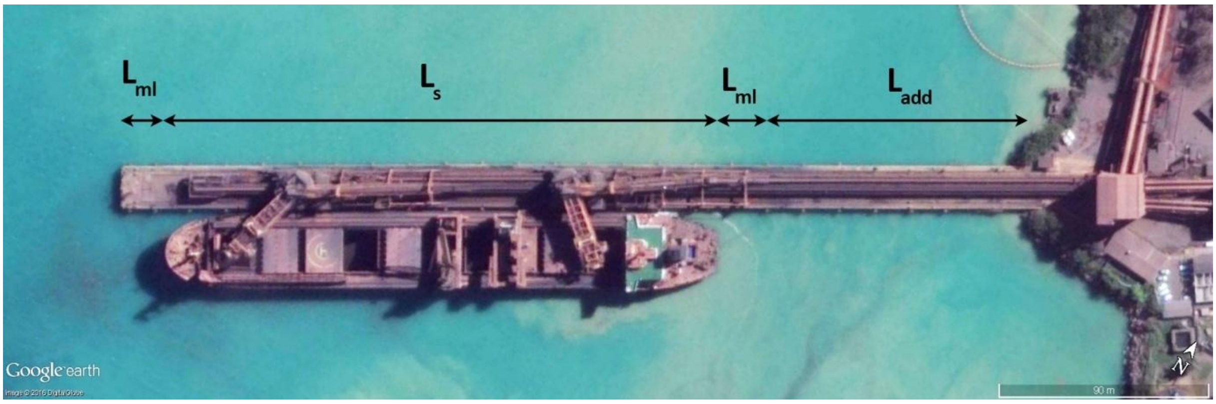


Figure 62: Finger pier type jetty with lengths overview. Porto de Tabarao, Brazil. Source: Google Earth

4.3.3.3 Terminal area calculation

- The storage utility type can be selected. For coal and/or iron ore a choice can be made between wind-row and storage shed. The difference, in the tool, between wind-row and storage shed is the price per square metre. For grains a choice can be made between storage shed and silos, for these the calculations differ.
- The calculation of the required area for a group of silos is thoroughly described in Section VI.1 of the appendices.
- The possible stacking and/or reclaiming equipment depends on the storage utility type. A bucket-wheel stacker-reclaimer has both stacking and reclaiming capabilities, a unit price is included. A scraper-reclaimer only has reclaiming capabilities. The stacking in storage sheds is often done by conveyors mounted right under the roof of the shed. Only a unit price for the reclaiming part is included.
- Conveyor belts are neither included in this study nor in the tool.

4.3.4 Liquid bulk terminal calculation

The most important liquid bulk terminal design equations and calculation methods are described in Section 2.3.3. The remaining liquid bulk calculations are treated in this subsection and are divided into general aspects, jetty and terminal area calculations.

4.3.4.1 General

- In order to limit the complexity of the tool the cargo type has to be selected. A choice can be made between: LNG, crude oil, one or two other liquids, crude oil and one or two other liquids. For each selected cargo type a separate calculation is made. The results of these separate calculations are displayed in the output section of the worksheet. The main terminal dimensions are of course dependent on all cargo types and thus are a summation of the individual results.
- The liquid bulk berth type is a jetty (island berth type).

4.3.4.2 Jetty calculation

- Island berth type jetties consist of a trestle and the berthing structure.
- The berthing structure length ($L_{berthing}$; centre-to-centre distance between outer mooring dolphins) is determined by the length of the design vessel (L_s) plus an additional length for the mooring lines for as well as aft of the vessel (L_{ml}). The length of the trestle ($L_{trestle}$) is an input variable that is dependent on the local situation. For an overview of these lengths see Figure 63.
- For the overall results a summation of all the jetty lengths is made, this is to give an indication. Only the trestle lengths are summed up. The individual jetty lengths and the required number of jetties are listed per cargo type separately.
- Pipelines are neither taken into account in this study nor in the tool.

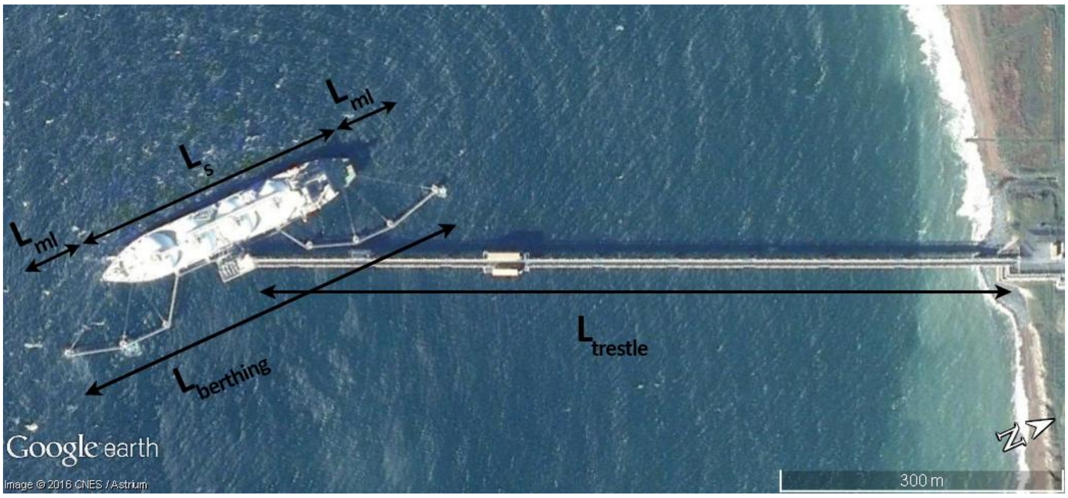


Figure 63: Island berth type jetty with lengths overview. Korsakov, Sakhalin, Russia. Source: Google Earth

4.3.4.3 Terminal area calculation

- The calculation of the required area for one or multiple groups of storage tanks is thoroughly described in Section VI.2 of the appendices.
- For certain cargo types safety distances between tanks or tank groups are recommended, more information can be found in Section 2.3.3.2. These minimum distances overrule the tank distance chosen by the user if applicable.
- Pipelines are neither taken into account in this study nor in the tool.

4.4 Tool verification

Models that describe physical processes such as river morphology or fluid dynamics require calibration and validation to tweak certain parameters or model schematisations in order to make sure they give reliable results. The tool -that can be seen as a model- does not describe physical processes. It mainly uses capacity/productivity equations with values of parameters that are provided by the user to calculate quantities such as required dimensions or certain units. Calibration and validation are therefore not required. The tool however has to be checked to make sure it works correctly. By this is meant that the interface, equations and coding logic have to be tested. This is done by choosing realistic input, based on real terminals, and doing a manual calculation of the dimensions and costs. This same completely deterministic input is used for the tool and one iteration is performed resulting in a single solution per calculation output (e.g. quay length, gross storage area, etc). When both the manual and tool outcomes are equal the tool is verified.

For container terminals one input combination is calculated. For dry and liquid bulk terminals three combinations each are calculated. This difference is made because for container terminals each calculation uses the same equations and logic. For dry and liquid bulk terminals this depends on the selected (combinations of) cargo type(s). Combinations can be for example ‘Coal & Iron ore’ for dry bulk or ‘Crude oil’ for liquid bulk terminals. The verification is completed successfully.

5 CASE STUDY

The case study is an application of the tool on one existing marine terminal. The design rules, guidelines and common values of parameters found in the literature and in the expert judgement studies are therefore applied. The case study shows what the tool can be used for and at the same time it is checked if it produces realistic results. In addition to this a sensitivity analysis is performed for this specific case.

Goal of the case study: Application of the tool on a real scenario and the identification of items[28] that greatly affect the construction costs.

5.1 Case description

For the case study the EMO terminal in Rotterdam, the Netherlands is selected. EMO (*Europees Massagoed Overslag BV*) is the largest European dry bulk handling terminal. The terminal serves the energy and steel sector by handling coal and iron ore. EMO itself was established in 1975 but its roots date back to 1954. The terminal is situated at the *Maasvlakte*, a man-made extension of the Port of Rotterdam, built in the sixties. The largest existing sea-going vessels are able to berth at the terminal due to the large water depth. EMO distinguishes itself because of the high level of automation. Currently the terminal has fully automated stacker-reclaimers, a sea-vessel loader, a coal wagon loader and sea-vessel unloaders. These machines are operated from a central control room. Information in this chapter originates from EMO (2016) unless indicated otherwise.

The EMO terminal is chosen for the case study since dry bulk terminals are underexposed in literature, compared to container terminals. For liquid bulk terminals it is very difficult to find sufficient information so this is only an option if the terminal management itself provides information. The big advantage of EMO is that there is a lot of information available on the website.

The terminal consists of a sea-going vessel quay and a separate barge quay. The sea-going vessel unloaders are gantry grab cranes. The storage yard consists of multiple wind-rows. These rows may or may not be divided by retaining walls to accommodate multiple material types in a single row. The handling of cargo at the stockpiles happens by means of stacker-reclaimers. The terminal has a railway connection providing a link to the vast hinterland. Services that are offered on the terminal are: the blending of different grades, processing, washing (removal of impurities) and screening (separation of cargo into different grades). Coal on the terminal can be compacted in order to reduce the oxygen in between the coal to avoid spontaneous combustion. A power plant is situated near the terminal, coal can directly be transported to the plant. An aerial picture of the terminal is presented in Figure 64.

[28] Items being variables and terminal elements.

Figure 64: Overview of the EMO dry bulk terminal in Rotterdam. Source: EMO (2016)

5.2 Actual terminal characteristics

The actual terminal properties are listed in Table 42. Some of these characteristics are based on information provided by EMO (2016), others are determined using Google Earth.

Table 42: Actual EMO terminal characteristics

Terminal property	Actual value	Source
Total quay length [m]	1,793	EMO
Total terminal area [ha]	171.5	Google Earth
Total gross storage area [ha]	121.8	Google Earth
Max. vessel draught [m]	23.0	EMO
Number of berths [pcs]	6	EMO
Number of unloaders [pcs]	5	EMO
Number of loaders [pcs]	1	EMO
Number of stacker-reclaimers [pcs]	7	EMO
Avg. stockpile length [m]	1,200	Google Earth

An overview of the terminal is depicted in Figure 65, with in blue the total terminal area and in red the gross storage area. The purple area represents a storage area in which the stockpiles are placed in a less structured way, no stacker-reclaimer is present in this area. The area is most likely used to store cargo which has to be transhipped to sea-going vessels. East of the terminal the *Engie* power plant is located. The storage area north-east of the power plant belongs to the plant, not to the terminal. The largest part of the southern quay wall is used to unload vessels. The quay wall south of the purple area in Figure 65 is used to load sea-going vessels. The western quay wall is used to load inland waterway vessels. The apron area of the western quay wall (including the loading equipment) is not taken into account, this is elaborated on in Section 5.3.

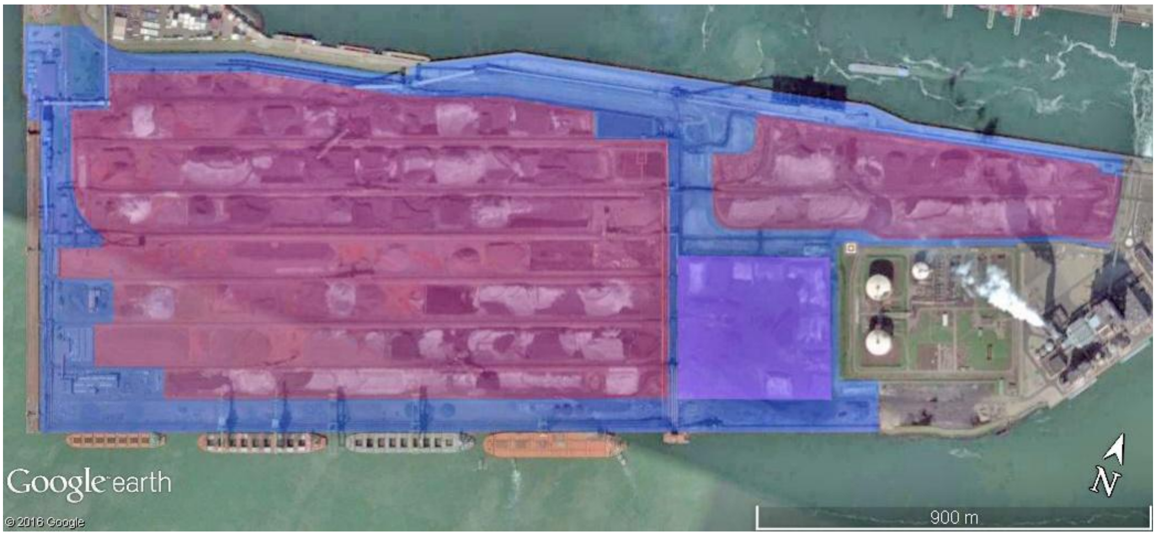


Figure 65: Satellite image of the EMO terminal with gross storage areas; wind-row stockpiles (red) and less structured stockpiles (purple) and the total terminal area (blue). Source: Google Earth

5.3 Input parameters

This section covers the tool input that is used to estimate the dimensions, quantities and costs of the EMO terminal. For the variables for which no information could be found the standard values of parameters of the literature study are used. The tool does not have the function to differentiate between sea-going and inland waterway vessels and the corresponding berths and equipment. The choice is therefore made to not include the barge quay -located on the Westside of the terminal- while still accounting for the transhipped cargo volume. Due to this simplification the amount of transhipped cargo is still used to compute the required storage area, only the loading equipment and quay length are not considered. The transhipment to other sea-going vessels is taken into account. Public information about the terminal and its operations is presented in Table 43. In the following subsections the tool input is specified.

Table 43: Terminal and operations information of EMO. Source: EMO (2016)

Variable	Value
Operational hours	7 days a week, 24 hours a day
Design throughput capacity	42 million tonnes
Actual throughput coal[1]	20 million tonnes (61%)
Actual throughput iron ore[1]	13 million tonnes (39%)
Actual transhipment coal[1]	56% (sea shipping 1%)
Actual transhipment iron ore[1]	56% (sea shipping 8%)
Design vessel - unloading berths	VLBC[2] with DWT_{max} = 400,000 tonne, L_s = 362 m
Design vessel - loading berths	DWT_{max} = 150,000 tonne, L_s = 232 m
Number of cranes - unloading	5 for 4 berths
Number of cranes - loading	1 for 2 berths
Grab capacity unloading equipm.	2 x 50 tonne and 3 x 85 tonne
Capacity loading equipm.	3,000 tonne/hour
Stacker-reclaimer - stacking capacity	6,000 tonne/hour
Stacker-reclaimer - digging capacity	4,500 tonne/hour

Note 1: Data from 2015
Note 2: VLBC = Very Large Bulk Carrier

5.3.1 Throughput

To compute the required terminal dimensions and number of equipment, etc. the throughput capacity has to be used instead of the actual achieved throughput. The ratio of achieved coal and iron ore throughput to the total throughput of 2015 is used to approximate the design coal and iron ore throughputs. This leads to the design throughputs of 25.5 million tonnes coal and 16.5 million tonnes iron ore. The terminal does not export cargo so the amount of outgoing cargo is equal to the transhipped cargo. Therefore the incoming cargo is 100% minus the transhipment percentages to sea-going vessels, from Table 43.

5.3.2 Vessel dimensions

According to the information from EMO the unloading and loading berths have different design vessels. To compute the required quay length the tool uses the average vessel length ($\overline{L}_s$); if the required number of berths is larger than one, see Equation (7). The average vessel length is taken from typical vessels that moor at the unloading and loading quays. Typical lengths of vessels that are unloaded are derived from Google Earth satellite images of 20-12-2016. The typical length of vessels at the loading quay (181 metre) is determined by using the inverse of Equation (7), with a quay length of 443 metres and 2 berths. The average is 250 metres, using an assumed uncertainty interval of ±10% results in the uniform distribution UNI[225; 275]. To compute the required water depth the draught of the VLBC is taken, this is 23 metres.

5.3.3 Estimated berth occupancy

Since in principle two different quays are taken into account the estimated berth occupancy is determined accordingly. The actual value will be somewhere in between the values corresponding to two and four berths, in Table 23. This leads to the distribution UNI[65; 80].

5.3.4 Gross productivities

EMO provides maximum capacities for their loading cranes and stacker-reclaimers, but provides no capacity for their unloading cranes. The unloading capacity is estimated by using public information from Ertsoverslagbedrijf Europoort C.V. (EECV) (2013) about their unloading capacities. The EECV cranes with 60 tonne grabs have a capacity of 2300 tonne/hour, their 65 tonne cranes have a capacity of 2600 tonne/hour. Using the average of the EMO grab sizes and linear extrapolation results in an estimated maximum capacity of 2960 tonne/hour of the EMO unloading equipment.

Instead of maximum capacities the tool requires gross productivities[29] for its computations. In Section 2.2.2.1 factors are used to determine the gross productivity from the typical rated capacity. The typical rated capacity is in theory not equal to the maximum capacity but they do not differ by much and no other information is available. The through-ship efficiency factor (for unloading 0.5 and for loading 0.7) and operational availability factor (0.8) are used. These factors are in theory only for (un)loading equipment, since no other factors could be found in literature they are also used for the storage yard equipment. (Un)Loading cranes and storage yard equipment are connected via belt conveyors, so if a crane is not working the stacker reclaimer is not working either. However cargo is sometimes repositioned by the stacker-reclaimers, which are then in-use while the cranes are not. On the other hand small downtimes can occur for the yard

[29] Gross productivity: Average amount of cargo moved between berthing completed and de-berthing started. This variable therefore includes unproductive intervals such as crane repositioning, moving hatches to/from quay and time between shifts.

equipment while the cranes are working fine. This assumption can therefore be considered as reasonable. The gross productivity of an unloader is 1,185 tonne/hour, of a loader 1,680 tonne/hour, stacking of a stacker-reclaimer 2,400 tonne/hour and reclaiming of the same machine 1,800 tonne/hour. For all gross productivities an uncertainty interval of ±25% is assumed.

5.3.5 Average dwell time

The average dwell time of cargo on the terminal is unknown. It can however be approximated by using the capacity ratios that are presented in Section 2.2.3.2. The capacity ratio indicates the amount of cargo that has to be able to be stored at a given moment of time. So if a steady annual throughput is assumed the capacity ratio percentage of the number of days in a year is an estimate of the average dwell time. Various ratios are proposed, they can be approximated by the triangular uncertainty distribution TRI[5; 16; 22]. The limits are not used for the dwell time since they probably are exceptions, therefore the mean value of 14.3% is used. This results in an average dwell time of 52 days with an assumed uncertainty interval of ±50%; to capture the large uncertainty of the dwell time. The resulting uniform distribution is UNI[26; 78].

5.3.6 Total terminal factor and estimated storage occupancy

Since common values do not occur in literature the distributions of the total terminal factor and estimated storage occupancy have been determined by Expert Judgement Elicitation (see Section 0), they are depicted in Figure 66.

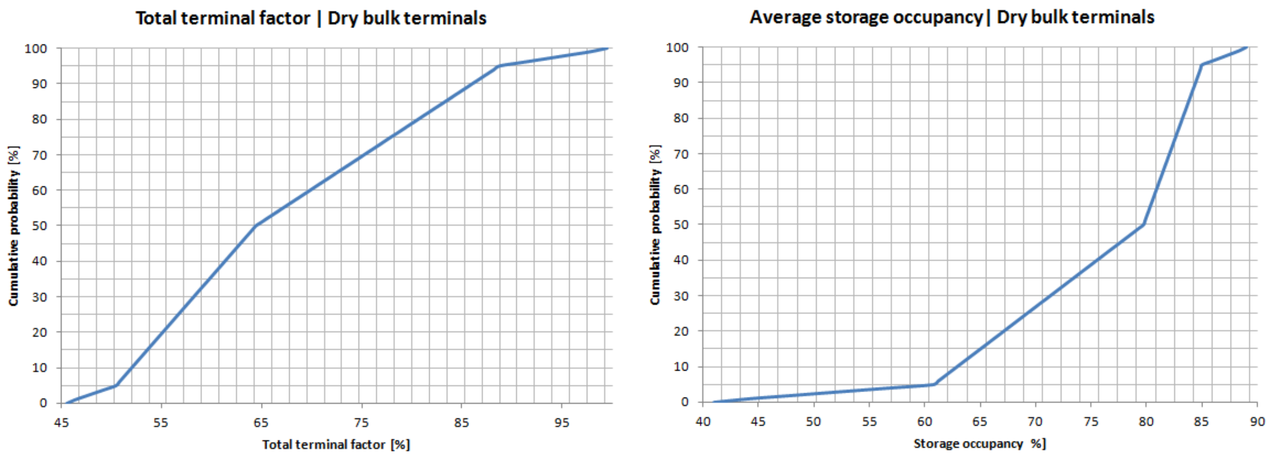


Figure 66: Expert Judgement Elicitation results that are used for the EMO case. Source: Own work

5.3.7 Stockpile properties

The horizontal stockpile lane dimensions (average lane length, width and additional width of the area surrounding the stockpiles) are estimated using Google Earth. The design pile height for a coal stockpile should be close to the maximum of 23 metre (according to the standard values of parameters). An assumption of a uniform distribution in between 21 and 23 metre is made. According to data from Actueel Hoogtebestand Nederland (2016) iron ore stockpiles are less high; a maximum of 19 metres is found. A somewhat larger uncertainty of the iron ore pile height is used ranging from 15 to 19 metres. Google Earth is used to estimate the number of lanes for the coal and iron ore stockpiles. The iron ore storage consists of approximately three lanes. The main terminal area counts about four lanes for coal. The northeast area is approximated to be 1.25 of an average lane. The area used for storage of sea-going vessel transhipment cargo is estimated to be

0.75 of an average lane (purple area in Figure 65). The derived average lane length is 1200 metres.

The tool computations do not include the conveyor belts (with a total length of 47 km) and the structures required for the additional services. However an approximation of the required area for the additional structures is made by using the total terminal factor.

5.3.8 Summary of the input parameters

The options that are selected in the tool are listed in Table 44.

Table 44: Selected options in the tool

Item	Selection
General	
Berth type	Quay wall
Wave conditions	Sheltered waters
Coal & Iron ore	
Unloading equipment	Gantry grab crane
Yard equipment	Bucket wheel stacker-reclaimer
Storage type	Open storage: Wind-row

The probability distributions that are used as input for the computations of the case study are summarised in Table 45. If the values for both coal and iron ore are the same one value is listed in the middle. For the variables additional distance stockpile[30], freeboard quay and sheet pile length factor it is not possible in the tool to specify an uncertainty distribution, the values are therefore deterministic.

Table 45: Parameter values used as input for the computations

Variable	Probability distributions		Unit	Source
	Coal	Iron ore		
Operational hours per year	DET[8,760]		hour	EMO
Total terminal factor	See Figure 66		%	Section 5.3.6
Draught design vessel	DET[23]		metre	EMO
Add. quay length mooring	UNI[15; 30]		metre	Ch. 2
Dredging tolerance	DET[0.60]		metre	Ch. 2
Throughput	DET[25.5x10^6]	DET[16.5x10^6]	tonne/year	Section 5.3.1
Incoming cargo	DET[99]	DET[92]	%	Section 5.3.1
Transhipment	DET[1]	DET[8]	%	Section 5.3.1
Average cargo density	UNI[0.52; 0 .93]	UNI[2.13; 3.03]	tonne/m^3	Ch. 2
Average vessel length	UNI[225; 275]		metre	Section 5.3.2
Design vessel length	DET[362]		metre	EMO
DWT design vessel	DET[400,000]		tonne	EMO
Avg. gross prod. unloader	UNI[890; 1,480]		tonne/hour	Section 5.3.4
Avg. gross prod. loader	UNI[1,260; 2,100]		tonne/hour	Section 5.3.4
Est. berth occupancy	UNI[65; 80]		%	Section 5.3.3
Average dwell time	UNI[26; 78] [1]		days	Section 5.3.5
Est. storage occupancy	See Figure 66		%	Section 5.3.6

[30] The width of the area surrounding the net storage area; so including internal infrastructure.

Variable	Probability distributions Coal	Iron ore	Unit	Source
Avg. gross prod. stacking	UNI[1,800; 3,000]		tonne/hour	Section 5.3.4
Avg. gross prod. reclaiming	UNI[1,350; 2,250]		tonne/hour	Section 5.3.4
Pile height	UNI[21; 23]	UNI[15; 19]	metre	Section 5.3.7
Lane width	UNI[78; 93]		metre	Section 5.3.7
Number of lanes	DET[6]	DET[3]	-	Section 5.3.7
Angle of repose	UNI[30; 45]	UNI[30; 50]	Degrees	Ch. 2
Add. distance stockpile	15		metre	Section 5.3.7
Storage factor	UNI[15; 25]	UNI[30; 40]	tonne/year/m^2	Ch. 2
Capacity ratio	TRI[5; 16; 22]		%	Ch. 2
Freeboard quay	3		metre	Ch. 2
Sheet pile length factor	1		-	Ch. 2

Note 1: In Section 5.4.2.2 the uncertainty distribution is changed to UNI[45; 80]
Other notes: DET = deterministic, UNI = uniform, TRI = triangular distributions

Computation properties

The number of iterations that is used for the Monte Carlo simulations is 1000.[31] The tool uses Latin Hypercube sampling (as is explained in Section 4.3.1) which allows for less iterations for the same accuracy compared to the standard Monte Carlo sampling. The prices are corrected for the 2016 price level with an assumed annual average inflation of 2%.

5.4 Tool application

A computation is performed to estimate the EMO terminal dimensions and quantities. The values/distributions that are used as input are specified in Section 5.3. This section presents the computation results. These results are compared to the actual dimensions (see Section 5.2). Finally conclusions are drawn and the resulting construction costs estimate is presented.

5.4.1 Computation results

The main results are presented by means of probability density plots. These plots are in other words relative frequency plots. The frequency that a result falls in a certain range (or bin) is determined. Each value on the horizontal axis represents the upper boundary of a bin, the previous value represents the lower boundary of the same bin. The lower boundary of the very first bin is not shown, yet the first bin has the same bin size as the other bins and includes the smallest outcomes.

The main results concerning the quay are presented in Figure 67. The left plot represents the required quay length for coal and iron ore combined. The 65th percentile is 1,797 metre and best represents the actual value of 1,793 metre. The right plot represents the combined number of required berths. The actual value is 6, the best representation by the tool is the 71st percentile.

[31] Dr. Morales-Nápoles stated in personal communication that 1000 iterations for this application is reliable.

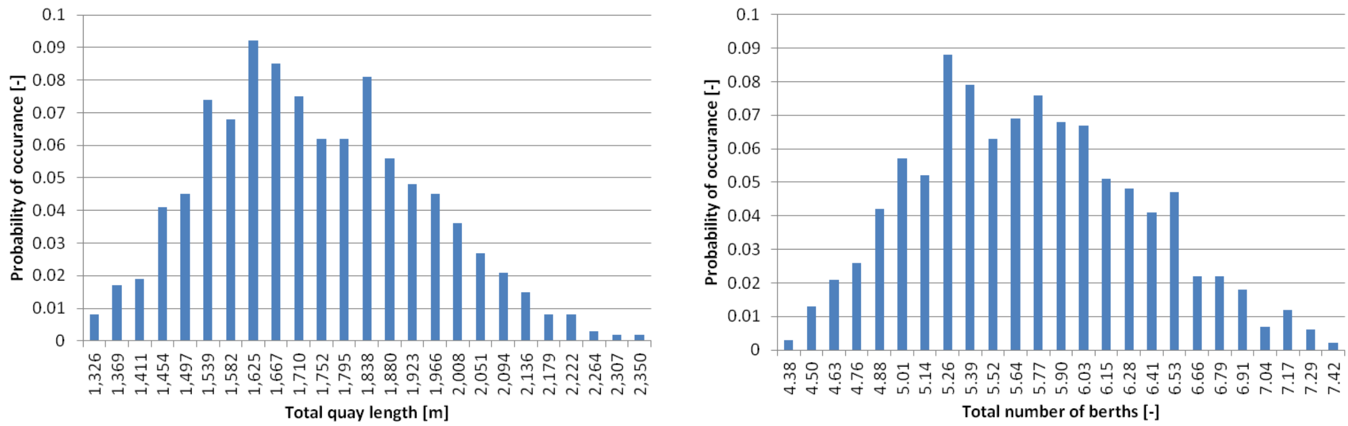


Figure 67: Calculation results; total quay length and total number of berths. Source: Own work

The total terminal area results are depicted on the left in Figure 68. The actual area is about 171.5 hectare. This is best approximated by the 85th percentile with 171.4 hectare. The required dredging depth is dependent on the wave climate, design vessel draught and the dredging tolerance. Since the variables are chosen to be deterministic the computation presents one result; a required depth of 25.90 metre. This depth is needed to allow a vessel with a 23 metre draught to access. No actual value of the dredging depth or water depth is available.

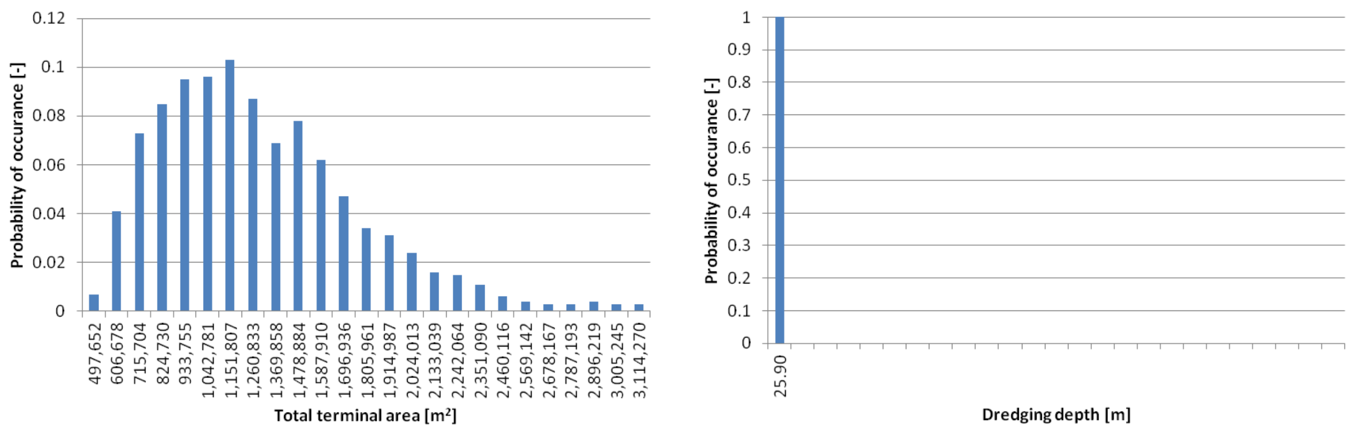


Figure 68: Calculation results; total terminal area and dredging depth. Source: Own work

5.4.2 Analysis of the results

From the comparison between the computation results and the actual terminal properties in Section 5.4.1 it can be noted that the best-estimate quantiles are in between 65% and 85%. According to Wolfert (2014) the 70% quantile is generally used for budgeting purposes. The percentiles of the best-estimates of the quay length and number of berths are very close to the proposed 70% quantile. The best-estimate of the storage area deviates a bit from the proposed quantile, but is not per definition incorrect. Possible reasons for the actual area being larger than the area estimate of the proposed percentile can be:

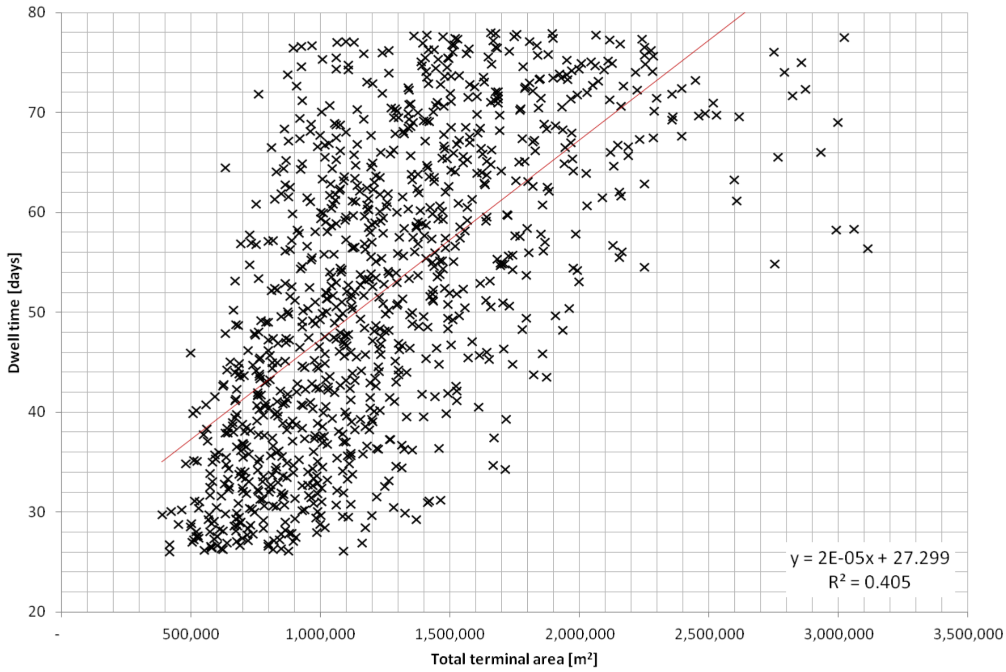
- The storage yard is dimensioned in a risk aversive way. In other words more area -than theoretically is required for the design capacity- is allocated to function as a buffer.
- The sea-going vessel transhipment storage yard (purple area in Figure 65) is not used for the typical storage of cargo. This since no stacker-reclaimers are used and the handling of cargo on the yard happens with bulldozers. The yard may be used for short or very long storage or functions as an intermediate place to store cargo that has to be transhipped. In

this case the tool predicts a smaller required area for the same throughput because it does not consider a buffer area.

- Estimated input values are incorrect. Variables that are uncertain in this case study (see Table 45) and that affect the storage area are: cargo dwell time, stockpile properties (height, lane width, number of lanes), storage occupancy, cargo density, angle of repose of cargo and the total terminal factor.

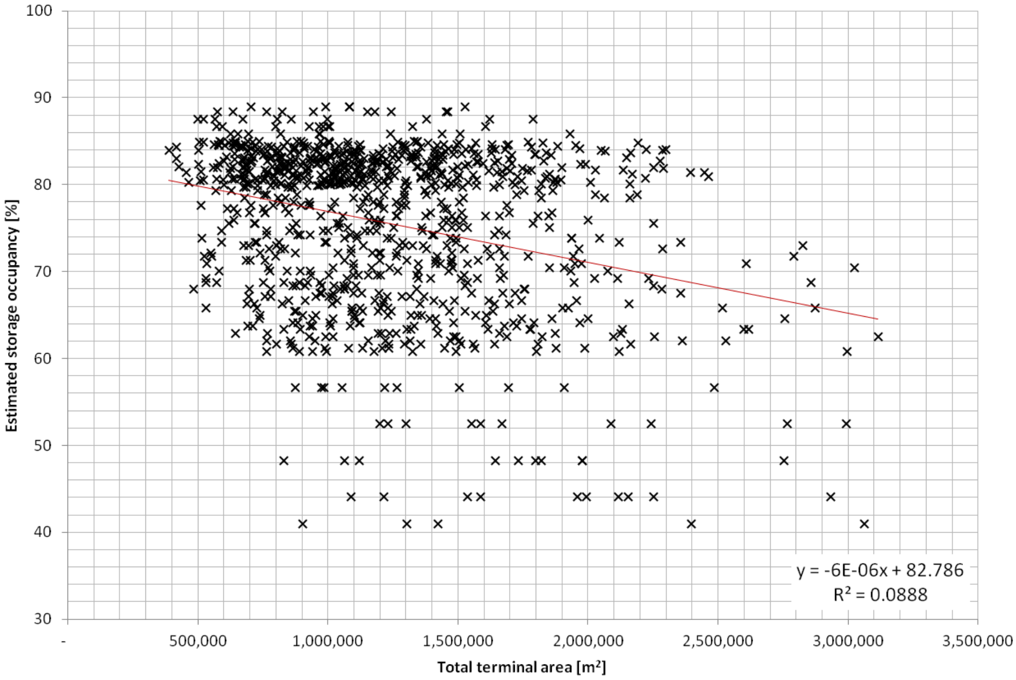
5.4.2.1 Variables of importance

This subsection takes a closer look at the influence of the mentioned variables on the total terminal area. The stockpile height, lane width, number of lanes, cargo density and angle of repose are represented by uncertainty distributions. These distributions are however based on best-estimates of information from Google Earth or trusted literature and therefore cannot really be improved. Consequently, this section focuses on the cargo dwell time, storage occupancy and the total terminal factor. The influence on the total terminal area is investigated by plotting the values of these variables against the related total terminal area for each iteration; in Figure 69 each point represents an iteration. It has to be noted that these input variables are only for the coal calculation.[32] However the same input distributions are used for both cargo types thus they give comparable scatter plots. The variable with the highest influence can be identified by the scatter plot that has a linear fitted curve that is the closest to a horizontal line and has a good *goodness of fit*[33]. As an increase or decrease of the random input variable on the y-axis then also corresponds to a large increase or decrease of the total terminal area. It can be observed that varying the average cargo dwell time has the largest effect on the total area. The slope of the curve is similar to that of the total terminal factor scatter plot, however the goodness of fit (quantified with the coefficient of determination R^2) of the linear curve for the dwell time is higher. The estimated storage occupancy scatter plot has a linear curve that is the most horizontal but it has a large error (low goodness of fit). From the scatter plot it can be observed that varying the storage occupancy does not per se lead to a larger total terminal area.



[32] The presented total terminal area is the sum of the total terminal areas of the separate coal and iron ore calculations.

[33] Goodness of fit is a measure of how good a curve fits the data. For quantification the coefficient of determination R^2 is used in this application; ranging from 0 to 1 where 1 is a perfect fit.



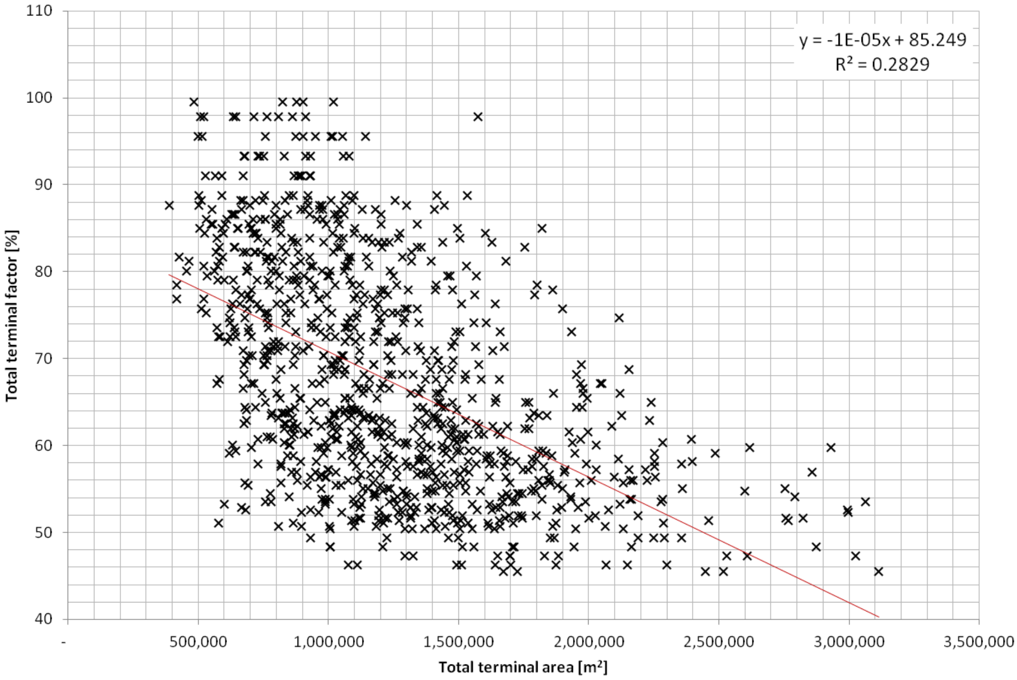


Figure 69: Scatter plots of three different input variables and the corresponding total terminal area. Linear curves are fitted; their equation and coefficient of determination are depicted as well. Source: Own work

Based on the analysis of the linear relationships between the random input variables and the resulting total terminal areas a conclusion can be made. This conclusion is that varying the average dwell time and the total terminal factor can impact the total terminal area. Another way of assessing dependence between random variables is by means of copulas (see Section III.2.1 of the appendices). Due to reasons that are given in the introduction copulas are not applied here.

5.4.2.2 Applying different values

Changing the original average dwell time (in days) from UNI[26; 78] to an assumed UNI[45; 80] distribution results in the actual terminal area (171.5 ha) being best approximated by the 75th

percentile (171.4 ha); see Figure 70. Changing the original total terminal factor (in %) -which is determined by experts- to an assumed UNI[45; 70] distribution also results in a best approximation by the 75th percentile (171.6 ha). These resulting quantiles better relate to the proposed 70% quantile.

Of the three reasons -for the total terminal area not being estimated well enough- the risk aversion and non-typical storage yard reasons are discarded since they cannot be proven. Of the remaining possible incorrectly estimated variables the total terminal factor is discarded. This, since the dwell time is more likely to differ from the estimate than the terminal factor, of which the latter has been estimated by experts. Therefore, for the remainder of this case study, in the input parameters, the average dwell time is changed to its new estimated uniform distribution UNI[45; 80]. This distribution is used both for coal and iron ore.

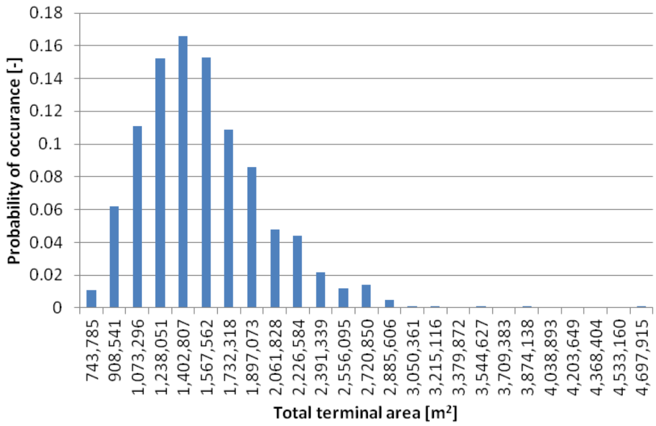


Figure 70: Total terminal area distribution resulting from a computation with an updated average dwell time distribution. Source: Own work

5.4.2.3 Direct costs analysis

So far the main terminal dimensions have been treated, the direct costs[34] are considered in this subsection. Direct costs are determined by multiplying the computed dimensions and quantities by the unit costs. Since these quantities are represented by probability density distributions the direct costs have the same form. The costs quantile is determined by taking the average of the quantiles of the main tool results (now ranging between 65% and 75%) as specified in Sections 5.4.1 and 5.4.2.2; this results in the 70th percentile. This value is exactly the value that is proposed by Wolfert (2014). The main cost elements for a dry bulk terminal are:

- Quay wall: Costs including the supply of material and the required man-hours. Determined by the empirical equation of de Gijt.
- (Un)Loading equipment: Investment costs of the loading and unloading equipment, excluding rails. The foundation is not directly taken into account, however a quay wall partly or fully bears the weight of the equipment. The foundation is partly included in the unit costs of the quay wall; since an empirical equation is used to derive the quay wall costs.
- Storage facilities: Costs including the supply and construction of terminal pavement, which is assumed to be used for stockpiles. This includes the stabilising sand layer underneath the pavement.
- Storage equipment: Investment costs of -in this case- the stacker-reclaimers, excluding rails and foundation.

[34] Direct costs are defined as costs directly related to the production or supply of a product or service. Construction cost estimates consists of direct costs, indirect costs and contingencies.

Terminal elements that are not included in the costs are belt conveyors, roads and buildings. For the EMO terminal with input described in Section 5.3 and with the updated average dwell time distribution the probability density distributions of the different main cost items are depicted in Figure 71. The lines of the quay wall and storage equipment seem to be oscillating, this is however due to the fact that the lines are based on histogram data with a limited resolution. The differences are in the order of one percentage.

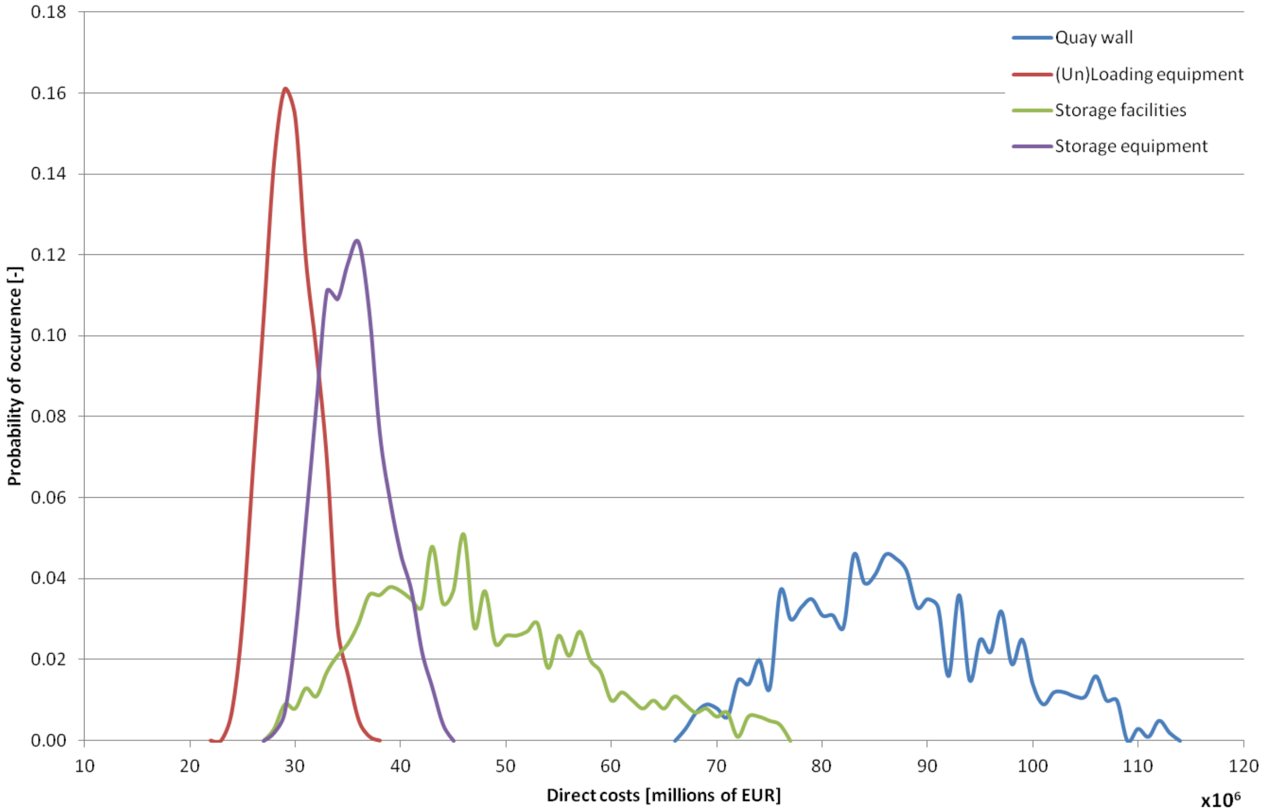


Figure 71: Probability density distributions of the main direct cost elements. Source: Own work

Aspects that immediately stand out are the narrow distributions with relatively low costs of the (un)loading and storage yard equipment, the similar width of the quay wall and storage facilities distributions and the quay wall being by far the highest contributor to the total direct costs. Both the distributions of (un)loading and storage equipment are narrow. This is due to the fact that the distribution widths of the computed number of equipment are relatively small; the result with the largest width is depicted in Figure 72 (left). Another reason are the relatively small widths of the investment costs distributions. The largest costs range corresponds to stacker-reclaimer investment costs ranging between 4.45 and 9.16 million euro per piece, depending on the machine’s capacity. The similar width of the quay wall and storage facility distributions is merely a coincidence since the only variable that they have in common is the throughput, they are dependent on many more different variables and different unit costs. The storage facilities distribution has a relatively long tail, this is due to a similar tail in the gross storage area distribution as depicted in Figure 72 (right).

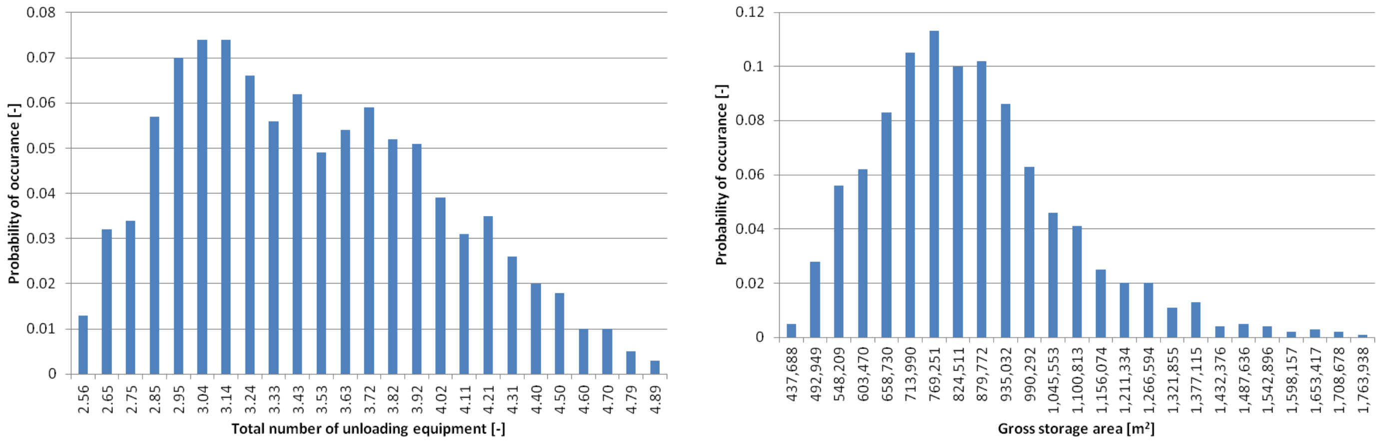


Figure 72: Calculation results; number of unloading equipment (left) and the gross storage area (left). Source: Own work

5.4.3 Conclusions & construction costs estimate

From Sections 5.4.1 and 5.4.2.2 it can be concluded that the best-estimate quantiles are in between 65% and 75%. As already is explained the costs of the terminal are estimated by taking the average of the best-estimate quantiles; the 70% quantile. According to Wolfert (2014) the same 70% quantile is generally used for budgeting purposes. This can lead to the following two conclusions:

1. The tool gives realistic design estimates for (coal and iron ore) dry bulk terminals when realistic assumptions for the values of the parameters are made.
2. The terminal itself was well designed.

The first conclusion can only be made when the second conclusion is true. In this case the fair assumption is made that Europe's largest dry bulk terminal is well designed. Since the tool gives realistic estimates of the terminal dimensions, other quantities and costs it can be concluded that it functions correctly in this case.

For the application of the tool in general the following recommendation for choosing the values of parameters must be made. It is advised to not use large uncertainties for variables since these variables will then dominate the resulting dimensions and costs. As a rule-of-thumb for uniform and triangular distributions the upper limit should not be more than twice the lower limit. Based on the current case this gives credible results.

Construction cost estimate

As can be observed from Figure 71 the quay wall has by far the largest contribution to the costs, followed by the storage facilities, the storage equipment and the (un)loading equipment. The construction costs -according to the SSK method- consist of the total of the direct costs, indirect costs and contingencies. To determine the latter two cost aspects certain percentages (see the confidential Appendix I) of the total direct costs are used. An overview of the costs is presented in Table 46.

Table 46: EMO case direct costs and construction costs corresponding to the 70% quantile

Direct cost elements		
Quay wall	€ 91,935,000	
(Un)Loading equipment	€ 30,270,000	
Storage facilities	€ 52,275,000	
Storage equipment	€ 36,610,000	+
Total direct costs	€ 211,090,000	
Total construction costs	**€ 358,853,000**	

The mentioned costs -corresponding to the 70% quantiles of the direct cost elements- are visualised in Figure 73; together amounting to the total direct costs.

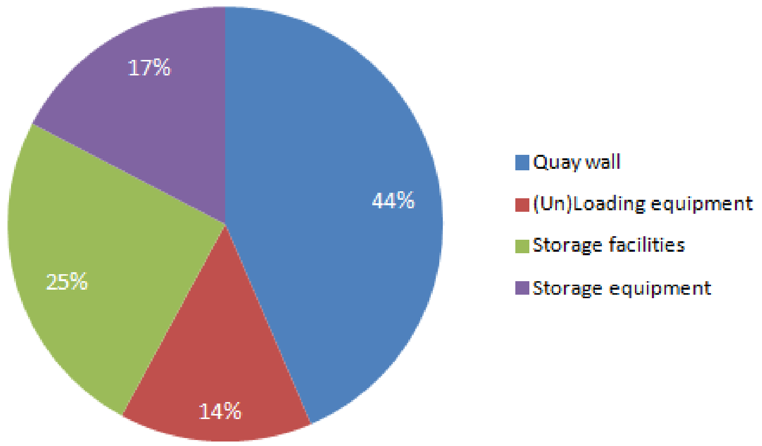


Figure 73: The contribution of the 70th percentiles of the cost elements to the total direct costs. Source: Own work

5.5 Sensitivity analysis

The goal of the sensitivity analysis is to identify the variables that have a large impact on the total costs. In a terminal design project costs are an important factor. In order to be able to decrease the costs terminals can be optimised. It is not practical to optimise many terminal elements so the knowledge of what element influences the costs the most is valuable. The sensitivity analysis is performed on the EMO case.

5.5.1 Comparing distributions

Since the cost outputs are probability distributions of different types, results cannot be compared in a straightforward way. A method to determine the degree to which two densities disagree is called the *Kullback-Leibler divergence*, as presented in Kullback (1997). This method computes the so called *Entropy* quantity (I) between two continuous probabilistic distributions (f_1 and f_2). The Entropy is defined as:

$$I(f_1, f_2) = \int f_1(x) \cdot \ln\left(\frac{f_1(x)}{f_2(x)}\right) dx \qquad (30)$$

Bluntly stated Entropy quantifies the amount of information that is lost when f_2 is used to approximate f_1. Entropy is in fact already used in this research, namely in Equations (31) and (32) of the appendices. The Entropy is not an absolute score but a relative measure, with a different scale for every application. For this sensitivity analysis the quantity is calculated between a base case (with input values as described in Section 5.3.8) and a case in which the distribution of a single variable is changed. When multiple cases -in which the distributions are changed- are considered, the effect of that variable on the costs result can be quantified. In order to put things into perspective the Entropy is also calculated for the tool's total direct costs output with exactly the same input as for the before mentioned base case but with various number of iterations. The results are listed in Table 47. Here for f_1 the density function of the total direct costs for i = 1000 is used. For f_2 also the total direct costs are used, which is however computed using a different number of iterations. A quantity of 0 resembles two perfectly matching distributions. Of course the lower the number of iterations the more information is lost with respect to a thousand iterations, and so the larger the Entropy will be.

Table 47: Entropy quantities of the total direct costs for constant variables but a varying number of iterations

Number of iterations	**Entropy I [-]**
1000 vs. 50	56.1260
1000 vs. 100	13.4339
1000 vs. 250	10.4004
1000 vs. 500	0.1467
1000 vs. 1000	0

To give more insight into these values the differences between the probability distributions of the total direct costs of a thousand iterations and respectively 500, 250 and 50 iterations are depicted in Figure 74.

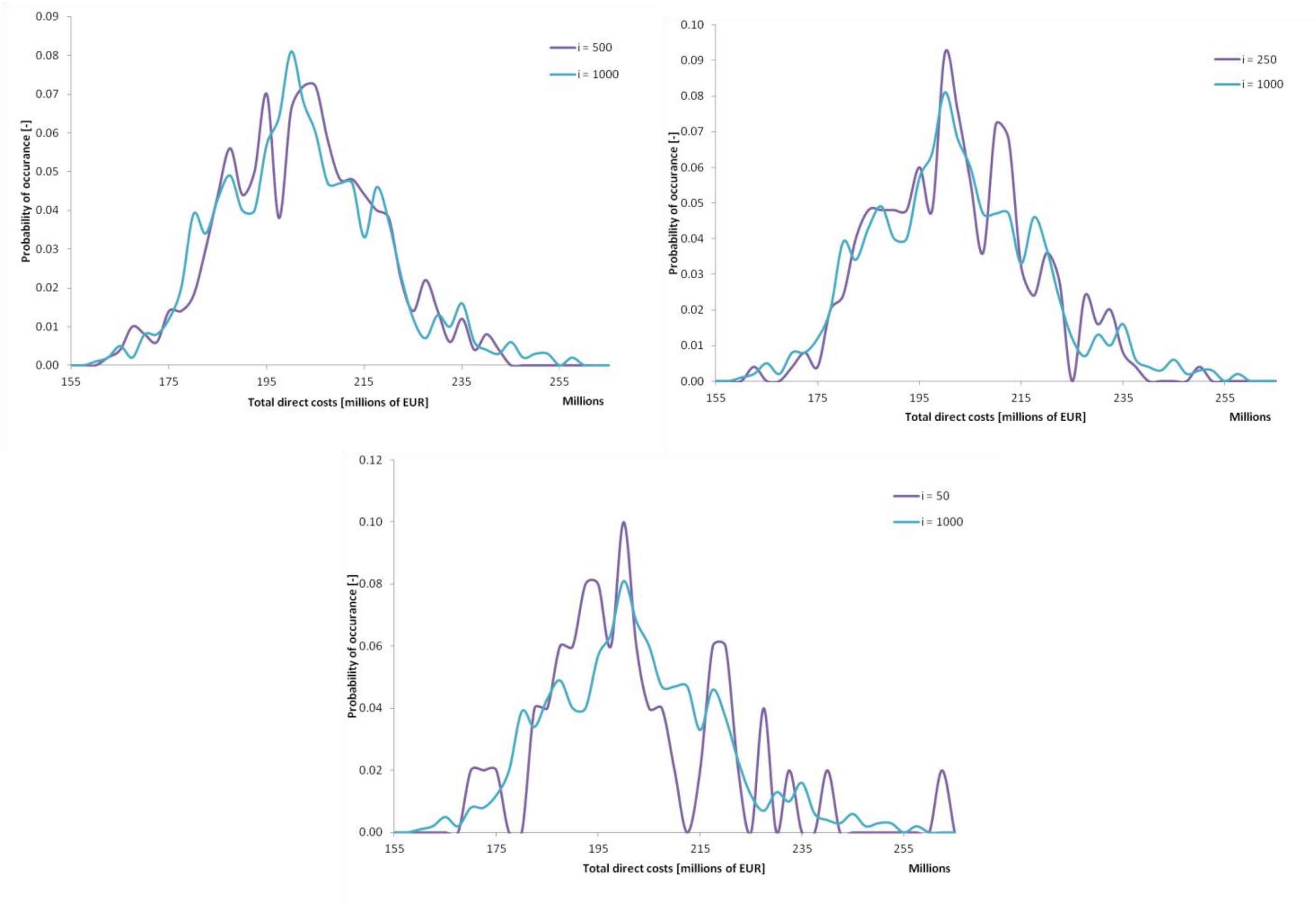


Figure 74: Probability density distributions of the total direct costs for various number of iterations. Source: Own work

5.5.2 Variables of interest

The cost elements that are computed in the tool are the quay wall, (un)loading equipment, storage facilities and storage equipment costs. The costs are determined by multiplying the specific output dimension or quantity with a unit cost. In this analysis the unit cost distributions are constants, the distributions of the variables are varied. Not all variables are taken into account due to reasons that are given in the introduction of this subsection. The variables that are provided by EMO are taken as constants. The values of variables that are uncertain and are therefore represented by a distribution are used for the sensitivity analysis. Per cost element the influencing variables that are considered for the sensitivity analysis are listed:

1. Quay wall costs:
   a) Average vessel length
   b) Estimated berth occupancy
   c) Gross productivity per loading equipment
   d) Gross productivity per unloading equipment
2. (Un)Loading equipment costs:
   a) Estimated berth occupancy
   b) Gross productivity per loading equipment
   c) Gross productivity per unloading equipment

3. Storage facilities costs:
   a) Cargo dwell time
   b) Estimated storage occupancy
   c) Stockpile height
   d) Stockpile lane width
4. Storage equipment costs:
   a) Gross productivity per stacking equipment
   b) Gross productivity per reclaiming equipment

For the analysis the distribution intervals of the variables are made smaller, thus smaller uncertainties are created. The boundaries are moved inwards a certain percentage (5%, 10% and 15% per boundary per step) of the base case interval length. The resulting probability distributions of the total direct costs f_2 are compared to the distribution for the base case f_1, in agreement with Equation (30). For this analysis all variables are assumed to have uniform distributions since narrowing a triangular distribution can also shift the mean value. This can have an extra impact on the resulting total costs distribution which makes the comparison of the Entropies less fair. The original distributions from Section 5.3.8 are used, in Table 48 the lower and upper limits of the base case uniform distributions and the narrowed uniform distributions are listed.

Table 48: The analysed variables with the base case and narrowed distributions per step. The lower and upper limits of the uniform distributions are presented.

Variable		**Base case**	**Step 1** 10% smaller	**Step 2** 20% smaller	**Step 3** 30% smaller
Average vessel length [m]		225.0 - 275.0	227.5 - 272.5	230.0 - 270.0	232.5 - 267.5
Estimated berth occupancy [%]		65.00 - 80.00	65.75 - 79.25	66.50 - 78.50	67.25 - 77.75
Gross prod. loading equip. [tonne/hour]		1,260 - 2,100	1,302 - 2,058	1,344 - 2,016	1,386 - 1,974
Gross prod. unloading equip. [tonne/hour]		890.0 - 1,480.0	919.5 - 1,450.5	949.0 - 1,421.0	978.5 - 1,391.5
Cargo dwell time [days]		45.00 - 80.00	46.75 - 78.25	48.50 - 76.50	50.25 - 74.75
Estimated storage occupancy [%]		60.00 - 85.00	61.25 - 83.75	62.50 - 82.50	63.75 - 81.25
Stockpile height [m]	Coal	21.0 - 23.0	21.1 - 22.9	21.2 - 22.8	21.3 - 22.7
	Iron ore	15.0 - 19.0	15.2 - 18.8	15.4 - 18.6	15.6 - 18.4
Stockpile lane width [m]		78.00 - 93.00	78.75 - 92.25	79.50 - 91.50	80.25 - 90.75
Gross prod. stacking equip. [tonne/hour]		1,800 - 3,000	1,860 - 2,940	1,920 - 2,880	1,980 - 2,820
Gross prod. reclaiming equip. [tonne/hour]		1,350 - 2,250	1,395 - 2,205	1,440 - 2,160	1,485 - 2,115

5.5.3 Analysis of the results

The sensitivity analysis does not test if the total costs increase or decrease given a certain change in the input but it tests how much the costs distribution changes for each adjustment to the input. These changes in the costs distribution are quantified by the Entropy quantity. Section 5.5.1 provides a reference for the Entropy quantities.

The Entropy is calculated per variable between the base case distribution and distributions of the different narrowing steps (10%, 20% and 30%). These quantities are presented in Table 49. To determine if a variable has a small, medium or large effect on the costs its Entropy quantities are compared to the Entropies of all variables. For the ratio of a variable's Entropies to the total the following three ranges -of equal size- are considered, in which 0.057 is the minimum occurring ratio and 0.167 the maximum. The overall effects are listed in Table 49 as well.

- Small effect when $0.057 \leq Q_i < 0.093$
- Medium effect when $0.093 \leq Q_i < 0.130$
- Large effect when $0.130 \leq Q_i \leq 0.167$

Where,

$$Q_i = \frac{\sum_{j=1}^{3} I_{i,j}}{\sum_{i=1}^{10} \sum_{j=1}^{3} I_{i,j}}$$

Where,

Q_i The ratio of a variable's Entropies to the total.
i The considered variable in the set, with i = 1, 2,..., 9, 10.
j The considered narrowing step, with j = 1, 2, 3.

By using these criteria it can be concluded that the average vessel length has the largest impact on the total costs. In other words a change of the average vessel length input results in a relatively large change of the costs. This can be explained by the fact that there is a linear relation between the vessel length and the quay length -Equation (7)- and because the quay wall costs by far have the highest contribution to the total costs; see Figure 71. The effect of the gross loading productivity is small, this can be explained by the small number of loading equipment and therefore the limited contribution to the total costs. The gross unloading productivity has a medium effect, compared to the loading equipment this is due to the larger required number of equipment. The cargo dwell time appears to have a small effect on the total costs. The estimated storage and berth occupancies both have a medium effect. This is somewhat unexpected since for the application of the Expert Judgement Elicitation it was expected that the storage occupancy is an important factor, this of course does not influence the EJE results. The height of the stockpiles has a large influence on the total costs. If the height decreases the cross-section of a stockpile lane also decreases resulting in a larger required lane length, this in turn increases the required storage area and thus the storage facility (or in this case pavement) costs. The stockpile lane width also determines the stockpile cross-section. Given the input values all possible occurring cross-sections are trapezoidal and not triangular. In this case the cross-section area is quadratically dependent on the height and linearly dependent on the width. The width therefore has a smaller effect. Both the gross stacking and reclaiming productivities have a small effect. Even though the storage equipment costs (thus the total stacker-reclaimer costs) are higher than the (un)loading equipment costs in Figure 71; especially the gross unloading productivity can have a larger effect since it also influences the required number of berths and thus the quay wall costs.

To put things into perspective; the effect of the average vessel length and stockpile height on the total costs can be compared to the effect on the costs distribution when the number of iterations is changed from 1000 to somewhere in between 250 and 500, according to the results from Section 5.5.1.

Table 49: Entropy quantities between the total direct costs distribution of the base case and the total direct costs distributions per step

Variable	**Entropy I [-]** Base case vs. 10% smaller	Base case vs. 20% smaller	Base case vs. 30% smaller	Overall effect on the total costs
Average vessel length	3.2052	4.8603	3.8454	Large
Estimated berth occupancy	1.1763	1.8447	5.2367	Medium
Gross prod. loading equip.	0.5369	3.0130	0.4930	Small
Gross prod. unloading equip.	6.4252	0.5055	0.0517	Medium
Cargo dwell time	2.9465	1.6049	0.5127	Small
Estimated storage occupancy	3.4070	0.9424	2.5306	Medium
Stockpile height	2.9572	0.5613	5.8776	Large
Stockpile lane width	0.0729	4.5865	1.6286	Small
Gross prod. stacking equip.	0.5182	2.7433	3.1863	Small
Gross prod. reclaiming equip.	1.8455	3.0149	1.1688	Small

It is expected that the smaller the widths of the uncertainty distributions become, the larger the Entropy quantities are. From the results this cannot be concluded since for most variables the Entropies are not increasing over all three narrowing steps. A cause could be that a too small number of bins is used for the histograms of the total cost distributions. However, after increasing this number from 50 to 100 the conclusion does not change. Another reason could be that the used number of iterations (1000) is too small. Computing the Entropy between the total cost distributions, resulting from two runs with exactly the same input, results in a very low Entropy (I = 0.075). This means that multiple runs give similar results and the number of iterations is therefore sufficient.

5.5.4 Conclusions

Variables that affect the direct cost elements and that are uncertain in the EMO case study are considered in the sensitivity analysis. The intervals between the minima and maxima of these uniform distributions are made smaller in steps of 10%, 20% and 30%. The total direct costs distributions resulting from the computations with the adjusted distributions are compared to the costs distribution corresponding to the base case. They are compared using Entropy. According to the analysis the average vessel length and the stockpile height have the most impact on the total direct costs. The typical differences in the cost distributions due to varying the input can be compared to the difference that occurs when a computation is run with a number of iterations in between 250 and 500, compared to a 1000. Due to the large effect on the costs distribution, optimising these two variables can lead to relatively large costs savings. The variables that have a mediocre effect on the total costs are the estimated berth occupancy, gross productivity of unloading equipment and the estimated storage occupancy. Variables with little effect are the gross productivity of loading equipment, cargo dwell time, stockpile lane width and the gross stacking and reclaiming productivities. It must be stressed that the considered variables are variables of which the values are uncertain. It can be expected that when more variables are included in the analysis the results will be different.

The conclusions that are drawn here are only applicable to this case; the EMO terminal. When some constant variables would differ considerably their influence on the total costs would too; this means that the impact of other variables also changes. As an example the gross productivity of loading equipment can be taken. When the percentage of outgoing cargo would be much larger (than the current 1% of the throughput) more loading equipment would be required. That number of course also depends on the productivity of the machines and dry bulk (un)loading equipment is quite expensive. Therefore the total costs, loading productivity and outgoing cargo flow are interrelated. Despite this the insights from this case study may well be of help in other design projects.

6 CONCLUSIONS AND RECOMMENDATIONS

The main research objective of this study is:

The development and application of a tool for computing the main required marine terminal dimensions and corresponding construction costs with a limited available amount of data and including uncertainties for the variables and costs.

In pursuance of this objective multiple research questions were posed. These questions are considered in the various chapters of this report. In the conclusions the main answers to the research questions are presented. Parts of the research that may require further study are specified in the recommendations.

6.1 Conclusions

The very first research question was: *What are the main terminal elements and the existing terminal design guidelines and design rules?*

Of all the essential terminal elements background information is provided. Moreover many design guidelines and rules for container, dry and liquid bulk terminals were collected. Only for the estimation of the required area for dry bulk silo and liquid bulk tank groups a calculation method was developed by the writer. Since so many rules have been collected, they are not listed here and reference is made to Chapter 2. The main design rules and guidelines -for dimensioning the terminal elements- are featured in an overview per terminal type. The overviews have been made clear and complete with the intent that they can aid terminal and/or port designers.

The second research questions was: *What are common values for the design rule parameters and what are common unit costs of terminal elements?*

Ultimately for all variables common values have been determined. As well as unit costs for all terminal elements. Again, since there are so many variables and cost items, reference is made to Chapter 2. In most cases the common values of variables are based on literature. The consulted literature does not provide common values for all parameters, examples are project specific parameters such as the throughput. For some other variables, that concern stockpile, silo or tank dimensions, existing terminals were investigated. Realistic common values could therefore be derived. For two important parameters a special method has been used to determine common values, this is elaborated on in the next research question. The first of the concerned variables is the *total terminal factor*, which is the percentage of the area required for storage with respect to the total terminal area. The second variable is the *average storage occupancy*, which is the percentage of the design capacity of the storage area that is actualy used. Unit costs can hardly be found in literature since construction companies and manufacturers are not very generous in supplying this kind of information. The considered unit costs are therefore predominantly based on information provided by *Witteveen+Bos*.

The third research question was: *What are the uncertainty distributions of the total terminal factor and the average storage occupancy factor and what are the correlations between average import, export and transhipment container dwell times?*

To be able to answer these questions the opinions of experts were scientifically combined by means of *Expert Judgement Elicitation* on respectively uncertainty and dependence. First four experts have been assessed by *Cooke's Classical model* in order to combine their uncertainty about common values of the total terminal factor and the storage occupancy of the three terminal types. The resulting cumulative probability distributions are depicted in Figure 75.

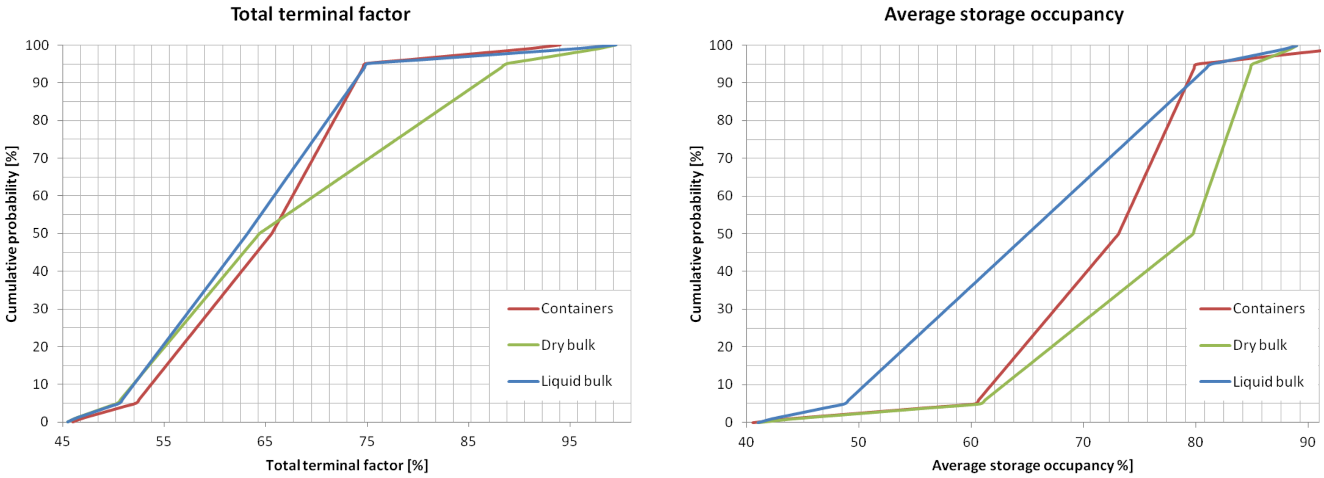


Figure 75: Cumulative probability distributions of DMit_op for the three terminal types

The experts were weighted based on their estimates of a sufficient number of seed variables. Various weighting schemes -or *Decision Makers* (DM's)- were considered. The *item optimised* DM gave the best scores. Its resulting probability distributions -consisting of combinations of the distributions of the four experts- were used.

To answer the second part of the research question; the same four experts have been assessed about their estimates of the correlations between container dwell times. For this the *conditional probability technique* was applied. From the combination of the experts' opinions it can be concluded that import, export and transhipment container dwell times are related. It can be observed that there are moderate positive relationships between import & transhipment and export & transhipment container dwell times. As well as a weakly positive relationship between import & export container dwell times. The rank correlations of these dependencies are depicted in a *Bayesian Network* (BN) in Figure 76.

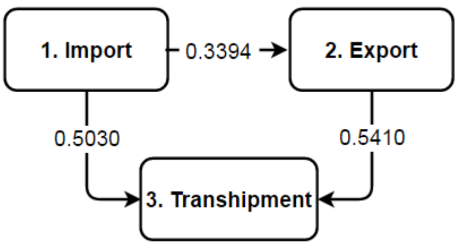


Figure 76: BN with rank correlations between the average container dwell times

The experts were again weighted based on their estimates of an unconditional dependency between two port-related variables, in other words the seed question. Two experts exactly estimated the actual rank correlation of the seed question. The *global weights* weighting scheme was used since it produced the highest *d-calibration* score of practically 1.0. This is due to the fact that the method discarded the estimates of two -slightly lower scoring- experts and gave the two selected experts the individual weights of 0.5. A measure to avoid this is presented in the recommendations. Although the estimates of two experts were not used, the final result of this case is a good representation of the individual estimates.

The answers to the previous three research questions provided the information required to be able to realise the tool. The tool satisfies the requirements as stated in the main research objective. It has been positively received by the 'client' Witteveen+Bos and the Port of Rotterdam has also shown interest in it. The writer therefore is confident it will be used in practice.

The fourth research question was: *What terminal elements contribute the most to, and what input parameters have the largest influence on, the total construction costs of one specific terminal?*

The considered terminal is Europe's largest dry bulk terminal; the *EMO* (*Europees Massagoed Overslag*) terminal at the *Maasvlakte* in Rotterdam. The terminal handles coal and iron ore. It can be concluded that for this specific case the quay wall has by far the highest contribution to the total costs, followed by the storage facilities. This can be observed in Figure 77, which depicts the contribution of the main terminal element costs[35] to the total construction costs, being € 358,853,000.

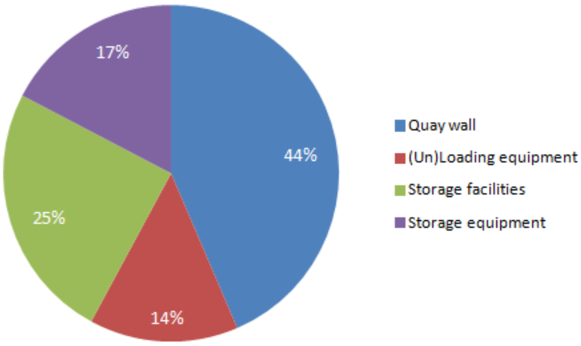


Figure 77: The contribution of the 70th percentiles of the cost elements to the total costs

In reality not the complete stockpile area is paved. Moreover the quay wall section used for ship-loading has a smaller retaining height than the section for ship-unloading, while in this case the latter is assumed for the entire quay for sea-going vessels. The estimated costs are simplified model outputs and will therefore vary from the actual costs. On average the actual main terminal dimensions correspond to the 70th percentiles of the probability distributions, resulting from the tool computation. This quantile is therefore also used to estimate the total costs. Generally the 70th percentile is used for budgeting purposes. Therefore, when it is assumed that the terminal was well designed in the past, it can be concluded from these realistic main dimensions that the tool gives credible results. It is advised -based on the case study- to not use large uncertainties for variables since these variables will then dominate the resulting dimensions and costs. As a rule-of-thumb for uniform and triangular distributions the upper limit should not be more than twice the lower limit.

To answer the second part of the research question a sensitivity analysis is performed. The distributions of variables with an uncertainty were adjusted and the effects on the total direct costs were analysed. The *average vessel length*, and consequently the quay wall, as well as the *stockpile height* appeared to have the highest influence on the costs. The total costs showed medium or low

[35] This cost estimate considers the quay wall for sea-going vessels, gantry grab cranes for unloading, loading equipment, stockpile pavement and stacking-reclaiming equipment. Terminal elements that are not taken into account are roads, buildings, train and crane rails, belt conveyors, the quay wall for barges and corresponding loading equipment.

sensitivity to the other considered variables. It must be stressed that these results are only for this specific case, other cases may give different results. It is therefore recommended to do a comparable analysis for every case when more insight is desired.

6.2 Recommendations

During this study certain assumptions were made due to for example lack of data or time. The research aspects that can be investigated further are presented in this section. The aspects are listed per chapter of this report.

Literature study

Terminal equipment manufacturers do not easily share information, such as capacities or weights, regarding their products. The dry bulk unloading, loading, reclaiming and stacking capacities of equipment that are listed in this study therefore have a high uncertainty. More detailed information would result in a more accurate overview and tool results. The same holds for the investment costs of these machines. In this study an estimate of dry bulk equipment costs is made by using a relation from Vianen, T. van (2015); between the capacity and the costs of stacker-reclaimers. A similar study for the other equipment types would give more accurate costs indications.

As already mentioned unit costs for terminal elements are hardly present in literature. Nevertheless this study presents unit costs for all main terminal elements. Some of these costs are rough estimates since they are based on little data and may therefore be less accurate or reliable. Further research into these costs is recommended, especially for: jetties, silos and the different types of liquid bulk tanks.

Expert Judgement Elicitation

Four experts were assessed for the Expert Judgement Elicitation. Although this number theoretically is sufficient more sources of information may give more complete results. The experts gave different motivations for certain questions. Including more experts may lead to even more different views on a problem and can therefore make a Decision Maker more complete. The field of expertise of most of the assessed experts are specifically container terminals. An option for a future study is to create separate questionnaires for container, dry and liquid bulk terminals and elicit corresponding experts. This way experts are scored purely on their field of expertise, which may improve their weights for the corresponding target variables. Then the chance that 'good' knowledge is lost, because of low weights, is smaller.

The weights of the experts for the dependence elicitation are based on only one seed question. Only one seed is used since these questions require data which is hard to come by. This was acceptable in this case since -although two experts got zero weight- all experts their opinions are well represented. Besides, another goal of the application of EJE in this study is to bridge the gap between theory and practice and to introduce the method to this field of expertise. For future applications of this method it is advised to include a more complex combination of seed variables. Accordingly it is recommended to use seed variables with a similar number of (conditional) dependencies as for the target variables. This decreases the chance that multiple experts give exactly similar estimates and dominate the pooling of the correlations.

BIBLIOGRAPHY

Actueel Hoogtebestand Nederland (2016), Website. http://ahn.arcgisonline.nl/ahnviewer/

Agerschou, H. (2004), *Planning and Design of Ports and Marine Terminals*, Thomas Telford.

Aspinall, W. (2008), Seventh session of the statistics and risk assessment section's international expert advisory group on risk modeling, *in* W. Aspinall, ed., 'Expert Judgment Elicitation using the Classical Model and Excalibur', number Round IV.

Böse, J. W. (2011), *Handbook of Terminal Planning*, Springer.

Cooke, R. (1991), *Experts in uncertainty: opinion and subjective probability in science*, Oxford University Press on Demand.

Cooke, R. M. & Goossens, L. L. (2008), 'Tu delft expert judgment data base', *Reliability Engineering & System Safety* **93**(5), 657–674.

dace (2015), 'Price booklet edition 31'.

de Gijt (2010), A History of Quay Walls, PhD thesis, Delft University of Technology.

de Gijt, J. & Broeken, M. (2005), *Handbook of Quay Walls*, CRC Press.

Drewry (2010), 'Global container terminal operators 2010: Annual review and forecast'.

EMO (2016), Website. http://www.emo.nl/en/

Ertsoverslagbedrijf Europoort C.V. (EECV) (2013), *Terminal Information Book*, 1.06 edn, EECV.

Eurosilo, E. (2016), 'Storage solutions for non-free flowing bulk materials', Website. http://eurosilo.com/

Fourgeaud, P. (2000), 'Measuring port performance', *The World Bank* .

Genest, C. & Favre, A.-c. (2007), 'Everything you always wanted to know about copula modeling but were afraid to ask', *Journal of Hydraulic Engineering* .

GreenPort (2016), 'Dry bulk covered storage options', Website. http://www.greenport.com/news101/Projects-and-Initiatives/dry-bulk-covered-storage-options

GSI (2016), 'Stiffened grain bins', Website. http://www.grainsystems.com/products/storage/grain-bins/4032.html

Het Financieele Dagblad (2016), 'Lng heeft nog een lange weg te gaan', *Het Financieele Dagblad* . Article in Dutch.

Heymann, E. (2006), 'Container shipping. overcapacity inevitable despite increasing demand', *Deutsche Bank Research* **2006**, 1–10.

Idrus, M., Samang, L., Adisasmita, R., Sitepu, G. & Ramli, M. I. (2012), 'A study on the container yard utilization of the major ports in indonesia eastern region'.

igg (2016), ‘Bouwkostenkompas: Woning- en utiliteitsbouw’.

Kersten, M. K. (2010), Master plan port romano bay, albania, Master’s thesis, TU Delft, Delft University of Technology.

Kleinheerenbrink, A. (2012), A design tool for dry bulk terminals, Master’s thesis, TU Delft, Delft University of Technology.

Kraan, B. C. P. (2002), *Probabilistic inversion in uncertainty analysis: and related topics*, TU Delft, Delft University of Technology.

Krol, R. (2007), Next generation storage tanks, Master’s thesis, TU Delft, Delft University of Technology.

Kullback, S. (1997), *Information theory and statistics*, Courier Corporation.

Ligteringen, H. & Velsink, H. (2012), *Ports and Terminals*, VSSD.

Lind, D., Hsieh, J. K. & Jordan, M. A. (2007), Tandem-40 dockside container cranes and their impact on terminals, *in* ‘Proceedings of 11th triannual international conference on American society of civil engineers’, pp. 1–9.

Lodewijks, G., Schott, D. & Ottjes, J. (2009), ‘Dry bulk terminal expansion or redesign?’, *Port Technology International* .

M. D. Mckay, R. J. B. & Conover, W. J. (2000), ‘A comparison of three methods for selecting values of input variables in the analysis of output from a computer code’, *Technometrics* **42**(1).

Mohseni, N. (2011), Developing a tool for designing a container terminal yard, Master’s thesis, TU Delft, Delft University of Technology.

Monday Nyema, S. (2014), ‘Factors influencing container terminals efficiency: A case study of mombasa entry port’, *European Journal of Logistics Purchasing and Supply Chain Management* .

Monfort, A., Aguilar, J., Vieira Gonçalves de Souza, P., Monterde, N., Obrer, R., Calduch, D., Martín, A. M. & Sapiña, R. (2011), Sea port capacity manual: application to container terminals, Technical report, Fundación VALENCIAPORT.

Morales-Napoles et al. (2016), Calibration and combination of experts’ dependence estimates. Unpublished.

Morales-Napoles, O., Hanea, A. & Worm, D. (2014), Experimental results about the assessments of conditional rank correlations by experts: Example with air pollution estimates, *in* ‘ESREL 2013: Proceedings of the 22nd European Safety and Reliability Conference" Safety, Reliability and Risk Analysis: Beyond the Horizon", Amsterdam, The Netherlands, 29 september-2 oktober 2013’, CRC Press/Balkema-Taylor & Francis Group.

Morales-Napoles, O., Kurowicka, D. & Roelen, A. (2007), ‘Eliciting conditional and unconditional rank correlations from conditional probabilities’, *Reliability Engineering & System Safety* **93**(5), 699–710.

Morales-Napoles, O. & Worm, D. (2013), Hypothesis testing of multidimensional probability distributions, Technical report, TNO.

Mwasenga, H. (2012), ‘Port performance indicators: A case of dar es salaam port’.

PCA Consultants (n.d.), *Technical pollution prevention guide for dry bulk terminals in the lower fraser basin*, PCA Consultants.

PIANC (1995), Report no. 30: Approach channels - preliminary guidelines, Technical report, The World Association for Waterborne Transport Infrastructure (PIANC).

PIANC (2012), Report no. 116: Safety aspects affecting the berthing operations of tankers to oil and gas terminals, Technical report, The World Association for Waterborne Transport Infrastructure (PIANC).

PIANC (2014*a*), Report no. 135: Design principles for small and medium marine container terminals, Technical report, The World Association for Waterborne Transport Infrastructure (PIANC).

PIANC (2014*b*), Report no. 158: Masterplans for the development of existing ports, Technical report, The World Association for Waterborne Transport Infrastructure (PIANC).

Quist, P. & Wijdeven, B. (2014), *Container Terminals*, VSSD, chapter 7, p. 276.

RiskAMP (2016), 'Latin hypercube sampling', Website. https://riskamp.com/kb/Latin-Hypercube-Sampling

Saanen, Y. A. (2004), *An approach for designing robotized marine container terminals*, TU Delft, Delft University of Technology.

Simio (2016), 'Port simulation software', Website. http://www.simio.com/applications/port-simulation-software/

Sztrik, J. (2012), *Basic Queueing Theory*, Sztrik, J.

TBA (2016), 'Timesquare: proven, valid, and accurate', Website. https://www.tba.nl/en/simulation/timesquare/

Terblanche, L. & Moes, H. (2009), 'Maritime highways to a port - modelling of maximum capacity'.

The Tioga Group (2010), 'Container port capacity study'.

Udny Yule, G., Kendall, M. G. et al. (1950), 'An introduction to the theory of statistics.', *An introduction to the theory of statistics.* (14th ed).

UNCTAD (1985), *Port development: A handbook for planners in developing countries*, second edition edn, United Nations.

Vianen, T. v., Ottjes, J. & Lodewijks, G. (2012), 'Stockyard dimensioning for dry bulk terminals'.

Vianen, T. v., Ottjes, J. & Lodewijks, G. (2014), 'Dry bulk terminals characteristics', *Bulk Solids Handling* .

Vianen, T. van (2015), Simulation-integrated Design of Dry Bulk Terminals, PhD thesis, TU Delft, Delft University of Technology.

VROM (2008), Publicatiereeks gevaarlijke stoffen 29: Richtlijn voor bovengrondse opslag van brandbare vloeistoffen in verticale cilindrische tanks, Technical report, VROM. Language: Dutch.

VROM (2013), Publicatiereeks gevaarlijke stoffen 18: Lpg: depots, Technical report, VROM. Language: Dutch.

VROM (2014), Publicatiereeks gevaarlijke stoffen 9: Cryogene gassen: opslag van 0,125 - 100 m3, Technical report, VROM. Language: Dutch.

Werner, C., Bedford, T., Cooke, R. M., Hanea, A. M. & Morales-Nápoles, O. (2016), 'Expert judgement for dependence in probabilistic modelling: A systematic literature review and future research directions', *European Journal of Operational Research* .

Whitlock, P. A. & Kalos, M. H. (2009), *Monte Carlo Methods*, second revised and enlarged edition edn, Wiley.

Wolfert, A. (2014), 'Projects risk management. introduction probabilistic costing & planning.', Lecture notes. Lecture from TU Delft course CIE4130.

Wu, M. (2012), A Large-scale Biomass Bulk Terminal, PhD thesis, TU Delft, Delft University of Technology.

APPENDICES

Appendix I Unit costs CONFIDENTIAL

Intentionally left out in this version.

Appendix II Interviews

II.1 Sip Meijer | Witteveen+Bos

Interview

Date:	**19-04-2016**
Time:	14:00 – 15:20
Location:	Deventer

Sip Meijer

Senior Port Specialist at Witteveen+Bos

1. *What steps do you perform during the design of a terminal in the feasibility phase of a port master plan?*
   Important are the costs, for the client a cost overview is the goal of a feasibility study. The type of soil is important for e.g. the quay wall structure and the yard pavement and thus the costs. Also terminal equipment forms a large part.

2. *What literature do you use for design rules and guidelines?*
   Containers: An addition to the literature list shown is Chapter 2 from 'Handbook of terminal planning', 2011 written by Birgitt Brinkmann. This contains information about the required number of equipment needed per STS crane and useful properties of the equipment.
   Dry bulk: the paper 'Dry bulk terminal characteristics' by Vianen et al.
   Liquid bulk: Meijer says he doesn't know much about this subject, normally Tebodin takes care of the calculations for these kind of terminals.

3. *Do unwritten rules of thumb exist for the calculation of terminal dimensions?*
   A common value for the depth of a container terminal is 500 meters. Furthermore capacity benchmarks exist for container terminals for example TEU/m/year for quay walls or TEU/ha/year for the storage yard (dependant on the type of storage; import, export, transhipment). Often used for import/export is 25000 TEU/ha/year and for transhipment is 35000 TEU/ha/year. These values are more used for checking the calculated values. They differ considerably across different regions in the world. Also existing ports are used as reference for values of variables.
   Master planning in this phase is working with a lot of uncertainties; for example the efficiency of a crane driver or the real working hours per year. You don't know this until the terminal is operational. Important is that every assumption you make you have to write down.

4. *By determining the total terminal area, what values do you use for the roads and additional buildings at the terminal?*
   For container terminals 75% of the total terminal area is the area of the stack. The required dimensions of dry and liquid bulk terminals are calculated by Tebodin so Meijer does not know the rules of thumb for these kind of terminals. They have more knowledge about what equipment is needed and how much space it requires to store the cargo. Tebodin has specialised dry bulk (in Deventer) and liquid bulk (in Den Haag) groups.

5. *What variables do you normally use during the calculation of terminal dimensions?*
   Variables, values and much more valuable information about (the design of) container terminals can be found in 'Sea port capacity manual: application to container terminals' by Monfort Mulinas et al. (2011).
   Common variables are: throughput, dwell time, peaking factor, occupancy rate storage yard, crane productivity, number of cranes, hours per year, occupancy rate quay, average and maximum ship length, throughput per call, arrival and service distributions, TEU factor, stacking height. Recently the most common value of the TEU factor worldwide is 1.60. The

arrival and service distribution is almost never known at this stage. The stacking height for empties is usually 7 to 8 boxes high. Normally stacks are not made higher than 2 or 3 boxes since otherwise the number of internal moves becomes too high. An average value of 2.5 for the stacking height is common, regardless the stacking equipment.

6. *Do you calculate with different values for the same variable in order to take into account the uncertainty?*
   Meijer does a sensitivity analysis for, for example, the number of moves per crane, the TEU factor and the dwell time. Terminal operators can influence the dwell time by changing the price to store a container. "We don't calculate with standard deviations".

7. *Do you use standard values for variables of which the values are unknown?*
   Yes, they are taken from literature and from experience. Clients expect the consultancy firm to know these things. When values are taken from surrounding ports they are used as a minimum since the new port must be better than the competitor's.

8. *Do you take the growth path of a port into account when calculating dimensions for a terminal?*
   The throughput is almost always provided by the client, including a low, average and high growth scenario. The growth path is split up into smaller parts of for example 5 years if the growth is significant. For these periods different calculations are made so that the investment for the entire terminal does not happen at once. Equipment is easier to acquire during the lifetime of the terminal.
   The advancement of regular cranes (per trolley) with respect to moves per hour is very low. Optimisations exist that more trolleys are used or that in one cycle a container is imported and exported, this however requires extensive planning.

9. *Do you use software during designing in the feasibility phase?*
   No, it is all done by hand. For some minor calculations excel is used. Multiple calculations are made but usually one typical outcome is presented in the report. Meijer: "It is a puzzle every time again."

10. *Do you know projects of Witteveen+Bos that include a container, liquid and dry bulk terminal that I can use for validation of the tool and for a case study?*
    For the Filyos and Taman projects only "vlekkenplannen" were made. So only the total required area and quay length was calculated. Benin is another project that is being done at this moment, the required storage area and quay length are calculated per transport direction. Meijer thinks that in the mentioned projects no liquid bulk terminal is included. Another option is a project in Cyprus (contact Johan de Boer), Witteveen+Bos did not determine the dimensions but we possibly do have documents that include this.

11. *Are in the feasibility phase costs determined?*
    Yes as already is discussed. The cost department of Witteveen+Bos does this. But also similar older projects are used as reference by the master planner. In the feasibility phase for, for example, a quay wall a similar wall with depth and terminal equipment is taken and the costs per meter wall are determined (including fenders, boulders etc.). In the (financial) feasibility phase of a project the goal is to determine if the project is viable. Therefore a cost estimate is made for different variants in order to see what the return on investment is.

12. a) *Do you try to minimise the costs during the design?*
       In the feasibility phase you should not be too optimistic with costs. It is better to be on the safe (higher) side.

b) *How do you get prices for e.g. equipment, dredging, structures, etc?*
   As was already mentioned the costs are determined at the cost department of Witteveen+Bos or older projects are used as a reference. Meijers does not know about the existence of an overview with costs, but says that maybe the cost department has something like that. Costs for dredging are usually determined by the dredging group of Witteveen+Bos, for this I can contact Niels Borgers or Marijn Huijsmans. Equipment costs are rather easy to acquire. There can however be large differences between for example European and Asian built equipment (e.g. a factor 2).

13. *Design rules*
    Capacity ratios can probably be found in Monfort Mulinas et al. (2011). Always the same standard rules are used. The queuing theory is almost never used in the feasibility phase since the distributions are not known and some variable values neither. It is an option to include the queuing theory in the tool as a supporting calculation. But when much information is not known a lot of assumptions have to be made, so what is then the value of the result?

14. *What would you like to have included in the tool?*
    Meijer has at this moment no wishes. He is content with the current ideas for the tool. Maybe when the tool is finished he will think of additions/changes.

15. *Are there more persons that you recommend me to interview?*
    People at Tebodin from the dry and liquid bulk group. Meijer will send me the contact information.

II.2 Robert Jan Smits van Oyen | Tebodin

Interview

Date:	**12-05-2016**
Time:	09:00 – 10:15
Location:	Den Haag

Robert Jan Smits van Oyen

Manager Logistics and Asset Management & Maintenance
at Tebodin Consultants & Engineers B.V.

1. *What literature do you use for design rules and guidelines?*
   PGS 29 exists, this document is about tanks with flammable content. These are guidelines but clients want them to be used in order to have safe facilities.
   Liquid and dry bulk terminals are very project specific. The terminal design is dependent on the type of terminal (i.e. gateway, storage and blending) and the business they are in. So some have multiple small tanks for various liquids and some have a few very large tanks for a few products.
   Smits van Oyen did a study on liquid bulk terminals in Antwerp and Rotterdam for the storage capacity and quay length.
   Smits van Oyen states that it is impossible to contain all terminals (dry bulk but especially liquid bulk) in a few design rules, there is too much variability.

2. *Do unwritten rules-of-thumb exist for the calculation of terminal dimensions?*
   At Tebodin they determine the layout of the terminal, distances, infrastructure (pipelines), tanks. Smits van Oyen focuses more on the logistic side of terminal design. For example using quay occupancy, the serving of vessels and required pump capacity.
   Smits van Oyen gives an example of a recent project where not the total throughput increased but the number of parcels per vessel with different liquids. This increases the complexity.
   There are no real rules-of-thumb for these terminals since they differ so much. For the berth occupancy a value between 50% and 65% is optimal says Smits van Oyen.
   For the percentage of the area of roads and buildings with respect to the total area there are no rules-of-thumb. Smits van Oyen says that most of these terminals are automated for a large part so not much personnel is needed.

3. *What variables do you normally use during the calculation of terminal dimensions?*
   The presented formulas are indeed used. But also ship characteristics such as parcel size for liquid bulk (because ships can transport multiple products). This leads to the question if all these goods must be imported/exported from the same berth or that the ship has to reposition to another berth. Also local conditions (such as restriction on number of ships in channel) play a role, this is however more suitable for a later design phase.
   The service time and arrival rate distributions are used in simulations. The arrival rate distribution is determined by randomly spreading the annual throughput over the year. This is delivered by the client. The service time distribution is dependent on het product (parcel size, viscosity or pump capacity), this is taken from historical data.

4. *Do you calculate with different values for the same variable in order to take into account the uncertainty?*
   Most or all data is provided by the client. Tebodin does sensitivity analyses so this takes into account uncertainty and is a form of risk management.

5. *How do you determine the terminal area of dry bulk terminals?*
   The client usually expresses the need for an open stockpile, shed or silo. When a shed is dimensioned the size of the pile is determined. Some dimensions have a maximum because of lack of space on the terminal. The area inside the shed, next to the pile is for equipment and access to the pile and structure. Usually 5 to 10 meters is used.

6. *How do you determine the terminal area of liquid bulk terminals?*
   For liquid bulk pipeways are used, these are often underestimated in size (with respect to future expansion). No rule-of-thumb exists since it is very much dependent on the sort and number of handled products and pipelines.
   A bund is only needed for safety reasons, so not all products need a bund surrounding the tank. Also tanks exist with a double wall, reducing the required area.
   The maximum pump capacity is determined by the type of product. A certain loading rate is required on a terminal.

7. *Do you use software during the feasibility phase?*
   Tebodin does static analysis by hand or by means of simple Excel worksheets for e.g. the stockpile dimensions. But no software like the product of this Thesis (the design tool).

8. *Where do you get costs of terminal elements for a cost analysis of a terminal project?*
   A rule-of-thumb in the feasibility phase for a liquid bulk terminal is between 500 and 1000 €/m^3 storage capacity. These values are costs for the whole landside of the terminal, so including tanks, pipelines and equipment. Terminals with large tanks are on the lower side of the cost range, terminals with multiple smaller tanks are on the higher side. Approximately 50% of these costs are for the tanks, the rest is for the other landside terminal elements.

Appendix III How to perform an Expert Judgment Elicitation

This appendix provides the reader with the probabilistic theories that are required to perform an *Expert Judgment Elicitation*. Separate theories are given for uncertainty and dependence assessments.

III.1 Uncertainty assessment | Classical Model (Cooke)

This section covers the steps to take when using performance-based elicitation of experts in order to determine (an) uncertainty distribution(s), specifically using *Cooke's Classical model*; Cooke (1991). To be able to understand this theory some knowledge about statistics is required. The theory described in this section is implemented in the free software *Excalibur*[36]. This section is entirely based on Cooke & Goossens (2008) unless indicated otherwise.

III.1.1 Elicitation

The 5th, 50th and 95th percentiles from each expert's subjective uncertainty distribution are elicited. This is done for a number of seed variables (a common number is ten questions), of which the true value is known to the researcher, and for a number of target variables. Using the three percentiles results in the intervals: (0; 0.05], (0.05; 0.50], (0.50; 0.95], (0.95; 1.00] with probability vector:

$$p = \begin{bmatrix} 0.05 \\ 0.45 \\ 0.45 \\ 0.05 \end{bmatrix}$$

If N seed variables are assessed all true realisations $x_1, \ldots, x_N$ of these variables must be in one of the percentile intervals. The total number of realisations in each interval divided by N is the sample distribution s_i of each interval i. All four sample distributions combined results in the sample distribution $s(e)$ of expert e.

III.1.2 Calibration

"Calibration measures the statistical likelihood that a set of experimental results correspond, in a statistical sense, with the expert's assessments", Cooke & Goossens (2008). The calibration score of expert e is:

$$P\{\, 2N \cdot I(s(e) \mid p) \geq r \mid H_e \,\} \tag{31}$$

Where,

N Number of seed variables.

$s(e)$ Sample distribution of expert e.

p Probability vector. In this case a 1 x n matrix with $n = 4$.

$I(s(e) \mid p)$ $= \sum_{i=1\,..\,4} \left\{ s_i \cdot \ln\left(\frac{s_i(e)}{p_i}\right) \right\}$ is the relative information of distribution s with respect to p. I is χ^2-distributed with n degrees of freedom. Where,

[36] Originally developed at TU Delft, now maintained by Lighttwist Software.
URL: http://www.lighttwist.net/wp/excalibur

$s_i(e)$ Sample distribution of interval i of expert e.
p_i Probability of interval i.

r Realisation of the variable (or true value).
H_e Hypothesis: *"the inter-quantile interval containing the true value for each variable is drawn independently from probability vector p"*. Is in this case assumed to be true since it is used to measure the degree to which the data supports the hypothesis.

The calibration score is the probability under hypothesis H_e that a deviation at least as great as r could be observed on N realisations.

III.1.3 Information

"The information in a distribution is the degree to which the distribution is concentrated", Cooke & Goossens (2008). Information cannot be measured absolutely; the expert's distribution is not compared to the realisation (or true value). Instead it is measured relative to another distribution; the background distribution. A commonly used background distribution is the uniform distribution.

The background distribution requires a so called intrinsic range. This range is defined as the interval with as lower boundary the smallest 5% quantile (q_5) of all experts per variable, and as highest boundary the largest 95% quantile (q_{95}) of all experts per variable. This results in interval Int = [q_5, q_{95}]. To also include the lowest and highest 5% of the expert's distribution the interval is extended to a wider interval. The Classical Model uses the *k% overshoot rule*, typically a value of k = 10 is used according to Aspinall (2008). The k-value is specified by the researcher. A higher value tends to make all experts look more informative. The extended interval according to the mentioned rule is:

$$\text{Int}^* = [q_L, q_H]$$

Where,

q_L $\quad q_5 - k \cdot \frac{(q_{95}-q_5)}{100}$

q_H $\quad q_{95} + k \cdot \frac{(q_{95}-q_5)}{100}$

With this information the cumulative distributions with minimum information with respect to the uniform distribution of all the experts can be determined. This since the distribution boundaries (q_L, 0) and (q_H, 1) are determined in the previous step. The rest of the distribution is determined by linear interpolation between the estimated quantiles of the expert. This should be done for each variable for each expert.

The information score of expert e then is:

$$\left(\frac{1}{N}\right) \cdot \sum_{i=1\,..\,N} \left\{ I\left(f_{e,i} \mid g_i\right) \right\} \qquad (32)$$

Where,
N Number of seed variables.
$I\left(f_{e,i} \mid g_i\right)$ $\quad = \sum_{i=1\,..\,4} \left\{ f_{e,i} \cdot \ln\left(\frac{f_{e,i}}{g_i}\right) \right\}$
$f_{e,i}$ Probability density of expert e for percentile interval i.
g_i Probability density of the background distribution for percentile interval i.

III.1.4 Aggregation

The Decision Maker (DM) combines the uncertainties of the experts per item (variable) by a pooling method. A pooling function is a weighted combination of individual judgments. The resulting distribution function of the DM is a normalised weighted linear combination of the experts' distributions per item, defined as:

$$G_n = \frac{\sum_{e=1..N_e} \left(w_e \cdot f_{e,n}\right)}{\sum_{e=1..N_e} \left(w_e\right)}$$

Where,

G_n	Distribution function of the DM for item n.
N_e	Number of experts.
w_e	Weight of expert e and/or per item n, depending on the weighting method.
$f_{e,n}$	Distribution function of expert e for item n.

This linear pooling is done for all four probability intervals (p) of the uncertainty distribution of an item. The DM is then scored the same way as the experts resulting in a calibration and information score of all items. Different DM's can therefore be compared. The un-normalised weight is the product of the calibration and the average information score over all the seed items per expert. An expert with a high un-normalised weight can be said to have "good expertise"; Aspinall (2008). DM weights can be determined by the following methods:

- Global weights: Uses the un-normalised weights. Per expert the weights are the same for all items.
- Item weights: A variation of global weights where each item can have a different set of weights. Uses the information scores of all experts per item separately instead of the average score over all items.
- Equal weights: The weights are the same for all experts; $w_e = {}^{1}/_{N_e}$.

The global and item weights can be optimised. When optimising an iteration is performed where the minimum allowable calibration score is varied. When experts do not meet the minimum score their uncertainties are not taken into account in the DM. The optimisation ultimately chooses the calibration score for which the un-normalised weight of the DM is maximum. The goal is to choose the DM with the best calibration and information scores.

III.2 Dependence assessment | Conditional probability technique

This section covers the steps to take when using performance-based elicitation of experts in order to determine rank correlations between variables, specifically using the *conditional probability technique*. To be able to understand this theory some knowledge about statistics is required.

III.2.1 Elicitation

Dependence can be visualised by a *Bayesian Network* (BN), where the objects are the random variables. As an example and in order to explain the theory the BN of Figure III-1 is considered which consists of four variables with (un)conditional correlations. The eliciting theory used for unconditional rank correlations is first summarised by Kraan (2002). The theory for conditional rank correlations is presented in Morales-Napoles et al. (2007). This section is entirely based on the latter source unless indicated otherwise. During the elicitation experts are asked for certain probabilities. An example of such a question is:

Suppose X_1 and X_2 and X_3 are each observed above their median values. What is the probability that X_4 will also be observed above its median value?

The probabilities, corresponding to the example BN, that are asked to the experts are given below. The example question above resembles question 3.

Question 1: $P_1 = P\left(F_{X_4}(X_4) > 0.50 \mid F_{X_3}(X_3) > 0.50\right)$

Question 2: $P_2 = P\left(F_{X_4}(X_4) > 0.50 \mid F_{X_2}(X_2) > 0.50, F_{X_3}(X_3) > 0.50\right)$

Question 3: $P_3 = P\left(F_{X_4}(X_4) > 0.50 \mid F_{X_1}(X_1) > 0.50, F_{X_2}(X_2) > 0.50, F_{X_3}(X_3) > 0.50\right)$

Where,

$F_{X_i}(X_i)$ The cumulative probability of variable X_i. Therefore $F_{X_i}(X_i) > 0.50$ means that variable X_i is observed above its median.

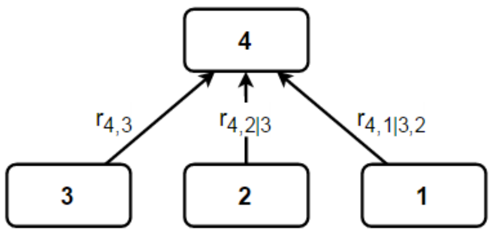


Figure III-1: BN of four variables (X_1, ..., X_4) with conditional relations. Source: Morales-Napoles et al. (2007)

Definitions

At this stage the expert has given probabilities as answer to the questions, these probabilities have to be 'converted' to rank correlations. After selecting a certain *copula* the rank correlation (*r*) corresponding to the expert's probability (*P*) can be found. A copula is a distribution of which the marginal probability distributions are uniform. Every continuous multivariate probability distribution can be represented by a copula, copulas can be used to analyse the dependence between random variables; the previous is based on Genest & Favre (2007). Random variables *X* and *Y* are joined by copula *C* if their joint distribution can be written as:

$$F_{X,Y}(x, y) = C\left(F_X(x),\ F_Y(y)\right)$$

Important statistical properties of a multivariate probability distribution are the *Pearson's product moment correlation* and the *Spearman's rank correlation*. The unconditional product moment correlation ($\rho_{X,Y}$) of random variables X and Y with expectations $E(X)$ and $E(Y)$, and variances $var(X)$ and $var(Y)$ is defined as:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \cdot \sigma_Y} = \frac{E(X \cdot Y) - E(X) \cdot E(Y)}{\sqrt{var(X) \cdot var(Y)}} \tag{33}$$

The rank correlation is the product moment correlation between the ranks of random variables X and Y. The unconditional rank correlation ($r_{X,Y}$) between random variables X and Y with cumulative distribution functions F_X and F_Y is defined as:

$$r_{X,Y} = \rho_{F_X(X),F_Y(Y)} = \frac{E\big(F_X(X) \cdot F_Y(Y)\big) - E\big(F_X(X)\big) \cdot E\big(F_Y(Y)\big)}{\sqrt{var\big(F_X(X)\big) \cdot var\big(F_Y(Y)\big)}} \tag{34}$$

Many different copula's exist, for this application however the *Gaussian copula* (or normal copula) is used. The *normal copula* is used since it has computational advantages, according to Morales-Napoles et al. (2014). The normal copula can be defined as the bivariate standard normal cumulative distribution (Φ_ρ) with correlation (ρ) and with the inverse of the univariate standard normal distribution function (Φ^{-1}), then:

$$C_\rho(u,v) = \Phi_\rho\big(\Phi^{-1}(u), \Phi^{-1}(v)\big); \quad u,v \in [0,1]$$

When using the normal copula a conditional rank correlation is equal to a partial correlation. The conditional correlation between two random variables is thus related to the unconditional correlation between the same variables. The partial correlation of X_1 and X_2 with respect to X_3 is given by:

$$\rho_{1,2|3} = \frac{\rho_{1,2} - \rho_{1,3} \cdot \rho_{2,3}}{\sqrt{\left(1-\rho_{1,3}{}^2\right) \cdot \left(1-\rho_{2,3}{}^2\right)}} \tag{35}$$

A correlation matrix (see Section III.2.2) has to be positive definite. In order for it to be positive definite unconditional correlations must be used. The relation between the rank correlation (r) and the product moment correlation (ρ) of the normal copula is given by:

$$\rho = 2\sin\left(\frac{\pi}{6} r\right) \tag{36}$$

Unconditional correlation of question 1

The exceedance probability P_1 can be calculated by taking the double integral of the bivariate standard normal density function $\phi(u, v, \rho_{u,v})$. So taking from the example of Figure III-1; X_3, X_4 and the corresponding unconditional product moment correlation $\rho_{4,3}$ results in the exceedance probability:

$$P_1 = 2 \cdot \int_0^\infty \int_0^\infty \phi\big(x_4, x_3, \rho_{4,3}\big)\, dx_4\, dx_3 \tag{37}$$

This exceedance probability, as a function of $\rho_{4,3}$, is equal to the probability given by the expert, thus:

$$P_1 = P\big(F_{X_4}(X_4) > 0.50 \mid F_{X_3}(X_3) > 0.50\big)$$

Solving this equation results in $\rho_{4,3}$. Using the inverse of Equation (36) for the normal copula results in the rank correlation $r_{4,3}$ corresponding to the expert's probability. The relation between the probability of exceedance and the unconditional rank correlation is depicted in Figure III-2.

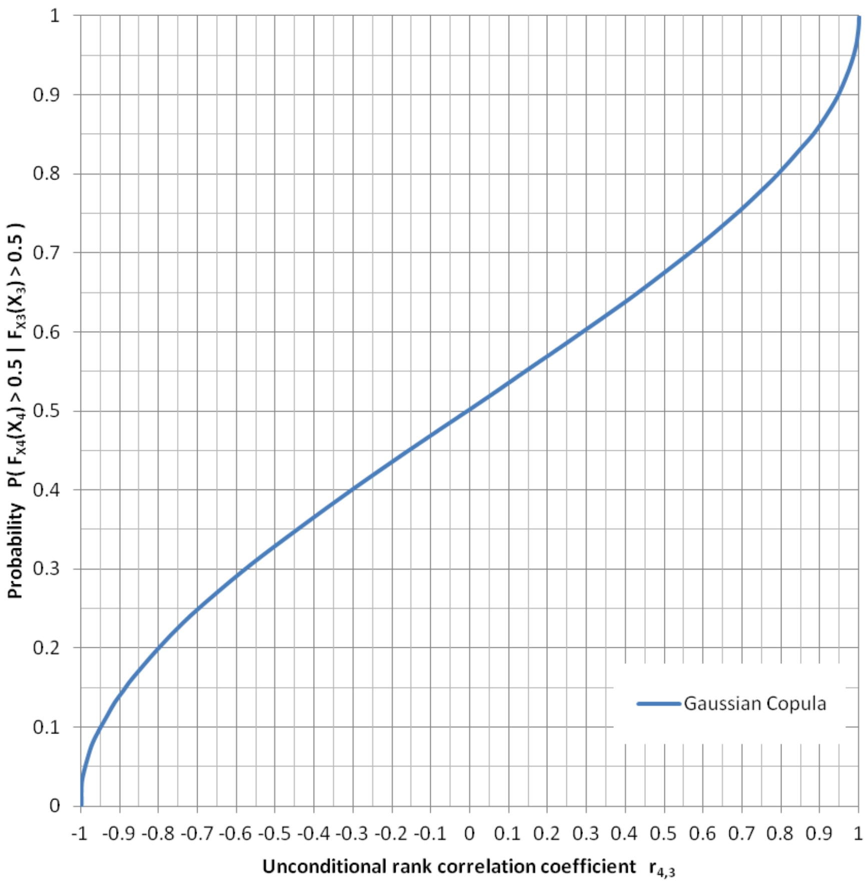


Figure III-2: Relation between the unconditional rank correlation and probability for the Gaussian copula. Source: Own work

Conditional correlation of question 2

The conditional rank correlations $r_{4,2|3}$ and $r_{4,1|3,2}$ of the example require a different calculation approach. When an expert gives as probability $P_1 = 0$ or $P_1 = 1$ (complete positive or negative correlation) to the question from the beginning of this subsection then X_4 would be completely described by X_3, so probability P_2 does not matter. When the expert thinks that X_2 and X_4 are independent then probability P_2 is equal to P_1. When the expert chooses P_2 to be anything but 0, 0.5 or 1 then he/she thinks that X_3 only partly explains X_4, so X_2 can only partly explain X_4. The domain of P_2 is therefore dependent on the expert's answer to P_1.

The exceedance probability P_2 can be calculated by taking the triple integral of the three variate standard normal density function $\phi(x_4, x_3, x_2, \rho_{4,3}, \rho_{4,2|3})$. Of which $\rho_{4,3}$ is fixed in the previous step and $\rho_{4,2|3} \in (-1, 1)$, thus:

$$P_2 = 4 \cdot \int_0^\infty \int_0^\infty \int_0^\infty \phi(x_4, x_3, x_2, \rho_{4,3}, \rho_{4,2|3})\, dx_4\, dx_3\, dx_2 \tag{38}$$

This exceedance probability, as a function of $\rho_{4,2|3}$, is equal to the probability given by the expert, thus:

$$P_2 = P\left(F_{X_4}(X_4) > 0.50 \mid F_{X_2}(X_2) > 0.50, F_{X_3}(X_3) > 0.50\right)$$

Solving this equation results in $\rho_{4,2|3}$. Using the inverse of Equation (36) for the normal copula results in the rank correlation $r_{4,2|3}$ corresponding to the expert's probability.

Conditional correlation of question 3

The computation of $r_{4,1|3,2}$ happens in the same way as for question 2. Now a quadruplet integral of the four variate standard normal density function $\phi(x_4, x_3, x_2, x_1, \rho_{4,3}, \rho_{4,2|3}, \rho_{4,1|3,2})$ has to be taken. Of which $\rho_{4,3}$ and $\rho_{4,2|3}$ are fixed in the previous step. This results in the exceedance probability P_3:

$$P_3 = 8 \cdot \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \phi(x_4, x_3, x_2, x_1, \rho_{4,3}, \rho_{4,2|3}, \rho_{4,1|3,2})\, dx_4\, dx_3\, dx_2 dx_1 \qquad (39)$$

III.2.2 Aggregation

The combining of the dependencies resulting from the experts' opinions can be done by pooling, similarly to the uncertainty elicitation. In this study the following linear pooling methods are considered: equal weights and global weights, where the latter is performance-based. The best pooling method is determined by the highest calibration score. These aspects are considered in this subsection which is entirely based on Werner et al. (2016) unless indicated otherwise.

For the aggregation the product moment correlations are inserted into a correlation matrix for each expert, see Table III-I which is also based on the example BN in Section III.2.1. A correlation matrix has to be positive definite.

Table III-I: Correlation matrix with unconditional product moment correlations per expert.

	X_1	X_2	X_3	X_4
X_1	1	0	0	$\rho_{1,4}$
X_2	0	1	0	$\rho_{2,4}$
X_3	0	0	1	$\rho_{3,4}$
X_4	$\rho_{1,4}$	$\rho_{2,4}$	$\rho_{3,4}$	1

Calibration score

A calibration score from uncertainty or dependence elicitation cannot be used for both according to Morales-Napoles et al. (2016). When conducting both assessments separate calibration scores have to be determined. The calibration score for multivariate assessments used in this research is the d-calibration score introduced in Morales-Napoles & Worm (2013), which makes use of the *Hellinger distance*. To be able to determine scores for the experts seed variables have to be used. This is similar to Cooke's Classical model, as presented in Section III.1 . For Gaussian copulas the Hellinger distance H is defined as:

$$H(\Sigma_C, \Sigma_E) = \sqrt{1 - \frac{det(\Sigma_C)^{1/4} \cdot det(\Sigma_E)^{1/4}}{\left(1/2\, det(\Sigma_C) + 1/2\, det(\Sigma_E)\right)^{1/2}}}$$

Where $\sum_C$ is a correlation matrix with the correlations of the seed variables and $\sum_E$ a matrix that consists of the correlations derived from the expert elicitation. The d-calibration score is defined as:

$$D = 1 - H(\sum_C, \sum_E) \tag{40}$$

The d-calibration score has the following properties, according to Morales-Napoles et al. (2016):

- When the assessment of an expert corresponds perfectly to the seed then D = 1.
- A score of D = 0 means that either at least two seed variables are linearly dependent and the expert does not express this. Or the expert expresses perfect linear dependence between two variables while the seed variables are not.
- In order for an expert to be highly calibrated he/she has to sufficiently approximate the dependence structure for each entry.

Equal weights method

For the equal weights method each expert has the same impact on the pooled correlation matrix. The d-calibration score has to be calculated from the seed variable correlation matrix and the averaged expert correlation matrix.

Global weights method

For the global weights method the d-calibration score is determined per expert. Then an iteration is performed where a calibration score threshold is increased in each step. The experts that are below this threshold are not taken into account. For the experts above this threshold the average of their weighted[37] correlation matrices is determined. For this weighted average matrix the d-calibration score is determined using the same seed correlation matrix. When the iteration is complete the calibration threshold that resulted in the largest calibration score of the weighted average calibration matrix is selected. Finally for the experts with calibration score above the threshold; the ratio of their score to the sum of the d-calibration scores of these experts determines their weight.

Pooling

Combining the target dependencies that are estimated by the experts leads to the resulting target correlation matrix $\sum_R$, which is defined as:

$$\sum_R = \sum_{i=1}^{N} \left(W(i) \cdot \sum_T(i) \right) \tag{41}$$

Where,

$\sum_R$	Resulting target correlation matrix.
W(i)	Weight of expert *i*.
$\sum_T(i)$	Target correlation matrix of expert *i*.
N	Number of experts.

[37] In this case weighted means the product of an expert's d-calibration score and his correlation matrix resulting from the assessment. This differs from the weights per expert that are the result of this method.

Appendix IV Expert Judgment Elicitation questionnaires

This appendix includes the uncertainty and dependence questionnaires that are used in this study. Hereafter the anonymised questionnaires completed by the experts are included. In the last section the realisations of the seed variables of both questionnaires are given.

IV.1 Expert Judgment questionnaire | Uncertainty

This questionnaire focuses on the percentage of the storage area with respect to the total terminal area and on the storage occupancy factor. The purpose of this questionnaire is to combine the opinions of experts in order to determine the uncertainty distribution of the variables of interest.

IV.1.1 Total terminal factor

The total terminal factor (α with unit %) is the percentage of all the gross storage areas with respect to the total terminal area; $\alpha = \frac{\sum A_{gr}}{A_t}$. The gross storage area only includes the stacks/stockpiles and internal infrastructure inside the storage area (including import, export, transhipment, empties stacks and container freight station). The total terminal area includes the total landside and waterside area (including quay, apron, other buildings, other infrastructure on the terminal, etc). The total terminal factor will be asked for container, dry bulk and liquid bulk terminals. This is denoted by subscript. See Figure 1 for an example of a container terminal, with in red the gross storage areas and in blue the total terminal area.

Figure IV-1: TCB, S.L. Port of Barcelona (Spain). Source: Google Earth

For dry bulk terminals the gross storage area includes the area covered by stockpiles and stackers/reclaimers and conveyor belts in between the stockpiles. As well as the area covered by storage sheds and silos including the surrounding area that is kept clear of objects. The total terminal area also includes the quay or jetty area used for berthing. For an example see Figure 2.

Figure IV-2: Dry bulk terminal in Immingham (UK). Source: Google Earth

For liquid bulk terminals the gross storage area includes the area covered by the storage tanks and the surrounding area that is kept clear of objects or the area that is surrounded by and including the bunds (earth walls). The jetty area used for berthing is included in the total terminal area. For an example see Figure 3.

Figure IV-3: ENGIE RC, Port of Rotterdam. Source: Google Earth

IV.1.2 Storage occupancy factor

The average annual storage occupancy factor (m_s with unit %) -or storage or yard utilisation factor- is defined as the number of occupied storage slots or occupied storage volume divided by the total number of storage slots or storage volume according to the design capacity. This factor takes into account the fluctuations in required storage capacity due to random arrivals and departures of cargo. The value asked is the average occupancy factor over 1 year of operation. The storage occupancy factor will be asked for container, dry bulk and liquid bulk terminals.

IV.1.3 How it works

First you will give estimates of 10 calibration variables. The true values of these variables are known to the researcher and the uncertainties of all the experts can therefore be scored. Of course your contribution is always valued, regardless of the score! You probably do not know the exact answers but you have an idea of the true value, this method is about specifying and comparing uncertainties.

After the calibration variables, estimates of 6 additional target variables whose true values are not known are asked.

You are asked to give 3 percentiles of your subjective uncertainty distribution per variable:

- 5% quantile means: In 5% of the cases the true value will be lower than your estimate. Or in other words in 95% of the cases the true value will be higher than your estimate.
- 50% quantile means: In 50% of the cases the true value will be lower/higher than your estimate.
- 95% quantile means: In 95% of the cases the true value will be lower than your estimate. Or in other words in 5% of the cases the true value will be higher than your estimate.

To make it more clear these three percentiles of a normal distribution are depicted in Figure 4.

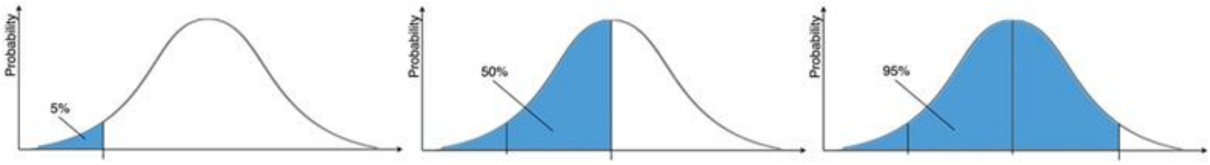


Figure IV-4: 5th, 50th and 95th percentile of a normal distribution.

You are asked to specify the estimates of the quantiles in a table like the one below. As an example a fictional expert's estimate, about the length that a *Beech* tree (*Beuk* in Dutch) on average grows every year in *Zuid Holland,* is given:

5% quantile	50% quantile	95% quantile
0.1 mm	*2.5* mm	*6* mm

Again; even if you do not know what to answer to the following questions, provide an estimate of your uncertainty distribution.

IV.1.4 Calibration variables

1. What is your estimate of the $\alpha_{containers}$ of the Global Gateway South container terminal in Los Angeles (California, USA)? *Containers are transported with chassis, the terminal has 2640 ground slots and it has a rail connection.*

5% quantile	50% quantile	95% quantile
%	%	%

2. What is your estimate of the $\alpha_{containers}$ of the MSC container terminal in Valencia (Spain)? *Containers are transported with tractor-trailer units and RTG's, the terminal has 2700 ground slots.*

5% quantile	50% quantile	95% quantile
%	%	%

3. What is your estimate of the $\alpha_{dry\ bulk}$ of the SIPG Luojing dry bulk terminal in Shanghai (China)? *Stored goods are: iron ore and coal. The storage capacity is 1.15 million tonnes.*

5% quantile	50% quantile	95% quantile
%	%	%

4. What is your estimate of the $\alpha_{dry\ bulk}$ of the Kinder Morgan dry bulk terminal in Newport News (Virginia, USA)? *Stored goods are coal. The storage capacity is 1.4 million tonnes and the terminal has a rail connection.*

5% quantile	50% quantile	95% quantile
%	%	%

5. What is your estimate of the $\alpha_{liquid\ bulk}$ of the Vopak Eurotank liquid bulk terminal in Antwerp (Belgium)? *Stored goods are: petroleum products, chemicals and gasoil. The storage capacity is 454,492 m^3 in 173 tanks and the terminal has a rail connection.*

5% quantile	50% quantile	95% quantile
%	%	%

6. What is your estimate of the $\alpha_{liquid\ bulk}$ of the Vopak TTR liquid bulk terminal in Rotterdam (Netherlands)? *Stored goods are: petroleum products, chemicals and biofuels. The storage capacity is 318,736 m^3 in 89 tanks and the terminal has a rail connection.*

5% quantile	50% quantile	95% quantile
%	%	%

7. What is your estimate of the average annual storage occupancy of the container terminal in Port Numbay in Jayapura (Indonesia, Southeast Asia) in 2010?

5% quantile	50% quantile	95% quantile
%	%	%

8. What is your estimate of the average annual storage occupancy of the container terminal in Dar es Salaam Port (Tanzania, Africa) in 2011?

5% quantile	50% quantile	95% quantile
%	%	%

9. What is your estimate of the average annual storage occupancy of the container terminals in Miami (Florida, USA) in 2008?

5% quantile	50% quantile	95% quantile
%	%	%

10. What is your estimate of the average annual storage occupancy of the container terminals in New York and New Jersey (USA) in 2008?

5% quantile	50% quantile	95% quantile
%	%	%

IV.1.5 Variables of interest

The variables of interest are for the design of new modern terminals in developed countries anywhere in the world in 2016.

1. What is in your opinion a realistic value for $\alpha_{containers}$ for the design of a new modern container terminal?

5% quantile	50% quantile	95% quantile
%	%	%

2. What is in your opinion a realistic value for $\alpha_{dry\ bulk}$ for the design of a new modern dry bulk terminal?

5% quantile	50% quantile	95% quantile
%	%	%

3. What is in your opinion a realistic value for $\alpha_{liquid\ bulk}$ for the design of a new modern liquid bulk terminal?

5% quantile	50% quantile	95% quantile
%	%	%

4. What is in your opinion a realistic value for the average annual storage occupancy for the design of a new modern container terminal?

5% quantile	50% quantile	95% quantile
%	%	%

5. What is in your opinion a realistic value for the average annual storage occupancy for the design of a new modern dry bulk terminal?

5% quantile	50% quantile	95% quantile
%	%	%

6. What is in your opinion a realistic value for the average annual storage occupancy for the design of a new modern liquid bulk terminal?

5% quantile	50% quantile	95% quantile
%	%	%

Thank you for your time!

IV.2 Expert Judgment questionnaire | Dependence

This questionnaire focuses on the average dwell time of containers on a terminal. The purpose of this questionnaire is to combine the opinions of experts in order to determine the dependence between the average dwell times of import, export and transhipment containers.

IV.2.1 Dependence

The (rank) correlation between two random variables quantifies their linear relation. Since no datasets of dwell times are available for this research the judgment of experts is used to give an estimate of these correlations.

IV.2.2 Average dwell time

The definition used for dwell time in this research is: the time between the moment that a container is unloaded from a vessel and the moment that same container leaves the terminal boundaries, and vice versa. The average dwell time is taken as the yearly average of dwell times of all containers within a certain cargo flow. The cargo flows that are taken into account in this research are import, export and transhipment since they can have different dwell times.

IV.2.3 How it works

First you will give an estimate of a dependency between two variables. The true value of this dependency is known to the researcher and the judgment of the experts can therefore be weighted. Of course your contribution is always valued, regardless of the score! You probably do not know the correct answer but you will have an idea of what the value could be.

After the calibration dependency, estimates of three additional target dependencies whose true values are not known are asked.

For the researcher to determine the dependency you are asked to give a probability that you think a certain situation will occur.

Again; even if you do not know what to answer to the following questions, please provide your estimate of the asked probability.

IV.2.4 Calibration dependency

Consider the quarterly container throughput[38] and quarterly number of container vessels[39] in the Port of Rotterdam for each quarter in between January 1997 and December 2014 (total of 72 quarters).

<u>QUESTION:</u>

1. What is in your opinion the probability that the quarterly **number** of visiting container **vessels** is larger than its median value (being 1,505), when it is **given** that the quarterly container **throughput** is larger than its median value (being 2,331,481 TEU)?

   Probability [0 - 100%] = ...

[38] Considering incoming and outgoing, loaded and empty containers.
[39] Considering all dead weight tonnages. Based on inward declarations from customs.

IV.2.5 Target dependencies

The dependencies between the average dwell times for the different cargo flows are depicted by the arrows in Figure 2.

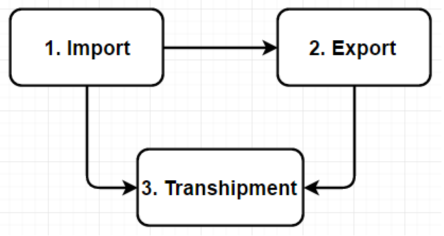
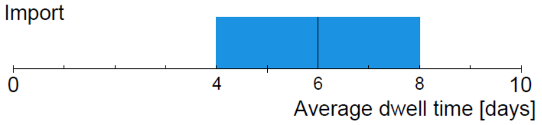


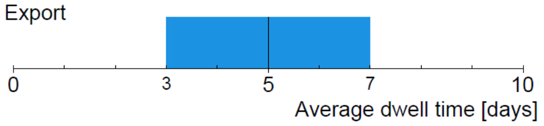
Figure IV-5: Relations between the average dwell times per cargo flow.

The probability distributions of the average dwell times are for modern terminals in developed countries. These distributions are based on literature and are as follows:

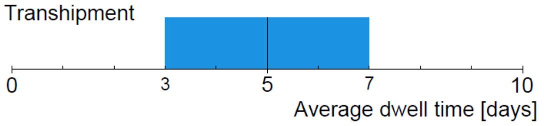
- Import containers; Uniform(4, 8) distribution:



- Export containers; Uniform(3, 7) distribution:



- Transhipment containers; Uniform(3, 7) distribution:



QUESTIONS:

1. What is in your opinion the probability that the dwell time of **export** containers is larger than its median value (being 5), when it is **given** that the dwell time of **import** container is larger than its median value (being 6)?

   Probability [0 - 100%] = ...

2. What is in your opinion the probability that the dwell time of **transhipment** containers is larger than its median value (being 5), when it is **given** that the dwell time of **export** containers is larger than its median value (being 5)?

   Probability [0 - 100%] = ...

3. What is in your opinion the probability that the dwell time of **transhipment** containers is larger than its median value (being 5), when it is **given** that the dwell time of **import** containers is larger than its median value (being 6) **and** it is **given** that the dwell time of **export** containers is larger than its median value (being 5)?

   Probability [........... - ....] = ...

Thank you for your time!

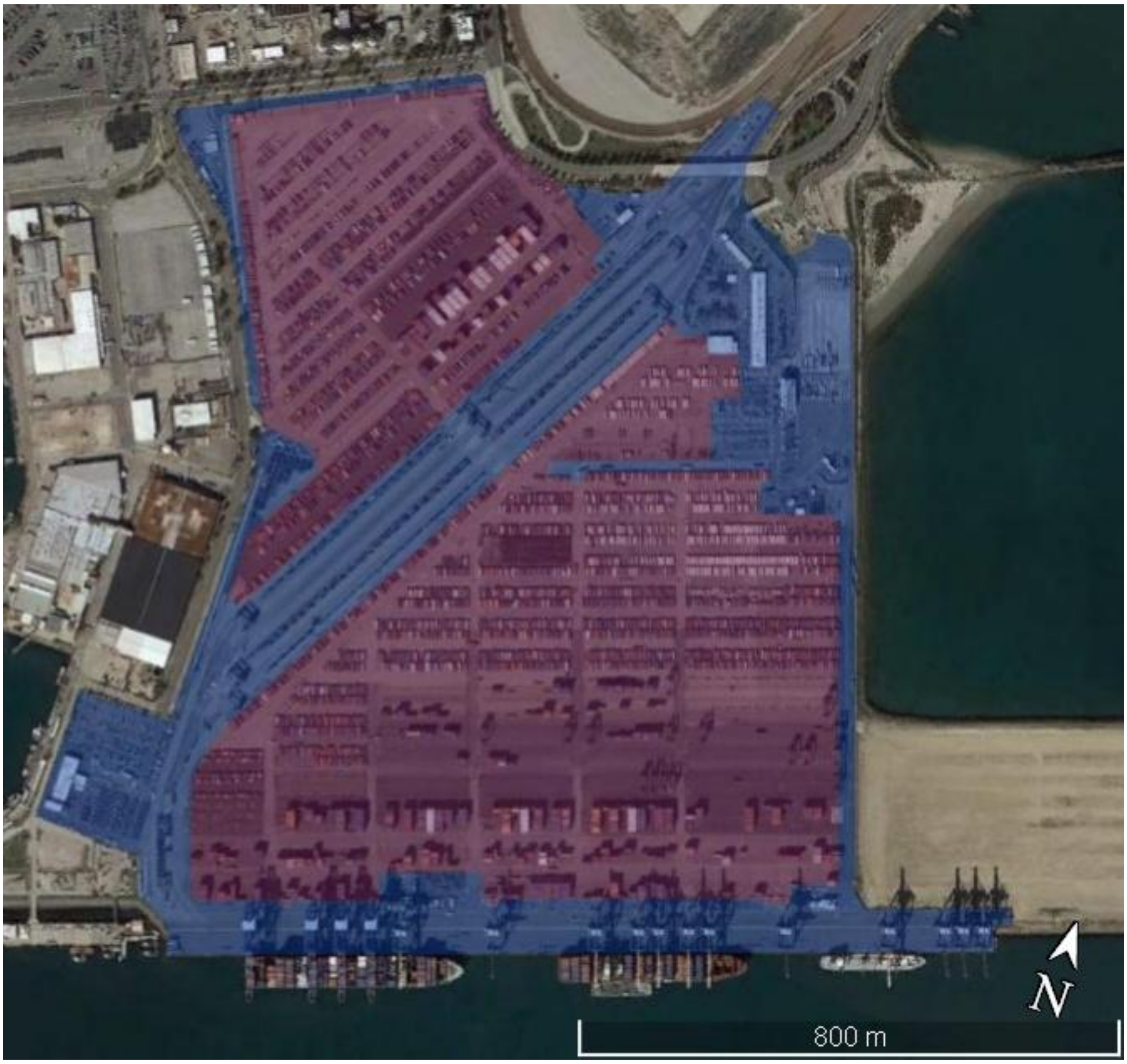
IV.3 Seed variable realisations

This section covers the realisations of the seed variables from the uncertainty and dependence questionnaires.

IV.3.1 Uncertainty

1. What is the $\alpha_{containers}$ of the Global Gateway South container terminal in Los Angeles (California, USA)?

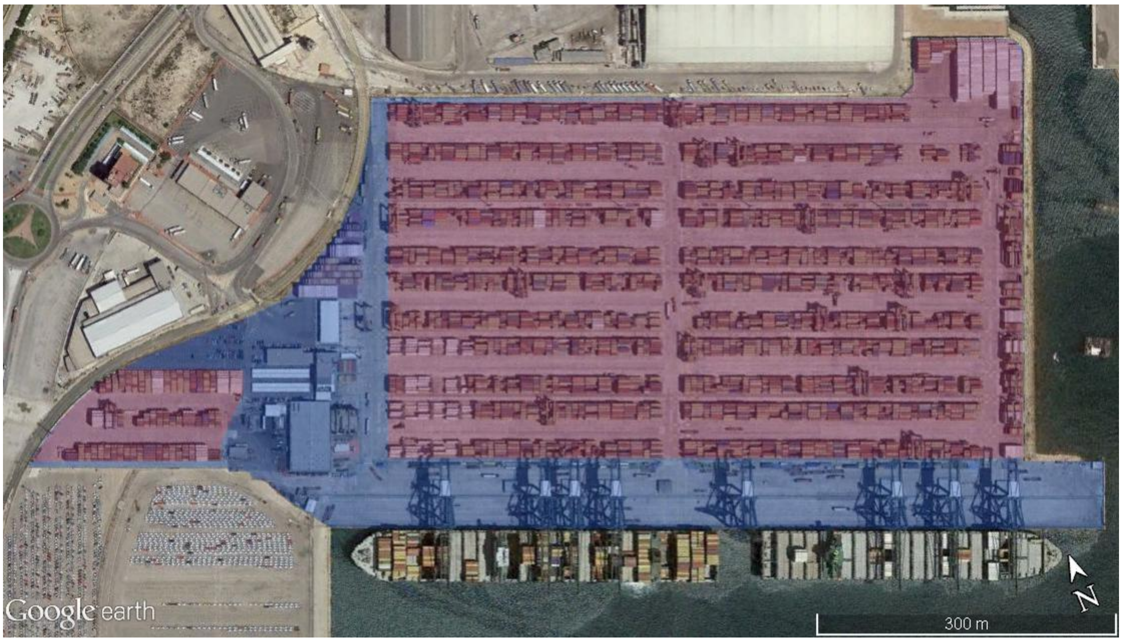
Equipment	Chassis
Terminal area $A_{gr,t}$ [x10^4 m^2]	120
Storage area $\sum A_{gr,i}$ [x10^4 m^2]	76.83
Gross storage coefficient a [%]	64



Source: Google Earth

2. What is the $\alpha_{containers}$ of the MSC container terminal in Valencia (Spain)?

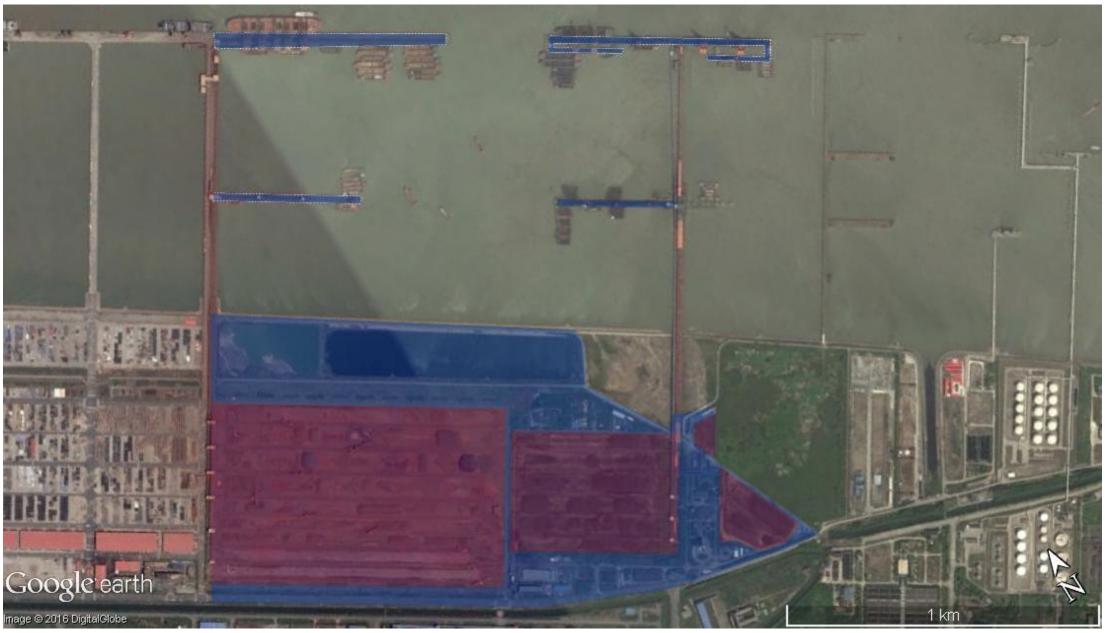
Equipment	TTU + RTG
Terminal area $A_{gr,t}$ [x10^4 m^2]	34.7
Storage area $\sum A_{gr,i}$ [x10^4 m^2]	25.3
Gross storage coefficient α [%]	73



Source: Google Earth

3. What is the $\alpha_{dry\ bulk}$ of the SIPG Luojing dry bulk terminal in Shanghai (China)?

Storage type	Open stockpiles
Terminal area $A_{gr,t}$ [x10^4 m^2]	146.49
Storage area $\sum A_{gr,i}$ [x10^4 m^2]	79.49
Gross storage coefficient α [%]	54



Source: Google Earth

4. What is the $\alpha_{dry\ bulk}$ of the Kinder Morgan dry bulk terminal in Newport News (Virginia, USA)?

Storage type	Open stockpiles
Terminal area $A_{gr,t}$ [x10^4 m^2]	70.60
Storage area $\Sigma A_{gr,i}$ [x10^4 m^2]	35.26
Gross storage coefficient α [%]	50

Source: Google Earth

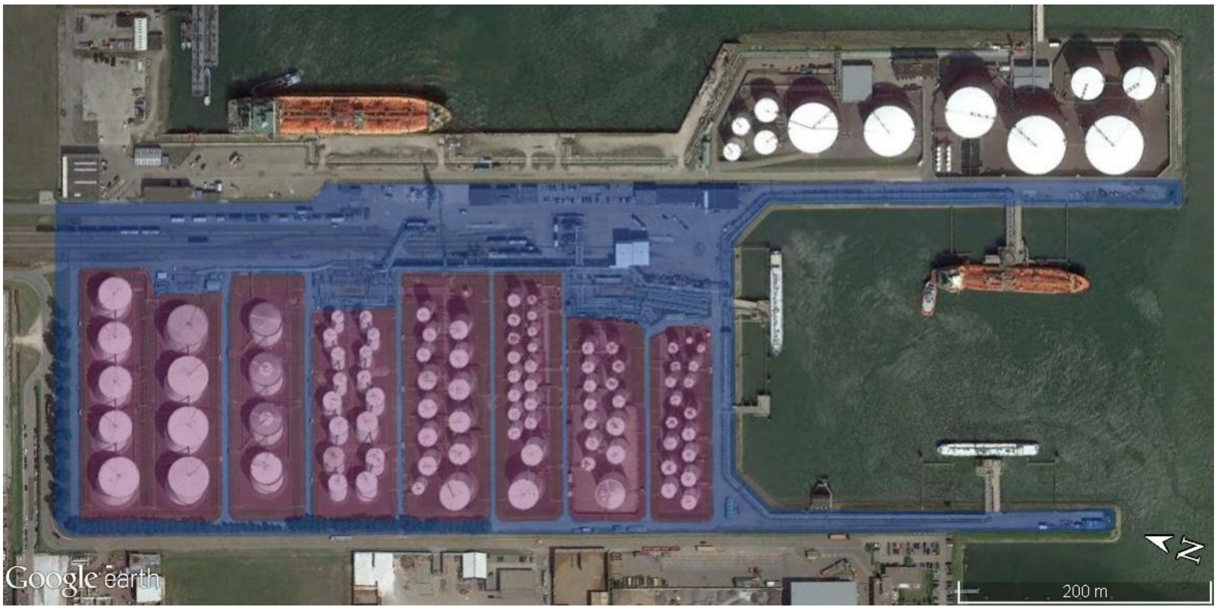
5. What is the $\alpha_{liquid\ bulk}$ of the Vopak Eurotank liquid bulk terminal in Antwerp (Belgium)?

Stored liquids	Petroleum products, chemicals, gasoil
Terminal area $A_{gr,t}$ [x10^4 m^2]	14.30
Storage area $\Sigma A_{gr,i}$ [x10^4 m^2]	7.9
Gross storage coefficient α [%]	55

Source: Google Earth

6. What is the $\alpha_{liquid\ bulk}$ of the Vopak TTR liquid bulk terminal in Rotterdam (Netherlands)?

Stored liquids	Petroleum products, chemicals, biofuels
Terminal area $A_{gr,t}$ [x10^4 m^2]	16.00
Storage area $\Sigma A_{gr,i}$ [x10^4 m^2]	8.49
Gross storage coefficient a [%]	53

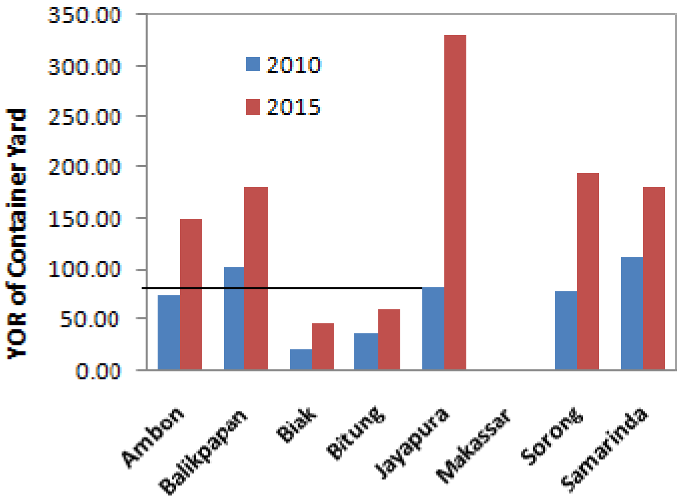


Source: Google Earth

7. What was the average annual storage occupancy of the container terminal in Port Numbay in Jayapura (Indonesia, Southeast Asia) in 2010?

   The storage yard occupancy rate (YOR) for 2015 is calculated by using an estimate for the container throughput of 2015, it can therefore be > 100%.

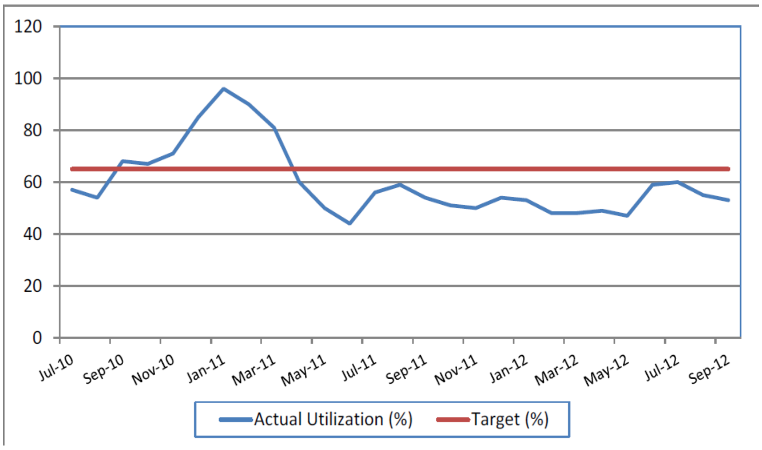
   $\mathbf{m_s}$ **= 82%**, value taken from the diagram.



Utilisation of container yard of various ports. Source: Idrus et al. (2012)

8. What was the average annual storage occupancy of the container terminal in Dar es Salaam Port (Tanzania, Africa) in 2011?

   $\mathbf{m_s}$ **= 63%**, value taken from the diagram.



Utilisation of container yard Dar es Salaam Port. Source: Mwasenga (2012)

9. What was the average annual storage occupancy of the container terminals in Miami (Florida, USA) in 2008?

   $\mathbf{m_s}$ **= 53%**, from The Tioga Group (2010).

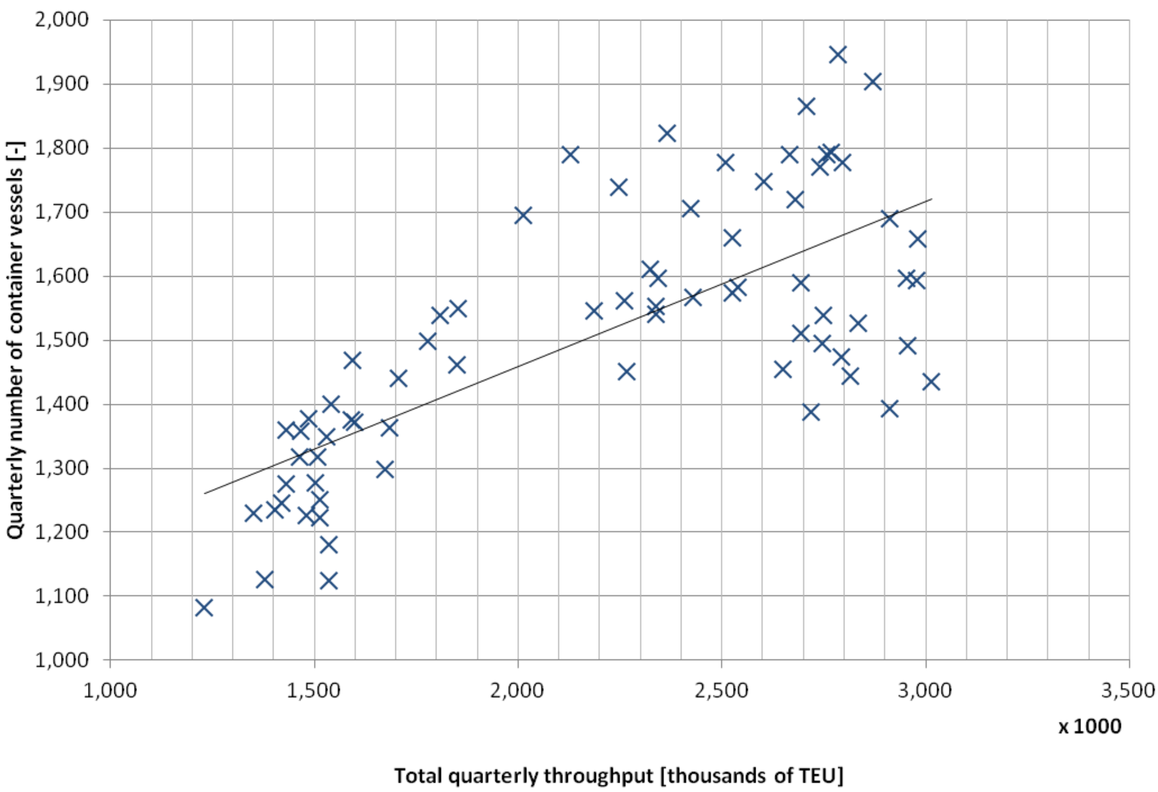
10. What was the average annual storage occupancy of the container terminals in New York and New Jersey (USA) in 2008?

    $\mathbf{m_s}$ **= 75%**, from The Tioga Group (2010).

IV.3.2 Dependence

1. What is in your opinion the probability that the quarterly **number** of visiting container **vessels** is larger than its median value (being 1,505), when it is **given** that the quarterly container **throughput** is larger than its median value (being 2,331,481 TEU)?

   Spearman's rank correlation r = 0.6909; from analysis of Eurostat data, see graph below. The corresponding probability P ≈ 0.75, assuming a Gaussian copula.



Quarterly number of container vessels versus quarterly container throughput in Rotterdam. Data source: Eurostat

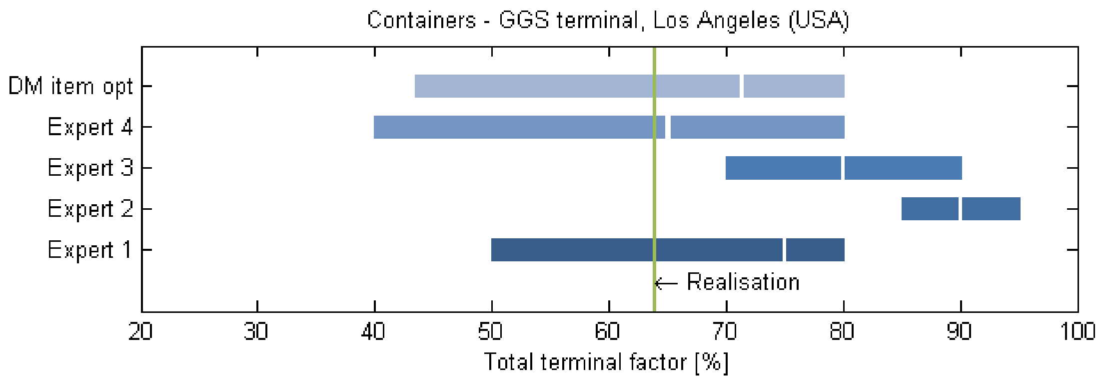
Appendix V Expert Judgment Elicitation results

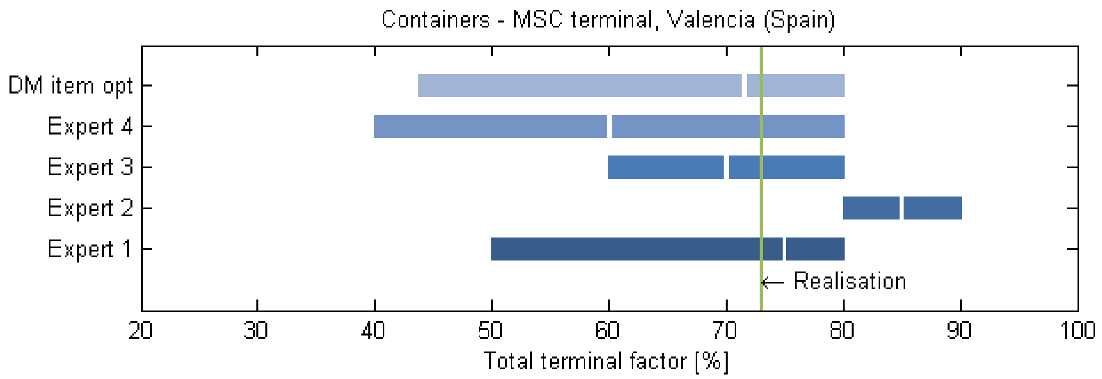
This appendix first graphically presents the results of the expert uncertainty assessments. The calibration and information scores of the chosen Decision Maker are presented as well. Hereafter the reasoning of the experts is provided for both the uncertainty and dependence assessments.

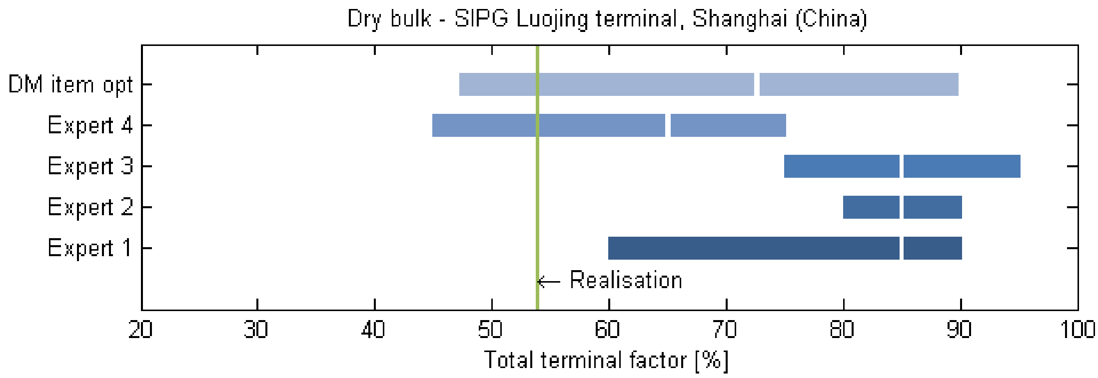
V.1 Uncertainty elicitation results

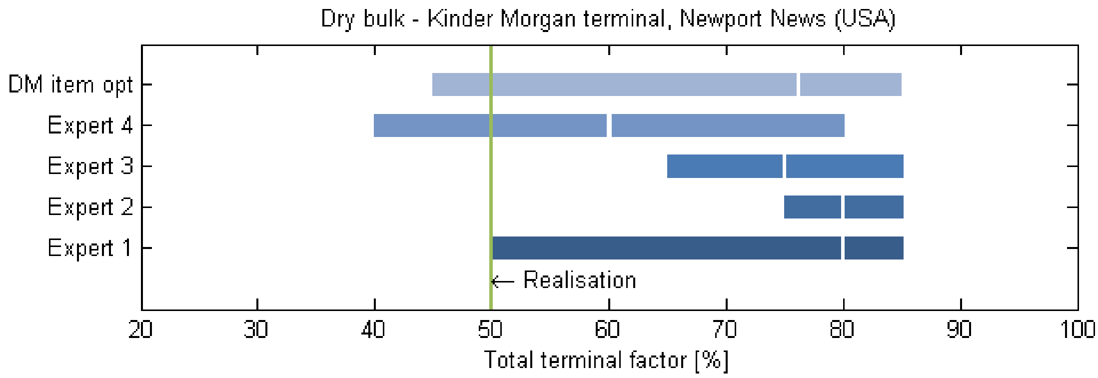
To be able to compare the estimates of the experts and the Decision Maker(s) their distributions are depicted in graphs. Each graph represents a question from the questionnaire, in the graphs each horizontal bar represents the uncertainty between the 5th and 95th percentiles of an expert. The white vertical bars represent their 50th percentile. For the seed variables the true value (or realisation) is depicted by a vertical green line. The resulting distribution of the chosen Decision Maker (with item optimised weighting scheme; see Section 3.4.1.3 of the report) is included in the graphs as well. First the seed variable results are given, followed by the target variable results.

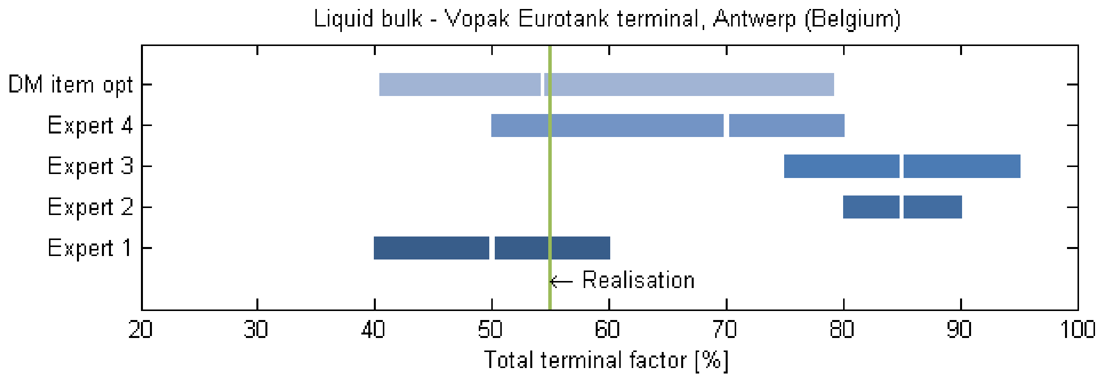
V.1.1 Seed variables

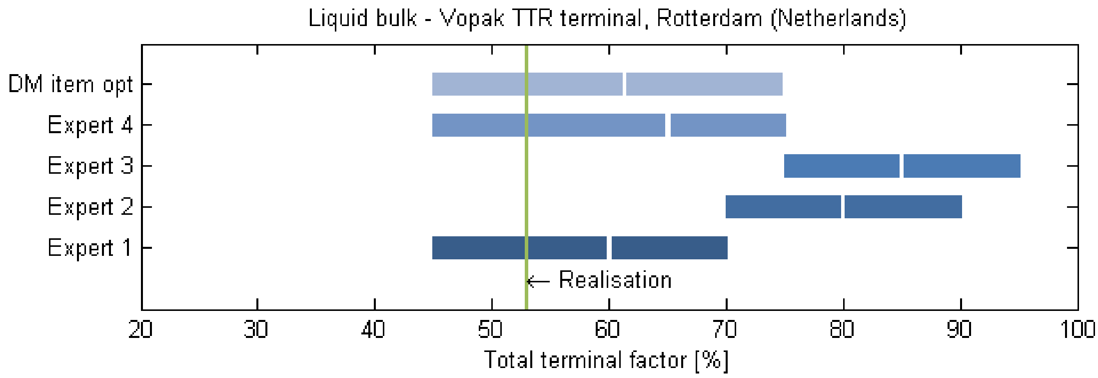





Dry bulk - SIPG Luojing terminal, Shanghai (China)
DM item opt
Expert 4
Expert 3
Expert 2
Expert 1
← Realisation
20 30 40 50 60 70 80 90 100
Total terminal factor [%]


Dry bulk - Kinder Morgan terminal, Newport News (USA)
DM item opt
Expert 4
Expert 3
Expert 2
Expert 1
← Realisation
20 30 40 50 60 70 80 90 100
Total terminal factor [%]


Liquid bulk - Vopak Eurotank terminal, Antwerp (Belgium)
DM item opt
Expert 4
Expert 3
Expert 2
Expert 1
← Realisation
20 30 40 50 60 70 80 90 100
Total terminal factor [%]


Liquid bulk - Vopak TTR terminal, Rotterdam (Netherlands)
DM item opt
Expert 4
Expert 3
Expert 2
Expert 1
← Realisation
20 30 40 50 60 70 80 90 100
Total terminal factor [%]

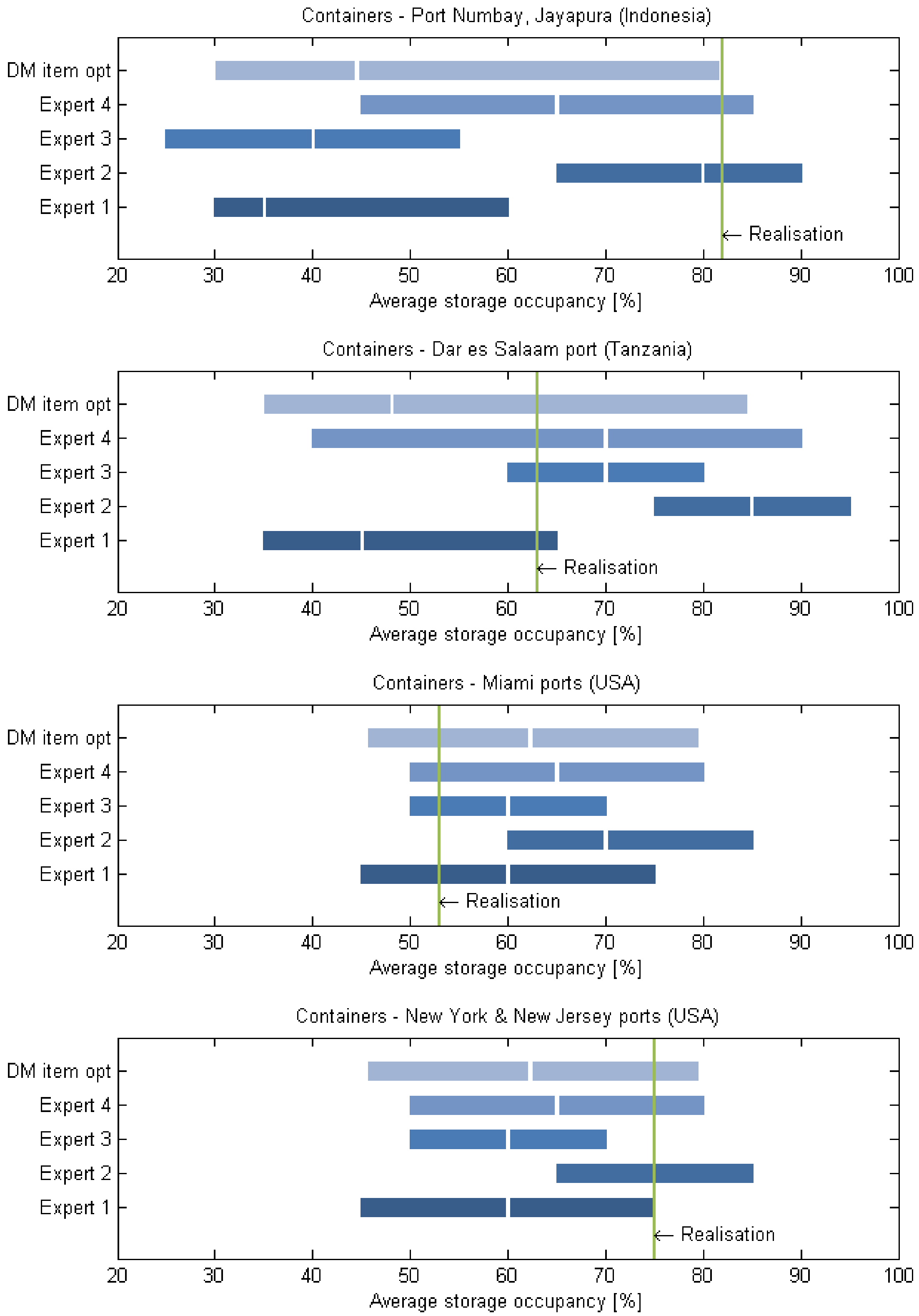
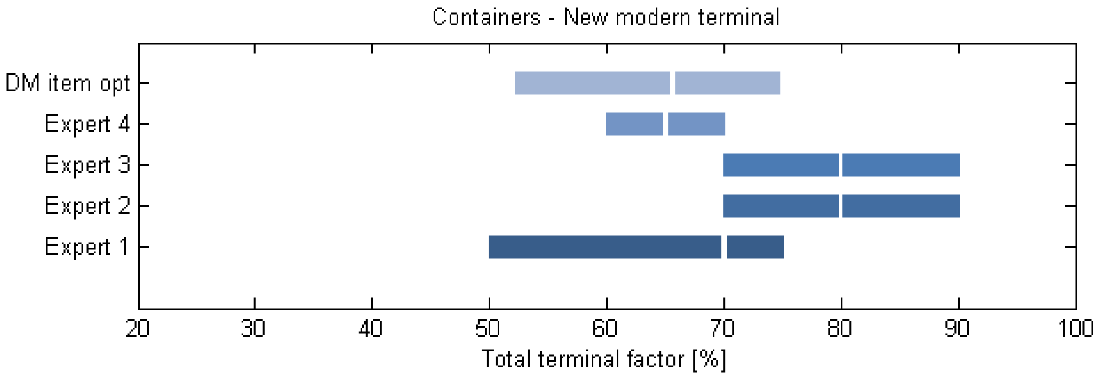
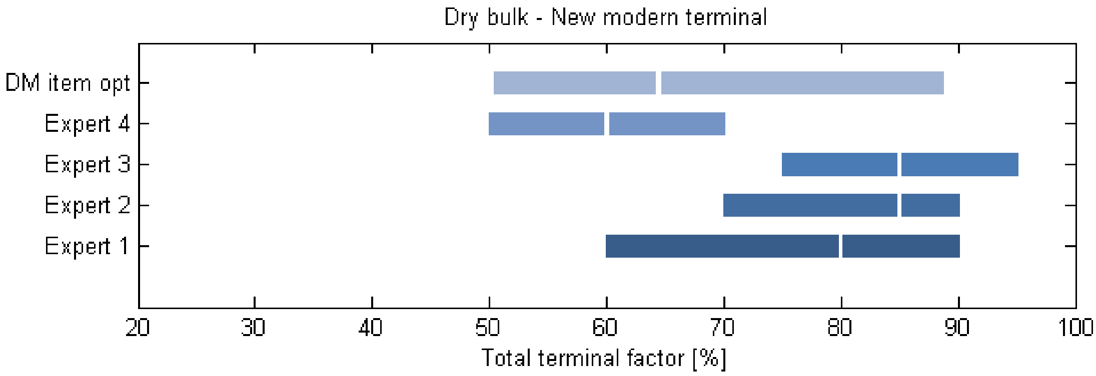
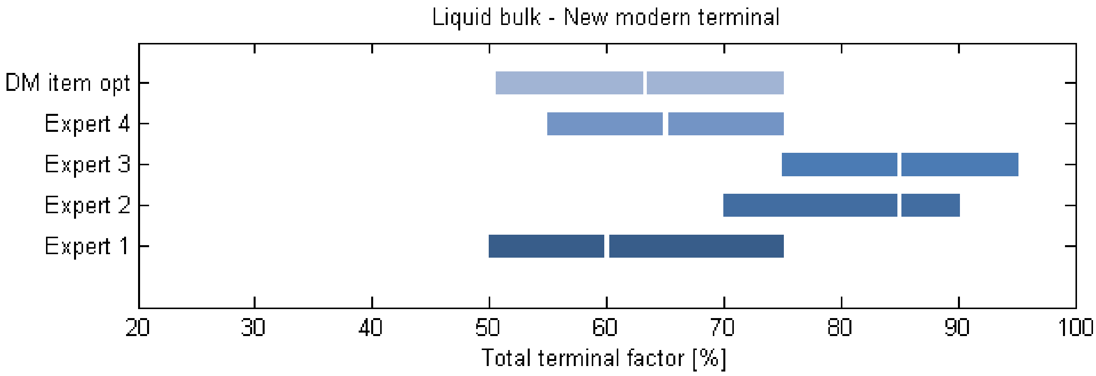


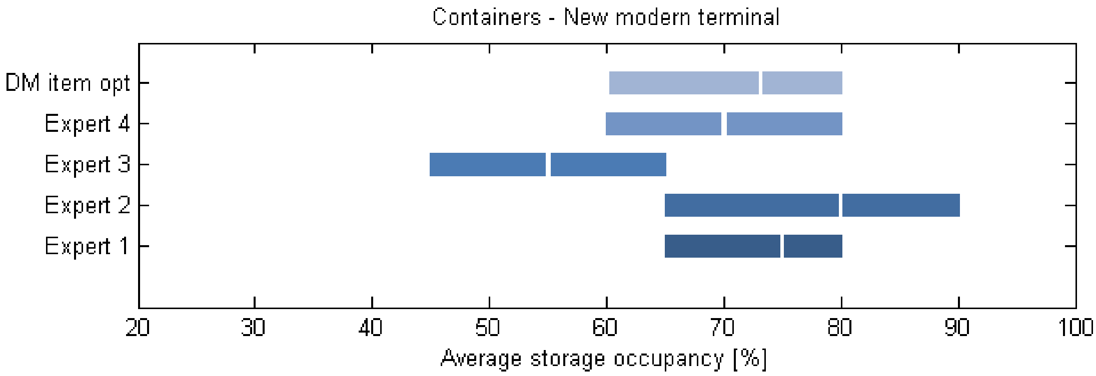
Figure V-1: Seed variable results per questionnaire item

V.1.2 Target variables









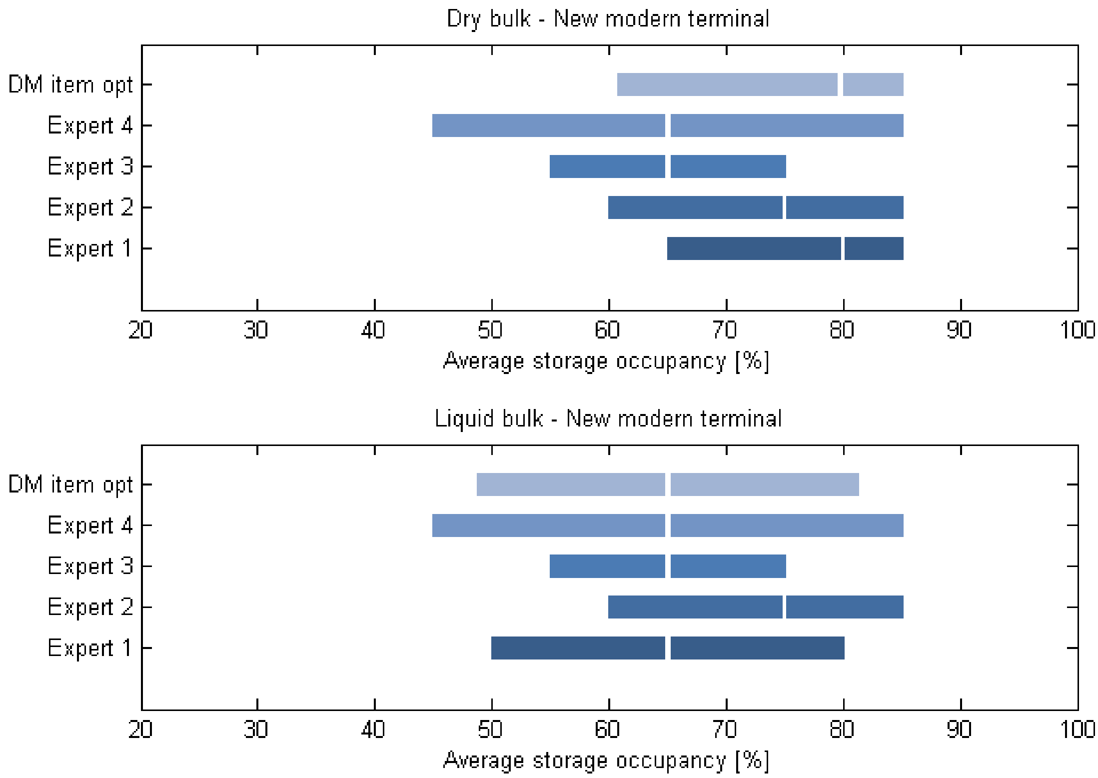


Figure V-2: Target variable results per questionnaire item

V.1.3 Decision Maker seed item scores

The Decision Maker of the chosen weighting scheme (DM item optimized) can be seen as a virtual expert. The DM estimates are also scored on calibration and information (with respect to the seed and target variables) to be able to compare the different DM's. The calibration and information scores of DMit_op are presented in Table V-I.

Table V-I: Calibration and global information scores of the seed variables for DMit_op

Nr.	Questionnaire item	Calibration score	Information score (seed variables)
1	Total terminal factor Containers - GGS terminal, Los Angeles (USA)	0.5710	0.2151
2	Total terminal factor Containers - MSC terminal, Valencia (ES)	0.5925	0.2754
3	Total terminal factor Dry bulk - SIPG Luojing terminal, Shanghai (CN)	0.7305	0.5720
4	Total terminal factor Dry bulk - Kinder Morgan terminal, Newport News (USA)	0.7305	0.5866
5	Total terminal factor Liquid bulk - Vopak Eurotank terminal, Antwerp (BE)	0.5710	0.2120
6	Total terminal factor Liquid bulk - Vopak TTR terminal, Rotterdam (NL)	0.5710	0.2131
7	Average storage occupancy Containers - Port Numbay, Jayapura (ID)	0.5710	0.2834
8	Average storage occupancy Containers - Dar es Salaam port (TZ)	0.4048	0.2964
9	Average storage occupancy	0.5710	0.2451

Nr.	Questionnaire item	Calibration score	Information score (seed variables)
10	Containers - Miami ports (USA) Average storage occupancy Containers - New York & New Jersey ports (USA)	0.5925	0.2824

V.2 Experts motivations

The reasoning, opinions and remarks of the experts with respect to their answers and the questionnaire itself are presented in this section.

V.2.1 Uncertainty

During the elicitation the experts (E1, E2, E3, E4) gave their motivations for certain choices or assumptions that they made. The main motivations are presented in this section, they are given per variable (questionnaire question).

Seed questions

General remarks for the total terminal factor: E3 notes that if empty containers are stored on the terminal itself it increases the required space. In this assessment it is assumed that empties are stored on the terminal.

1. E2/E3 think that the difference between storage and total area is small due to the use of trailers. The alpha is therefore large.
   E3 subtracts 10% from the value he originally had in mind, since a rail connection is present.
   E4 thinks that because of the required manoeuvring space relatively more space is needed outside of the storage area, so that leads to a smaller alpha.
2. E2/E3 note that RTG's are space efficient and therefore lead to a smaller storage area with respect to the total area.
   E4 thinks that because the gross storage area also includes internal roads (and thus space efficiency does not matter) the answers to questions 1 and 2 are quite similar.
3. E2 thinks that for dry bulk terminals the alpha is similar to container terminals.
   E3 thinks that because the environment in China is less of an issue water basins are not present on the terminal, this decreases the total area and increases alpha. He thinks the factor is still relatively high since on dry bulk terminals not much other space is required.
   E4 notes that dry bulk terminals are highly mechanised, so high percentages of storage area with respect to total area are realistic. He also notes that compared to a container terminal the percentage of storage area is large but no large apron is needed.
4. E2/E3/E4 think that the alpha is smaller than for question 3 because of the presence of a rail connection.
   E3 also notes that dry bulk trains are (un)loaded while driving so a waiting area is not required. A smaller alpha is chosen.
5. E1/E3/E4 think that alpha is high because bunds are part of the storage area and therefore lead to a large storage area.
   E1 also notes that not all liquid bulk terminals have bunds so this can make a big difference and that due to safety distances the storage area will also be larger.
   E3 also thinks that not much space is required for buildings and that liquid bulk terminals with a rail connection do need a waiting area which takes up space.

6. E2 notes that this terminal is smaller than for question 5, for smaller terminals the alpha is relatively large.
   E4 thinks that less area is covered by storage due to the smaller number of tanks, therefore the alpha is lower.

General remarks for the storage occupancy:

- E1 notes that for newer terminals there still is overcapacity and thus a lower storage occupancy (or utilisation); therefore a terminal's age matters. Also for some terminals the occupancy is asked in or around the financial crisis, this may have led to lower throughputs and therefore lower occupancies.
- E3 notes that the occupancy is determined by the throughput, when it is near the maximum capacity the utilisation will be high and inefficiencies will occur. It also depends on the management of the terminal. When supply and thus utilisation are large the dwell time increases but the management does not want high dwell times but also does not want to deny customers.

7. E1/E3 think that the remote location of this terminal reduces the throughput and thus occupancy.
   E2 thinks the utilisation is certainly not larger than 90%.
   E4 thinks that Asian terminals are well organised which leads to a lower occupancy.
8. E2/E3 think that this terminal is near its maximum capacity since an expansion is planned, therefore utilisation will be high.
   E3 also states that for container terminals an occupancy of 70% is high while for dry and liquid bulk terminals the percentages are lower.
   E4 thinks that dwell times in Africa are larger so that probably leads to a higher yard utilisation. In Africa strange situations can occur so the expert has a large uncertainty.
9. E1/E4 think that the efficiency between this and the terminal of the next question does not differ much, so the occupancy factors are similar.
   E2 thinks that the utilisation is less than in other countries because the storage area can be larger since land is more available here. He notes that he is not very certain.
   E3 thinks this terminal is also near its maximum capacity.
10. E2 states that New York is more compact and crowded, therefore less space is available and the terminal has to use its space more efficiently, so he chooses a high utilisation but again with a large uncertainty.
    E3 thinks this terminal is also near its maximum capacity.

Target questions

General remarks for the target variables:

- E1 thinks the values for the target variables are higher than for the seed variables, because the seed variables are actual situations while the target variables are a little bit more idealistic.
- E3 assumes that the terminals are without a rail connection.
- E4 notes that modern terminals are space efficient so they have a relatively high terminal factor. However they can also use advanced equipment like AGV's, these require a large apron and therefore lower the terminal factor. Therefore the expert thinks that modern terminals do not really differ much from other terminals with respect to the terminal factor. The expert also notes that he chooses the uncertainty intervals smaller since here you don't try to capture a value but you try to direct the terminal to a certain state by means of your design. He uses the same median value as for the seed variables but takes a smaller uncertainty interval.

1. E2 assumes that a modern terminal is medium to large in size and he therefore thinks it has a lower alpha compared to smaller terminals.
2. E2 thinks that the factors for dry and liquid bulk (next question) are comparable. The expert thinks that the additional area for container terminals is smaller than for the other terminal types, therefore leading to a larger alpha. He thinks that 30% of the total area is a maximum for this additional area.
3. E2: see previous question.
4. E2 notes that this is dependent on import and export quantities, so also peak throughputs. He thinks that at a utilisation of 90% peaks cannot be handled anymore, so the average utilisation should be lower. He also thinks that very low utilisation can occur, it is all dependent on the type of terminal.
   E3 takes 55% as median value, he uses this low value since shipping companies demand low dwell times.
5. E2/E4 state it depends on the type of terminal (storage, import/export).
   E2 notes that it also depends on the predictability of the vessel calls. If these are well manageable the occupancy will be higher. Also if large vessels call at the terminal a large buffer is required therefore decreasing the occupancy.
   E3 states that it is very much dependent on the cargo. Different gradations of a single cargo type or multiple cargo types on the terminal have to be separated and therefore take up more space, this lowers the occupancy.
   E4 compares the buffer of a container and dry bulk terminal and thinks that bulk trade is less predictable so a lower occupancy is required.
6. E2 thinks that a liquid bulk terminal has a more constant supply of cargo in comparison to dry bulk but finally he assumes that dry and liquid bulk terminals are quite similar.
   E3 uses the same motivation as for question 5.
   E4 thinks that there are more fluctuations in the liquid bulk trade, so he uses a larger uncertainty interval.

V.2.2 Dependence

During the elicitation the experts (E1, E2, E3, E4) gave their motivations for certain choices or assumptions that they made. The main motivations are presented in this section, they are given per questionnaire question.

Seed question

1. E1/E4 think that there also is a dependency with the call size of the vessels. Because the higher the call size the higher the throughput for a given number of vessels.
   E2 thinks that vessel sizes have increased over the years so this has a negative influence on the correlation, he still thinks that the correlation is positive.
   E3 also thinks that the ship size has increased over the time period so for constant throughput the number of ships decreases; so a negative relation. He reasons that the throughput increased over the years so this is a positive relation. Therefore they cancel each other out which leads to a probability of 50%.
   E4 also states that the container vessels travel in circles between some ports. Therefore an increase in throughput does not necessarily mean an increase in number of vessels. He thinks the relation is positive but not too much due to the call sizes.

Target questions

General remarks for the dependence between the three different dwell times: E3 says that transhipment is a different business compared to import and export. The development of transhipment depends on the location and the development of a terminal. He states that the realisation of Greenfield transhipment terminals is not often done. He further remarks that he thinks the provided dwell time distributions seem high for a modern terminal in a western country.

1. E1/E2 state that import and export both are impacted by customs.
   E1 also thinks the dwell times will be dependent on the costs of a container slot, which will be more or less the same for import and export. Expert therefore thinks that the correlation is positive.
   E2 also thinks that it depends on the type of country, agreements with clients and regulations. It also depends on the main cargo flow, if import percentage is the highest then import dwell times will be lower. He reasons that if there is something wrong in the port this will probably be the case for both cargo flows.
   E3 states that export and import dwell times are intertwined.
   E4 thinks that import and export are independent since they use two different transportation modes. A jam in the inland transport does not necessarily mean an increase of dwell times for both export and import.
2. E1/E2 think that transhipment containers are not influenced by customs. They choose a smaller dependence, but still a positive one.
   E3 thinks they are not much related since export can be planned pretty well but transhipment is more difficult to schedule. He still chooses a small positive correlation.
   E4 thinks the relation is much stronger than from question 1. As an example he says that when the capacity of an STS crane is impeded this affects both export and transhipment.
3. E1/E2/E4 think in this scenario the terminal does not work in a efficient way. The experts think that in this case the transhipment dwell times are also higher.
   E1 also thinks that transhipment is not affected by customs which does affect import and export, a combination of the arguments results in a medium positive correlation.
   E2 thinks that this results in a higher probability.
   E3 thinks because transhipment is not correlated to export nor import that these variables are independent.
   E4 chooses a very high correlation.

Appendix VI Calculation of silo and tank group dimensions

This appendix contains separate calculations for the required area of dry bulk silo groups and the required area of liquid bulk tank groups.

VI.1 Dry bulk silo groups

For this calculation silos are imagined to each be positioned in tiles. These tiles are square areas in which the silo is located with an 'empty' area surrounding it. A group of silos therefore is a group of tiles.

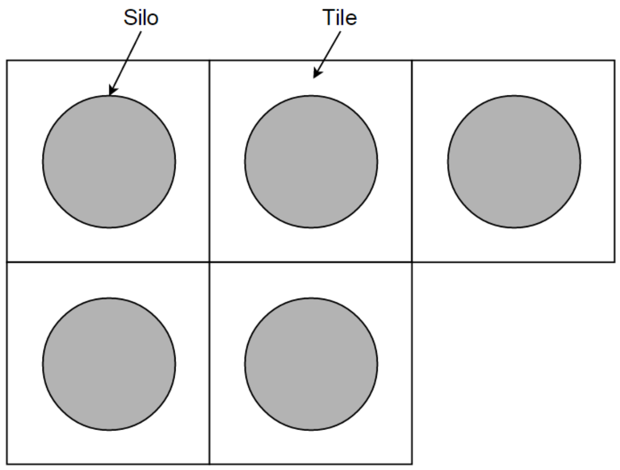


Figure VI-1: Overview of tiles with one silo each. Source: Own work

In the calculations the following assumptions are made:

- A tile has a square shape.
- A silo has a cylindrical shape.
- One silo is positioned in the centre of a tile.
- The centre-to-centre distance (s_{silos}) between silos is equal to the distance between the edge of a silo and the edge of a tile.
- All silos in a group are of equal diameter and equal height. And all groups that store the same commodity are identical.
- The tiles are positioned in the most efficient form. This means that tiles are combined in such a way that the tile group form corresponds as much as possible to a rectangle.

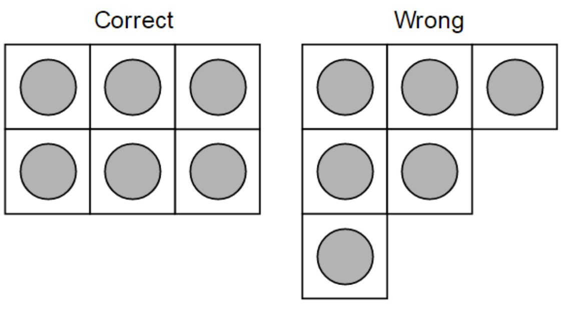


Figure VI-2: 'Rectangle-like' placement of tiles. Source: Own work

The total area of the tiles of a silo group can be calculated by multiplying the number of tiles with the tile area. Then for all external boundaries of the tile group a stroke with a width of 0.5 s_{silos} must be added in order to comply to the assumption that the distance between silo edge and tile edge is equal to s_{silos}.

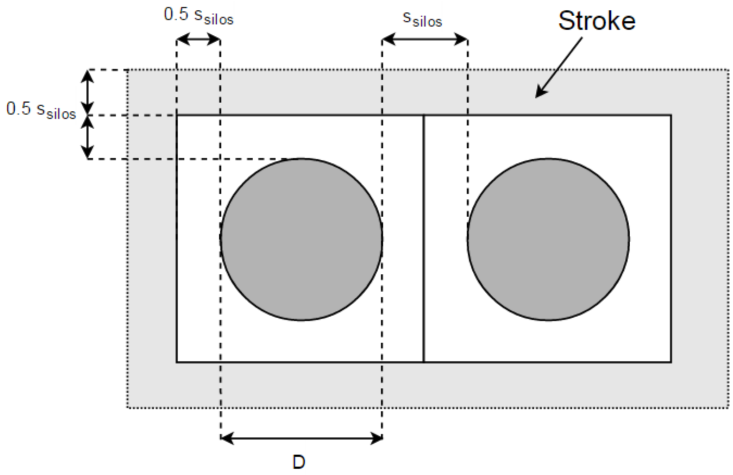


Figure VI-3: Silo tiles with surrounding stroke (light gray). Source: Own work

In order to determine the outer stroke area first the number of external boundaries (n_{eb}) must be calculated of a given number of tiles. The following equation is empirically determined:

$$n_{eb} = 4 \cdot \left[\sqrt{n_{silos}}; \text{roundup with } 0.5\right]_{\text{roundup}}$$

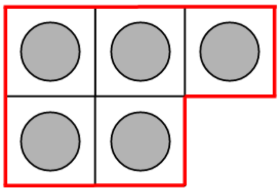


Figure VI-4: External boundaries in red. Source: Own work

The area of the outer stroke consists of parts with length $D + s_{silo}$ and width 0.5 s_{silo}. The area of the 4 remaining corners[40] is determined with $4 \cdot \left(\frac{1}{2}s\right)^2 = s^2$. The total area of the outer stroke can then be calculated with:

$$A_{os} = n_{eb} \cdot \frac{1}{2} \cdot s_{silos} \cdot (D + s_{silos}) + {s_{silos}}^2$$

[40] This is the case for a square tile group. For irregularly shaped groups (like in Figure VI-4) this holds as well since one corner area is counted double and one corner area is not counted, therefore they cancel each other out.

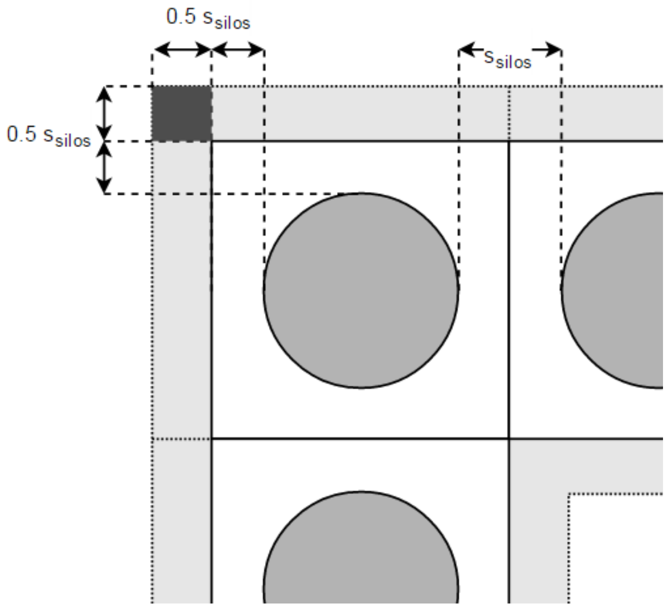


Figure VI-5: One of the four corner areas of a tile group. Source: Own work

This leads to a total area for the tiles plus stroke that can be calculated with:

$$A_{gr,i} = A_{os} + n_{silos} \cdot (D + s_{silos})^2$$

VI.2 Liquid bulk tank groups

When a tank group is not surrounded by a bund the calculation of the required area is identical to the calculation for silos. For a bunded tank group the calculation of the required area and the required bund volume is given in this section.

All assumptions that hold for silo groups are used for tank groups as well, and additionally:

- A tank has a cylindrical shape.
- A tile can consist of one or multiple tanks; and thus represents a tank group.
- Between two tank groups a single bund is used.
- A bund wall surrounding a tank group is simplified to have a square form.
- The total area required for a tank group is specified as the area between the outer toes of the bunds.

The effective bund height (h_{eff}) is the level to which the liquid can be contained; this is also called waterline. The real crest height (h_{crest}) should be 0.25 metre higher because of possible wind waves according to VROM (2008). Also the settlement of the soil may be taken into account.

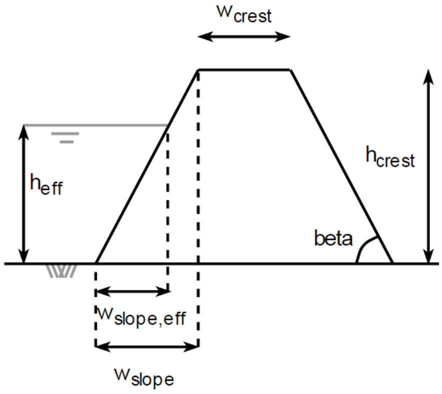


Figure VI-6: Cross-section of a bund. Source: Own work

The effective height is therefore:

$$h_{eff} = h_{crest} - 0.25$$

The unknown centre-to-centre distance between opposite bunds is $w_{pit,CtC}$, see the figure below. This width will be determined in the following calculation.

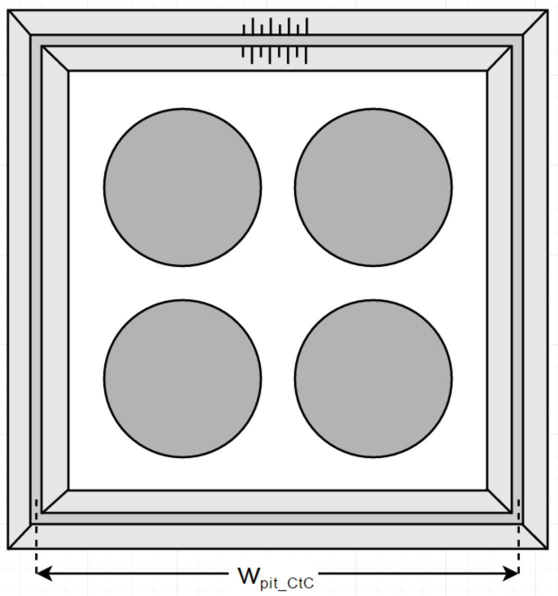


Figure VI-7: Overview of bunded tank group with centre-to-centre distance between bunds. Source: Own work

To calculate the storage capacity of the pit (the area or volume between the bunds) first the area must be computed. Here a simplification is made by neglecting the four corner parts, this is conservative. For the area see the figure below.

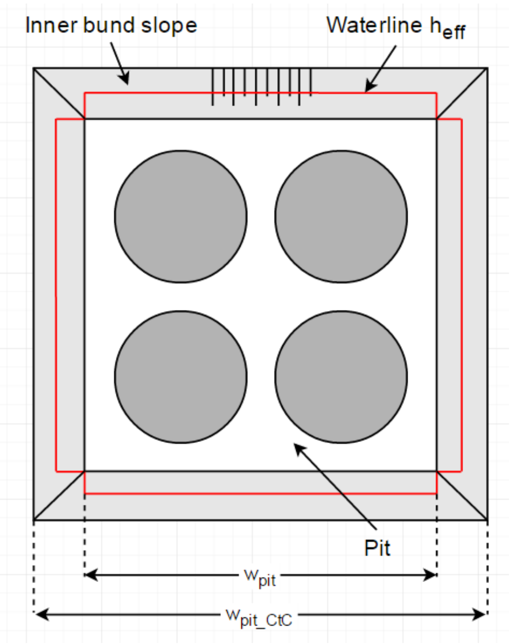


Figure VI-8: Overview with waterline h_{eff} (red) on inner slope in bunded tank group. Source: Own work

The storage volume can be calculated by multiplying this area with the effective height subtracted with the bunds' slope volumes and the effective tank volumes (volume of a tank for the effective height). The effective slope width ($w_{slope,eff}$) can be calculated, using slope angle β, with:

$$w_{slope,eff} = \frac{h_{eff}}{\tan \beta}$$

The width of the bund crest is w_{crest} and the width of the slope with maximum crest height can be calculated with:

$$w_{slope} = \frac{h_{crest}}{\tan \beta}$$

The pit width (w_{pit}) can be calculated with:

$$w_{pit} = w_{pit,CtC} - 2 \cdot \left(w_{slope} + \frac{w_{crest}}{2}\right)$$

The effective pit width ($w_{pit,eff}$) is the width between two opposing waterlines and can be calculated with:

$$w_{pit,eff} = w_{pit} + 2 \cdot w_{slope,eff}$$

The effective tank volume of tank with diameter D is:

$$V_{tank,eff} = h_{eff} \cdot \frac{1}{4} \pi \cdot D^2$$

The effective volume of the pit ($V_{pit,eff}$) is:

$$V_{pit,eff} = {w_{pit,eff}}^2 \cdot h_{eff}$$

The slope volume ($V_{slope,eff}$) of one bund that is beneath the waterline is:

$$V_{slope,eff} = \frac{1}{2} \cdot w_{slope,eff} \cdot h_{eff} \cdot w_{pit}$$

The number of tanks in a tank group is n_{tanks}. The real pit volume or capacity (V_{pit}) then is:

$$V_{pit} = V_{pit,eff} - 4 \cdot V_{slope,eff} - n_{tanks} \cdot V_{tank,eff}$$

In order to determine the unknown required $w_{pit,CtC}$ the real pit capacity must be larger than or equal to the full capacity of one tank (V_{tank}) plus 10% of the capacities of other tanks in the same pit, according to VROM (2008).

$$V_{pit} \geq (0.1 \cdot (n_{tanks} - 1) + 1) \cdot V_{tank} \text{ for } n_{tanks} \geq 1$$

After this step it must be checked if the tanks fit in the pit. If this is not the case $w_{pit,CtC}$ should be increased accordingly. The cross-section of a bund is calculated with:

$$A_{xs,bund} = h_{crest} \cdot w_{crest} + w_{slope} \cdot h_{crest}$$

For a less complex calculation the bund volume per tank group is simplified as in the figure below. The volume can then be calculated with:

$$V_{bund} = 2 \cdot A_{xs,bund} \cdot \left(w_{pit,CtC} - \left(\frac{w_{crest}}{2} + w_{slope}\right) \cdot 2\right) + 2 \cdot A_{xs,bund} \cdot \left(w_{pit,CtC} + \left(\frac{w_{crest}}{2} + w_{slope}\right) \cdot 2\right)$$

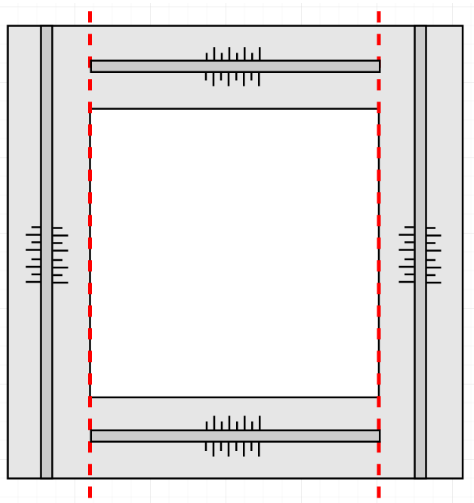


Figure VI-9: Simplification for the calculation of the bund volume. Source: Own work

In order to calculate the total bund volume of multiple adjacent tank groups the number of bunds that function as a dike for both sides must be determined first. A function is found that determines the number of internal boundaries given a number of tiles.

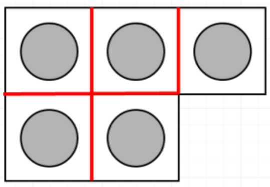


Figure VI-10: Internal boundaries in red. Source: Own work

The function is determined by fitting a quadratic curve to related sets of number of tiles (up to 12) and number of internal boundaries, that are determined by hand. This results in the following dataset and curve.

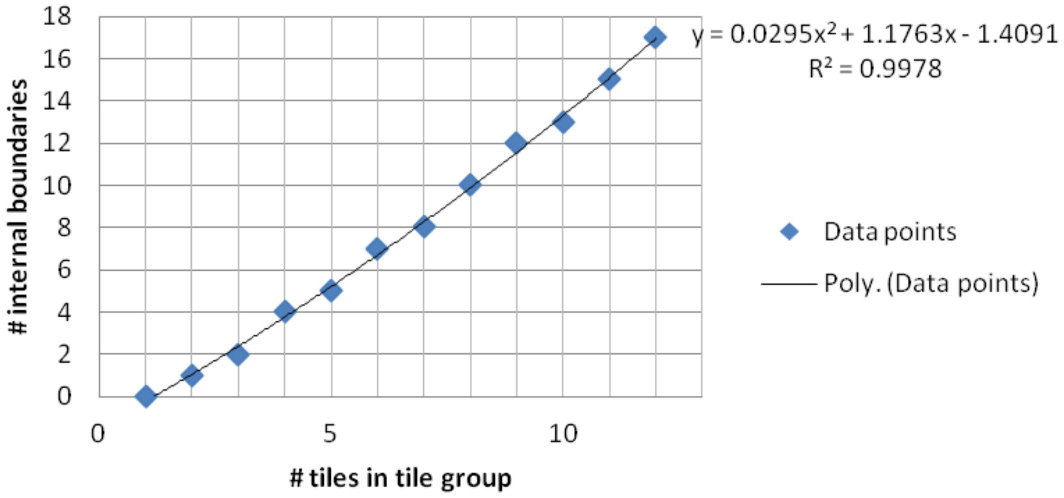


Figure VI-11: Quadratic curve fitting in order to find relation between number of internal boundaries and tiles.

The equation for the number of internal boundaries (n_{ib}) therefore is:

$$n_{ib} = \left[0.0295 \cdot {n_{groups}}^2 + 1.1763 \cdot n_{groups} - 1.4091; \text{round to integer}\right]_{\text{round}}$$

The situation when multiple tank groups are combined is depicted in the following figure.

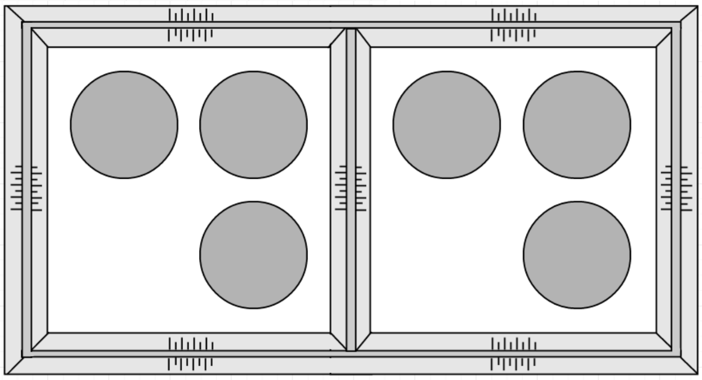


Figure VI-12: Combination of two tank groups. Source: Own work

The equation for the total bund volume ($V_{bund,total}$) of multiple tank groups is:

$$V_{bund,total} = n_{groups} \cdot V_{bund} - n_{ib} \cdot A_{xs,bund} \cdot \left(w_{pit,CtC} + \left(\frac{w_{crest}}{2} + w_{slope}\right) \cdot 2\right)$$

The number of external boundaries n_{eb} is considered in Section VI.1 . The total area of all groups (A_{gr}) is then:

$$A_{gr} = n_{groups} \cdot {w_{pit,CtC}}^2 + n_{eb} \cdot w_{pit,CtC} \cdot \left(w_{slope} + \frac{w_{crest}}{2}\right)$$