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Generic simulation model for green grain terminal operations

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He that breaks a thing to find out what it is has left the path of wisdom.

Gandalf The Gray

Preface

This report is the result of my graduation assignment of the study Mechanical Engineering at the Delft University of Technology, in the Multi-Machine Engineering track.

This assignment has been carried out at Bulk Handling Center of Expertise of Royal HaskoningDHV.

My research focused on the development of a generic simulation model for grain terminal able to investigate the system behaviours in different scenarios, helping the engineers of the group in their day-to-day work. Furthermore, given the current planetary situation and the key role of engineering in solving the issue, the possibility of simulating emissions-reducing operations was investigated and implemented in the model.

I would like to thank my TU Delft supervisors Dr. Frederik Schulte and Dr. Yilin Huang, for their feedback and support throughout this project.

I would also like to express my gratitude to my supervisors at Royal Haskoning, MSc René van Duijn and MSc Angelos Giannis for their continuous support during this research, both from a an engineering point of view and from a personal one. Furthermore, I would like to thank all the colleagues of Royal HaskoningDHV for my very pleasant and interesting first work experience in the engineering field.

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I am very grateful for all of my friends, the far ones, the close ones, the old ones, and the new ones. I would hardly be obtaining this achievement if it was not for their presence in my life, and I would surely be way less happy in doing so if I could not share my joy with them.

Lastly, I would like to express my gratitude to Rogier and my colleagues from De Gist who taught me, with unrestrained patience towards my numerous errors, that making mistakes is a fundamental part of the learning experience.

Delft, October 2024

Abstract

Due to the increasing trade of bulk cargo and the growing attention to efficiency in all steps of a supply chain that continuously becomes more complex, a thorough understanding of dry bulk terminal operations is crucial. While research on dry bulk terminal operations exists, it remains scarcely comprehensive. Existing studies primarily focus either on the storage space allocation problem, often in conjunction with berth allocation or on the simulation of the system, usually built for a specific case study. Furthermore, environmental factors have received limited attention in this context. Incorporating environmental considerations into this topic is crucial for sustainable and efficient terminal operations, especially when dealing with such a vastly spread sector as bulk cargo handling.

This work proposes a generic simulation model for grain terminals featuring a storage space allocation heuristic and the option to include cold ironing operations and unloading operations involving wind-assisted carriers. The generic character of the model is obtained by understanding what processes are common to different terminals and to what minimal level of detail they have to be modelled in order to obtain reliable simulation results. Moreover, the model gains further versatility due to its parametric and period-based character. These two features enable users to effortlessly conduct reliable simulations throughout all stages of design or revamping projects. This includes using information typically available at the start of a project as well as more detailed data that becomes available in later phases. The model includes the possibility to visualise and investigate the energy consumption of the system, crucial information to face present-day challenges such as the adaptation and enlargement of the electrical grid and the capacity estimation for the installation of new green energy production plants. The effectiveness of the model and its generic quality are validated with different study cases from real-world terminals. Additionally, in order to show the genericity of the model and its potential, this study features multiple experiments to investigate different aspects of terminal operational and energetic efficiency, involving the changes in operations caused by the introduction of shore power connections and wind-assisted carriers, a comparison of different unloading technologies, and a validation of the industrial common practices in the field.

List of symbols

Symbol	Definition	Unit
$a_{i,s}$	aomunt stored in silo s in time step i	
Bk_t	breakdown time index	[-]
c_i	number of cargoes per carrier in period i	[-]
C_i	effective capacity of equipment i	[T/h]
C_s	capacity of silo s	[T]
C_{ratio}	connection ratio	[-]
IAT_{trucks}	trucks inter arrival time	[h]
M_t	maintenance time index	[-]
n	number of servers/silos	[-]
$n_{i,m}$	number of cargoes of material m in period i	[-]
n_{trucks}	number of trucks	[-]
N_i	number of carriers in period i	[-]
N_t	non-working time index	[-]
P_i	length of period i	[h]
s_t	simulation time	[h]
$t_{outtake}$	outtake time	[h]
t_u	utilization time	[h]
T_{amount}	amount of a parcel carried by a truck	[T]
$T_{i,m}$	throughput of material m in period i	[T]
T_size	amount carried by one truck	[T]
w	wasted space	[-]
W_i	weather time index	[-]
λ	service rate	[1/h]
μ	arrival rate	[1/h]

List of abbreviations

Abbreviation	Definition
DES	International Standard Atmosphere
RHDHV	Royal HaskoningDHV
DE	Discrete Events
KPI	Key Performance Indicator
SC	Straddle Carrier
RTG	Rubber Tyred Gantry Crane
URCS	Underground Reefer Container Storage
MILP	Mixed-Integer Linear Programming
ABM	Agent-Based Modeling
PROPER	PROcess PERformance
FCFS	First Come First Served
HEF	Highest Earning First
SPTF	Shortest Processing Time First
EDD	Earliest Due Date
HDF	Highest Demurrage First
BAP	Berth Allocation Problem
QCSP	Quay Crane Scheduling Problem
QCAP	Quay Crane Allocation Problem
GHG	GreenHouse Gas
OPEX	OPerating EXpenses
OPS	Onshore Power Supply
SSE	Shore Side Electricity
SP	Shoreside Power
CI	Cold Ironing
UK	United Kingdom
DWT	Dead Weight Tonnage
LVSC	Low Voltage Supply Connection
HVSC	High Voltage Supply Connection
CMS	Cable Management System
IEC	international Electrotechnical Commission
AC	Alternate Current
DC	Direct Current
WPT	Wind-assisted ship Propulsion Technologies
WASP	Wind-Assisted Ship Propulsion
EEOI	Energy Efficiency Operational Indicators
VLCC	Very Large Crude Carrier
USA	United States of America
IAT	Inter Arrival Time
FIFO	First In First Out
MTTR	Mean Time To Repair
MTBF	Mean Time Between Failures
COVID	Coronavirus Disease
OOP	Object-oriented Programming

Contents

1
Introduction

Dry bulk trade made up for more than 50% of the total marine commerce in 2023 [94], amounting to more than 5 billion tonnes. These figures show this trade's vital role in the global economy and today's society. Such a significant exchange of raw materials is motivated by the fact that some locations in the world dispose of large minerals, food reserves, or production facilities, but still have little local demand. On the other hand, other sites find themselves in the opposite situation, requiring inputs for processing, distribution, or manufacturing.

Dry bulk is generally divided into major bulk and minor bulk. The former comprises iron ore, coal and grain (oats, wheat, millet, corn, sorghum, rice, soybeans, sunflower seeds, etc.) making up respectively 20, 24, and 10 % of the dry bulk trade, these being thus dedicated materials for many routes and terminals. The latter includes all the other materials traded in bulk such as other minerals and agribulk being responsible for the remaining 46 % [94].

In this context, grain trade is of crucial importance being fundamental for the availability of nourishment for a large portion of both the human and animal population in the present world [107].

It is agreed that the current climate crisis will affect the cultivation of different crops around the world [43]. This will possibly lead to changes in grain trade routes and volumes, due to the new climatic conditions of traditionally producing and consuming countries. Another possible outcome will be an important decrease in the amount of grain harvested around the world, making efficient transport without losses of paramount importance. Furthermore, the predicted world population growth [95] will definitely influence food trade in an extreme way, not only intensifying the trade but also forcing society to find new solutions to meet the population's needs. Finally, current and future political unrest in different producing countries could have a major effect in grain production and export.

The grain supply chain is thus a fundamental cog in the wheel of today's economics and way of life, in particular in the more developed countries. However, it appears to be a not extremely efficient cog with major losses in different phases of the chain [33], in some cases accounting for up to 60% of the harvested quantities. In fact, in comparison with other dry bulk materials, grains have the peculiar characteristic of being perishable and require special storing and handling solutions and conditions to face this issue.

Given these reasons, it is evident that a deeper understanding of the grain supply chain is crucial. The implementation of more effective methodologies to address the issues affecting it is essential to tackle the current challenges facing the world with the proper means. By doing so, the efficiency and resilience of this field can be enhanced, ultimately contributing to global food security and sustainability.

In every dry bulk supply chain, an essential element is commonly recognised in the marine terminals. The terminals essentially act as buffers between different transportation means characterised by different schedules, sizes and logistical issues. The presence of the terminal thus allows the two different branches of the chain to behave in relatively decoupled manners with less detrimental effects on each other. Because of this decoupling nature terminal operations can be quite complex and are nowadays unthinkable without effective and efficient use of information technology as well as appropriate optimization and operations research methods.

Most of these research methods are normally utilised to help terminal managers to face operational decisions such as scheduling and planning. In particular, a great challenge in terminal management is storage space allocation. The storage space allocation problem deals with finding the most suitable parcel-storage coupling taking into account particular storing characteristics of the material, dwell time and terminal-specific storage policies. These decisions can have a great influence on both the terminal yearly throughput, product cost, and and client satisfaction. Furthermore, an efficient storage space allocation policy influences the actual space needed for storage, affecting greatly the capital costs during the design phase.

Another important issue in dry bulk terminal design is equipment selection. The selection of the right equipment is crucial for the system to obtain positive performance and, just as storage space, has a great influence on capital costs [23]. The material handled by the terminal is the first discriminant to choose the right machines. Still, many different combinations of technologies, capacities and rated power are possible inside a group of devices able to handle the same material.

To study these problems, numerous experts have turned to Discrete Event Simulation (DES). DES modeling involves simulating real-world operations within a controlled computer environment. This method offers a logical and quantitative approach to enhance understanding of the outcomes resulting from different proposals. A DES model is built by treating each physical item as a discrete entity, characterized by its distinct set of defined properties or attributes. These entities simulate the operational activities that constitute the processes being analysed. Activities have finite execution times, introducing delays to the modelled system. Both these delays and other process times can be stochastic in nature, and various methods are normally used to generate randomly induced delays based on data and operational rules specific to each process or piece of equipment. The combination of logical and random events aims to reflect the most likely operational environment.

In this context, not enough attention to energy consumption and environmental issues had been put into terminal operations optimization. In particular, almost no study including these aspects in a simulation model has been found. However, new laws taking effect in the near future are expected to change radically the way port operations are led, especially in Europe. For example, ports will be obliged to guarantee shore power connections to container and passenger ships starting from 2030 [77], and dry bulk is expected to follow shortly after.

Furthermore, in most recent studies a detachment between coefficients and industrial common practices suggested in classical handbooks such as [103] and [51] and the reality of the terminals has been underlined ([97],[48],[101]). Understanding where reality lies and thus which coefficient to utilize when designing a new terminal or evaluating the efficiency of an existing one becomes a crucial issue. This problem claims even more attention in a time in which precise design becomes of paramount importance in order to meet environmental goals and approximation coefficients are looked upon as wasteful.

Amongst the users of DES there are not only academics and theory experts concerned with cutting-edge innovation and research. In fact, DES is a powerful tool, often applied by professionals in their work. By its intrinsic nature, simulation is an instrument that synergizes perfectly with technical consultancy practices. The study, analysis, and modelling of a system to understand its shortcomings and strengths is something common in this work field, that can thus exploit massively the potentials of simulation.

Royal HaskoningDHV is a technical consultancy firm with many different branches and engagements. In particular, the Bulk Handling Center of Expertise is a group of professionals specialised in dry bulk maritime terminals and other logistic hubs. The group carries on very different kind of projects such as greenfield terminal designs, equipment selection, studies for terminal, and due diligence projects.

These projects are usually approached with the technical knowledge of the professionals composing the group and relying on industrial common practices mostly taken from handbooks such as [103]. Furthermore, the Center of Expertise makes use of DES models too. However, as agreed by many experts in the field ([9],[81],[49]), producing a simulation model from scratch can be a very cumbersome and long process, even if using a commercial simulation software. Thus, this tool is commonly used only as a dedicated service for clients that particularly request it and not a basic instrument that could help the Royal HaskoningDHV engineers in their work.

In this environment, a generic tool featuring the standardised operations of a terminal could revolutionize the way simulations are managed. This tool would allow for the rapid integration of simulations into static calculations during the initial phases of projects, enabling quick analysis of multiple different situations. In this way, simulation would no longer be seen as a specific service, but as a versatile and easily applicable element, improving the efficiency and flexibility of project processes.

1.1. Objective and scope

In this work, a generic DES model for grain terminals is developed. The model is meant to approach the system in a generic way so that it could be applied to the great majority of terminals with minor modifications, and in case expanded to other kinds of dry bulk terminals. In this model, the option to simulate shore power supply and the arrival and service of wind-assisted carriers is included in order to allow users to understand better what changes these implementations mean for such a system. Furthermore, the model is able to collect energy consumption data from the simulation run, valuable information for energy transition-related problems such as grid expansions and sizing of new renewable energy farms. Other than various case studies to validate the model, an attempt to evaluate the validity of the commonly used industry practices and a consequent discussion is presented. Finally, a comparison of the influence of pieces of equipment with different specific consumption on the total terminal energy consumption is provided.
The research question was thus formulated as follows:

To what extent is a DE generic simulation model able to give useful insights into grain terminal operations and energy consumption?

In order for it to be answered comprehensively and in a structured way, the main research question is broken down into the following sub-questions :

- What are the minimum requirements and characteristics for a generic model?
- Is it possible to define a methodology to obtain a generic simulation model for a certain system? If yes, what would the main steps of this methodology be?
- To what extent will the introduction of shore power affect terminal operations and energy consumption? How does the terminal size relate to the characteristics of the shore power connections (number of served berth ranges)?
- What other possible emission-reducing operations can be included in the model and how would they affect the system?
- What is the most energy-consuming process inside the terminal? How do different installed powers and capacities affect the energy consumption of the terminal?
- Are the industrial common practices still a reliable guideline when designing or redesigning a terminal?

1.2. Structure

The organization of the work is described below. Chapter 2 proposes a literature review of dry bulk and other cargoes terminals simulation-related works. In Chapter 3, a description of the utilised methodology is provided, together with the introduction of a newly developed methodology to face generic simulation problems. Chapter 4 provides a thorough description of the generalised operations taking place in grain terminals, underlining the similarities and differences between import and export systems. In Chapter 5 the modelling of the previously described operations is described in detail. Chapters 6 and 7 respectively describe the verification and validation process of the model. In Chapter 8 the design of the various experiments set up to answer the different sub questions are depicted, together with the consequent results. Lastly, Chapter 9 presents the conclusions about the whole model and the developed experiments together with future research lines.

2
Literature review

In this chapter, a review of the relevant literature found and analysed for this study is reported. Due to the lack of literature on grain terminals and grain terminals simulation and to the variety of other topics faced in this work, the chapter is divided into dry bulk terminal simulation literature, general terminal simulation literature and storage space allocation literature.

2.1. Dry bulk terminal simulation

It is interesting to mention that almost no study dealing with grain terminal simulation was found. This shows the lack of research in this direction. However, many studies were carried out on iron ore and coal terminal simulation, probably because of the larger dimension of the trade and the higher economic interests in it. The differences between these systems are not small in reality, still, they remain similar from a modelling point of view, thus a literature review of this kind was deemed satisfying as a first approach to the field.

The first application of DES to a dry bulk terminal environment was found in [10]. In this work, a feasibility study for an expansion of a coal terminal on Batam Island, Indonesia. The focus of the simulation was the ship arrival patterns and the consequent loading and unloading operations. Only the large ore carriers' inter-arrival times were generated through a distribution while the smaller ships' arrivals were simulated based on the travelling times to the served customers.

On the other hand, in [28] was made use of a DES model to test different storing strategies in an iron ore terminal connected with a mine. The need for the ore to dry was taken into account, making it an interesting case to compare with similar grain terminal operations.

Amongst many other models developed for different specific cases, in [24] is discussed the design of a dry bulk terminal DES general tool featuring both a port equipment library and optimization capabilities. A Genetic Algorithm was applied to solve the optimization problem, focused on the design and scheduling of operations.

In [69] a new approach to the system was proposed. This new modelling path consisted in schematising the terminal as a job shop made of different equipment line groups and transport jobs. Each equipment line consists of various pieces of equipment with different characteristics and results available only if all of them are. Different equipment assignment options were evaluated together with several breakdown behaviours.

A whole doctorate thesis [101] was dedicated to developing a complex DES tool for dry bulk design and study and applying it and its variants in multiple investigations. The main objective of the project was to provide port planners with a useful tool during the design process. The model featured different dedicated modules to simulate only the seaside, the landside, the stockyard, and the routing system.

In [98], two different levels of simulation concerning a short horizon were developed to help terminal managers in making routing decisions. One simulated the terminal dynamics while another took care of the routing simulation based on the output of the first. The selection of the best route was made in three phases taking into account respectively total time, waiting time and needed electricity. With [102] a simulation-based approach was applied to the dimensioning of the stockyard for dry bulk terminals including shipload splitting and piles relocation options in the simulation tool. The study showed quite some discrepancies with and amongst generally used rules of thumb, with some of them corroborated by academia but in discord with common industrial practices and vice versa. The investigation of the design of a conveyor belt network by simulating its behaviour for different storage policies and layouts was described in [99]. The work took into account stochastic processes and conveyor breakdown. One of the findings was that installing the maximum number of connections does not necessarily lead to better performance of the system. In [100] the simulation tool was applied to reschedule stacker-reclaimers operations in order to increase the terminal's performance. An operations interruption option and a wide-lane/dedicated layout option were part of the simulation and analysed in the study.

A new discrete event simulation model for the analysis of the unloading operations in RUSAL Aughinish Alumina refinery was introduced in [19]. The model took into account both deterministic and stochastic processes including tidal constraints. Furthermore, a heuristic queue sorting mechanism based on cost reduction was developed and integrated into the simulation. In [18] the model was improved and the scope enlarged, taking into account the transport and storage operations, maintenance activities and unloading hatch sequences, a detail often not taken into account in these models but that can greatly affect loading and unloading times.

In [110] a simulation model was implemented to identify terminal throughput capacity. Other than taking into account classical factors used in similar simulations such as equipment efficiency and ships' and trains' arrival frequency, a typical characteristic of this model was to divide the stockyard into small grids in order to better describe it. An interesting characteristic of this model was the attempt to connect train arrivals to the ship arrival plans, as usually happens in reality.

As one can see most of the models are clearly focused on the seaside of the terminal, probably because of the economic importance of the shipping industry. Furthermore, it seems to be commonly agreed that badly planned seaside operations typically have more detrimental effects on terminal operations than inefficient landside planning. However, it has been seen that this lack of attention to landside planning can lead to serious disruptions in the supply chain. For these reasons, in [64] a discrete event simulation was applied to a wood chip export terminal in Australia to investigate congestion on the terminal's landside. The model analysed the effects of the variations of the terminal's configuration, the application of a terminal appointment system and the implementation of a gate automation technology in four different truck arrival frequency scenarios. By taking into account different products and truck sizes it was found that the introduction of an appointment system can reduce turnaround times by approximately 20% while adding unloading capacity obtains a relatively small improvement. Furthermore, in [62] more possible improvements were proposed in terminal management to avoid gate congestion and in [63] a similar model was applied to study them with an additional view on environmental issues. Integrating data collected from weighbridges and truck geo-positioning systems, the already studied improvements of a terminal appointment system and a new terminal configuration were compared with the introduction of an integrated weighbridge database and the use of higher-capacity trucks. Other than classical KPIs such as turnaround times, waiting times and turnaround time reliability, engine idling emissions were taken into account during this research.

Table 2.1 reports a comparison of the just described works with the present one under a series of specifications. As one can quickly grasp from the diagram, a relatively large attention to the production of generic models is present in the field, especially represented by van Vianen's works [101]. However, the generic model was often developed based on a case study or adapted by it, without precise initial attention to develop such a tool. Oftentimes, simulation of such a system is not approached as a problem on its own but mostly as a tool to demonstrate or prove the validness of results obtained in other ways. The possibility of simulating different policies or scenarios in a computer environment without a real-world implementation is indeed the main advantage and objective of simulation. Still, in order to obtain reliable results the topic itself should deserve more attention and dedicated study, without being a sidekick in works dedicated to other matters.

It is interesting to point out the difference made between the two parameters ”Terminal” and ”Storage” in the classification of the works. With ”Terminal” the modelling and simulation of the stockyard operations was meant. On the other hand, with ”Storage” the possibility of setting a maximum capacity for the storage area was indicated. In fact, a relatively common practice found in these works was to leave no maximum constraint to the storage space capacity (and thus describe the whole storage as one infinitely large bin). By running simulations in this fashion, the maximum capacity needed under a series of determined factors (equipment fleet, throughput, etc.) could be easily estimated. However, it

is clear that a certain detail in the simulation of stockyard operations is lost.
Furthermore, with the exception of Dipsar's [28] and Zhu's [110] works, no example of a model able to simulate the whole system was found, with a major interest in the seaside subsystem, for reasons that were already stated.

Table 2.1: Comparison of dry bulk terminal simulation works with the present work

Work	Generic model	Seaside	Terminal	Storage	Landside	Alt. Operations	Energy
Baunach et al. [10]		√	√				
Dipsar et al. [28]		√	√	√	√		
Dahal et al. [24]	√	√	√				
Ottjes et al. [69]	√	√	√	√			
van Vianen [101]	√	√	√	√			
van Vianen et al. [98]	√	√	√				√
van Vianen et al. [102]	√		√	√			
van Vianen et al. [99]	√						
van Vianen et al. [100]	√	√	√	√			
Cimpeanu et al. [19]		√					
Cimpeanu et al. [18]		√	√	√			
Zhu et al. [110]	√	√	√	√	√		
Neagoe et al. [64]				√	√	√	
Neagoe et al. [62]				√	√	√	
Neagoe et al. [63]				√	√	√	√
This work	√	√	√	√	√	√	√

2.2. Other terminal simulation

Since port simulation is a very extended field and the works found that strictly dealt with dry bulk terminal simulation were not deemed to be in sufficient number, or still the impression was that there was more to understand about this field, the literature review was extended to port simulation in general (mostly container trade ones). A few of the articles found are reported in the following paragraph, trying to delineate a brief history and state of the art of port simulation.
One of the earliest works found dealing with port simulation is [57]. In this study, the key issues of the application of modelling and simulation for the management of the Riga Harbour Container Terminal were discussed. Thanks to the financing of the European Commission, this research studied problems and approaches to solve them that are typical for growing harbours, producing results that could be used as a guideline for solving analogous issues in similar systems. The simulation model was divided into a micro level, where separate technological operations were simulated in order to investigate their durations, and a macro level, where results of micro-modelling were used within the overall model of the container terminal.
In the same years, in [34] a process-oriented DES model was used to validate solutions to the resource allocation problem obtained through different optimisation methods. In the model, the different objects were classified according to their "intelligence" obtaining three different classes: Planners, Operators, and Components. External events such as trucks, trains, and carriers' arrivals trigger responses from the simulation agents, which in turn operate on the simulation components.
In [29] a distributed simulation model was developed including all the characteristics of container handling between the ships and the container stack. The model was decomposed into small, easy to understand sub-models communicating with each other: the Quay System, the Transport System, the Container System, and the Control System.
Again, in [46] the role of computer simulation in the evaluation of the performances of a container terminal was investigated in relation to its handling techniques and their impact on the capacity of the terminal. Furthermore, the authors addressed the crucial issue of performance criteria and the model parameters when dealing with port terminal congestion and terminal capacity.
With [71] a peculiar modular DES modelling approach was developed and applied to the logistic chain

of the northwestern Italian port system. The main container terminals in the area are modelled using a modular structure that is able to efficiently represent both the logistic activities and the interconnection phases between each mode of transport, allowing the user to modify parameters and rules in each module without changing the functional behaviour of the global model. In particular, the constituting modules of each terminal were schematised in the ship berthing, the truck gate and the rail yard.

In [85] DES was applied to investigate the optimization of an internal transport cycle for a marine container terminal managed by straddle carriers (SC). The system was divided into the three classical subsystems: landside transportation, container storage in the yard, and quayside transportation. The model was used to compare SC operational strategies, different-sized fleets of handling equipment optimization algorithms for the assignment, and optimization algorithms locating import and export containers in the yard.

Arena [20] software was used in [21] to develop a complex simulation model of the Seville Port, taking into account all the materials handled by it, namely: containers, cereals, cements, scrap, iron ore and fertilizers. In this work, particular attention was given to the modelling of the estuary leading to the port and all the carriers approaching the process. Furthermore, since the model covered the whole port, a dock assignment procedure based on the material carried by the ship was featured. Each of the different locks was characterised by policies based on the material handled and the specific company managing it. A very peculiar feature of this model was the simulation of human resources (coastal pilot, mooring rope workforce, etc.) usually overlooked in this kind of work.

In [1] DES was applied to understand the operational costs of a container terminal. To obtain this objective, three different models were developed: a macroscopic model to simulate terminal and port operations, a microscopic one capturing the adjacent road network behaviour, and a cost model that processed the inputs obtained from the previous two produced results of economical nature. The macroscopic model was used to simulate the behaviour of 14 container terminals simultaneously. In order to do so, a flow paradigm was applied, losing the possibility to track single entities but allowing the model to handle large systems.

In [87] the development of a general simulation platform, named MicroPort, is described. The tool was meant to provide an integrated and flexible modelling system for evaluating the operational capability and efficiency of different designs of container terminals. The platform featured several decision processes, covering almost all decision problems in major container terminals. The option to input decision algorithms was part of the model. However, complex and thorough decision procedures were part of the platform and available to users.

Arena [20] was once more used in [47] to build a generic discrete-event simulation model to investigate container terminals operations, with a focus on throughput, resource utilization and waiting times. The model covered the whole system with a high level of detail, including port operations, and movement of ships, trucks and trains and featuring a wide range of different resources such as quay cranes, RTGs, berths and storage areas.

With [52] an investment planning problem for the seaside operations of the container terminal in Humen Port was addressed. The simulation model was developed using Arena [20] and featured various types of container ships and cranes, flexible berth allocation and dynamic crane scheduling. As in other cases, the model was decomposed into four subsystems working independently as well as interacting with each other.

In [44] a study on the impact of using a new intelligent vehicle technology (Intelligent Automated Vehicles) on the performance and total cost of a European port is presented. In order to do so, a low-level DE simulation model and a cost model were developed.

Some attention to environmental issues was given in [108], in which a study on the quantification of the impact of mitigation strategies on carbon emissions from port operations and shipping inside container terminals was carried on. For this purpose, a carbon emission quantification DE simulation model was developed by use of Arena [20]. A formulation to calculate carbon emissions was introduced together with a series of mitigation strategies: reduced speed in waterway channels, reduced auxiliary time at berth, onshore power supply, alternative fuels, and increased working efficiency of port equipment. In this work too, the simulation model included different sub-models: ship arrival and berth assignment sub-model, ship going through waterway sub-model, ship handling operation sub-model, and external truck operation sub-model. Obtaining the working time for each piece of equipment in the terminal through the simulation model and embedding the presented carbon emission formulation, the emissions for each kind of component were given as model output.

Table 2.2: Comparison of other terminal simulation works with the present work

Work	Generic model	Seaside	Terminal	Storage	Landside	Alt. Operations	Energy
Kavakeb et al. [44]		√	√			√	√
Cortés et al. [21]		√	√	√	√		
Lin et al. [52]		√					
Soriguera et al. [85]	√	√	√	√	√		
Kotachi [47]	√	√	√				
Moros-Daza et al. [59]	√	√	√	√	√	√	√
Feng et al. [31]		√					
Yun et al. [108]	√	√	√	√		√	√
Duinkerken et al. [29]	√	√	√	√			
Abadi et al. [1]	√	√		√	√	√	
Gambardella et al. [34]	√	√	√	√	√		
Parola et al. [71]		√	√	√	√		
Merkuryev et al. [57]		√	√	√	√		
Kia et al. [46]	√	√	√	√	√		
Sun et al. [87]	√	√	√	√	√		
This work	√	√	√	√	√	√	√

Various detailed simulation models were developed in [31] in order to examine how different seaside infrastructure improvement measures of a marine crude oil terminal could increase its maximum oil throughput, reduce tanker delays, and minimize the total system cost over a certain planning horizon. The models featured special navigation constraints for oil tankers, realistic tidal constraints, and practical priority rules for different tanker types at the Rizhao Shihua Oil Terminal in China. Only the seaside of the system was modelled, diving it into two different subsystems: a navigation subsystem that contains tanker anchorages and a one-way channel connecting to the dockyard and a dockyard that contains dwelling berths and a turning basin where tankers make turning manoeuvres before entering berths and after exiting berths. The different infrastructure improvement measures were compared based on the annual crude oil throughput for each of the above improvement measures, and their resulting average tanker delays under given demands.
Recently, the viability of an innovative infrastructure termed Underground Reefer Container Storage (URCS) was assessed in [59]. This measure was meant to mitigate the significant and increasing energy demand posed by reefer containers in ports. A DES model was used to evaluate the feasibility, environmental implications, and cost-effectiveness of three distinctive URCS infrastructure designs. In order to measure the impact of all the resources of a port, not only the reefer container operations were simulated, but the entire port operations. The DES model included all the elements of a foreign trade supply chain, from the arrival/departure of trucks to the arrival/departure of vessels.
Just as in the previous paragraph, Table 2.2 compares the just reported works with the present one. The trends described in the previous paragraph still hold, with minor differences. In particular, a larger amount of generic models was found in this different field together with a way larger number of studies simulating the system in its entirety. This could be explained by the way higher economic interests are involved in this field. However, it is important to remember how the intrinsic discrete nature of the container is more easily coupled with DES if compared with the continuous processes typical of dry bulk trade.

2.3. Storage space allocation

Another great issue in terminals is storage space allocation. In recent times a relatively large amount of studies on the topic has been carried out using simulation but mostly addressing the problem as an optimization one. In [105] a constraint programming approach was developed to solve the Stockyard Management Problem studying the strategy of allocating stockyard space to coal stockpiles dynamically such that the overall utilization of stockyard space could be maximized.
In [70], a real-world storage space allocation problem at an export bulk terminal was considered for-

mulating the problem as MILP (Mixed Integer Linear Programming) and proposing a heuristic method inspired by bin packing problem to solve large-scale data sets while minimizing the cost of tardiness and undesired mixing.

Furthermore, some attention to environmental issues has been taken into account in the approach to these problems. For example, [84] proposed a formulation for a stockyard planning problem focused on minimizing energy consumption during operations. On the other hand, a first study [88] proposed a similar approach minimizing the total travel distance of incoming ores as a proxy to reduce energy consumption and operational time. Later [89] enlarged the problem scope by integrating stacker-reclaimer and mist cannons operations to decrease the amount of dust emitted from the terminal. Lastly, [30] developed a mathematical formulation to solve and integrated energy and transport scheduling of terminal operations, taking into account the electric network and bunkering system modelling.

The literature review carried out highlighted a significant gap in research specifically focused on grain terminal simulation, despite the critical role these terminals play in global trade. While numerous studies have been conducted on iron ore and coal terminals, the unique challenges and requirements of grain terminals remain underexplored. Existing research primarily addresses specific case studies or focuses on particular aspects such as storage space allocation and equipment selection, often neglecting environmental considerations. Furthermore, other than case-specific and problem-specific research, most of the works found focused on only a portion of the terminal, not trying to grasp the complexity of the balancing of relatively uncoordinated supply and demand that takes place in such a system.

Despite the enumerated deficiencies, significant insights can be drawn from studies on dry bulk terminals and general terminal operations. Both the dry bulk and the other materials terminals studies had as main simulation goals the optimization of terminal efficiency, reduction of operational costs, and enhancement of throughput capacity. In both kinds of works the principles of the principles of efficient space utilization, resource allocation, and process optimization were vastly applied, even if with the due differences.

From a chronological point of view, we can see that methods have evolved from simple deterministic models to more sophisticated approaches, including discrete event simulation (DES), agent-based modelling (ABM), and hybrid models that combine various techniques. These advancements allowed for more accurate and comprehensive analyses of terminal operations, accommodating the complexities and dynamic nature of modern logistics.

From the studies reported, two key insights emerged that shaped this work. First, the complex system can be effectively managed by subdividing it into smaller subsystems, specifically seaside, storage, and landside. Additionally, classifying the various simulation components based on the intelligence required for their operations proved essential.

3 Methodology

This chapter gives a brief overview of the two methodologies applied during the development of this work.
The first one presented reflects the outcome of the thoughts, experiences, mistakes, and lessons learned throughout this work on creating a generic model. The result is a methodology applicable to the process of creating a generic simulation model, independent of the kind of simulated system.
The second, The Delft System Approach and more in particular the PROPER model, is a widely known and applied methodology in industrial systems management. It was used in this work to approach the analysed system with a structured approach.

3.1. Generic model approach

As already stated one of the main goals of this work was to produce a model that would be generic.
Thus, the first and most important step was understanding what generic actually means and how generic such a model could be, without hindering the quality of the results.
Two other words were found that convey the same message intended by the author with "generic": versatile and flexible. In fact, the generic character of this model is mostly the ability to be easily applied to different scenarios and situations. However, "general" was also found to fit quite well under certain circumstances. A generic model should thus be flexible and versatile enough to be able to adapt itself to the variety of scenarios it could be applied. Still, it should have some general characteristics that remain consistent, usually the ones characterising the group of systems the model will be used to simulate.
The genericness of the model was thus expressed in five different aspects of a simulation model:

- Resources
  One of the first issues that comes to mind when applying the same model to multiple scenarios is the obvious fact that the scenario will be different. In particular, the resources of the actual system, and thus the actual structure of the system itself, will be different in numbers and characteristics. It thus becomes an essential characteristic of a generic model to not rely on specific elements of the system but give the user the possibility to vary them and their characteristic at will.

- Inputs
  Another difference between the scenarios that the user could be willing to simulate with a generic tool resides in the inputs the system receives from the environment and are thus not part of the system itself. It is clear that the capability to variate the system inputs becomes essential in a generic model, giving the possibility to compare the simulated performance of the same system in different conditions or of the same system in the same conditions.
  Furthermore, quite some effort was spent understanding the time flexibility needed in a generic model. In fact, oftentimes inputs need to change not only from one scenario to another, but inside the same scenario too (and thus simulation run). Another important feature of a generic tool was

thus individuated in the possibility to not only vary the system inputs scenario by scenario but to be able to vary them and their rate of change inside the same scenario.

- Policies
  Systems can differ not only for inputs and resources but for policies too.
  To some extent, a policy could be seen as a specific type of external input. However, three main differences were individuated between these two aspects of a system which made it more logical to categorise them into two different groups. Firstly, a policy is something that does not come from the outside environment (such as weather, or carrier's arrival in the system discussed in this work). Secondly, policies are not intrinsic characteristics of the system but can be varied without having to change the physical nature of the system (such as equipment capacity, breakdown rate, and storage layout). Thirdly and most importantly, policies are the outcomes of managerial or operational decisions made by the system's operators concerning the way the system faces different situations. Examples of a policy related to the discussed system are the order in which carriers are served or the way parcels are allocated inside the terminal's storage.
  Oftentimes, simulation studies are used precisely to understand the behaviour of the same system if managed according to different policies.
  However correct the previous reasoning is, another turn was taken during the development of this work. In fact, policies are usually one of the hardest parts to model in a simulation environment, often involving cumbersome optimizations or heuristic logics that try to mimic (or optimize) the operational decisions taken by systems' managers, which cannot be easily specified by the user without having to quite radically change the model itself.
  The outcome on the matter would thus be that in this case, the generic model should steer more towards the general side. Understanding what policies are the most commonly used in the specific field and integrating into the tool should be a fundamental part of the model development. If more than one policy is individuated, the implementation of all of them could be a good practice, giving the option to the user to choose the preferred one. Still, the possibility to create and implement alternative options should not be a requirement for a generic tool.

- Objectives
  The simulation of a system can have very different objectives under the common one of exploring an alternative scenario to the real one, without the efforts and circumstances needed to make it happen. Normally, a simulation model is built to explore a specific characteristic of a system. Furthermore, it is clear to all simulation experts that ”There is No Such Thing as General Validity” and that ”A model is only validated with respect to its purpose. It cannot be assumed that a model that is valid for one purpose is also valid for another.” [80].
  However, a generic model should at least try to be able to cover multiple objectives and be reliable for different kinds of studies. In order to achieve this, a thorough review of the most common objectives of simulation studies in the specific field and a consequent validation is taken as best practice. Furthermore, overall attention to all the taken assumptions and how they could affect all the activities taking place in the model would surely help in achieving this desirable multi-objectivity.
  Still, it should be clear to the developer that a certain explicit hierarchy in the objectives should be set based on the available inputs. In other words, one objective should be set as the end goal of the model if all the other inputs are available. If some are missing, the main objective becomes dependable and this dependency should be made explicit. Otherwise, if the model is generic enough the investigation could be shifted towards the missing inputs.

- Outputs
  The last aspect analysed is the model outputs. Such as the objectives, the outputs of a simulation model are highly variable and strongly depend on the former.
  However, some common ground can always be found inside the specific field. The idea is thus to keep the model more towards its ”general” character than its ”versatile” one with respect to this element.
  Just as with the policies, a review of the most common outputs of interest in the field is advised and an automatised generation of easily understandable plots and graphs featuring them should be embedded in the tool. Still, the possibility to access relatively raw output data should be left to the user in order to extract factors and indices of their likes.

3.2. Delft System Approach and PROPER model

The Delft Systems approach is an analysis and design method that employs an interdisciplinary perspective to examine and describe a system and its interrelationships. The main principle of this approach is the holistic concept of 'thinking in systems,' which focuses on studying the entire system rather than its individual components.

A system is defined as a collection of elements that can be identified within the broader reality. These elements are interconnected through mutual relationships and also have connections with other elements in the overall reality. Elements reflect a real entity, in particular the smallest one considered in the system. The size and complexity of a single element depend thus on the system considered by the researcher and the level of detail applied.

A steady-state model is chosen as the basic function model of the Delft Systems Approach [96]. Then again, an important flaw of this choice is that it only models one aspect at a time while an industrial system is properly described by three different flows: the material flow, the order flow, and the resource flow.

To tackle this issue, the PROPER (PROcess PERformance) model was developed in [96], comprising three steady-state models for these three aspects as shown in (Figure 3.1). The three different flows make up the transformation function.

Another property of the PROPER model is the control function, acting as a translator of data flows between the environment and the transform function. In one direction the requirements coming from the environment are converted to standards, in the other the transformation results are measured and reworked into performances, a source of information about the system.

According to the PROPER model, the design of industrial systems is divided into two main steps: function design and process design. From an analysis point of view, the two steps are translated to function analysis and process analysis:

1. Function analysis
   The PROPER model defines Function design objectives as "determining a system configuration that can provide a required performance optimally". Function analysis is thus translated into the study of an already existing configuration that provides a required performance. In other words, during this phase, all 'what' questions about the system are answered.

2. Process analysis
   Process design is defined as "specifying how the system will work and defining structure, processes and resources ". Process analysis becomes thus the investigation of the working way of an already existing system. In other words, during this phase, the main 'how' questions are answered.

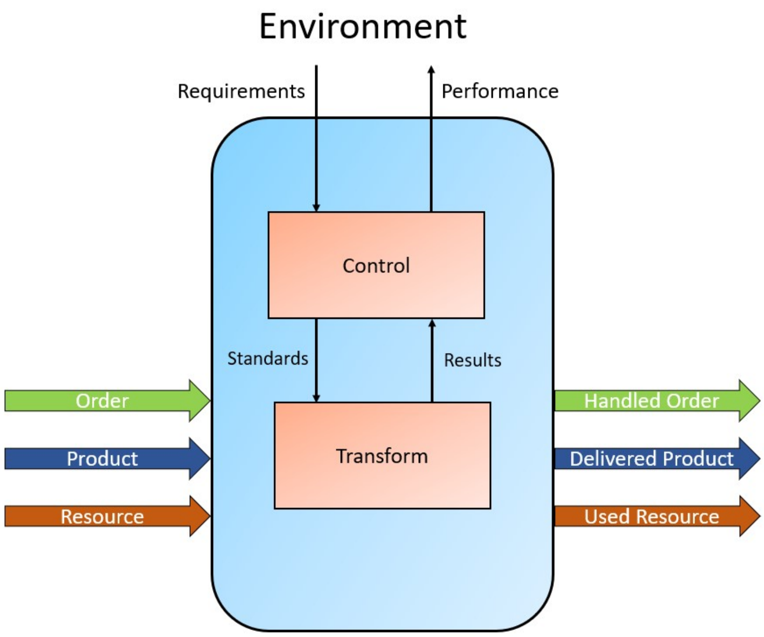

Figure 3.1: The PROPER model of an industrial system

4 Terminal operations description and challenges

4.1. Terminal structure

As already stated, dry bulk terminals often represent the bottleneck in the supply chain of raw materials due to their intrinsic nature. Being the connection between two or more modes of transport, operations can become very complex inside them. This section aims to briefly describe the typical layout, characteristics and operations of a general dry bulk terminal, and grain terminal specifically. For a more in-depth and technical description, the reader is advised to check [103] or other technical reports.

In contrast with containerized transportation terminals, dry bulk terminals are designed to handle different grades of a specific product or a group of very similar products in a loose form and without any containment, hence bulk. In fact, since the material is directly in contact with the equipment, the different characteristics of the product strongly determine the way of handling it and thus the machines that can be utilised in such a system.

A terminal could handle different materials in the case that the products are very similar and thus the same equipment can be used for all of them without any substantial change in configuration and with little and inexpensive cleaning operations.

Otherwise, the terminal could own dedicated equipment for all the materials handled and even have dedicated berths in order to prevent cross-contamination. In this case, it would be wiser to talk about different terminals each one handling one material but located in the same port and thus sharing a channel and other infrastructures.

Based on the kind of material handled, terminals can be generally divided into mined ores terminals, processed minerals terminals, and organic products terminals.

Mined ores terminals (e.g. iron ore, coal) handle mineral products shipped in their natural state without any chemical or concentrating process. The terminal sometimes provides services such as washing, drying, screening, crushing and blending in order to obtain different grades and quality of the handled mineral.

Processed minerals terminals handle mined ores that have been subjected to physical or chemical processes to produce a product ready for use or content-rich mineral for direct feed to an industrial process for the production of metal. The range of processed minerals transported by sea is significant and the properties and hazards in each instance vary widely.

Organic product terminals handle foodstuff or other organic products that are suitable for transport by sea in loose bulk form. Some examples are the various kinds of grains, sugar and wood chips. Generally speaking, these materials are chemically stable but biologically active and do not present a high risk of hazard from that point of view, although self-heating and explosion hazards have to be kept into account.

Another division that is usually made amongst terminals is their purpose. In fact, as a consequence of the material-specific nature of the terminals, it is very logical that the flow direction of the material is specific to the system too. Furthermore, the complexity of operations is quite mitigated by such a practice.

We can thus individuate import terminals, export terminals and, in a smaller amount, transhipment terminals. Obviously, their purpose has a substantial influence on the characteristics of the terminal, ranging from equipment to general layout.
Import terminals are located in those regions or locations in need of determined raw materials. They are usually single-product terminals with high to moderate throughput, even though multi-product import terminals exist where volumes are lower and asset utilisation favours a more flexible facility servicing more than one product. This is often the case of industry-owned terminals that import multiple materials to sustain their processes (e.g. steelmaking). Very often import terminals are coupled with energy production centres needing a continuous supply of raw material (coal, biomass) to keep the plant running. Unloading operations require smaller wave (current)-induced vessel motions in comparison with loading ones, as the equipment makes direct contact with the product. Import terminals are thus almost always located in protected harbours or naturally sheltered calm water.
Furthermore, import terminals have higher rated equipment and storage capacities than export terminals with similar throughput. This is usually explained by the fact that import terminals have less decisional power on the arrival of carriers and of the landside logistics and thus higher capacities allow terminals to be able to almost always handle ships in relatively quick times.
On the other hand, export terminals are built in those regions with high availability of raw materials but without a comparable amount of demand. Export terminals' location is thus dictated by the proximity to the product source. In fact, the easier loading operations, in which the product is simply poured into the holds, allow for picking less protected locations in comparison with import terminals.
Export terminals are usually single product terminals linked with one or multiple production facilities. The terminal can be operated, owned or partially owned by the facility itself and thus operations run more smoothly than in import terminals since options to regulate the flow of material to the terminal's stockyard are available. This explains the lower storage and equipment capacity generally installed in export terminals.
Transhipment terminals may be needed in particular cases to perform both the import and export of dry bulk. In some cases, the infrastructure is shared between the two processes, in others dedicated equipment and infrastructure are allocated to the two tasks.
Usually handling a variety of materials, major problems for such a terminal are product hazards and cross-contamination. These terminals are normally built in the vicinity of an inland waterway or another installed terminal with draught or traffic restrictions for determined vessels. A typical example is a terminal positioned (offshore or not) at the mouth of a river along whose banks another terminal is positioned. Since seagoing vessels are not able to go up the river, barges are utilised to transport the material from the inland terminal to the transhipment one where sea-going vessels will be loaded.
Regardless of the purpose and the material handled by a terminal, its operations are divided into three sections: seaside operations, stockyard operations, and landside operations.

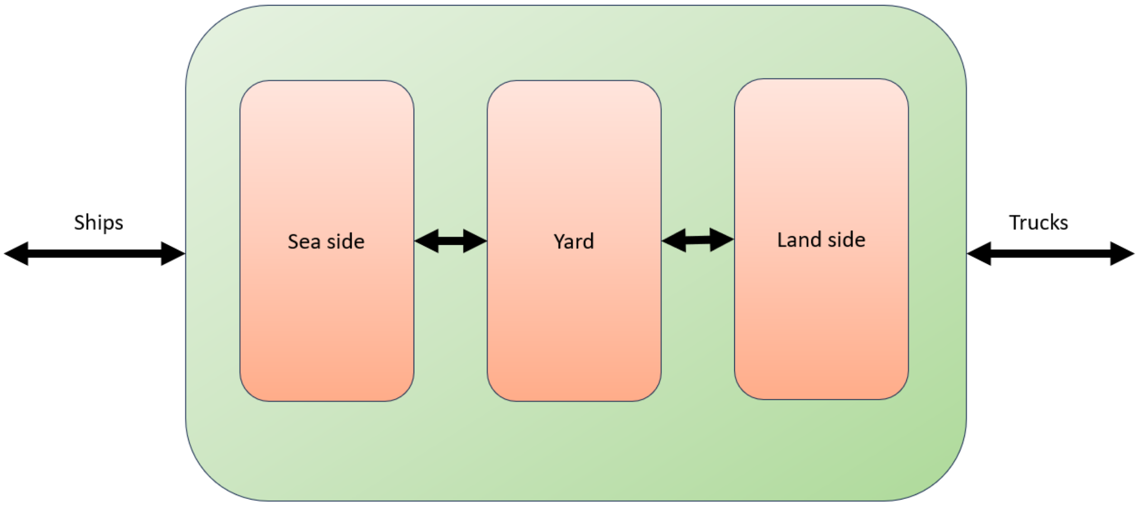

Figure 4.1: Dry bulk terminal explanatory diagram

4.1.1. Seaside operations

Seaside operations consist of various steps involving berths, ships, and seaside equipment. After arriving at the port a ship is sent to anchorage, a relatively open sea zone where carriers can wait their turn to be served. As soon as its turn has come, the ship is pointed to a specific berth based on capacity, drought or material restrictions. Travel to berth and berthing operations take place in which the ship is secured to the berth and made ready to (un)load products.

Interaction with ships during these operations can be quite a difficult and dangerous procedure for various reasons. One of them is the ship balance. Since the cargo makes up for a large percentage of a fully loaded ship weight, its draft varies largely during (un)loading operations. For this reason, (de)ballasting (pumping water in or out designated tanks in order to keep the ship draft and balance relatively stable) operations have to take place, during, before or after (un)loading. Furthermore, the balance of the ship is influenced not only by the quantity of material present in the holds but by its positioning as well. Therefore, a specific hold order has to be followed during (un)loading operations usually determined by the ship's captain. These two crucial operations make the sea-side process a relatively cumbersome one. Furthermore, both the unloading and loading capacity of the equipment varies greatly during the filling or emptying of a hold depending on the quantity of material still present in the hold itself. Additional equipment can be needed in the ending phase of both operations to level up the created pile or to clean up the hold.

Once a ship is completely (un)loaded and other administrative procedures are taken care of, the ship unberthing operations can begin and after that, the carrier can sail away and leave the port as a new vessel starts the berthing process.

Vessel arrival process and distribution depend greatly on the kind of terminal, materials handled, and contracts standing with clients. Many studies have been carried out to fully model and predict such patterns, obtaining the best results with an Erlang distribution, with the shape parameters depending on the planning ability of the terminal ([103],[51]). Erlang-II was found best suited for small terminals with low planning and prediction capabilities, while Erlang-VIII is a good fit to model the arrivals of carriers in larger terminals where the supply chain is better understood and controlled [103].

Furthermore, seaside operations are strongly influenced by different environmental constraints such as high tides, storms, snow, and high winds that impair the normal procedure of operations.

Finally, it is crucial to understand that charting contracts usually entail clauses regarding demurrage (fines that the terminal has to pay for vessels' delays) and despatch (fines paid to the terminal by clients if the terminal is able to service a ship before the agreed terms), thus timely seaside operations are essential for the economic performance of a terminal.

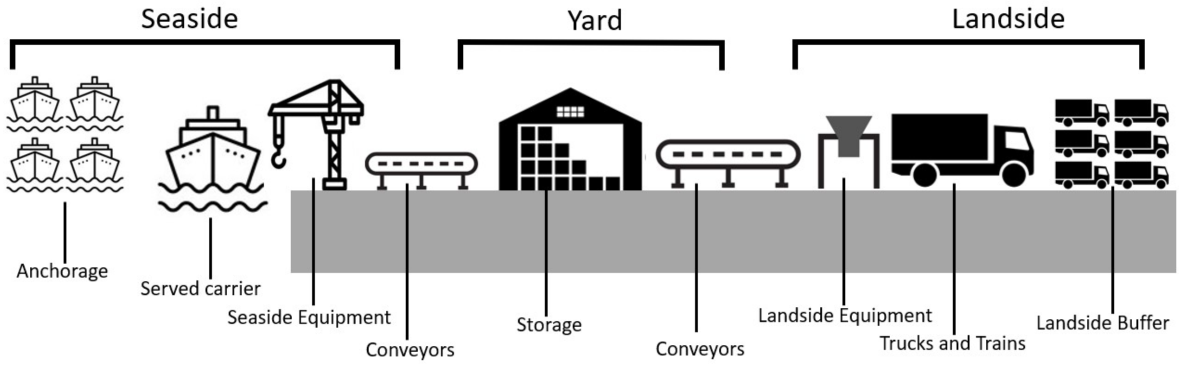

Figure 4.2: Diagram of the different subsystems

Seaside logistic problems

On dry bulk terminal seaside, several logistic problems can be individuated.
Firstly, once the ships arrive at the port they have to be sorted to the different berths based on tidal, draught, capacity and material constraints. The first two problems are thus the scheduling and the berth allocation of ships.
The scheduling problem deals strictly with the order in which to serve the different ships. Sometimes terminals observe strict policies about this matter such as FCFS (First Come First Served), HEF (Highest Earning First), SPTF (Shortest Processing Time First), EDD (Earliest Due Date) or HDF (Highest Demurrage First). However, other strategies for optimization are possible and often taken into account and studied.
The Berth Allocation Problem (BAP) is concerned with finding the optimal ship berth combination when given some constraints. When the order of the vessels is a variable, the BAP can be seen as a larger version of a scheduling problem. A large number of approaches to BAP are found in literature and a relatively strict definition of the different BAP problems can be found in [12] and [72].
One way to categorise BAPs is by the way the berth(s) is modelled, dividing them in discrete (in which the berth is divided into sections and only one ship can berth in each section), hybrid (in which the berth is divided in multiple berths but more than one ship can berth in each section, if fitting), and continuous (in which ships can berth freely at the berth if they fit).

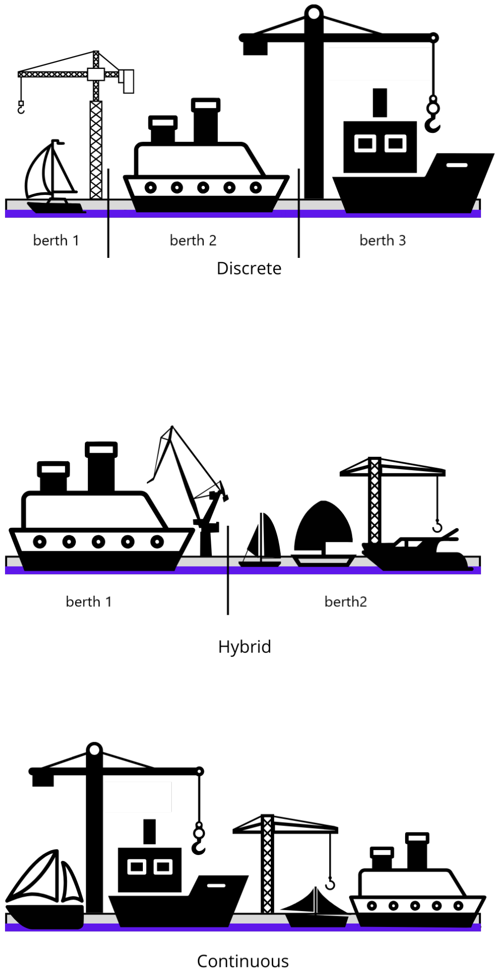

Figure 4.3: Different kinds of berth modelling

Another way to categorise BAPs is by the arrival of ships. In static BAP, all the ships are already present in the port and no new arrivals are taken into consideration, making it a sorting problem. On the other hand, dynamic BAP takes into account the arrivals of ships at the port thus changing the vessels to be allocated during the duration of the problem.

Furthermore, some BAPs take into consideration the difference in handling time at the different berths when allocating ships and in calculating when they will be freed.

BAPs can be modified and enlarged with a long list of constraints bringing them closer or further from real situations. Tidal windows, capacity constraints, and drought constraints are only the most commonly taken into account in literature.

Other problems arising on the seaside of the terminal are the Quay Crane Allocation Problem (QCAP) and the Quay Crane Scheduling Problem (QCSP).

As in the BAP, these logistic problems deal with the allocation of quay cranes to berths and thus to arriving ships. The amount of constraints that can be taken into account is quite vast in this case as well, ranging from berth fixed equipment to material-specific ones and capacity restrictions.

In container literature, these two problems are often faced on their own. Conversely, in the literature found about dry bulk terminals these two problems are always linked and integrated into the BAP mak-

ing it very specific to the dry bulk terminal system.
In fact, in container terminals all cranes exhibit the same general characteristics and no specific equipment is required for a specific cargo. On the other hand, in dry bulk terminal equipment choice is highly dependent on the material handled and thus the connection of the QCAP and the QCSP with BAPs becomes completely logical.

4.1.2. Stockyard operations

Yard operations consist of all the procedures taking place inside the stockyard of the terminal. These comprise not only the movement of material from the seaside and from the landside to the stockyard and vice versa, but internal rearrangements as well. Furthermore, drying, blending and recirculation of products are usually counted as yard operations. A great amount of pieces of equipment is used during yard operations based on the kind of product handled, not only stackers or reclaimers but all kinds of assisting machines utilised to fully clean stockpiles or covered storage. Planning of movements and coordination with land and seaside is crucial in order to optimize yard operations. Furthermore, sampling and weighing of materials is normally performed at the moment the product enters the yard.
The horizontal movements of material that happen thus inside the terminal are usually entrusted to two different kinds of equipment: conveyors and vehicles.
Conveyors are relatively effective pieces of equipment with relatively low operational costs and high energy efficiency. They rely on electrical motors for their functioning making them a perfect choice from an environmental point of view. However, the capital costs and installation times linked with this kind of technology are relatively high. Furthermore, due to the inherent nature of fixed equipment, they have some major flexibility limits during operations.
On the other hand, wheeled vehicles can be used as a connection between the yard and the seaside of the terminal. This option has very low capital costs in comparison with a conveyor system but the operational costs are usually higher due to the necessity of drivers while the capacity of such a system is relatively low. Vehicles are thus generally used in an initial phase of operations or in a temporary terminals, where the construction of a conveyor system is not deemed profitable.
The choice among the different kinds of conveyor systems depends on numerous factors. As usual, the product handled is one of the most crucial since different technologies are feasible for different materials. Furthermore, risks of spillage and explosion involved with the material are another critical selection criterion. Finally, energy consumption, capacity and space available in the terminal can have a fundamental influence in such a decision as well.
In the particular case of grain handling terminals, conveyors are usually preferred if capital is available, making the terminal more efficient and the operations environmentally friendly.

Stockyard logistic problems

A dry bulk terminal yard is a complex system with many agents conducting many different linked and not-linked processes. It is then obvious that many operational problems arise in such an environment and a robust and thorough optimization and planning procedure is not only beneficial but almost necessary to avoid disturbances and mistakes.
Since the yard can basically be looked at as a storage, one of the main problems faced when managing one is the parcel allocation problem. When a cargo arrives at the terminal both from the landside or the seaside it usually has to be stored for a certain period of time constrained by contracts and fines. Since the sizes of the parcels handled cause their allocation or relocation to take up to some days, their optimal positioning in the stockyard becomes of crucial importance.
Furthermore, the characteristics of each parcel create numerous constraints to be taken into account. For example, not all materials can be stored in the same way and position and some space between different materials has to be left empty to avoid contamination.
Another problem arising in the yard system is the routing one. While in a container terminal finding an optimal solution to the parcel allocation problem could be a already a satisfactory step towards an operational improvement on its own, that is not the case in a dry bulk terminal. In fact, routes do not consist of roads or passages travelled via wheeled equipment but in most cases of fixed conveying systems that occupy the whole path. It is thus a way less flexible system that requires a higher level of planning and most importantly a precise definition of the required functionality during the design phase

of the terminal. In this case, as well, the duration of the movement of a parcel also influences greatly the importance of operational decisions.
Optimally solving the routing problem thus consists of finding the best solution to bring a specific parcel in the destined location taking into account the limited number of routes and equipment available.
It is clear that only finding a common solution to these problems actually proposes a new operational plan for yard management, while taken singularly these issues become scientifically and mathematically interesting issues but without real application. Therefore, these two problems or part of them are usually combined in different fashions (either integrally or hierarchically), often adding other operations (such as blending or mist cannon operations) and a variety of constraints and objective functions.

4.1.3. Landside operations

Landside operations consist of the interaction of the terminal with the hinterland logistic system taking care of the redistribution or supply of products. This process can be seen as a mirroring one of the seaside one, with the due differences. Given the sizes of the vehicles, the amount of trucks or railcars involved in such a process is way higher than the ships berthing on the seaside. This brings to a different level of complexity and thus approach to entering, registering and weighing procedures. Usually, a series of weighbridges is utilised to gain information about trucks and wagons weight when entering and leaving the terminal and thus calculating the amount of product that either left or entered the system.
Again because of the large amount of vehicles that take part to this process, the arrival pattern is normally hard to predict and control. Different policies are envisioned in contracts with clients, featuring maximum days of possible layover in the terminal and fines in case of an extended stay of the product. In the case of export terminals, the situation can be slightly different since the terminal is often at least partially operated (or owned) together with the supplying facility and thus some kind of control on the arriving material is possible.
From an equipment point of view, these operations are way less demanding than the other two kinds since the machines involved are usually smaller and simpler. However, especially when dealing with organic products the landside of the terminal can be affected by a strong seasonality that can create large disruptions in operations.
Furthermore, landside operations deal with cargo split into different terrestrial modalities: trucks and trains. Managing these two different kinds of operations characterised by different necessities and constraints can become a difficult challenge if not addressed with the right amount of preparation.
Another crucial activity that happens on the landside of an export terminal, particularly in organic products ones, is cargo sampling. In fact, in export terminals, every single truck and wagon is sampled in order to check that the material entering the terminal fulfils the requirements of the specific batch. As cargo capacities of ships are way larger than the ones featured by landside modalities, the number of entities entering the terminal on the landside is quite higher than on the seaside. This operation (even if not involving large and costly pieces of equipment) requires thus a high amount of workforce, time and preparation or a series of automated probing stations.
Lastly, it is important to underline a major difference between an import terminal and an export terminal structure. In fact, in an import terminal, a component can often be found that is not present in an export one. In order to avoid overuse of the conveyor belts and to improve the efficiency of landside loading operations, import terminals are often times equipped with loading bins. Loading bins are smaller-size bins that work as a buffer between the actual terminal silos and the vehicles visiting the terminal. Once the terminal gathers the information about a fleet or vehicles starting the reclaiming campaign for a specific client, a proportionate amount of the specific parcel is moved from the main silos to a number of assigned loading bins. In this way, the lengthy reallocation of material towards a truck or a wagon from a silo is simplified without the involvement of conveyor belts, that can be utilised for other parcels. The timely refilling of the loading bins in order to be ready to serve trucks and trains is a fundamental operation to obtain the proper functioning of an import terminal landside.
In an export terminal, the presence of loading bins is not needed since carriers contain such a large amount of material that the allocation of a conveyor belt to the loading operation of a single carrier is beneficial, without the necessity of a buffer bin.

Landside logistic problems

The main problems on the landside of a dry bulk terminal derive from the fact that the number of entities interacting with this part of the system is much higher than the seaside, due to the sizes of the single entity. In fact a relatively large truck can carry up to 40 T of material and a wagon up to 150 T, various orders of magnitude smaller than the amount that can be stored in a carrier. Thus, even if the actual unloading time per vehicle is quite low, all the rest of the operations that accompany this process, and the fact parking space for trucks is often underestimated, make congestion on the terminal land side quite common.
Adding to the problem is the lower costs associated with this logistic chain and thus the smaller attention given to solving the related issues in comparison with the seaside ones. In fact a fleet of trucks operating a reclaiming campaign has a relatively small cost in comparison with the figures featured in vessels chartering contracts.
These two factors lead the landsides of terminals to be way busier and more chaotic parts of the systems, with many actors interacting and often leading to great congestion.
In order to solve this issue many policies and technologies have been tested such as scheduled arrivals and automated weight bridges. Still, very often the application of new policies leads to one or more players using them to gain a short-term advantage over the competitors or other actors part of the supply chain. Strategies and policies that would guarantee a more collaborative behaviour of this peculiar sector of the supply chain would surely bring numerous long-term advantages.

4.2. Environmental friendly operations

The objective of limiting the rise in global average temperature to below 2°C, as outlined in the Paris Agreement [61], is becoming increasingly challenging. This is due to the slow pace of global action, and the necessity for all greenhouse gas-emitting sectors to achieve significant decarbonization within the next few decades.
Transportation and in particular maritime transportation play a large role in this challenge. In fact, according to [22] transportation accounted for 20% of global CO2 emissions in 2022, [40] reports that shipping was responsible for 2.89% of global anthropogenic greenhouse gas (GHG) emissions in 2018, and in [67] 13% of the NOx emissions, and 12% of sulfur oxides (SOx) emissions was attributed to this sector. Furthermore, in a business-as-usual scenario with a world trade that will be tripling in size and without any further measures taken, emissions are expected to increase up to 150% by 2050 [40]. In this scenario, ports, even if accounting for a small portion of shipping emissions, are a hotspot for pollution due to significant anthropogenic inputs, primarily from their high fossil fuel consumption and the inevitable emissions due to concentrated maritime transport ([25],[93],[36]).
Nevertheless, local air pollutants continue to be the primary concern for port authorities [35] while reductions in greenhouse gas emissions occur incidentally [74].
Studies on the reduction and mitigation of GHG emissions in ports are widely spread, showing the importance of this topic both from an academic point of view and from a societal one.
In particular, [2] and [14] are two brilliant examples of reviews of this field. In order to understand how to introduce the option to simulate green operations in the developed tool these two works were analysed and compared with the simulated systems.
At the actual state, grain terminals are already quite electrified (taking out the rare cases in which trucks are utilised for horizontal transport) thus the amount of operations that could change the environmental impact of a terminal is quite limited. Many of the energy management measures suggested in [2] could cut the amount of emissions in grain terminals, still the great majority involve policies that are not reproduced in the model or fall out of the tool's generic character. Thus the focus was shifted to the measures affecting terminals's clients (shipping industry and land logistics companies) that would still involve the terminal, the so-called Ship-port Interface Measures [2].

The following aspects/technologies were thus found in line with the scope of this work:

- Energy Usage Inventory
  Creating an energy usage inventory is the initial crucial step in the port's emission reduction strategy. This practice is relatively straightforward and aligns with international climate change

concerns. However, very few terminals actually keep track of energy consumption on individual equipment level but merely check the total energy consumption of the system in order to estimate and justify OPEX.
The results of the inventory offer an analysis to identify effective and appropriate measures, implement GHG reduction strategies, track and benchmark emissions, and ultimately position the port at the forefront of sustainability.

- OPS
  Onshore Power Supply (OPS) refers to the practice of providing a connection to the local grid to carriers berthed at the port. This allows the ships to completely shut down their engines and thus do not consume any fossil fuel during their stay. OPS technology and operations are further explained in section 4.2.1

- Wind assisted shipping
  In recent years a quite ancient trend has become popular again: propelling carriers using the power of the wind. The practice of retrofitting ships with sails or other kinds of equipment in order to harvest wind power when the conditions are favourable and thus save fuel is one of the most promising ones in cutting shipping emissions. Further details and what this technology entails for a terminal are discussed in 4.2.2

4.2.1. Shorepower

In 2009, [25] discovered that 5% of fuel consumption from ships occurs while they are at berth. Additionally, [40] indicates that an average of 16% of CO2 emissions happen when ships are either at berth or anchorage. From a port perspective, [86] notes that emissions from ships at berth can account for up to 50% of total ship emissions in port areas.
Looking at the air quality, in [58] it was found that 90% of NOx and SO2 depositions in Prince William Sound, Alaska, were caused by ship emissions. Similarly, in [6] is reported that the Port of Piraeus, in Greece, contributed to 2% of NOx, 2.5% of SOx, and 0.23% of PM10 of the country's total emissions.
It is evident that both air quality and greenhouse gas emissions could be significantly improved with the widespread adoption of shore power. Since the first commercial shore power system for cargo ships was installed in the port of Gothenburg, Sweden, in 2000, its use has been growing globally.
When ships are berthed, they typically use onboard diesel auxiliary engines to generate electrical power for essential operations like lighting, ventilation, pumps, cranes, and other equipment needed for loading and unloading cargo. These auxiliary engines are necessary because the main ones are usually shut down while at berth. During cruising, ships generate electrical power using generators attached to the main engine shafts.
Auxiliary engines, which can run on various fuels such as marine gas oil, marine diesel oil, and residual oil, are connected to electrical generators. Ships often have multiple auxiliary engines, with the total installed capacity usually exceeding the average load required, so not all engines operate simultaneously. However, the use of low-quality fuel and the power demands of ships mean that auxiliary engines emit significant amounts of pollution and greenhouse gases.
Shore power (also called Onshore Power Supply (OPS), Shoreside Power (SP), Shore Side Electricity (SSE), and Cold Ironing (CI)) replaces the use of onboard auxiliary engines by connecting ships to a shoreside power supply while they are berthed. Although this does not completely eliminate emissions from docked ships (since boilers may still need to operate and auxiliary engines are used as thrusters during docking and manoeuvring) it significantly reduces atmospheric emissions from ships at berth.
Many quantitative studies have been carried on to analyse the possible benefits of the utilisation of shore power connections. The results obtained by [111] and [39] are reported in Table 4.1

Pollutant	World Wide Reduction [111]	UK Reduction [39]
GHG emissions	48% - 70%	-
CO2 emissions	3% - 60%	91.6%
SO2 emissions	40% - 60%	75.6%
NOx emissions	57% - 70%	45.8%
CO emissions	-	24.5%
Black carbon (BC) emissions	57% - 70%	-

Table 4.1: Reduction in emissions using shore power

Since one of the major factors that slows down the wide implementation of this technology are the large costs of investment, various studies on the economic aspects were produced as well.
In [106] it was found that the potential to reduce carbon emissions through SSE implementation in Europe can reach 800,000 T of CO2, a reduction in yearly CO2 emissions for all maritime shipping of 39%. Furthermore, the possible health impacts of shore power connections in Europe and their monetization were investigated.
A similar approach was applied in [7] to 2012 cruise ship traffic data in Copenhagen, showing that the total potential external health cost benefit of 60% of cruise vessels using cold-ironing (while 40% use AE-generated power) would amount to approx. € 2.8 million annually.
In [112] and [113] the fleet owners' economic perspective was analysed too, building a case on the fact that, at the current electricity price levels, on-shore electricity is less expensive than the electricity generation on board. The cost of retrofitting was taken into account and payback periods for both the port and the shipe were estimated.
Lastly, a specific study on the effect of SSE of bulk carriers was reported in [26] showing that the efficiency of a 34 564 DWT carrier could increase by 1.2%-10% depending on its calculation procedure.
Although the effects just reported are clearly positive, it is important to remember that the use of shore-side power does not eliminate greenhouse gas and priority pollutant emissions, but merely outsources them to the power generation industry. In fact, the GHG emission reduction capability of shore power is impressive mainly because of the inefficiency of generating electricity from diesel engines, the low grade of fuel used to power auxiliary engines onboard ships, and the lack of any post-combustion pollution control systems on many ships. It is thus important to consider that the energy production mix present in a determined region has a strong influence on the actual effectiveness of this technology. The fact that in some countries electricity from the grid has higher CO2 emissions than electricity from onboard auxiliary engines and that there are transmission and energy conversion losses associated with cold ironing (2% and 8%, respectively) must be included when evaluating the application of SP. In not-so-rare cases, the implementation of shore power could actually bring an increase in CO2 emissions instead of a decrease ([39],[113]).
Still, the other main outsourcing realised through OPS is geographical. Shore power implementation is in fact able to move the pollutant emissions from populated areas such as the port regions to more remote areas where power plants are usually located. Therefore SSE would lower emissions' explicit damages such as health impacts in those regions [106].

Technological description

The technological aspects of a shore power connection system are relatively out of scope, still a brief description is reported in the following paragraph.
Correctly dimensioning a shore power connection is not a simple process and many studies dealt with this topic in the past, such as [41] and [38]. Furthermore, many companies (RHDHV in the first place) are specialised in the design of these systems and many others in the production. In order to design an efficient system, a careful study of the fleet visiting the terminal and its load profile has to be carried out so that the proper characteristics can be selected.
As explained in [5], cold ironing systems can use two types of connections: Low Voltage Supply Connection (LVSC) and High Voltage Supply Connection (HVSC). The key differences between these two options are the cable requirements and the limitations in supply capacity.
The first examples of shore power connections relied on Low Voltage Supply Connection (LVSC), typically ranging from 380 to 690 V, which necessitates numerous connection cables.

In more recent times HVSC (6.6 to 11 kV), has become a preferred option due to its ease of handling with just 1 or 2 high-voltage cables. This technology also offers the flexibility to supply electricity to various ships with different voltage requirements, including those needing low voltage. However, an onboard transformer is necessary on the served ships. Additionally, the high voltage results in heavier cables, requiring a Cable Management System (CMS), such as a crane. Still, the CMS not only facilitates easy cable handling but also ensures adequate cable length and periodic tension checks.
A general HVSC-based setup of an OPS system as described in [45] and [73] consists of the following and is depicted in Figure4.4.

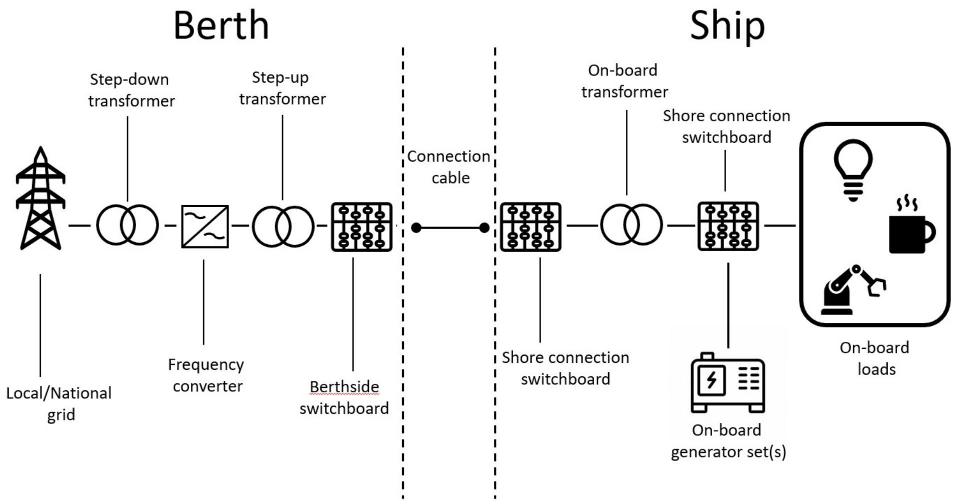

Figure 4.4: HVSC OPS generic setup

On the shoreside, the frequency converter is needed to convert the electrical frequency provided by the utility supply to that demanded by ships. Besides, shore transformers are necessary both to provide galvanic isolation and voltage step-up/down to match the voltage of shore supply and ships. In addition, onboard transformers are required to perform voltage matching to ensure that ships whose onboard voltage level is different from the supplied can still connect shore supply. Berth side switchboards and shore connection switchboards are also required in OPS systems which provide protection respectively to the ship-to-shore connecting cables and the rest of the downstream system of ships.
According to IEC standards, each berth side connection necessitates a shore transformer while a frequency converter can be used by multiple berths. Given these constraints and the choice of having an AC or a DC system, various systems topologies are possible. The classification and the consequent differences between these options are described in [5], [73], and [75].
From an operational point of view, the most interesting characteristics of an SSE system are whether or not it is mobile and how many berths it can provide with a power connection simultaneously or not.
Lastly, another important characteristic of an OPS connection is its Cable Management System. In fact, CMS can vary from very simple appliances to more complex ones. The most important CMS characteristic is the range of a berth it can cover. So-called ”fixed” CMS are cheaper options for terminals, imposing stronger constraints on ship berthing. On the other hand, mobile CMS require higher investments but do not alter berthing operations since they can reposition themselves in order to make connections more favourable.
It is important to mention that many kinds of shore power connections exist and not all of them were covered in this brief review. In particular, ship cable solutions were not mentioned. These kinds of solutions involve a higher investment on the ship side and make connection operations quite more complex than shore cable options. For these reasons and given that this thesis is focused on terminal operations, these solutions and their application were not considered in this work.

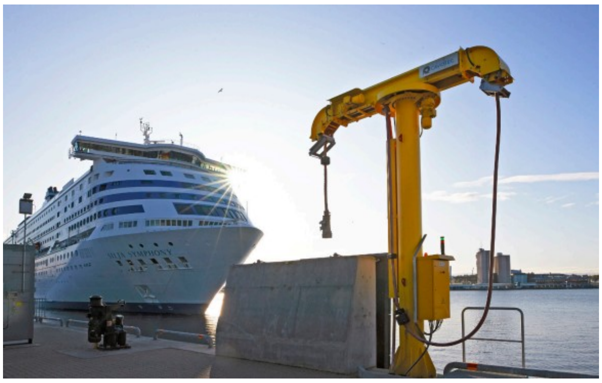

Figure 4.5: Fixed CMS
From *Shore Power, by CAVOTEC*
(https://www.cavotec.com/en/your-applications/ports-maritime/shore-power)

Figure 4.6: Mobile CMS
From *Mobile Cable Positioning Device, by Watts Marine*
(https://static.wixstatic.com/media/b4c77e_b4c10271553745719c9e1052047866bd~mv2.jpg/v1/fill/w_613,h_664,al_c,q_85,usm_1.20_1.00_0.01,enc_auto/b4c77e_b4c10271553745719c9e1052047866bd~mv2.jpg)

4.2.2. Wind-assisted shipping

Wind propulsion for ships, an ancient technology, has made a comeback as part of efforts to decarbonize the shipping industry.
Nowadays, a wide range of wind propulsion devices are being developed with the primary purpose of cutting down on fuel usage and thus decreasing air pollution emissions. These technologies can exploit wind either in a complementary set-up with conventional power sources such as batteries [90], hydrogen [83] fossil fuel [53] (wind-assisted ship propulsion technologies (WPTs)) or as the primary source of propulsion when the conventional engine is used only exceptionally [11]. Following technological advancements in the 1980s, wind propulsion adaptation as a retrofit for existing ships to help reduce fuel consumption has been preferred to a role as the main propulsion method [4]. Hybridization, in which wind propulsion assists the main traditional fossil fuel running engines which serve to ensure the schedule is maintained, is thus seen as crucial for the broader adoption of wind propulsion technologies in shipping fleets [55].
Many studies have been carried out to investigate the environmental and economic advantages obtainable with the application of this technology. However, since the adoption of technologies of this

type is still in the early stages and depends on a wide range of variables (wind conditions, ship hull design, type of wind propulsion device, setup of these devices, engine setup, etc.) results are still a bit controversial and do not always point in the same direction [8].
Still in [17] the following advantages of this technology are summarised:

- 10–40% improvement in the EEOI (Energy Efficiency Operational Indicators)
- 1–50% CO2 emission reduction
- 2–60% fuel saving; particularly suitable for high sea shipping
- No infrastructure required
- Proven technology from long-term development
- High cost-effectiveness (negative marginal abatement cost)

Various wind propulsion technologies have been developed, each operating slightly differently. However, they all share the common goal of providing propulsion power as wind speed increases, thereby reducing voyage time and fuel consumption [8]. Different authors have grouped them in several categories, based on their functioning ([55],[82],[17]. We report here a brief description of them:

- Flettner rotors:
  Flettner rotors, initially patented by Anton Flettner, are rotating cylinders installed on deck that work under the Magnus Effect, which generates lifting and drag forces in the spinning electric motor-aided cylinder aboard the vessel [3].
  At the current moment, this technology is deemed one of the most promising given the large fuel reduction potential (14%-30% [91]) and flexibility ([109], [92], [66]). Given these characteristics, they have attracted the attention of policymakers, shipping firms, energy companies, and academic institutions that have been conducting research on several parameters that influence its aerodynamic performance [13].
  Since Flettner-rotors generate propulsive power over a wider range of wind directions, particularly thriving on sideway winds [56], their performance is less sensitive to geographic location and weather conditions.
  In terms of scalability, this technology has the potential to scale up as the ship size increases and the power contribution is expected to increase linearly with the number of rotors [50]
  While absolute fuel savings from rotors increase with ship speed, relative fuel savings decrease. This is because, as energy demand rises, the ship's power requirements have a greater impact on fuel consumption than the rotors' contribution [54].

- Towing kites:
  Towing kites provide thrust to ships with the lift generated by high-altitude winds. Commercial applications of towing kites are nowadays produced almost exclusively by Skysails while Airseas, Airbus Group, is in the developing phase of automated products.
  Because of their more complex functioning, kites have a smaller range of ideal and acceptable working conditions. For example, kites produce the largest amount of propulsive power under tailwind with this amount quickly decreasing under sideways wind. For this reason, the power output of kites is more volatile than that of other simpler and more reliable technologies [92].
  However, kites have a number of advantages, as they can catch stronger winds that are at higher altitudes, as well as having a lower attachment point to the ship and therefore create a smaller roll heeling moment [60]. Furthermore, they make up for a lower scalability, with the fact that they do not take much deck space [65].
  Lastly, in comparison with Flettner rotors, kites not only generate more savings in relative terms under lower speed, but they also generate more or equal absolute savings, as the apparent tailwind is likely to be stronger [76].

- Suction wings:
  Suction wings generate an upward lifting force similar to aeroplane wings. One notable developer in this field is eConowind. Their products are non-rotating wings equipped with vents and internal fans that create force through boundary layer suction.
  Even though not many producers and developers were found in the commercial phase until the recent past, this technology is currently facing a rise of popularity due to its low costs [17].

- Rigid sails:
  Rigid sails, or wing sails, are adjustable foils designed to generate aerodynamic forces. Japanese ship owners experimented with this technology already in the 1980s but faced operational challenges that led to the projects being discontinued. Recently, the “Wind Challenger Project” has revived this development. Besides, in 2018 Dalian Shipbuilding Industry Corporation Chinese completed the construction of a Very Large Crude Carrier (VLCC) equipped with two aerofoils for the ship owner China Merchants Energy Shipping [17].
  A fuel consumption reduction of between 10% and 30% was obtained by the application of this technology in the 1980s. However, it has been reported that neither of these concepts is commercially viable due to their high cost [4]

- Soft sails:
  Soft sails are traditional sails with modern features. Until the recent past, this technology was applied in a limited measure on commercial ships although it is gaining popularity given its manoeuvrability and safety characteristics [54].

- Wind turbines:
  Wind turbines installed on a ship’s deck generate thrust or electricity for propulsion. However, their use on large commercial ships is still limited due to the technology’s size and the relatively small amount of energy that can be harnessed. At the moment, they are mostly used on yachts [42]

- Hull sails:
  Hull sails are hulls that use relative wind in combination with their symmetrical hull foils to generate aerodynamic lifts. Currently, the application of this technology on commercial ships is limited [65].

SkySails

Figure 4.7: A mooring ship retrofitted with a towing kite WPT
From *MV Beluga SkySails, by Marine Service Noord*
(https://marine-service-noord.com/en/projects/mv-beluga-skysails/)

As already stated, the application of this technology is only at its beginning and a small number of companies are already putting it in place on their carriers.
Other than its newness, the reasons for this low popularity are individuated in uncertainties in economic

benefits and low levels of knowledge amongst shipping firms [16].
For this reason, many studies were developed to better understand how to support the spreading of this innovation. Installation and use subsidies, market-based measures, and stimulation of knowledge about WPTs amongst industry players were identified as the best solutions ([8],[16],[78],[82]).
It is important to mention that researchers have pointed out the importance of the type of vessel when it comes to the financial benefits to be gained, with particular reference to ocean-going low-speed bulk carriers and oil tankers. In fact, this kind of vessel has a wider capacity to easily accommodate additional wind propulsion structures on deck [66].
However, tankers face stricter safety regulations compared to other cargo ship types, complicating the installation of permanent wind propulsion devices. As a result, tankers are not well-suited for WASP devices. Bulk carriers, with design speeds below 15 knots, appear to be more suitable. Additionally, cargo ships are costly to build and have a lifespan of 25–30 years, with WASP ships being even more expensive than traditional cargo ships. Therefore, retrofitting existing vessels with wind propulsion devices is a more cost-effective and quicker option to increase the number of wind-assisted sailing vessels [8].
Given these facts, it is safe to presume that in the coming years, this technology will be applied in this shipping sector. Investigating its operational risks and performance is thus of paramount importance, especially for what concerns the interactions and possible interferences with port infrastructure [78].

4.3. Seasonality

Grain production is inherently seasonal, closely tied to nature's rhythms. Each specific grain has its own planting (spring for corn, soybeans and spring wheat, and fall for winter wheat), growth, and harvest period (early summer for winter wheat, early winter for corn and soybeans, and late summer for spring wheat) depending on its characteristics and the ones of the land where it is cultivated. This seasonality clearly extends to trade, with demand and prices fluctuating throughout the year due to the dynamics between so so-called ”Old Crop” and ”New Crop” [37].
During the planting months, the source of grain that is available for sale or purchase by end users is from the crops that were harvested during the previous harvest season (”Old Crop”). On the other hand, during the harvest months, the newly harvested crop comes to market and supply is higher (”New Crop”).
From a trade perspective, for each commodity one new crop month futures delivery month is defined while the remaining 11 are designated as old crop months. During the old-crop months, when supply is typically lower, grain tends to be priced higher with prices growing over the course of the other old-crop trading months. When a new crop is harvested, there is once again a higher level of supply. This is why many of the grain markets tend to reflect their lowest seasonal prices during the new crop trading month.
These variations in prices and thus amounts traded significantly impact operations, as the volume of cargoes and ships required changes over the year, leading to a system that is constantly in variation.
As an example, in 4.8 we report data from the USA wheat trade.
Some of the features described in the previous paragraph are recognisable in the data such as the high peak of both import and export from the beginning of summer until early fall (both for the northern and the southern hemisphere). However, it is important to remember that grain trade cannot be simplified to a simple supply-demand balance. In the current globalised world, many different players and factors such as economy and politics have a great influence on this kind of matter, making it very difficult to establish a fixed pattern.

Figure 4.8: USA wheat trade overview

As another example of the high variability of this sector, in 4.9 the (un)loading activities of the ports in the USA Gulf area are reported.

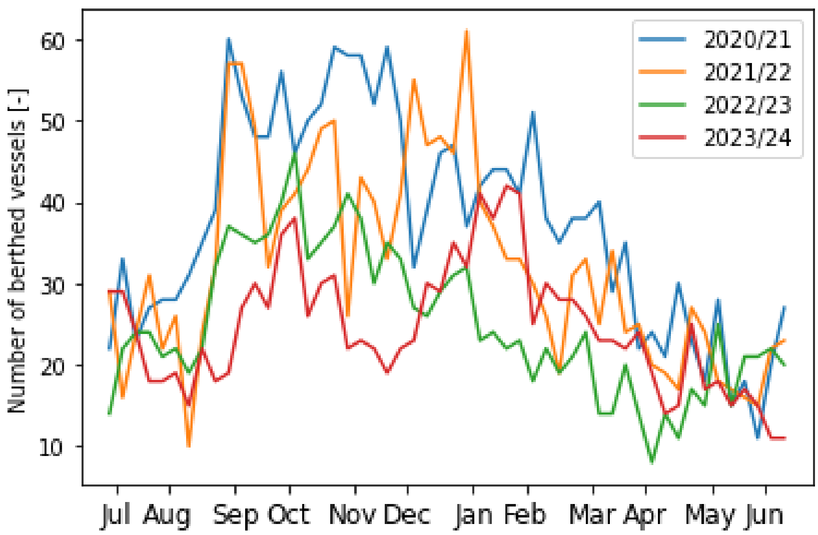

Figure 4.9: Grain carriers (un)loading activities in the USA Gulf in the last four years

In order to obtain reliable results from a simulation model input data are of paramount importance. In the case of a terminal, the carriers' arrival times are the main input data, representing the arrival rate of the entities that flow through the system.
Numerous studies have been conducted on the matter as shown in [103], common practice is to use the Erlang distribution to represent the carriers' IAT since it has been seen that they fit relatively well to real times. However, by using whatever sort of distribution along the whole year the seasonal behaviour of the system is lost.
The link between terminal throughput, carriers' IAT and seasonality is almost never explicitly discussed. Since terminal throughput is one of the most accessible and determining pieces of information about this kind of system, establishing a connection between these two input becomes a crucial matter to which a relatively straight-forward solution has been proposed in 5.7.4 and 5.6.4

4.4. External factors

A terminal is not a completely closed system and thus its operations strongly depend on many external factors. In this work, it was deemed an ”external factor” whatever event (even if planned) obliges operations to deviate from the most efficient (physical or temporal) path, without taking into account other transport operations in this list. According to this definition, the external factors having an influence on the analysed system were summarised in:

- Weather
  Since the terminal is an open-air system not all operations can proceed in all kinds of weather. In particular, while stockyard operations and landside operations usually happen in covered areas, loading and unloading operations on the seaside always suffer hard weather such as intense wind, rain, and snow. When one of these conditions takes place, operations are usually suspended and start again once the situation allows it.
  As with the seasonality of the supply, weather strongly depends on the time of the year and the location of the terminal.

- Non-working time
  As in almost every industrial system, there are not only machines working in the terminal but people too. Shift work, holidays, and periodic closures are essential to ensure continuous operation and workers well-being.
  Holidays and periodic closures provide workers with necessary rest, reducing fatigue and preventing burnout, which in turn enhances productivity and safety.

- Maintenance
  Maintenance in industrial systems is essential for ensuring the smooth and efficient operation of machinery and processes. Regular maintenance helps to identify and address potential issues before they lead to breakdowns, thereby minimizing downtime and costly repairs. Furthermore, it extends the lifespan of equipment, ensuring that it operates at optimal performance levels, and it contributes to workplace safety by preventing accidents caused by equipment failures. Overall, a robust maintenance program is crucial for sustaining productivity, reliability, and safety in industrial operations.

- Breakdown
  Even if periodic maintenance and checks are performed flawlessly, breakdowns in industrial systems are inevitable and even if are commonly taken as setbacks and a loss of resources and time, they serve as critical indicators of system weaknesses, highlighting areas that require immediate attention and improvement and ensuring that minor issues are addressed before they escalate into major problems. Additionally, breakdowns can drive innovation by prompting the development of more resilient and efficient processes and technologies, ultimately enhancing the overall reliability and performance of industrial operations.

- Tides
  Oftentimes, ports are located in protected stretches of coast with peculiar characteristics. However, not always is possible to satisfy all the desirable conditions either for economical, environmental or technical restrictions.
  One of the most frequent limitations a port encounters is the draft of the channel, not always deep enough to allow large carriers to enter or leave the port at all times. In fact in order to avoid expansive and complex dredging works, channels are often times dimensioned so that the draft during high tides is enough to let larger ships transit only during that time window.
  In these cases, monitoring tide windows and patterns becomes crucial for the optimal functioning of the terminal.

Along with the possibility to incorporate various input distributions, the ability to model external factors is a fundamental strength of simulation compared to static calculations. By dynamically simulating events such as weather conditions, equipment breakdowns, and maintenance schedules, simulations provide a more realistic and adaptable representation of terminal operations. This flexibility allows for a deeper understanding of system behaviour under different scenarios, leading to more informed decision-making and optimized performance.

5

Simulation model

This chapter describes how the operations described in Chapter 4 were translated into the simulation model with the application of the methodologies described in Chapter 3.

5.1. PROPER model application

As already stated the PROPER model prescribes the use of three steady-state models in order to represent the three different flows that constitute the transformation process. Furthermore, the PROPER methodology suggests developing a conceptual model by "increasing aggregation layer", or in other words zooming into the system by opening up the black box created to describe the previous level.

5.1.1. First aggregation layer

Applying this approach, in the first aggregation layer we consider the whole terminal as a single black box in which the transformation function is not yet divided into the three different flows. The transformation function takes the explicit form of the final objective of the system. For the studied system the final objective was synthesized as: "offer transportation and temporary storage of grains, and thus decouple material flows different in size, times, type, and direction".
Furthermore, in Fig 5.1 the Control function is shown as well, with the double role of translating the "Environment Requirements" into "Terminal Decisions" and "Terminal Results" into "Performance Output" once the transformation function is completed.

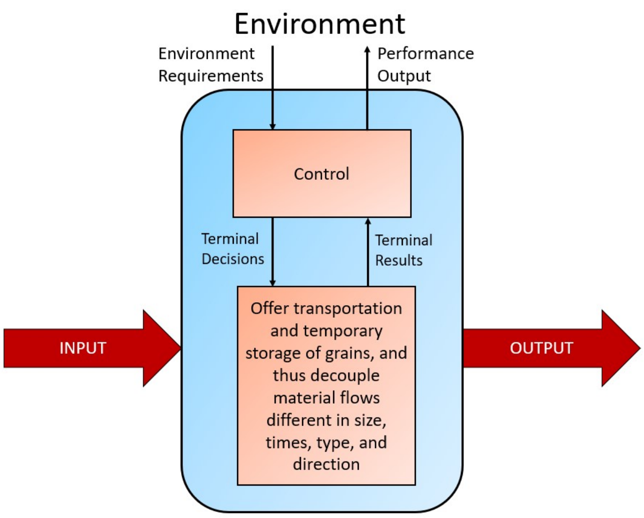

Figure 5.1: PROPER aggregation layer 1

5.1.2. Second aggregation layer

In the second aggregation layer the transformation function is decomposed into the three flows, each of them reinterpreted according to the studied system: the order flow becomes thus the (de)coupling requests one, the product flow the material one, and the resource flow the equipment one. Consequently, the transformation function is split into (de)couple, handle, and use. It is clear by this choice that this kind of modelling leads to two different models for import and export terminals due to the crucial difference in the order flow.
Furthermore, in this step, the ”environment requirements” and the ”performance outputs” are made explicit.
The former summarises the requests the system receives from its surroundings: economic individuals such as shipowners, importers or terminal owners but external events as well such as the atmospheric weather or tides. Each of these entities has different requirements or constraints for the terminal. Grouping them together, provides all the general inputs the control function needs to steer the system in the correct way, done through the setting of standards.
The latter is the translation of the results obtained by the system after processing the orders, handling the material and utilising the resources under the aforementioned requirements. In other words, the answers to the request made by the environment.
In Fig 5.2 the PROPER model of an import terminal is reported.

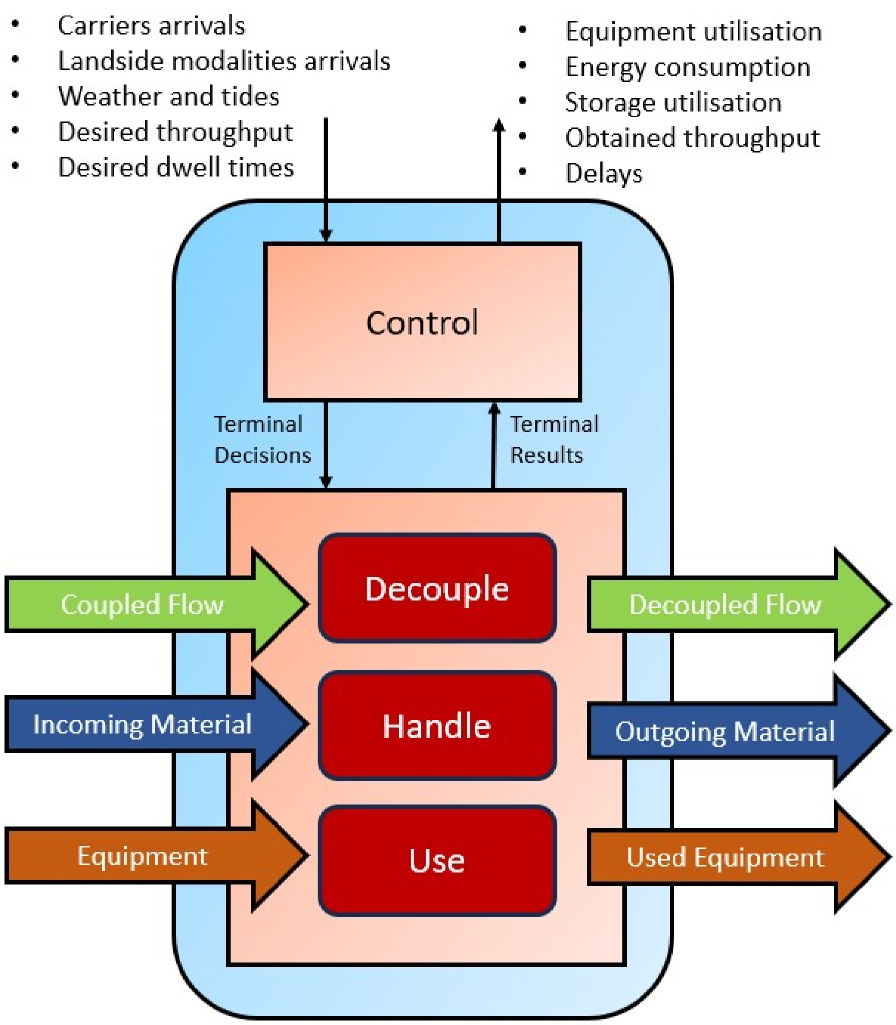

Figure 5.2: PROPER aggregation layer 2

This brief analysis through an established methodology was fundamental to better understanding the system's nature and objectives. The three different flows individuated, their interaction inside the terminal, and the definition of the requirements and the outputs were the basis for the development of the model structure exposed in the following paragraph.

5.2. Model structure

Starting from the description obtained in the previous section, the model was further structured following two different axes, one vertical and one horizontal that allowed to categorise each component present in the system based on two characteristics.
The horizontal axis, and thus categorisation, was chosen based on the many examples seen in Chapter 2 and the operational characteristic of the single component, leading to a division of the model into three different sub-models: seaside, landside and stockyard.
The division was made only from a formal point of view, all the three sub-models are actually part of one single simulation model, running on the same simulation clock, without the need of any special communication between the three. Still, grouping the different agents into different operational sets made the activities, interactions, and information flows easier to schematise, helping to clearly state which components interacted with each other and which did not.
The other axis was strongly inspired by [34], in which the components are categorised by their intelligence. In this work three different levels of intelligence were defined:

- Allocator/Manager
  The Allocators are at the highest level of intelligence and they represent the local control function of the PROPER model, translating requirements of the environment external to their sub-system into operational tasks to assign to components of lower intelligence. Their role is to make operational decisions based on the current state of the terminal such as allocating resources and tasks to operators or components. In other words, the Allocators represent the policies implemented by the terminal manager and trigger the other agents to start, interrupt or stop a process.

- Operator
  The Operators represent the core of the terminal, carrying out the actual operations and representing the higher level of the transformation function of their sub-system. Still, Operators have some decisional capabilities and can switch from one process to another based on their states or the states of the components they are interacting with, without the intervention of an Allocator. Furthermore, being the main agent of changes in the terminal state, are the principal triggers of Allocators' activities.

- Component
  The Components are the lowest rank of the terminal in terms of intelligence and represent the lower level of the transformation function of their sub-system. They can either have no processes and just represent a terminal entity with specific characteristics that change or are changed over time or they can have a process that simulates some sort of operational activities. Still, the process is set, and once triggered is not stopped, interrupted or changed by the component itself but only by the intervention of an Allocator or an Operator.

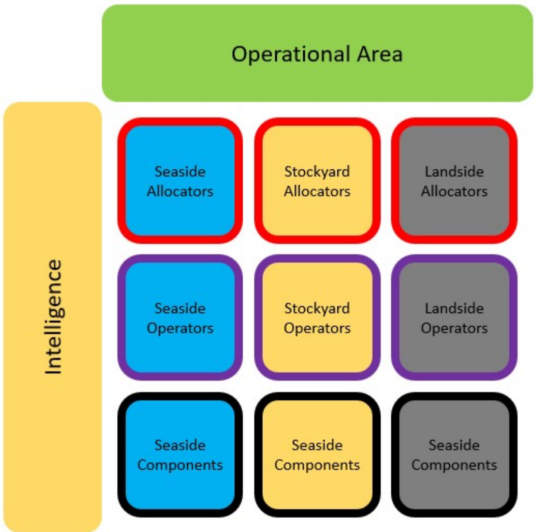

Figure 5.3: Model structure diagram

5.3. Generic character

This section explains how the generic model characteristics individuated in Chapter 3 were integrated in the model.

5.3.1. Resources

To address the resource challenge inherent in a generic model approach, the concept of parametrization was applied. This term is widely used in many different fields with different meaning. What is meant in this work by the use of the word parametrisation can be easily explained with a parallelism with Object-oriented programming (OOP).
OOP is a programming paradigm that revolves around the concept of objects. These objects can hold data, known as attributes or properties, and code, known as methods or procedures. In OOP, programs are constructed by creating objects that interact with each other. Furthermore, by defining a series of fixed objects, similar programs with minor differences can be easily and quickly created only varying their number and properties without having to radically change the nature of the objects themselves and the way they interact.
A simulation model can be developed using the same procedure, creating objects with specific properties and methods that represents the different entities and processes present in the simulated system. Applying this method, the typical resources used in a grain terminal were categorised and translated into simulation agent classes. Each class is defined by a series of specific characteristics that detail its features and capabilities within the system.
Through an interface, which is described more in detail in 5.10, users have the flexibility to select the number of different resources available in the system. Additionally, they can specify the values for each characteristic, allowing for an easily customizable simulation environment. This approach provides thus the users with the tools to tailor the simulation to their specific needs and scenarios.

5.3.2. Inputs

To resolve the input issue, a period-based approach was implemented. This feature allows users to specify different distributions for the various inputs required for a simulation, such as weather distributions and inter-arrival time distributions.
Given the numerous distributions used to replicate the behaviours of different processes in a terminal and the possibility that different users might prefer different distributions, the option to choose from the most commonly used distributions was provided. Consequently, every stochastic variable can be generated using a constant distribution, a normal distribution, or a custom probability density function (PDF), which theoretically can represent any other distribution. Additionally, the option to use the Er-

lang distribution for inter-arrival time generation was included.
As previously mentioned, the patterns of different inputs can vary not only between different simulations but also within the same simulation run. Therefore, users are given the ability to specify the number of periods into which the simulation time is divided for each variable input. This allows users to have different distributions not only for different inputs but also for the same inputs in different periods of the simulation, choosing a different period length and thus the rate of change for each one of them. This feature is crucial for simulating systems involving processes such as the arrival of ships and trucks and seasonality, which vary significantly throughout the year and would otherwise be oversimplified by a single distribution covering the entire simulation time. This innovative feature allows the user to analyse not only the systems behaviour in different conditions throughout the simulation time, but the transient behaviour consequent to these changes too.

5.3.3. Policies

In Section 3.1, an approach favouring generality over versatility was proposed and subsequently applied in this work concerning the policies aspect of a simulation. This approach involved conducting a comprehensive study of the common policies used in the field. From this study, the most popular and fitting policies for a generic simulation model were selected. The chosen policies aim to balance the need for a broad application with the practical requirements of specific scenarios. By focusing on widely applicable policies, the model ensures a robust framework that can be adapted to various situations without compromising on the core principles. The detailed descriptions of these applied policies can be found in Sections5.6 and 5.7, where their implementation and relevance to both import and export terminal models are thoroughly discussed.

5.3.4. Objectives

Two different ways of utilisation of the model were defined, which lead respectively to two different objectives: operations investigation and inputs investigation.
The former, defined as the main objective of the model, entails applying fixed inputs to a varying system in order to gain operational insights into it. In this scenario, the resources and their characteristics should be varied and their performances monitored. This kind of experimentation is particularly useful during design or redesign projects in order to understand the behaviour of the system before actual changes or investments are made.
A great example of this kind of application is storage dimensioning. The accurate sizing of storage facilities in order to allow a desired throughput while guaranteeing client satisfaction is a cumbersome process. In fact, not only the total capacity of the storage has to be determined, but its discretisation too. By applying this kind of investigation the user would test different storage layouts in the same situation and understand which is the most suitable.
The second kind of experimentation deals with the investigation of an existent terminal, whose layout is not challenged. By fixing the system, the user can test its performances in different situations, either to monitor its performances under other circumstances than the real ones or to gain better insights into the system itself.
Varying the arriving amount of materials to an existing terminal is an example of this kind of utilisation.

5.3.5. Outputs

Seen the objectives in the previous section and the considerations made in Section 5.3, a series of standard outputs were defined and an automatic generation of plots reporting them was embedded in the simulation tool. The list of outputs is reported in table 5.3.5.

	storage	material	berth	carrier	channel	scale/sampler	route	path	seaside equipment	landside station	shorepower
utilisation	√				√	√	√	√	√	√	√
idle rate	√		√		√	√	√	√	√	√	√
non-working index						√	√		√	√	√
breakdown index						√	√		√	√	√
waiting index	√		√			√	√	√	√	√	√
weather index									√		
maintenance index						√	√		√	√	√
set up index							√	√	√		√
cleaning index							√		√		
average utilised space	√										
amount	√	√									
throughput		√									
average dwell time		√									
occupancy			√								
commitment			√								
transiting factor			√								
operational time				√							
berth time				√							
anchorage time				√							
shorepower time				√							
working time								√	√		√
energy consumption								√	√		√

Depending on the output shown, the model can produce three different kinds of plot: period-based, factor-based and time-based, as shown in Fig. 5.4, 5.5, and 5.6.

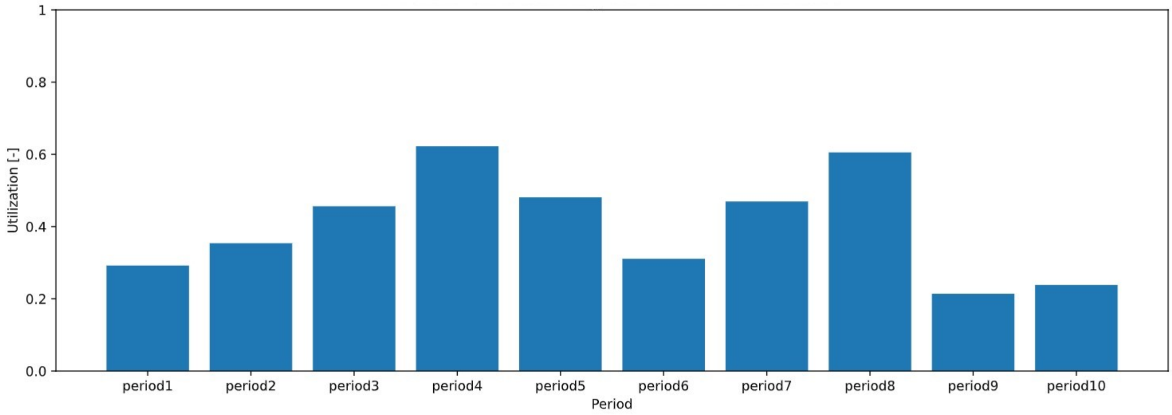

Figure 5.4: Silo average utilised space (example of a period-based plot)

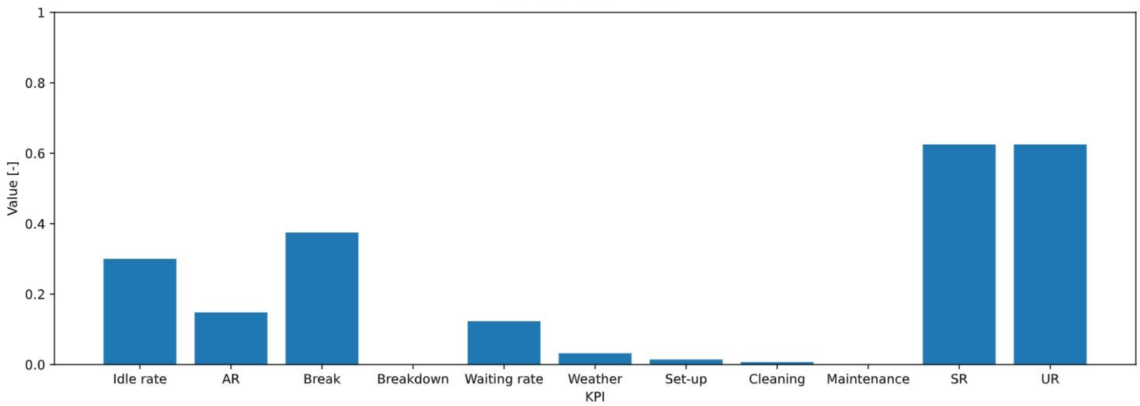

Figure 5.5: Unloader statistics (example of a factor-based plot)

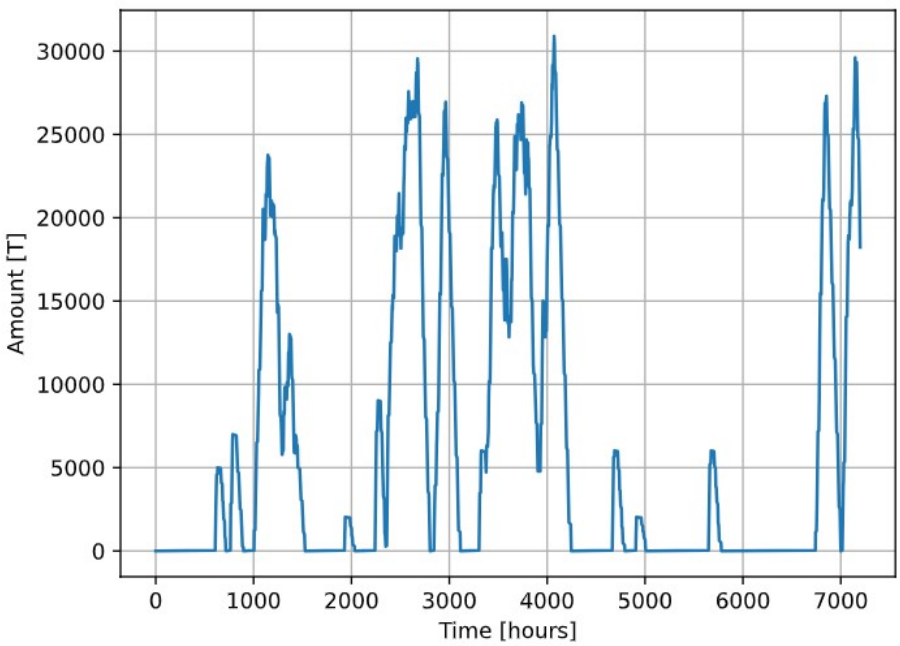

Figure 5.6: Wheat amount in storage (example of a time-based plot)

Furthermore, the data from which these outputs are derived are made available to the users through simulation-generated .txt files.

5.4. Implementation set up

Analysing the operations described in the previous chapter from a system theory point of view, the terminal can be categorised as a dynamic, time-invariant, non-linear, discrete-state, event-driven, and stochastic system [15].
This this kind of systems rarely conform to usual assumptions made to simplify them in order to obtain analytical solutions. Furthermore, when this is not the case and a system of equations is obtainable, the tools to solve them often do not exist.
In this situation, simulation becomes a very interesting tool to study these systems. Simulation is a process through which a system model is evaluated numerically, and the data from this process are used to estimate various quantities of interest. In particular, DES modeling involves replicating real-world operations within a controlled computer environment. This technique provides a logical and quantitative means to better understand the outcomes of various proposals. In a DES model, each physical item is treated as a distinct entity with its own set of defined properties or attributes. These entities simulate the operational activities that make up the processes being analyzed. Activities have specific execution times, which introduce delays into the modeled system. These delays, along with other process times, can be stochastic. Various methods are used to generate these random delays based on data and operational rules specific to each process or piece of equipment. The combination of logical and random events aims to accurately reflect the most likely operational environment.
Three main approaches to discrete system modelling (and thus simulation) can be individuated [68]:

1. Event-scheduling approach:
   In this approach each event is described through a specific event routine. The role of the executive routine is thus only to process a time-ordered calendar of events and select one for execution. Consequently, the event with the earliest scheduled time is processed first. The clock is always updated to the time of the next event, the one which will occur first. Furthermore, events can be added, removed and sorted.
2. Activity-scanning approach:
   Essentially groups the events in order to describe an activity carried out by every entity: the start event and completion event. The executive routine scans the activities for satisfied time and conditions and executes the actions of the first activity whose conditions are satisfied. When execution of an activity completes, the scan begins again.
3. Process-interaction approach:
   The process interaction worldview focuses on the flow of entities through a model. This strategy views systems as sets of concurrent, interacting processes. A process class describes the behavior of each class of entities during its lifetime. The executive routine uses a calendar to keep track of forthcoming tasks. However, apart from recording activation time and process identity, the executive routine must also remember the state in which the process was last suspended.

A process-interaction approach was deemed most suitable for modelling a terminal in an object-oriented way and thus fulfilling the parametric characteristic that was previously individuated as basic need of a generic model 5.3.1.
The suitable use of object-oriented programming to model process interaction simulations was already outlined in [79] and many simulation softwares rely on it.
Among the many viable options, it was chosen to develop the model using the Python discrete event simulation package Salabim. The package was developed exactly to model systems of the nature of the one discussed in this work with a process-interaction approach. The package comprises discrete event simulation, queue handling, resources, stores, statistical sampling, and real time 2D- and 3D-animation and video production.
Lastly, the fact that both Python and Salabim are open source resources was seen as an added value.

5.5. Continuous process discretization

Two options were considered to model the movement of material in the terminal: time discretization and mass discretization.
The first one is based on a user-selected time-step in which the material moved is calculated through the capacity of the equipment in question. This allows to discretize the process according to time and thus generates an event with a specific time length after which other events will happen (such as breakdown, non-working times or maintenance). The strict control on the duration of the moving event leads thus to the option to better model external events without losing precision due to the modelling or at least being more in control of the loss. However, the inconsistency of the mass moved in every time step brings to "weird" amount in the different storage facilities, especially when the capacity of the pieces of equipment is sampled from a distribution. This option forces thus to implement various checks on the amount stored before starting new operations involving said material, making the model more complex.
The second one is based on a user-selected mass-step in which the time used to move the material is calculated through the capacity of the equipment in question. This method works thus in a diametrically opposed way to the first one. In order to apply this method cargo quantities have to be "fixed" when arriving in order to be in an integer number of mass-steps. This second option leads thus to irregular time-steps due to the varying of the equipment capacity, producing some irregularities in the modelling of external events.
In order to avoid increasing the complexity of the model with numerous checks on the material and having checked that with mass steps under a certain measure the subsequent irregualarities do not alter the model beaviour in a substantial way, the second method was chosen.

5.6. Import terminal

This section deals with the specifics of the import terminal model and its functioning.

5.6.1. Seaside operations

Carriers IAT are sampled by a dedicated distribution and used to generate the carriers' calls. At the call moment, carriers activate the parcel allocator that will apply a heuristic to find a favourable position to allocate the carrier cargoes. After their call, carriers take a certain amount of time, again sampled from a dedicated distribution, to reach the anchorage. Once at anchorage, carriers request a berth. A berth is found according to different parameters, most importantly a carrier is allocated to a berth only if one of its cargoes has already been fully assigned to the storage. After obtaining a berth, the carrier triggers the search for a shore power connection (if equipped with shore power technology) and one or more unloaders. Once the unloaders are found, the needed routing to connect each of them to the first of the assigned storage positions is looked for. Meanwhile, the ship requests use of the channel. If the channel is free to use, the carrier proceeds to transit in. After the transit time, the carrier arrives at the berth where berthing and administrative operations can take place. If the unloader and the routing are already in place at this moment, unloading operations can start and won't stop until the carrier is empty. Once the carrier is completely empty, post-operational procedure and unberthing can take place and the channel use is requested once more. Once the channel is free, the carrier is allowed to transit out and leave the system.
The modelling of seaside operations features the following Allocators, Operators, and Components.

Seaside Allocators

- Berth Allocator
  The Berth Allocator is activated by the arrival of carriers at the anchorage, a carrier leaves a berth or a new parcel has been allocated.
  After checking that at least one of the parcels has been allocated, the free berth with the minimum wasted length is selected and assigned to the handled carrier.
  If no berth has been found, all free berths are scanned a second time adding the length of the contiguous berth to them to check if the handled carrier can be allocated in this enlarged resource.

Once the berth is assigned, the Unloader and Shore Power Allocators are triggered and the carrier enters the channel requesting queue.

- Unloader Allocator
  The Unloader Allocator is triggered by the allocation of a carrier to a berth or the end of operations on a different carrier.
  Since different transported parcels are assigned to different storage locations and thus require different routing, the Unlaoder Allocator handles the parcels and not the carriers themselves. In particular, each unloader is assigned to a specific parcel storage location, allowing the maximum number of unloaders serving the same parcel to be the number of locations in which the parcel will be stored. Once a parcel storage location enters the unloader allocation procedure, a check on the maximum number of unloaders allowed to serve the specific carrier is done. If the maximum number has not been reached yet the unloader with the higher capacity available on the berth is chosen to unload the specific portion of the handled parcel to the assigned storage location. Once the unloader has been assigned, the Routing Allocator is triggered.
  If no free unloader has been found through this procedure, unloaders serving other carriers are checked and, if one of the serving unloaders meets the specific requirements, one of them is reassigned to the new carrier. Parcel portions whose unloading process has been interrupted rejoin the unloader allocation queue with higher priority than untouched portions.
  This procedure thus has as a main objective to maximise the number of carriers served at the same time and as a secondary objective to maximise the number of unloaders serving each carrier.

- Channel Allocator
  The Channel Allocator is activated whenever a carrier requests channel usage or a carrier finishes its transit in or out. Once activated it proceeds with checking all the carriers requesting the channel usage. For every carrier the live channel draft is compared with the carrier's draft, if this check is passed and the channel longitudinal capacity still allows it, the carrier's process "transit in" or "transit out" is activated. In performing this process, priority is always given to the carrier requesting transit in, in order to optimise the unloading operations and lower demurrage costs.

Seaside Operators

- Unloaders
  Unloaders are modelled as Operators with the following properties.
  - Capacity: fixed capacity of the unloader, used for the allocation process.
  - Capacity distribution: capacity distribution, sampled every mass-step to better model the unloading process.
  - Set up time distribution: distribution of the time needed to ready the unlaoder to operate on a carrier.
  - Cleaning time distribution: distribution of the time needed to clean the unloader after operating on a carrier.
  - Switching time distribution: distribution of the time needed to ready the unloader to operate on a new parcel on the same carrier.
  - Power: rated power of the equipment, needed to calculate energy consumption.
  - Power coefficient: coefficient (usually 0.7) used to calculate the actual energy consumption of the equipment.
  - Wind coefficient: hindering coefficient used to simulate operations on wind-assisted carriers.

  As previously stated the unloading process is discretised through mass-steps. Every mass-step an operational check for external factors takes place and a comparison between the sampled unloader capacity and the selected routing fixed capacity is carried out in order to select the lower amongst the two. Furthermore, the process is discretised on a higher level based on the different destinations of the parcel being unloaded.
  Furthermore, Unloaders possess the following processes.

  - Set up: the unloader gets ready to proceed with operations on a new carrier. After checking that the assigned routing is in place, the unloading of a batch of parcel assigned to the same storage destination is carried out. If another batch of the same parcel is available on the carrier ”Next destination” process is carried out. Otherwise, the carrier is checked for a different parcel. If a parcel is available ”Next cargo” process is carried out. In the case no other batch or parcel is available maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
  - Next destination: once the cleaning time has elapsed and the availability of the assigned routing is checked unloading of a batch of parcel assigned to the same storage destination is carried out. If another batch of the same parcel is available on the carrier ”Next destination” process is carried out. Otherwise, the carrier is checked for a different parcel. If a parcel is available ”Next cargo” process is carried out. In the case no other batch or parcel is available maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
  - Next cargo: the unloader samples the Switching time distribution, once the switching time has elapsed and the availability of the assigned routing is checked unloading of a batch of parcel assigned to the same storage destination is carried out. If another batch of the same parcel is available on the carrier ”Next destination” process is carried out. Otherwise, the carrier is checked for a different parcel. If a parcel is available ”Next cargo” process is carried out. In the case no other batch or parcel is available maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
  - Clean up: Cleaning time distribution is sampled, after the cleaning time has elapsed the unloader is set free and becomes available to serve a new carrier.
  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed the Unloader is set free and becomes available to serve a new carrier.

- Berths
  A hybrid approach has been chosen to model the terminal’s berth. One berth is thus a portion of the quay in which a maximum one carrier is allowed to berth (if conditions are met). However, the model is able to use multiple contiguous berths to let a larger carrier berth at the terminal. Modelled berths thus do not coincide with real entities since the latter are often arbitrarily determined for organizational or operational reasons.
  Berths are modelled as Operators with the following properties.
  - Draft: berth’s allowed draft.
  - Length: berth’s length.
  - Transit in time distribution: distribution of the time needed for a carrier to reach the specific berth from anchorage.
  - Transit out time distribution: distribution of the time needed for a carrier to leave the system from the specific berth.
  - Pre-operation time distribution: distribution of the time needed to carry on berthing operations and other bureaucratic procedures.
  - Post operation time distribution: distribution of the time needed to carry on unberthing operations and other bureaucratic procedures.
  - Unloaders: unloaders able to work on the specific berth.
  - Shorepowers: shore power connections able to serve carriers berthed at the specific berth.
  - Contiguous berths: berths connected on the left or on the right of the specific berth, available to be used to host a large carrier in collaboration with the specific berth.

  Furthermore, Berths possess the following processes.
  - Berthing: the berth samples the pre-operation time distribution and thus simulates berthing and other bureaucratic procedures. After this process unloading operations can start.

- Unberthing: the berth samples the post-operation time distribution and thus simulates unberthing and other bureaucratic procedures. Shore power connections are disconnected from the served carrier and after this process, the berth is set free and open to serve new carriers.

- Shore power connections
  Shore power connections are modelled as Operators with the following properties.
  - Set up time distribution: distribution of the time needed to connect a shore power connection to on a carrier and perform the synchronization.

  Furthermore, Shore power connections possess the following processes.
  - Set up: the shore power gets ready to serve with a new carrier.
  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed the shore power is set free and becomes available to serve a new carrier.

Seaside Components

- Anchorage
  A queue where carriers wait their turn to enter the terminal.
- Channel
  Channels are modelled as Components characterised by the following properties.
  - Transit in capacity: the number of carriers that can proceed in a line while transiting towards the terminal.
  - Transit out capacity: the number of carriers that can proceed in a line while transiting towards the open sea.
  - Draft: maximum allowed carrier draft to transit in the channel.
  - Cross: boolean value that indicates if the channel is wide enough to allow two carriers going in opposite directions to cross each other.
- Carriers
  Carriers are modelled as Components characterised by the following properties.
  - Length: carrier's length, sampled from a dedicated distribution selected based on the amount of material transported by the ship.
  - Draft: carrier's draft, sampled from a dedicated distribution selected based on the amount of material transported by the ship.
  - Number of cargoes: number of different parcels carried by the ship, sampled from a dedicated distribution based on the simulation period.
  - Time to anchorage: time between carrier's call and arrival at anchorage, sampled from a dedicated distribution based on simulation period.
  - Cargoes: list of parcels transported on the carrier.
  - Wind assisted: boolean value indicating if the carrier is equipped with wind-assisted technology, sampled by a dedicated distribution based on simulation period.
  - Shore power equipped: boolean value indicating if the carrier is equipped with shore power technology, sampled by a dedicated distribution based on simulation period.
  - Installed power: rated power of carrier appliances supplied during connection to the local grid, sampled from a dedicated distribution selected based on the amount of material transported by the ship.

  Furthermore, Carriers possess the following processes.
  - Call: after the travelling time to the anchorage has elapsed, the carrier enters the anchorage and activates the berth allocation process.
  - Transit in: the carrier leaves the anchorage and travels to the berth, activating it.
  - Transit out: the carrier leaves the berth and uses the channel to leave the system.

Other Seaside processes

- Carrier and cargo generation
  The carriers, the transported cargoes and the relative characteristics are generated based on user's input and the procedure described in 5.6.4.

- Cargo correction
  As already discussed, the choice of a mass discretisation of continuous processes calls for a correction of the amount handled by the terminal. This procedure is applied in the following way. When a cargo is generated based on the given distribution, an initial train amount (the amount of the parcel that will be taken out by train) is calculated through a percentage sampled from a dedicated distribution. This initial amount is then checked and compared with the train dimensions connected to the parcel (also sampled by a distribution). If the initial amount does not fit perfectly in an integer amount of trains the remainder is shifted to the truck moved amount, obtaining a final train amount. At this point the just obtained initial truck moved amount is checked and approximated (by excess) in order to fit precisely in an integer amount of trucks.
  Furthermore, the mass step used during moving operations is the same truck size used for the previously explained calculations.
  Given the size of trucks currently used in grain transportation in comparison with the entire parcel size, this method should not produce worrying mistakes in the model. Furthermore, the small size of the mass step should not make unbearable the negative effect regarding external events, leading in fact to a relatively small time-step (capacity of conveyors and equipment are usually in the order of the multiple hundreds T/h, while a large truck size is about 40T, thus a consequent time-step between 5 and 15 minutes).

5.6.2. Stockyard operations

In the model, stockyard operations are of secondary importance. In fact, no real operations happen in the stockyard itself since the moving of materials is mostly dictated by Allocators and Operators belonging to the other two sub-systems. However, handling the different cargoes inside the system is a very complex procedure since many different batches of the same cargo are often flowing through it and the amount of every single one of them determines different decisions and behaviours.
The following paragraph describes the modelling solution developed in this work in order to solve this problem:
As soon as a parcel is allocated, the different storing locations and relative stored amounts are generated and stored.
Once the unloading operations begin, a copy of cargo is generated to keep track of the amount flowing inside the terminal and oversee the unloading operations. The initial amount of a stored parcel is set to 0, the increase of this number and the decrease of the original amount model the flow of material from the carriers to the storage on a high level.
Furthermore, for each storage destination, an additional stored cargo is generated to keep track of the exact amount stored in the specific bin. These "lower level" stored parcels are generated with a starting amount of 0 as well and a total amount equal to the specific allocated amount, the comparison of these two numbers models the flow of material from the carriers to the storage on a lower level, involving the specific destination bin.
Furthermore, for both the high-level and low-level cargoes an available amount is used to manage operations. This variable represents the amount of the parcel present in the terminal not yet allocated to any loading bin, essential since allocation on actual transport happens at different times due to operational delays and unforeseen circumstances.
Unloading operations take amounts from the cargo and move it to both parcels and stored cargo simultaneously.
As soon as the first mass-step of a parcel arrives inside the storage, a parcel-dedicated outtake manager is generated and triggered. The functioning of the outtake manager is explained in 5.6.3.
The modelling of stockyard operations features the following Allocators and Components.

Stockyard Allocators

- Parcel Allocator
  The way parcels are allocated in the terminal is of paramount importance and the right use of silos of different sizes can make a great difference in yearly throughput.
  Once a carrier calls the terminal the Parcel Allocator is activated. The process consists of a simple heuristic trying to mock the minimization of wasted space and freeing time of silos.
  The first thing the Parcel Allocator does is check if there is enough space in the terminal to allocate the incoming cargo. If there is not enough space then the carrier will wait at anchorage.
  If there is enough space the Allocator tries to fit all the cargo in the largest silo available until they are always completely full (0 wasted space). If the last silo encountered in this process is not completely full the wasted space $w = 1 - \frac{amount}{capacity}$ is calculated. If the wasted space of this last silo is under a user-selected threshold the silo will be used for that particular cargo. Otherwise, if the wasted space is above the user-selected threshold, the Allocator will check silos with a smaller size and repeat the process. If no silo satisfying the threshold is found the cargo will be allocated in the best-fitting silo found during the described process.

- Stockyard Path Allocator
  Since two different kinds of agents (unloaders and stations) request path utilization in the different zones of the terminal, Path allocation is divided into stockyard Path allocation and landside Path allocation. In this paragraph, the former is explained.
  The Stockyard Path Allocator is triggered by the allocation of an unloader to a specific parcel storage destination. The Allocator checks all available Paths in an established order for their start and end in order to find the correct one. Once a Path is selected, it becomes temporarily linked with the unloader and its setting up procedure is triggered.

Stockyard Components

- Routes
  Routes are the building blocks of the Paths components, and depending on the level of modelling chosen by the user can either represent a single piece of equipment (conveyor, bucket elevator, etc.). Routes are thus used to be able to model a single piece of equipment without great attention to its position and role in the terminal.
  Routes are characterised by the following properties.

  – Distance: distance covered by the piece of equipment, either vertical or horizontal based on the kind of equipment. Used together with the speed to calculate the flowing delay of the material.
  – Capacity: fixed capacity of the equipment, used to simulate the material flow.
  – Speed: average speed of the piece of equipment. Used together with the distance to calculate the flowing delay of the material.
  – Set up time: time needed to ready the piece of equipment to operate.
  – Cleaning time distribution: distribution of the time needed to clean the piece of equipment after operating on a parcel.

  – End: endpoint of the equipment, if different than another piece of equipment.
  – Start: start point of the equipment, if different than another piece of equipment.
  – Power: rated power of the equipment, needed to calculate energy consumption.
  – Power coefficient: coefficient (usually 0.7) used to calculate the actual energy consumption of the equipment.

  After all the Routes are input, the model generates a table where the user can connect them providing the information needed to model the real routing system of the terminal.
  Furthermore, Routes possesses the following processes.

  – Clean up: Cleaning time distribution is sampled, after the cleaning time has elapsed the piece of equipment is set free and becomes available.

  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed the equipment is set free and becomes available.

- Paths
  Paths are generated by the model using the information provided by the user about the Routes and their relative connections. When a Path is selected for operations its components are temporarily linked to the Path and made unavailable to other Paths.
  Paths are Components characterised by the following properties.

  - Components: list of Routes that compose the Path.
  - Capacity: fixed capacity of the series of Routes, used to simulate the material flow. The Path capacity is the lowest of the Components' capacities.
  - Set up time: time needed to set up the series piece of equipment to operate. It is assumed that the different components can be set ready at the same time, thus the Path set-up time is the highest of the Components' set-up times.
  - Start: starting point of the Path, obtained from the Components.
  - End: ending point of the Path, obtained from the Components.
  - Time: time needed for a batch of material to cross the whole path. Obtained by the sum of the time needed to cross each of the pieces of equipment listed in the Paths Components.
  - Power: power consumed by the Path. Obtained by the sum of the rated powers of the different components, multiplied by the relative power coefficient.
  - Furthermore, Paths possess the following processes.
  - Carrier set up: after setting up time has elapsed, the path is ready to be used in seaside operations.
  - Inland set up: after setting up time has elapsed, the path is ready to be used in landside operations.
  - Clean up: clean up of all the components is triggered and the components are freed from the temporary Path dependency.

- Silos
  Silos are only characterised by their capacity, consistently, floored in order to obtain an integer multiple of the mass-step (truck size) of each parcel.

5.6.3. Landside operations

Once the first mass-step of a parcel arrives at the assigned storage location, its dwell time starts running. Once the parcel dwell time has elapsed trucks and trains to collect the material are generated and arrive at the terminal and a portion of the material is moved to the loading bins serving the landside stations.
From a landside modality point of view, once arrived at the terminal, trucks and trains are queued in the parking and in the marshalling yard respectively. As soon as a station handling the requested material is available the modality is served and then sent to the scales to be checked, always simulating service times and movements through dedicated distributions. Once weighted, the modality is free to leave the terminal.
The modelling of landside operations features the following Allocators, Operators, and Components.

Landside Allocators and Managers

- Outtake Manager
  As explained in Section 5.6.2, an Outtake Manager linked to a specific parcel is generated as soon as the first mass-step reaches the storage. The outtake manager keeps track of the dwell time the parcel is supposed to stay in the terminal and once this has elapsed takes care of the trucks and trains generation according to the cargo characteristics.
  The trucks and trains IAT calculations are described in Section 4.3.

Furthermore, the user has the possibility to give as input a preparation time to the outtake manager. This value is used to simulate the terminal knowledge about the customer reclaiming campaign of a particular parcel. In other words, the preparation time is the interval of time between the moment the terminal receives information about the arrival time of the first train or truck to reclaim a specific parcel and the arrival time itself. Once the terminal receives this information, preparation to make loading operations as smooth as possible takes place and thus the Loading bin allocators are triggered.

- Truck and Train Loading bin Allocators

  Once activated the Loading bin Allocator proceeds to allocate part of the material stored in the main storage into the loading bins serving the landside stations according to the following procedure.
  The allocation of material to truck loading bins depends on the number of stations used to load the specific parcel. A maximum amount of stations per parcel is set by the user, and a heuristic based on queue theory manages the number of stations allocated if the maximum is not reached. The heuristic tries to steer the system towards a steady state, according to the following equation:

$$\overline{\mu} \leq \overline{\lambda} n \tag{5.1}$$

  where $\overline{\mu}$ is the average truck arrival rate, $\overline{\lambda}$ is the average truck service rate (calculated by adding up the average service time and the average transit time), and n is the number of loading station allocated to the specific parcel.
  Between the two conditions, the maximum number of stations is set as the stricter one. Furthermore, the heuristic can be activated or deactivated by the user.
  If both (or only the first if the heuristic is not activated) conditions are not met the allocator looks for a new station to assign the parcel to.
  Other than assigning new stations, the allocator takes care of the refilling of already assigned when needed.
  Firstly, all stations are checked. The amount stored in the loading bin connected to the ones already utilized for a specific parcel is controlled. If one of the quantities falls under the user-set threshold, the relative loading bin is filled up.
  In this case, the amount allocated is selected according to the following algorithm:
  If the remaining amount of the truck-handled cargo is larger (or equal) than the capacity (or empty space) of the selected bin there are two options.

  – The parcel available amount is more (or equal) than the bin capacity(or empty space). So the allocated amount will be set equal to the bin capacity (or empty space) and taken out of the truck-handled cargo amount and of the parcel available amount.

  – The parcel available amount is less than the bin capacity(or empty space). The allocated amount will be set equal to what is available and this amount will be taken out of the truck-handled cargo amount and of the parcel available amount.

  Otherwise, if the amount of truck-handled cargo is less than the bin capacity there are two alternative options.

  – The parcel available amount is more (the train also gets fed by this same parcel) or equal to the truck handled amount. Thus the allocated amount is the whole remaining truck handled amount, which is then set to zero.

  - The parcel available amount is less than the truck handled amount. Thus all the parcel available amount is allocated.

  The allocated amount is linked to the selected bin and the loading process of the bin is triggered. In the case that a not allocated station is selected to handle a parcel, the parcel is linked both to the station and the bin connected to it. The amount allocation proceeds in the same way described above.
  Once an amount is allocated the loader linked to the specific bin is activated.
  The allocation of material to train loading bins follows the same procedure, but given that the trains reclaiming a parcel are typically way less in number than the trucks and their arrival is more scheduled, no option to use the heuristic was integrated in the model.

- Truck and Train Allocator
  The truck Allocator is triggered whenever a new truck enters the parking and whenever a loading station becomes free.
  The Allocator checks the handled parcel of the available stations in determined order. Once an available station handling the same parcel as the requesting truck is found, the truck and the station are linked and transit in process of the truck activated. The Allocator serves thus the following truck.
  The Train Allocator follows the same procedure.

- Scale Allocator
  The scale allocation process is triggered as a truck enters the post-operational parking or as a scale becomes available.
  As with most of the other allocation processes described, the scale Allocator checks the available scales in a prescribed order. Once a free scale is found it is linked to the requesting truck. The truck is then removed from the post-operational parking and the weighting process is activated.

Landside Operators

- Loading bin loader
  Once activated, the loader checks the amount allocated to the served bin and searches the relative parcel for the storage locations and the relative connections to the bin following the same procedure as the Stockyard Path allocation process. Once found, it activates them and through mass-steps, it simulates the moving of material.
  Gathering material in the right order can have a crucial influence on terminal operations and achievable throughput. Since grain is a perishable product whose quality and characteristics can suffer from long still standing periods, is essential to respect FIFO (First In First Out). However, if the product is allocated according to the process previously described in Section (5.6.2) this would mean gathering first the full silos, leaving a possible half-full silo (the one on which the wasted space was checked) storing grain for the longest time amongst the silos containing material from the same parcel. For this reason during gathering operations, priority is given to silos with a higher wasted space among the same parcel and then a FIFO policy is followed.

- Truck loading stations
  Truck loading stations are modelled as Operators with the following characteristics.

  - Capacity: loading capacity of the loading station.
  - Set up time distribution: distribution of the time needed by the truck loading station to serve a new truck.
  - Post operational time distribution: distribution of the time needed by the truck loading station to become available again after serving a truck.
  - Amount limit: the relative amount that triggers the stop of operations and the subsequent refilling of the bin.

Furthermore, Truck loading stations possess the following processes.

- Load: After the sampled set-up time has elapsed, loading operations take place. The mass step used for the operations is the size of a truck and thus this process does not loop. After the loading of one truck has taken place, the sampled post-operational time has elapsed and a check on external events has been carried out, the station becomes available to serve a new truck.
- Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed, the station is set free and becomes available.

• Train loading stations
Train loading stations are modelled as Operators with the following characteristics.

- Capacity: loading capacity of the loading station.
- Set up time distribution: distribution of the time needed by the train loading station to serve a new train.
- Post operational time distribution: distribution of the time needed by the train loading station to become available again after serving a train.
- Amount limit: the relative amount that triggers the stop of operations and the subsequent refilling of the bin.

Furthermore, Train loading stations possess the following processes.

- Load: after checks on external events have been carried out and the sampled set-up time has elapsed, loading operations take place. The mass step used for the operations is the size of a wagon and thus this process does not loop. After the loading of one wagon has taken place, a check on the remaining number of wagons in the train is carried out. If the train is finished a post-operational time is sampled and let elapse and the station becomes free to serve a new train. Otherwise, the next wagon process is triggered.
- Next wagon: after checks on external events have been carried out, loading operations take place. The mass step used for the operations is the size of a wagon and thus this process does not loop. After the loading of one wagon has taken place, a check on the remaining number of wagons in the train is carried out. If the train is finished a post-operational time is sampled and let elapse and the station becomes free to serve a new train. Otherwise, the next wagon process is triggered.

• Scales
Scales are modelled as Operators with the following characteristics.

- Service time distribution: distribution of the time needed by the station to weigh a truck.

Furthermore, Scales possess the following processes.

- Weight: the station let the sampled service time elapse to simulate weighting operations. After this, checks on external events are carried out.
- Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed, the station is set free and becomes available.

Landside Components

• Parking
A queue where trucks wait their turn to be served by the loading stations.

• Post operational parking
A queue where trucks wait their turn to be served by the scales.

• Marshalling yard
A queue where trains wait their turn to be served by the loading stations.

- Loading bins
  Loading bins are modelled as Components with the following properties.
  - Capacity: the amount of cargo the bin can hold, consistently rescaled (down) in order to obtain a multiple of the mass-step (truck size) of the stored parcel.
  - Station: station served by the bin.
  - Check amount: the relative amount that triggers the refilling of the bin.

  It is important to note that train loading bins have an inherent check on the minimum amount of material that can be stored in them, equal to the wagon size of the handled parcel.
- Trucks
  Trucks are modelled as Components with the following characteristics.
  - Cargo: parcel the truck has to load.
  - Size: amount that can be carried by the truck.
  - Transit time distribution: distribution of time needed by a truck to reach a station from the parking.
  - Scale time distribution: distribution of time needed by a truck to reach a scale from a station.

  Furthermore, Trucks possess the following processes.
  - Transit in: the truck leaves the parking and after the transit time has elapsed reaches the assigned station and activates it.
  - Scale transit: the truck leaves the station and after the scale time has elapsed reaches the post-operational parking.
- Trains
  Trains are modelled as Components with the following Characteristics.
  - Cargo: parcel the train has to load.
  - Size: amount that can be carried by one wagon.
  - Transit time distribution: distribution of time needed by a train to reach a station from the marshalling yard.
  - Number of wagons: number of wagons in the train.

  Furthermore, Trains possess the following processes.
  - Transit in: the train leaves the marshalling yard and after the transit time has elapsed reaches the assigned station and activates it.

5.6.4. Seasonality and modalities generation

Due to the characteristic of seasonality of the arrival of carriers and cargoes the following method was developed to capture it.
The method consists in dividing the simulation time into periods of length P and allocating a certain amount of the total annual throughput of a certain material $(T_{i,m})$ to that specific period.
Furthermore an average cargo size per material$(\overline{s}_{i,m})$can be specified for that same period, the average number of cargoes $(\overline{n}_{i,m})$ per period is thus calculated as:

$$\overline{n}_{i,m} = \frac{T_{i,m}}{\overline{s}_{i,m}} \tag{5.2}$$

Summing up all the different materials handled during the considered period we obtain the total number of cargoes handled:

$$\sum_{m} \overline{n}_{i,m} = \overline{n}_{i,tot} \tag{5.3}$$

Introducing the average number of cargoes per carrier $(\overline{c}_i)$, we can calculate the average number of carriers $(\overline{N}_i)$ as:

$$\overline{N}_i = \frac{\overline{n}_{i,tot}}{\overline{c}_i} \tag{5.4}$$

The average inter arrival $(\overline{iat}_i)$ time is finally obtained as:

$$\overline{iat}_i = \frac{P_i}{\overline{N}_i} = \frac{P_i \overline{c}_i}{\sum_m \frac{T_{i,m}}{\overline{s}_{i,m}}} \tag{5.5}$$

Starting from this factor the user still has freedom to decide what kind of distribution to use (Pdf, Eerlang K, Normal) and the parameters required for it to be fully defined.
Having thus an IAT, the arrival time of different carriers can be generated. When a carrier is generated the number of cargoes the carrier is transporting is sampled from a dedicated distribution (which average was used in the previous calculations) together with the type of the different cargoes and their amount, conditional to this last information (each cargo type has its distribution for cargo amount).
Since the amount of the different cargoes taken from different distribution independent of each other and that now consider the presence of another cargo on the same ship, the total amount carried from a ship could become quite high and not realistic. The possibility to set checks for the generated ships (e.g. max amount of material transported) is part of the model. Based on these last numbers (thus on the total amount transported by the carrier), the length and draft of the carrier are set as well. The user can in fact define a series of DWT thresholds and link each one of them to a length and a draft distribution, from which these two characteristics are sampled.
This method guarantees reliable IAT, total throughput per material and cargo amounts per material in line with the data used to generate the distributions.

Starting from the parcel amount due to be transported by truck (T_{amount}) and the truck size (T_{size}), the amount of needed trucks is obtained:

$$n_{trucks} = \frac{T_{amount}}{T_{size}} \tag{5.6}$$

The average of the IAT ($\overline{IAT}_{trucks}$) distribution is found by dividing by this number the outtake time ($t_{outtake}$), a parcel characteristic sampled by a dedicated distribution influenced by the parcel amount, by the truck number.

$$\overline{IAT}_{trucks} = \frac{t_{outtake}}{n_{trucks}} \tag{5.7}$$

The other parameters to define the IAT distribution are calculated as fractions of the average, based on user inputs.
The calculations to obtain the train IAT distribution follow the same procedure, using the train size instead of the truck one.

5.7. Export terminal

This section deals with the specifics of the import terminal model and its functioning.

5.7.1. Landside operations

Landside operations of an export terminal naturally mirror the behaviour of the seaside ones in an import one. As soon as a modality (either truck or train) arrives at the terminal its content is sampled and the modality is sent to a waiting parking in order to wait for the sampling results. Once the good-to-go is obtained and the quality of the material is certified trucks and trains are sent to the respective station, connected to the specific silo where the parcel was allocated.

The modelling of landside operations of the export terminal features the following Allocators, Operators, and Components.

Landside Allocators

- Truck and Train station Allocator
  Just as for the import model, the number of stations dedicated to a specific cargo is handled by a dedicated allocator. However, since no loading bins are involved in this process the allocation process is quite simplified. When a cargo is allocated to a storage location it enters the station allocation queue and the station Allocator is activated. After checking the number of stations handling the specific cargo, the Allocator proceeds to find a free station. If a station is available, the cargo is assigned to it together with a target storage location and the Routing Allocator is activated.
  A user-set maximum constrains the number of stations assigned to one cargo. After allocating a station to a cargo, if the maximum is not reached the Allocator attempts another search, otherwise, the process stops.

- Truck and Train Allocator
  The truck Allocator is triggered whenever a new truck enters the parking and whenever a loading station becomes free.
  The Allocator checks the handled parcel of the available stations in determined order. Once an available station handling the same parcel as the requesting truck is found, the truck and the station are linked and transit in process of the truck is activated. The Allocator thus serves the following truck.
  The Train Allocation follows the same procedure.

- Sampling station Allocator
  The sampling station allocation process is triggered as a truck enters the pre-sampling parking or as a station becomes available.
  As with most of the other allocation processes described, the scale Allocator checks the available scales in a prescribed order. Once a free scale is found it is linked to the requesting truck. The truck is then removed from the post-operational parking and the weighting process is activated.

- Destination Allocator
  The Destination Allocator is activated whenever a train station interrupts the unloading operations because the current destination is completely full or an uncompleted destination becomes available for loading. The allocation procedure simply consists of a scan of the remaining free destinations where the parcel was allocated. If a free destination is found, the Path Allocator is activated. Otherwise, the requesting station stays in the queue and will be the first one to be processed at the new activation.

Landside Operators

- Truck unloading stations
  Truck loading stations are modelled as Operators with the following characteristics.
  - Capacity: unloading capacity of the unloading station.
  - Set up time distribution: distribution of the time needed by the truck unloading station to serve a new truck.
  - Post operational time distribution: distribution of the time needed by the truck unloading station to become available again after serving a truck.

  Furthermore, Truck unloading stations possess the following processes.
  - Load: After the sampled set-up time has elapsed, unloading operations take place. The mass step used for the operations is the size of a truck and thus this process does not loop.

After the unloading of one truck has taken place, the sampled post-operational time has elapsed and a check on external events has been carried out, the number of served trucks belonging to the handled cargo is adjourned and the station becomes available to serve a new truck.
Furthermore, a check on the assigned destination and the assigned cargo is done. If the destination is full the station becomes available for the assignment of a new cargo and the served cargo reenters the station requesting queue. Otherwise, if the trucks carrying the cargo have all already been served, the station becomes available to handle a new cargo and the cargo is considered completely arrived at the terminal (from the truck side).

  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed, the station is set free and becomes available.

- Train unloading stations
  Train unloading stations are modelled as Operators with the following characteristics.
  - Capacity: unloading capacity of the unloading station.
  - Set up time distribution: distribution of the time needed by the truck unloading station to serve a new train.
  - Post operational time distribution: distribution of the time needed by the truck unloading station to become available again after serving a train.

  Furthermore, Train unloading stations possess the following processes.
  - Load: after checks on external events have been carried out and the sampled set-up time has elapsed, unloading operations take place. Differently from the import model, the mass step used for the operations is the size of a truck, to allow materials coming from both landside modalities to enter the same storage without discretisation problems. After the unloading of one mass step has taken place, a check on the served train and the served destination is made. if the served train is fully unloaded or the served destination is completely full, operations stop. In the first case, after a post-operation delay sampled by the dedicated distribution, the destination and the station are set free. In the second, the destination is labelled as full, while the station enters the destination allocator queue in order to receive a new destination to continue unloading. If both checks are passed, next step process is triggered.
  - Next step: after checks on external events have been carried out, unloading operations take place. Once more, after the unloading of one mass step has taken place, a check on the served train and the served destination is made. if the served train is fully unloaded or the served destination is completely full, operations stop. In the first case, after a post-operation delay sampled by the dedicated distribution, the destination and the station are set free. In the second, the destination is labelled as full, while the station enters the destination allocator queue in order to receive a new destination to continue unloading. If both checks are passed, next step process is triggered.

- Sampling station
  Sampling Stations are modelled as Operators with the following characteristics.
  - Service time distribution: distribution of the time needed by the station to sample material from a truck.

  Furthermore, Sampling stations possess the following processes.
  - Sample: the station lets the sample service time elapse to simulate sampling operations. After this, checks on external events are carried out.
  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed, the station is set free and becomes available.

Landside Components

- Trucks
  Trucks are modelled as Components with the following characteristics.
  - Cargo: parcel the truck is carrying.
  - Size: amount carried by the truck.
  - Transit time: time needed by a truck to reach a station from the post-sampling parking (also used to model the analysis operations if needed).
  - Sample time distribution: time needed by a truck to reach a scale from a station.

  Furthermore, Trucks possess the following processes.
  - Transit in: the truck leaves the post-sampling parking and after the transit time has elapsed reaches the assigned station and activates it.
  - Sample transit: the truck leaves the sampling stations and after the sample time has elapsed reaches the post post-sampling parking.
- Trains
  Trains are modelled as Components with the following Characteristics.
  - Cargo: parcel the train is carrying.
  - Size: amount carried by one wagon.
  - Transit time distribution: distribution of time needed by a train to reach a station from the marshalling yard.
  - Number of wagons: number of wagons in the train.

  Furthermore, Trains possess the following processes.
  - Transit in: the train leaves the marshalling yard and after the transit time has elapsed reaches the assigned station and activates it.
- Pre-sampling parking
  A queue where trucks wait their turn to be served by a sampling station.
- Parking
  A queue where trucks wait their turn to be served by an unloading station.
- Marshalling yard
  A queue where trains wait their turn to be served by an unloading station.

Other Landside processes

- Parcel and carriers generation
  The carriers and the transported cargoes are generated based on the user's input and the procedure described in 5.7.4.
- Cargo correction
  The same procedure described in 5.6.1 is applied to correct the cargoes' amounts in order to avoid discretization problems.

5.7.2. Stockyard operations

As already stated no real operations happen in the stockyard itself since the moving of materials is mostly dictated by Allocators and Operators belonging to the other two sub-systems. The cargo handling procedure described in 5.6.2 was applied in the export terminal too.
The modelling of stockyard operations of the export terminal features the following Allocators and Components.

Stockyard Allocators

- Path Allocator
  The Path Allocator is triggered by the allocation of a loader or an unloading station to a specific parcel storage destination. The Allocator checks all available Paths in an established order for their start and end in order to find the correct one. Once a Path is selected, it becomes temporarily linked with the requesting entity and its setting up procedure is triggered.

- Parcel Allocator
  Once a cargo is generated the terminal the Parcel Allocator is activated. The process consists of a simple heuristic trying to mock the minimization of wasted space and freeing time of silos.
  Since the complete allocation of the generated cargoes linked to one carrier is an important trigger for carrier and landside modalities generation, the Parcel Allocator tries to allocate every cargo belonging to the same carrier following the heuristic described in Section5.6.2. If one of them does not fit in the storage, the allocation is suspended and will start again as soon as a storage space gets free. Otherwise, the allocation is confirmed and the generation of landside modalities is carried out by the Parcel Allocator according to the procedure described in Section 5.6.4.

Stockyard Components

The Stockyard Components of the export terminal were modelled just as the ones reported in 5.6.2.

- Routes

- Paths

- Silos

5.7.3. Seaside operations

Seaside operations begin as soon as a carrier calls. After this, carriers take a certain amount of time, sampled from a dedicated distribution, to reach the anchorage. Once at anchorage, carriers request a berth. A berth is found according to different parameters, most importantly a carrier is allocated to a berth only if the parcels desired by it are already fully stored inside the storage. After obtaining a berth, the carrier triggers the search for a shore power connection (if equipped with shore power technology) and one or more loaders. Once the loaders are found, the needed routing to connect each of them to the first of the assigned storage positions is looked for. Meanwhile, the ship requests use of the channel. If the channel is free to use, the carrier proceeds to transit in. After the transit in time, the carrier arrives at the berth where berthing and administrative operations can take place. If the loader and the routing are already in place at this moment, loading operations can start and won't stop until the carrier is completely full. Once the carrier is completely full, post-operational procedure and unberthing can take place and the channel use is requested once more. Once the channel is free, the carrier is allowed to transit out and leave the system.
The modelling of seaside operations features the following Allocators, Operators, and Components.

The modelling of seaside operations of the export terminal features the following Allocators, Operators, and Components.

Seaside Allocators

- Loaders Allocator
  The Loader Allocator is triggered by the allocation of a carrier to a berth or the end of operations on a different carrier.
  Since different transported parcels are assigned to different storage locations and thus require different routing, the Laoder Allocator handles the parcels and not the carriers themselves. In particular, each loader is assigned to a specific parcel storage location, allowing the maximum

number of loaders serving the same parcel to be the number of locations in which the parcel is stored. Once a parcel storage location enters the loader allocation procedure, a check on the maximum number of loaders allowed to serve the specific carrier is done. If the maximum number has not been reached yet the loader with the higher capacity available on the berth is chosen to load the specific portion of the handled parcel reclaiming it from the assigned storage location. Once the loader has been assigned, the Routing Allocator is triggered.
If no free loader has been found through this procedure, loaders serving other carriers are checked and, if one of the serving loaders meets the specific requirements, one of them is reassigned to the new carrier. Parcel portions whose loading process has been interrupted rejoin the loader allocation queue with higher priority than untouched portions.
This procedure thus has as a main objective to maximise the number of carriers served at the same time and as a secondary objective to maximise the number of loaders serving each carrier.

- Berth Allocator
  As previously stated, the Berth Allocator is activated by the arrival of carriers at the anchorage or by a carrier leaving a berth.
  After checking that all the parcels are fully present in the terminal, the free berth with the minimum wasted length is selected and assigned to the handled carrier.
  If no berth has been found, all free berths are scanned a second time adding the length of the contiguous berth to them to check if the handled carrier can be allocated in this enlarged resource. Once the berth is assigned, the Loader and Shore Power Allocators are triggered and the carrier enters the channel requesting queue.

- Channel Allocator
  The Channel Allocator is activated whenever a channel requests channel usage or a carrier finishes its transit in or out. Once activated it proceeds with checking all the carriers requesting the channel usage. For every carrier the live channel draft is compared with the carrier's draft, if this check is passed and the channel longitudinal capacity still allows it, the carrier's process "transit in" or "transit out" is activated. In performing this process, priority is always given to the carrier requesting transit in, in order to optimise the loading operations and lower demurrage costs.

Seaside Operators

- Loaders
  Loaders are modelled as Operators with the following properties.
  - Capacity: fixed capacity of the loader, used for the allocation process.
  - Capacity distribution: capacity distribution, sampled every mass-step to better model the loading process.
  - Set up time distribution: distribution of the time needed to ready the laoder to operate on a carrier.
  - Cleaning time distribution: distribution of the time needed to clean the loader after operating on a carrier.
  - Switching time distribution: distribution of the time needed to ready the loader to operate on a new parcel on the same carrier.
  - Power: rated power of the equipment, needed to calculate energy consumption.
  - Power coefficient: coefficient (usually 0.7) used to calculate the actual energy consumption of the equipment.
  - Wind coefficient: hindering coefficient used to simulate operations on wind-assisted carriers.

  Just as the unloading process, the loading process is discretised through mass-steps. Every mass-step an operational check for external factors takes place and a comparison between the sampled unlaoder capacity and the selected routing fixed capacity is carried out in order to select the lower amongst the two. Furthermore, the process is discretised on a higher level based on the different destination of the parcel being unloaded.
  Furthermore, Unloaders possess the following processes.

- Set up: the loader gets ready to proceed with operations on a new carrier. After checking that the assigned routing is in place, the loading of a batch of parcel assigned to the same storage destination is carried out until the storage is empty or the carrier is full. In the first case ”Next destination” process is activated. Otherwise, if a different parcel is requested by the carrier ”Next cargo” process is carried out. In the case no other destination or parcel is requested maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
- Next destination: the loader samples the Cleaning time distribution and once the cleaning time has elapsed and the availability of the assigned routing is checked, the loading of a batch of parcel assigned to the same storage destination is carried out until the storage is empty or the carrier is full. In the first case ”Next destination” process is activated. Otherwise, if a different parcel is requested by the carrier ”Next cargo” process is carried out. In the case no other destination or parcel is requested maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
- Next cargo: the loader samples the Switching time distribution, once the switching time has elapsed and the availability of the assigned routing is checked, the loading of a batch of parcel assigned to the same storage destination is carried out until the storage is empty or the carrier is full. In the first case ”Next destination” process is activated. Otherwise, if a different parcel is requested by the carrier ”Next cargo” process is carried out. In the case no other destination or parcel is requested maintenance request is checked and either ”Clean up” process or ”Maintenance” process is carried out.
- Clean up: Cleaning time distribution is sampled, after the cleaning time has elapsed the loader is set free and becomes available to serve a new carrier.
- Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed the loader is set free and becomes available to serve a new carrier.

• Berths
A hybrid approach has been chosen to model the terminal’s berth. One berth is thus a portion of the quay in which a maximum of one carrier is allowed to berth (if conditions are met). However, the model is able to use multiple contiguous berths to let a larger carrier berth at the terminal. Modelled berths thus do not coincide with real entities since the latter are often arbitrarily determined for organizational reasons.
Berths are modelled as Operators with the following properties.

- Draft: berth’s allowed draft.
- Length: berth’s length.
- Transit in time distribution: distribution of the time needed for a carrier to reach the specific berth from the anchorage.
- Transit out time distribution: distribution of the time needed for a carrier to leave the system from the specific berth.
- Pre-operation time distribution: distribution of the time needed to carry on berthing operations and other bureaucratic procedures.
- Post operation time distribution: distribution of the time needed to carry on unberthing operations and other bureaucratic procedures.
- Unloaders: unloaders able to work on the specific berth.
- Shorepowers: shore power connections able to serve carriers berthed at the specific berth.
- Contiguous berths: berths connected on the left or on the right of the specific berth, available to be used to host a large carrier in collaboration with the specific berth.

Furthermore, Berths posses the following processes.

- Berthing: the berth samples the pre-operation time distribution and thus simulates berthing and other bureaucratic procedures. After this process unloading operations can start.

  - Unberthing: the berth samples the post-operation time distribution and thus simulates unberthing and other bureaucratic procedures. Shore power connections are disconnected from the served carrier and after this process, the berth is set free and open to serve new carriers.

- Shore power connections
  Shore power connections are modelled as Operators with the following properties.

  - Set up time distribution: distribution of the time needed to connect a shore power connection to on a carrier and perform the synchronization.

  Furthermore, Shore power connections posses the following processes.

  - Set up: the shore power gets ready to serve with a new carrier.
  - Maintenance: the specific maintenance interval is sampled and maintenance is carried out. Once the maintenance time has elapsed the shore power is set free and becomes available to serve a new carrier.

Seaside Components

- Anchorage
  A queue where carriers wait their turn to enter the terminal.

- Channel
  Channels are modelled as Components characterised by the following properties.

  - Transit in capacity: number of carriers that can proceed in a line while transiting towards the terminal.
  - Transit out capacity: number of carriers that can proceed in a line while transiting towards the open sea.
  - Draft: maximum allowed carrier draft to transit in the channel.
  - Cross: boolean value that indicates if the channel is wide enough to allow two carriers going in opposite directions to cross each other.

- Carriers
  Carriers are modelled as Components characterised by the following properties.

  - Length: carrier's length, sampled from a dedicated distribution selected based on the amount of material transported by the ship.
  - Draft: carrier's draft, sampled from a dedicated distribution selected based on the amount of material transported by the ship.
  - Number of cargoes: number of different parcels carried by the ship, sampled from a dedicated distribution based on the simulation period.
  - Time to anchorage: time between carrier's call and arrival at anchorage, sampled from a dedicated distribution based on simulation period.
  - Cargoes: list of parcels transported on the carrier.
  - Wind assisted: boolean value indicating if the carrier is equipped with wind-assisted technology, sampled by a dedicated distribution based on simulation period.
  - Shore power equipped: boolean value indicating if the carrier is equipped with shore power technology, sampled by a dedicated distribution based on simulation period.
  - Installed power: rated power of carrier appliances supplied during connection to the local grid, sampled from a dedicated distribution selected based on the amount of material transported by the ship.
  - Campaign time distribution: time the carrier is actually generated and calls the terminal after the start of supply of the carried parcels began.

  Furthermore, Carriers possess the following processes.

- Call: after the campaign time has elapsed, the carrier simulates the travel to the anchorage through the given distribution. After this, the carrier enters the anchorage and activates the berth allocation process.
- Transit in: the carrier leaves the anchorage and travels to the berth, activating it.
- Transit out: the carrier leaves the berth and uses the channel to leave the system.

5.7.4. Seasonality and modalities generation

As with the import model, a method was developed to manage seasonality in the export model. The main issue in this case, is that usually detailed arrivals and operations logs are only available for the seaside, because of the more conspicuous costs linked to that branch of the supply chain.
Therefore, the methodology to derive carriers' average IAT is the same as described in 5.6.4, but its application differs slightly. In fact IAT distribution obtained is used to generate cargo arrivals instead of carriers. Cargoes belonging to one carrier are generated together following the same procedure previously described, sampling the various user-provided distributions in order to determine the different characteristics. However, after being tested against the maximum allowed carrier tonnage, an attempt to allocate all the cargoes belonging to one carrier is made. If this attempt fails, cargoes are queued just as carriers at anchorage, and a new allocation effort is made whenever a new storage position becomes free. As soon as all the parcels carried by one ship are allocated, the generation of the carrier and landside modalities takes place. To the former a campaign time is associated, reflecting the time the parcel owner will take to gather the specific parcel in the terminal. Once this time elapses, the carrier will call and then arrive at the anchorage.
By applying this method, it is thought that disruptions in the supply chain and different client behaviours can be better simulated. It is important to note that carriers' waiting times highly depend on the campaign time set by the user and will capture the delay in retrieving the single group of parcels, not the overall nonperformance of the terminal, as is done in the import model. To have a more general overview, the difference between obtained throughput and generated throughput (representing the cargoes waiting to be allocated in the terminal) must be considered.
Furthermore, the derivation of IAT for landside modalities follows the same procedure described before, based on the user-provided input "intake time."

5.8. Enivronmental friendly operations

5.8.1. Shorepower

As explained in 4.2.1, shore power connection operations differ for many factors depending on the technology used. Depending both on the physical connection and the electrical toponomy of the system a shore power connection can be able to serve one or multiple berths, and more in particular a specific section of a berth or the whole berth.
Based on the berth modelling developed in this work as explained in 5.6.1, both these limitations can be modelled. Shore power connections are in fact linked to one or more berths. Being modelled berths able to describe either a whole physical berth or only a portion of it, cold ironing devices can be associated to either of them. However, berthing restrictions due to the shore power connection positioning are not part of this model, since the only discriminant taken into consideration is if the berthing ship is using or not the specific portion of the berth. If this is the case, the ship is eligible to be connected.
The flexibility obtained with this approach allows the user to simulate different fleets of shore power connections, varying both by number and technology. The latter is described by their capability of covering one or more berths, or portions of it.

5.8.2. Wind-assisted shipping

As mentioned in 4.2.2, a significant concern with adopting wind-assisted carriers is their potential interaction and interference with port infrastructure. While new wind-assisted carriers can be designed to avoid these issues, retrofitted ones might face challenges where the addition of wind propulsion devices hinders normal port operations. Furthermore, not all technologies listed in 4.2.2 face this problem. For instance, towing kites, which are highly flexible and occupy minimal deck space, do not cause such

issues.
For bulk carriers, the primary concern is that loading and unloading operations could be severely impacted by the placement of rotors or masts. The model addresses technologies like Flettner rotors and wingsails, which significantly alter the carrier's layout, potentially slowing down these operations and reducing the terminal's loading or unloading capacity.
The model allows users to set a distribution for the percentage of carriers arriving at the terminal with these problematic retrofits. These carriers will apply a hindering factor to the capacity of the seaside equipment serving them, reducing it and thus simulating the real-world difficulties associated with such retrofits.

5.8.3. Energy consumption

One of the natural outputs of an industrial system simulation model is the working times of each machine involved in the process. By knowing their rated power and an efficiency factor, it becomes straightforward to estimate their energy consumption. Although the procedure is simple, many terminals do not monitor this, and during design phases, energy consumption is often calculated in even simpler ways. It was thought that even a small improvement, such as obtaining working times through simulation instead of static calculations, could enhance the overall understanding of the system.
This approach relies on the user providing accurate data about power consumption, which is not always easy to find. However, it is expected that the rated power for the equipment can be located, and [40] offers useful data to estimate the installed power of ships based on their tonnage. In fact, the ship's rated power dictates the amount of energy consumed by shore power connections.

5.9. External factors

As highlighted in 4.4, the ability to estimate the impact of unexpected events on normal operations is what makes simulation such a powerful tool for understanding systems too complex for other analysis methods. Therefore, correctly modelling these factors is a crucial aspect of a simulation study. The following paragraph describes how the various external factors previously listed were addressed in this project.

5.9.1. Weather

Since weather is highly time-dependent, the user is given the possibility to divide the simulation time in a certain number of periods to better capture the atmospheric behaviour.
For each of these periods, the user has to provide a weather distribution reporting the percentage of time of that period in which the weather is not favourable for seaside operations.
Furthermore, the user provides a time step. At every time step the distribution is sampled and the weather characteristics of the following time-step are determined and passed to the seaside pieces of equipment in order to behave consequently. In this way the user is able to discretise the behaviour of the weather according to the available data and the weather behaviour of the region where the terminal is positioned

5.9.2. Non-working time

Non-working time is estimated to be a quite recurrent and periodic event, modelling shift changes or the closure of the terminal (or one of its subsystems) in determined hours. For example, the landsides of terminals are usually not open 24/7.
The user can thus input the different active or non-active shifts for every component of the system, in order to accurately represent its daily schedule. The total sum of the inputs is expected to amount to 24 hours and the model was thought so that a maximum of four daily interruptions can be part of a component behaviour.
Just as all the other external factors, the inputs regarding non-working time are period-dependent, allowing the user to model the variation of these patterns throughout the simulation time.

5.9.3. Breakdown

As in almost all operational simulation studies, breakdown behaviour was modelled through the use of Mean Time Between Failures(MTBF) and Mean Time To Repair(MTTR). The former is the average amount of working time between two consequent breakdowns, while the latter represents the average time needed after a breakdown for the specific resource to be able to resume operations.
In this tool, the user is allowed to input a stochastic distribution for both of these parameters and a time step to monitor the working time of the specific equipment.
As soon as the resource starts its operative time a value is sampled from the MTBF distribution and a counter is started, monitoring the working time of the resource. As soon as the counter reaches the sampled value, a breakdown is simulated and an MTTR value is sampled from the respective distribution. After the repairing time has elapsed, the counter is set to zero and the component can be used in operations again.
The possibility to vary the distribution along the simulation time was given to the user in order to model the different sensibilities of the pieces of equipment to different environmental circumstances (high-low temperatures, humidity, etc.).

5.9.4. Maintenance

Differently from the other external events, maintenance was modelled without a periodic behaviour in mind, since maintenance periods can vary significantly during the year and be scheduled very differently due to high or low business of the system.
For this reason, the user is asked to input a non-period-dependent time series reporting all the maintenance occurrences and the intervals between them. Once one of these intervals is reached by the simulations, a trigger is sent to a specific piece of equipment triggering its maintenance process. Once this is completed, the resource is again available to be used and the MTBF counter previously mentioned is set to 0. As explained in 5.6 and 5.7, each class of equipment handles maintenance differently, proceeding to it only in specific circumstances to better reflect the actual operational decisions made in the real system.

5.9.5. Tidal behaviour

Similarly to non-working time, the tidal behaviour of the system was modelled with a daily cycle in mind since this is the pattern of tides around the world. The user is allowed to input up to two tidal windows and three intervals dividing them during which the channel draft decreases of a set depth, not allowing carriers with higher draft to enter or leave the port.
However, the draft check is done only at the moment of a carrier's request for use of the channel and thus does not consider the transiting time. Due precautions to properly model this behaviour have to be taken by the user, shifting the high tides windows appropriately.

5.10. Interface and Animation

In order to make the model user-friendly, an essential but efficient graphic interface was developed. An Excel file was linked to the Python code to allow the user to quickly change the input required for the model to run.
Each sheet featured in the interface file deals with a different aspect of the model, making the set-up of a new simulation run a relatively simple process. Two examples of the interface sheets are reported in Fig. 5.7 and 5.8.

Unloader	Capacity	capacity distribution	capacity distribution parameters	set up time distribution	set up time distribution parameters	breakdown periods	MTBF distribution	MTBF distribution parameters	MTTR distribution	MTTR distribution parameters	breakdown time-step	cleaning time distribution
unloader name	rated capacity (for selection)	type of distribution used fot the unloader capacity	parameters for the unloader capacity distribution if pdf input in the following way: [value1,pecentage1,value2,percentage2...] If constant input in the following way: [value] if normal input in the following way: [mean,sd]	type of distribution used fot the unloader set up time	parameters for the unloader set up time distribution if pdf input in the following way: [value1,pecentage1,value2,percentage2...] If constant input in the following way: [value] if normal input in the following way: [mean,sd]	number of period to divide the simulation time in to discretiuze the breakdown behavior of the unloader	type of distribution used for MTBF	parameters for the MTBF distribution for each period if pdf input in the following way: [value1_period1,pecentage1_period1,value2_period1,percentage2_period1...]:[value1_period2,pecentage1_period2,value2_period2,percentage2_period2...]:etc. If constant input in the following way: [value1_period1,value2_period2,value3_period3,etc.] if normal input in the following way: [mean_period1,sd_period1]:[mean_period2,sd_period2]:etc.	type of distribution used for MTTR	parameters for the MTTR distribution for each period if pdf input in the following way: [value1_period1,pecentage1_period1,value2_period1,percentage2_period1...]:[value1_period2,pecentage1_period2,value2_period2,percentage2_period2...]:etc. If constant input in the following way: [value1_period1,value2_period2,value3_period3,etc.] if normal input in the following way: [mean_period1,sd_period1]:[mean_period2,sd_period2]:etc.	time-step used to count operating hours for breakdown behaviour	type of distribution used fot the unloader cleaning time
unloader1	1200	Pdf	[720.0,15.5,600.0,18.2,9	Constant	[1]	1	Constant	[13500]	Constant	[5]	0.1	Constant
unloader2	600	Pdf	[360.0,15.5,300.0,18.2,4	Constant	[1]	1	Constant	[13500]	Constant	[5]	0.1	Constant
unloader3	600	Pdf	[360.0,15.5,300.0,18.2,4	Constant	[1]	1	Constant	[13500]	Constant	[5]	0.1	Constant

Figure 5.7: Unloaders interface sheet

Fig. 5.8 shows a resources input interface sheet, the unloaders one. In order to input a new unloader in the model, the user has to simply fill in a new line of cells specifying all the requested parameters and pieces of information. To make the process easier, an explanation cell about the specific parameter and the syntax to input it was featured.

Connections	BC105	BC106	BC223	BC224	BC225	R33	R34	R14
BC105								
BC106								
BC223	Connected	Connected						
BC224	Connected	Connected						
BC225	Connected	Connected						
R33			Connected					
R34			Connected					
R14				Connected				
R13				Connected				
R15					Connected			
R35					Connected			
V33104						Connected		
V33103						Connected		
V33102						Connected		
V33101						Connected		
V34304							Connected	
V34203							Connected	
V34403							Connected	
V34303							Connected	
V34202							Connected	
V34402							Connected	
V34302							Connected	
V34201							Connected	
V34401							Connected	
V34301							Connected	
V35504								
V35503								

Figure 5.8: Routing connections interface sheet

Fig. 5.8 reports the routing connections interface sheet. With the piece of information reported on this sheet, the building of Paths from Rotues is made possible. The sheet is automatically generated after all the routing components are input and it allows the user to simply define which of them are interconnected.

Furthermore, a simple 2D animation was developed in order to check the system's behaviour. Just like the model, the animation is parametric and it automatically adapts to the different specifications of the simulated system. Fig 5.9 reports an examples.

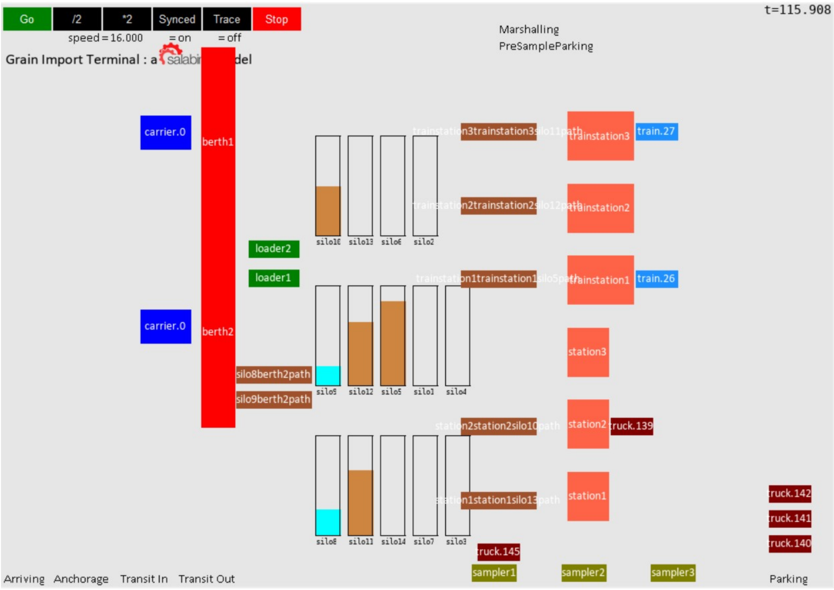

Figure 5.9: Animation example

6 Verification

This chapter deals with the verification process of the model. the techniques chosen to develop it, the different experiments, and the obtained results.

6.1. Definition and utilised techniques

[27] defined verification as ”the process of ensuring that the model design has been transformed into a computer model with sufficient accuracy”. In other words, making sure that the model was build right, with ”right” meaning in the way it was envisioned by the modeller. Put in an even easier way, verification is the process of checking that the model behaves as it is meant to behave.
Simulation verification is almost a science on its own and a great deal of literature exists on the matter, involving very different techniques and practices from the very informal ones to the most rigorous and formal ones. In this study, the techniques described in [49] were taken into consideration and the ones deemed appropriate for the scope and time on this work were applied.

6.2. Through work techniques

Many verification techniques take place during the development of the model itself and are meant to ensure the avoidance of the most futile errors, normally generated during the translation of a logic statement into a coding line. Still, applying these ”debugging” techniques guarantee a robust method to save time and effort, obtaining a partially verified model as soon as the model is completed and reducing the cumbersomeness of what is commonly referred to as the verification process.

6.2.1. Modules and subprograms coding

One of the techniques reported in [49] is probably the most cited and commonly recommended practice in software engineering and programming in general. The method consists in writing and debugging the simulation program in modules of subprograms. In fact, given a large simulation model, it would be malpractice to code the entire program without any attention to debugging and it would surely bring to a ruinous first execution, with multiple hardly identifiable errors.
These techniques thus advise to write and debug the model’s main program and a few of the key subprograms, representing the other required subprograms as “dummies” or “stubs”. Step by step, and only after the correct functioning of the previously coded bits, additional subprograms or levels of detail are to be added and debugged.
During this work, this principle was thoroughly applied. Every newly introduced class and its interaction with the previously created ones were tested before starting to work on the next component. In particular, great attention was given to the allocators’ behaviours and policies, testing different scenarios to ensure the correct functioning of their multiple processes.

6.2.2. Trace

Another ”through work” technique vastly applied in verification is the utilisation of the Trace. A Trace represents the state of the simulated system (i.e., the contents of the event list, the state variables, certain statistical counters, etc.) just after the occurrence of each single event. It is thus evident how a Trace is a powerful debug and verification tool. Furthermore, its feature when applying the previously described practice makes the checking of every new module extremely efficient, being able to quickly grasp the effect of the introduced sub-program on the whole system.
Still, due to the amount of data included in a Trace, checking it can become quite a cumbersome operation. For this reason, in the present work, self-developed traces were developed to check the behaviour of specific components or processes. These traces are included as an output of the simulation, making the user always able to check the weird or unnatural behaviour of the system in specific circumstances.

6.2.3. Animation

As already stated, a Trace can be a cumbersome object to analyze and even the self-developed component-specific traces are mostly suitable to understand an error or misbehaviour of the system previously individuated. In order to do so, a system animation is often times advised. In fact, an animation can give superficial but fundamental information (such as position and currently held quantity) that clearly steers the mind of the verifier towards the individuation of a malfunctioning that can then be investigated further.
As described in 5.10, a simple 2D animation was implemented to be able to check the main processes happening in the system (loading/unloading of bins, resource allocation, queuing, etc.).

6.3. A posteriori techniques

Another kind of verification techniques is the one applied once the model is (thought) complete. These methods are thus extra procedures to perform on top of the simulation modelling and are usually more rigorous than the ”through work” ones.

6.3.1. Distributions check

As already stated, one of the most crucial parts of a simulation model is the different distributions used to generate stochastic inputs for it. A thorough check of the correct functioning of these distributions is thus fundamental when verifying the model since wrong inputs mean undoubtedly wrong outputs.
The most common way to verify the correctness of the used distributions is by analysing their average and standard deviation over a large enough population of samples. Furthermore, when distributions are truncated, it can be useful to compare the shape of the original distribution with the truncated one and evaluate if the difference is negligible.
The distributions used in this work were generated through the Salabim library and thus evaluation was not deemed necessary. However, especially in the generation of carriers and cargoes, truncation takes place as explained in 5.7.4 and 5.6.4, and thus the previously mentioned comparison was carried on.

Carriers and cargoes generation distribution check

The distributions used to verify the model were built based on data from the Study Case 1 7.2.1.
Firstly, the procedure to calculate the average IAT starting from throughput and vessel size data described in 5.6.4 was applied, obtaining an average IAT of 208.8 hours.
The analysed case provided IAT data that were thus used for comparison. The real average IAT (obtained from the terminal data) amounted to 188.9 hours, leading thus to a 4.9% error.
Secondly, the throughput and length data from the terminal were used to generate distributions to input into the model. The results, averaged over 10 simulations, were in turn compared to the original data. The following plots summarise the results.

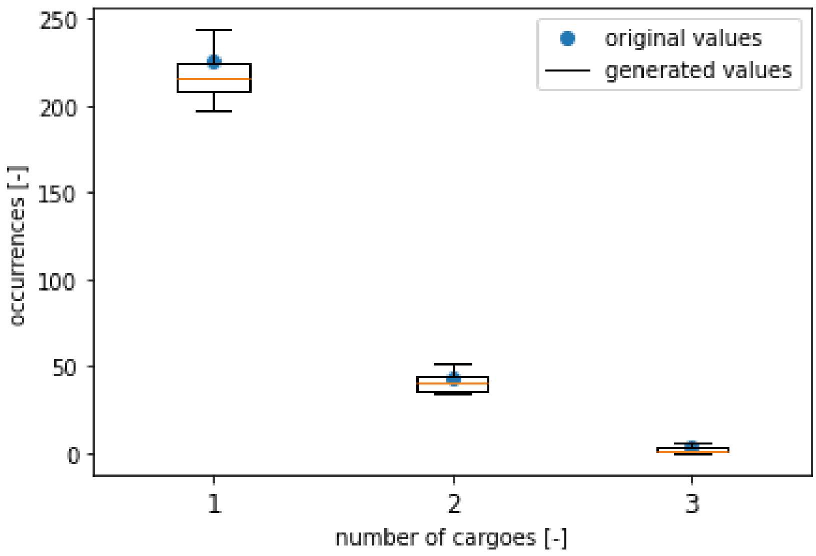

Figure 6.1: Number of cargoes per carrier comparison

Figure 6.1 reports the comparison of the generated number of cargoes per vessel and the relative data obtained from Case Study 1. As expected, the results are quite promising. The wider range of generated ships carrying one cargo in comparison with carriers with two or three cargoes is due to the truncation of the distribution. In fact, the truncation taking place (a check on the maximum amount of material brought by the ships) influences only the two last groups, because of the possible overlap of two large cargoes in the same carrier.

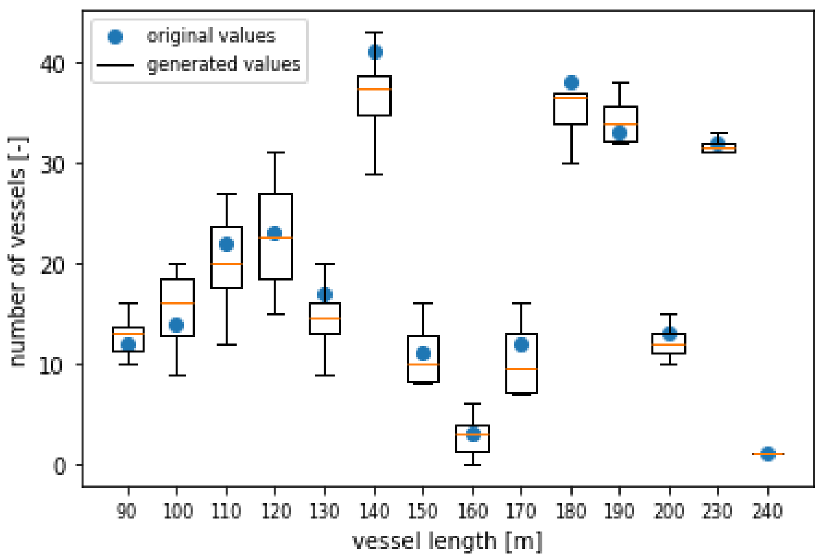

Figure 6.2: Vessels' lengths comparison

Figure 6.1 reports the comparison of the generated ship lengths and the relative data obtained from Case Study 1. The spread of the various results is quite high. This is due to the specific length selection mechanism chosen and applied as described in 5.6.1. In this particular case, an analysis of the available data was carried on and specific PDFs were built for each amount range. A more in-depth analysis with smaller lengths and amount bins could probably obtain better results.
Still, it is important to underline that a strict correlation between ship length and amount carried is not always obtainable due to the nature of grain trade (carriers could be arriving at the terminal after

another stop, thus carrying only a fraction of their maximum dwt). Instead of using historical data from a terminal, another option for the user is to define carrier classes based on shipyard standards and thus with strict specifications on dimensions and dwt.
The ship length data used to build the different distributions are reported in 6.3.

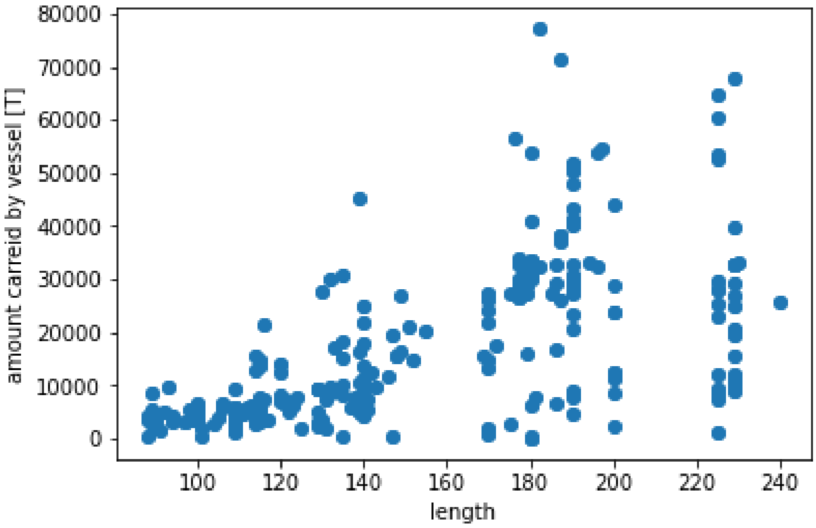

Figure 6.3: Original vessel length and carried amount data

Figure 6.4 reports the comparison of the generated cargo size and the relative data obtained from Case Study 1. The same considerations made for the comparisons of number of cargoes per carrier hold in this case. Smaller cargoes are slightly more likely to be generated in comparison with larger ones as a consequence of the truncation mechanism.

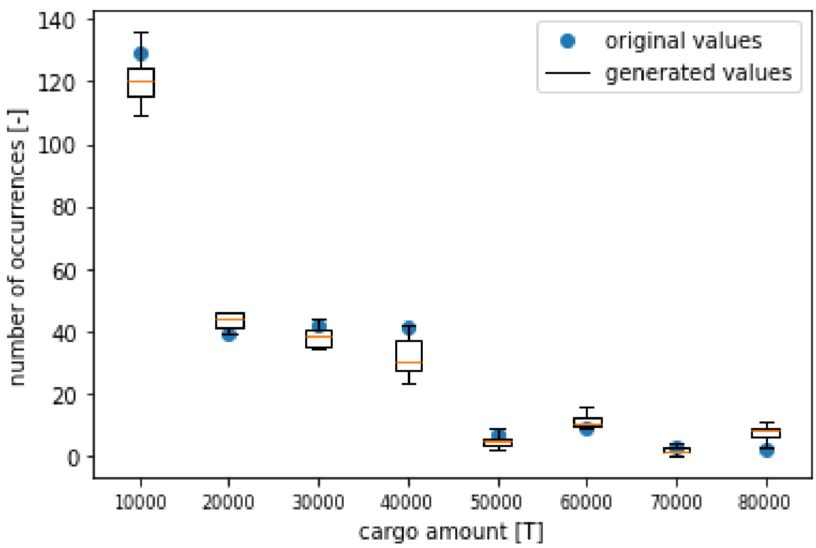

Figure 6.4: Cargoes amounts comparison

Figure 6.5 and 6.6 report the comparison of the generated throughput per material and of the generated cargoes per material with the relative data obtained from Case Study 1. Results appear to be in line with the distributions obtained from the data.

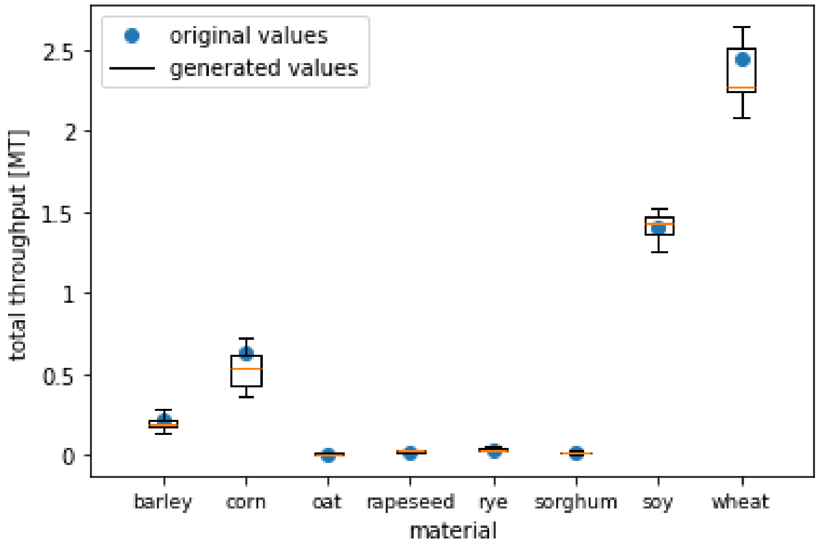

Figure 6.5: Throughput per material comparison

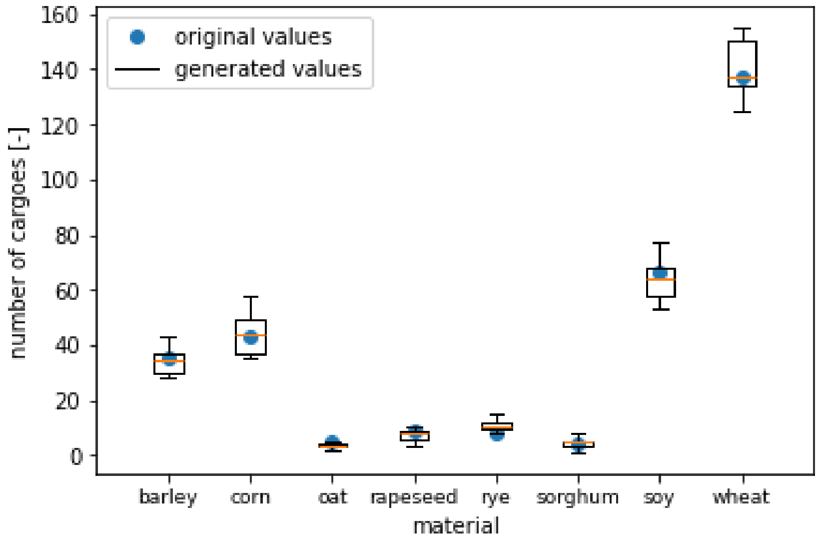

Figure 6.6: Number of cargoes per material comparison

Figure 6.7 and 6.8 report the comparison of the generated cargo size and the relative data obtained from Case Study 1 for two of the various materials handled by the specific terminal. The two materials were chosen because deemed representative of all the material analysed, one being the second for the total amount of material and the other being the third to last. It appears clear that the spreads for these cases are quite high. Still, the results are deemed acceptable since the high variability depends on the distributions used. Furthermore, since the total throughput per material results exact, a larger error on the exact size of each cargo is deemed not excessively detrimental for the simulation model.

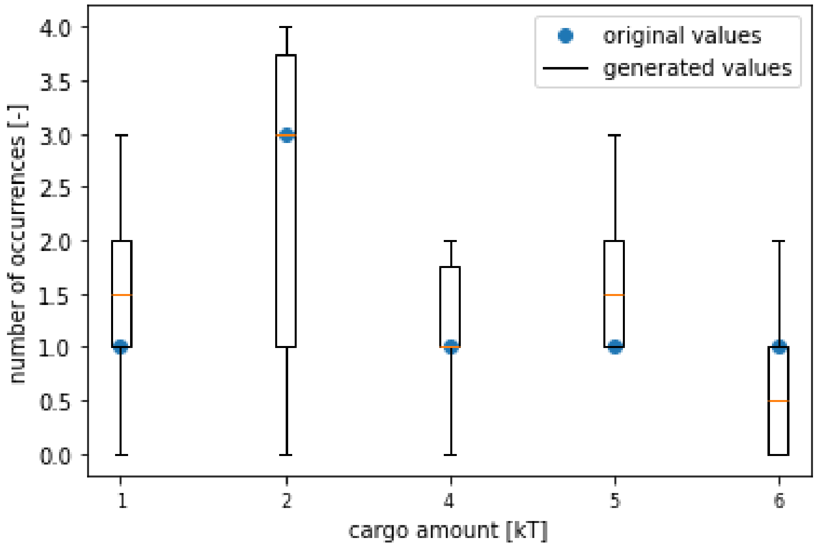

Figure 6.7: Rapeseed cargoes amount comparison

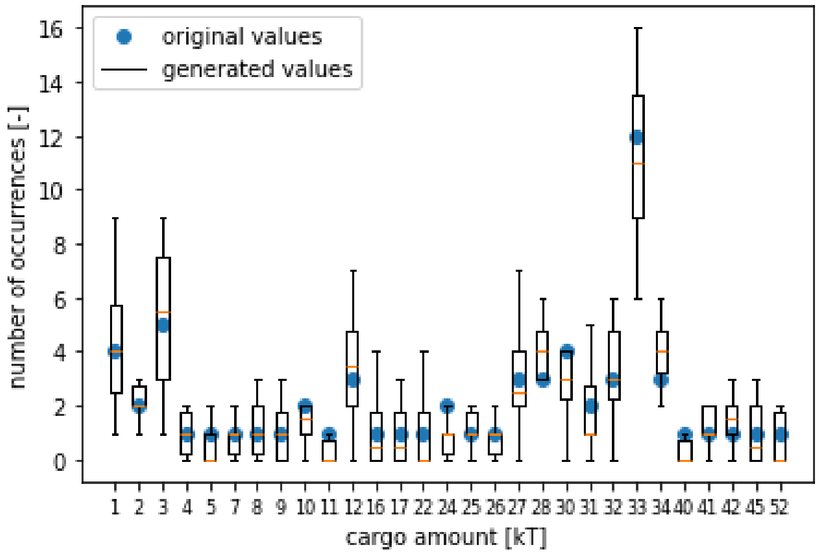

Figure 6.8: Soy cargoes amount comparison

6.3.2. Experimental verification

The most common and known kind of verification is probably the so-called experimental verification. This procedure consists in the setting up of a series of experimental scenarios in which outputs are known (not by real-world data, otherwise this would overlap with validation) or obtainable in a different way than using the simulation model. Often times these scenarios are simplified versions of the simulated system, each one of them thought to make a different aspect of it easily derivable by static calculations or other means.
In this work, experimental verification was applied to various processes. The following paragraphs describe the different cases and the procedures applied.

External events verification

As already stated, a quite complex system of external events interaction was developed in this work in order to bring the simulation environment a step closer to reality. Since the interaction of the different

events with normal operations involves a wide range of states, many different scenarios that bring to different behaviours, and a relatively complex hierarchy it was decided to carry on a verification process dedicated to it.
By setting quite simple distributions, the behaviour of the external events can be easily calculated with static calculations and then compared with the simulation results.
In the following paragraph, we report the results obtained by carrying on the verification study on the external behaviours affecting the Unloaders.

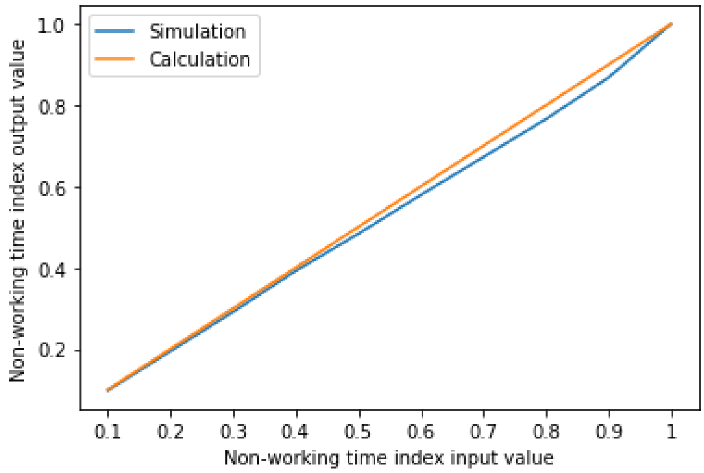

Figure 6.9: Unloader non-working time index comparison

The different external events were investigated separately, varying the dedicated distributions in order to obtain a different behaviour of the system but leaving the rest of the inputs unchanged unless the external events hierarchy pushed towards other choices.
Figure 6.1 depicts the effects of variation of the non-working time inputs on the non-working time index B_t, defined as:

$$N_t = \frac{non - working\ time}{simualtion\ time} \tag{6.1}$$

It is clear to see that the results obtained through the simulation are very close to the ones obtained through static calculations. The small discrepancy can be attributed to the mass-step discretisation described in 5.5, which leads to a small system delay.
Furthermore, the non-working state is on top of the external events hierarchy and thus is not affected by their distributions, thus further investigation was not deemed required.

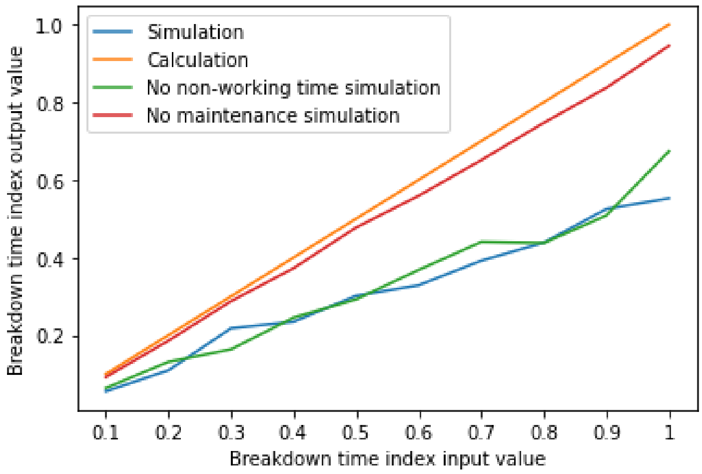

Figure 6.10: Unloader breakdown time index comparison

In figure 6.10 we report the results of the same study but concerning the breakdown time index, defined as:

$$Bk_t = \frac{breakdown\ time}{working\ time} \tag{6.2}$$

We can see how the results obtained with the normal setup of the simulation are pretty far from the expected behaviour. Removing the non-working times from the system did not change the situation, even though the non-working state has a higher hierarchy than the breakdown one.
Once the maintenance was removed from the simulation, satisfying results were obtained. This is in line with the desired behaviour, in fact after maintenance is performed the working time counter that leads to a breakdown is set to 0, as explained in 5.9.3. The still visible differences with the expected results can once more be justified with the previously discussed delay. Furthermore, in the modelling of the breakdown behaviour, a time step is involved to keep track of the working time that leads to further delay and thus justifies the larger distance.

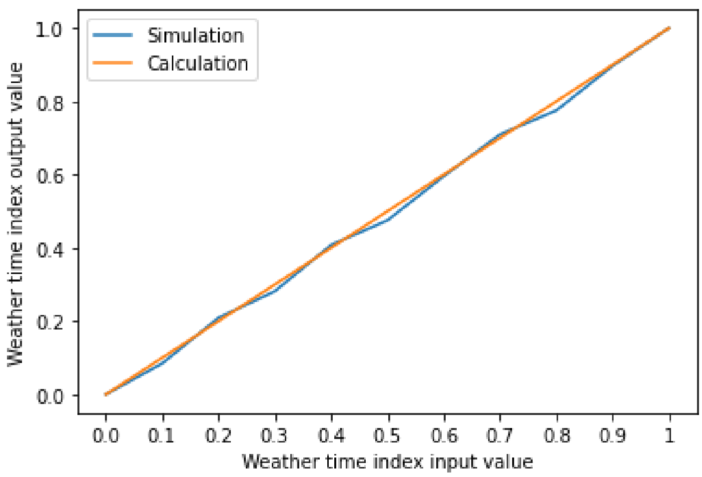

Figure 6.11: Unloader weather time index comparison

Figure 6.11, shows the results of the weather behaviour verification. In particular, the plot reports a comparison of the weather time index W_t, defined as:

$$W_t = \frac{weather\ time}{simulation\ time} \tag{6.3}$$

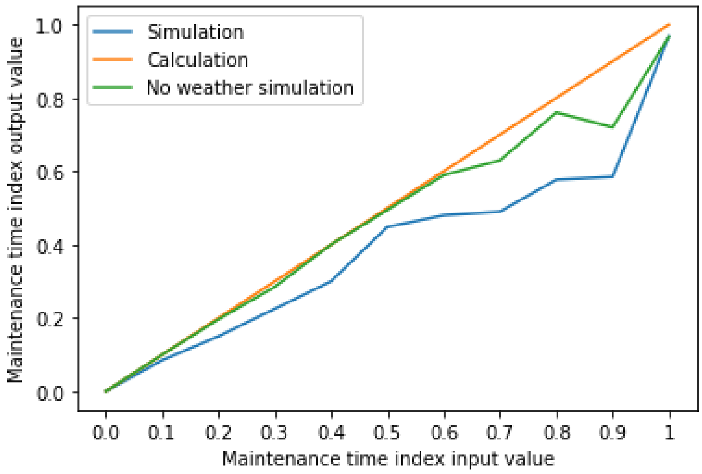

Figure 6.12: Unloader maintenance time index comparison

In Figure 6.12 the same comparison for the maintenance time index M_t, defined as:

$$M_t = \frac{maintenance\ time}{simulation\ time} \tag{6.4}$$

is reported.
Both a normal run and a "no weather" run were reported. In fact the weather state has a higher hierarchy than the maintenance one and thus has an influence on the index shown.
Results could seem quite off both for both situations, but that is not the case. In fact, as explained in 5.9.4, the maintenance process heavily depends both on the user inputs and the equipment behaviour. Maintenance is in fact delayed if the equipment is involved in operations. The time in which the delayed maintenance operations will be carried on depends on the specific equipment and in some cases they could easily overlap with other scheduled maintenance operations, resulting in less equipment maintenance time. For example, unloaders will postpone maintenance until the end of the operations on the served carrier, making it quite easy to skip one or more scheduled maintenance operations.

Moved material verification

The fundamental process of the model is the movement of material, it was thus deemed essential to verify its correct behaviour and its connection to equipment utilisation.
A common way to calculate general equipment utilization times (often used to estimate energy costs and other OPEX) is the following:

$$t_u = \frac{Troughput}{\sum_i C_i} \tag{6.5}$$

where C_i is the effective capacity of a piece of equipment i belonging to a specific group of machines. Obviously, the machines belonging to the analysed group have to work in parallel in the system, otherwise, the proposed calculation loses validness.
Comparing the utilization times obtained through this static calculation with the utilization times obtained by the model set up with predictable capacity distributions was the chosen method to verify the material transport process.
Fig 6.13 reports the results obtained during this process over multiple simulations based on data from Study Case 1.

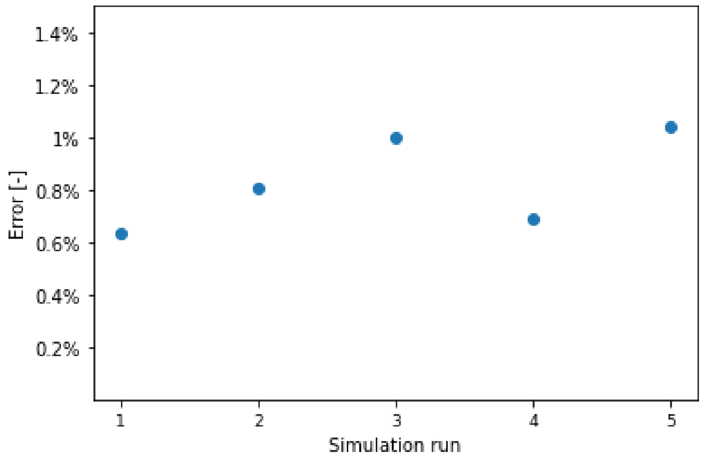

Figure 6.13: Moved material verification results

7 Validation

7.1. Definition

According to [32]: ”Validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study”.
Although often left as the last (and even optional) step of a simulation study, validation is a crucial part of such a kind of work and only a model that is considered to be ”valid” should be used to make decisions about the simulated system.
When tackling the validation process of a model, it is crucial to keep in mind that its ease or difficulty strongly depends on the system’s complexity and whether an existing version of the system is available. Furthermore, a fundamental assumption is that a simulation model of a complex system can only approximate the actual system.
Generally, time and money invested in model development are linked with a direct linear correlation to the validity of the model. However, the most valid model is not the most cost-effective per se. For example, improving a model’s validity beyond a certain point could be very costly due to extensive data collection, but still not yield significantly better insights or decisions.
Finally, when validating a model it should be clear that the model has been developed for specific objectives and applications and thus, regardless of the effort put into model building, absolute model validity is neither achievable nor desirable. Furthermore, since the model will be used to make decisions about a system, the KPI’s taken into consideration in the decision-making process should be not only unambiguous but used as main guidelines during the validation.
The main difference between validation and verification is thus the stronger relationship of the former with reality and real data. The availability, format, and precision of the data about the system performance become the major constraint to the possibility of validating the model simulating it.
In this chapter, the validation process of the developed model is discussed, in relation to the data made available by Royal Haskoning DHV concerning past clients and projects.

7.2. Model validation process

As already stated, the data that us most commonly made available by a terminal manager or owner are the vessels’ arrival and operational log and the throughput, both with various kinds of time-frames. Besides this practical reason, These data summarise in a quite straightforward way the performance of a rather complex system. Furthermore, from a purely economical point of view, the throughput of a terminal and the time at the anchorage of the served carriers are the main sources of income and loss for this kind of system.
Being thus the two high-level KPIs of a dry bulk terminal, they are commonly used for validation purposes and will be used in this work as well. The standard practice is thus to generate vessels’ (and thus cargoes’) arrivals according to historical data (or a historical data based distribution) and then check if the achieved throughput is in line with the available data. At the same time, operational KPIs such as carriers waiting and (un)loading times, utilisation of different equipment, and parcel dwell time are compared with industrial practices or further data, if available.

In this work, the same approach is followed.

7.2.1. Import

The Import Case Study to which the model was applied concerns an import terminal with a yearly throughput of approximately 1 MT in the years 2017-2021 (with the exception of the period interested by the COVID pandemic).
The following paragraph summarises the terminal's layout, and how it was modelled in this work.

- Quay
  The quay of the terminal is 290 m long and is served by a conveyor gallery 288 m long, making thus possible to unload two carriers of a maximum length of 130 m simultaneously.
- Seaside equipment
  The seaside pieces of equipment available to the terminal are a mechanical unloader with a rated capacity of 1200 T/h and two pneumatic unloaders with rated a capacity of 600 T/h each. However, as explained in the next point only two unloaders can work at the same time.
  Policy-wise, priority is given to the mechanical unloader being the one with the highest capacity.
- Conveying lines
  Two 2.5 km long main conveying lines with 1200 T/h and 600 T/h capacity respectively connect the seaside of the terminal to the storage and landside. This layout imposes a strict constraint on unloading operations, allowing only two unloaders at a time to work on served carriers.
  Furthermore, the two main conveying lines are connected to all the terminal's silos not constraining the choice of the line based on the storage destination of the parcel.
- Storage
  The storage facilities of the terminal consist of 24 silos with a 2200 T capacity and 12 silos with a 400 T capacity.
- Landside equipment
  Concerning the Landside, the terminal is provided with 7 truck loading stations with an average capacity of 200 T/h. The stations are served by 12 loading bins with a capacity of 316 T each. Since the built model only allows one loading bin per station, the landslide layout was modified and modelled with 7 loading bins with a respective capacity of 540 T, obtained by dividing the total capacity by the number of stations. The reason for this peculiar layout is that the terminal loading bins are not provided with any sensors, thus the second loading bin was added as a backup to feed the station when the first one is empty without having to wait for its refilling.

The data made available were the following:

- Arrivals log
  The carriers' arrival log of the terminal was the most important data obtained from this system. The dataset reported arrival times, types of cargo, amounts of each cargo and length of every ship for four years. With this data, it was possible to generate distribution for the IATs and the arriving cargoes.
- Storage log
  Another important dataset provided by Royal HaskoningDHV's client was the storage log, reporting the amount of material entering and leaving the terminal daily.
  For this data, it was possible to generate type-specific dwell time distributions and size-specific outtake time distributions, as explained in 5.6.3. Furthermore, by comparing the daily intake with the rated capacities of the unloading equipment it was possible to generate unloading capacities distributions. Lastly, the average truck size was derived from this data as well.
- Operational information
  The terminal provided some operational information as well.
  The terminal is normally open from 6:45 to 22:30 and maintenance operations take place during

closing times. Furthermore, the weather downtime was estimated at 5% of the total year equally distributed between January and March. Lastly, breakdowns and operational disturbances were reported to take up to 10-15% of the working hours.

Based on the terminal characteristics and the data provided it was decided to validate the model by comparing the original throughput obtained by the storage data, the generated arrived throughput, and the obtained throughput while monitoring utilisation KPIs, in particular the average waiting time of carriers.
Figures 7.1 and 7.2 report the obtained results on 10 simulation runs, one of them based on the historical data and the other nine based on distributions generated based on the data.
The duration of the simulation runs was 10 months since reliable storage data were available only for that duration. Furthermore, a mass imbalance between the arrived amount and the outgoing one was detected in the data without having the possibility to explain the reason behind it. Still, the original throughput is reported in 7.1 as a reference.

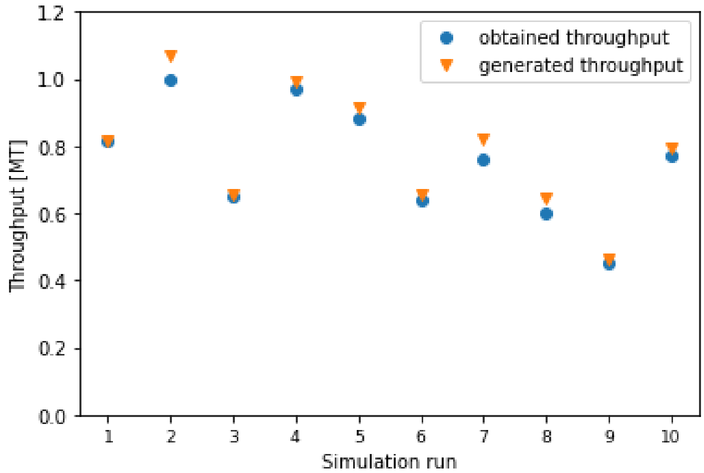

Figure 7.1: Throughput validation results

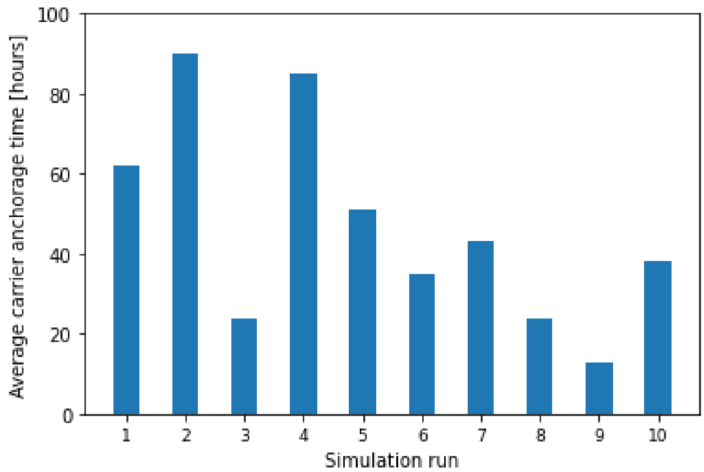

Figure 7.2: Carriers average waiting time

The results obtained are deemed satisfying, in fact, the deviations seen in the plot can be attributed to the partial (or total) unloading of one carrier (of different size) that the terminal was serving (or starting to serve) when the run was interrupted. Furthermore, discrepancies of the order of 10-30% are considered acceptable, given the generic character of the model and the situations it should be applied

to.
The carriers' anchorage times obtained were in line with standards too and with a notable correlation with the obtained throughput, showing that the terminal was behaving in a healthy way.

Convergence and warm-up time

To use a simulation model effectively, it's essential to have accurate performance metrics. This necessitates making decisions in two critical areas: warm-up period and the number of replications. To determine the duration and frequency needed for the simulation model to yield satisfactory results, these aspects must be thoroughly examined.
It is important to underline that the study of these parameters and their values is not relevant to the model in general but only to a specific set up. Every time the set up of the system, thus the simulation input, are varied this study has to be repeated, producing results ans insights to be taken into account the single simulation study.
However, the process to determine these parameters during the validation is reported here as an example and to give some general insights about the performance of the model.
The study of the convergence of a model deals with the determination of the number of replications (a replication is a simulation run of a set-up in which the random seed used to generate stochastic variable is changed) in order to obtain trustful results regarding a specific simulation output.
Amongst the many methods to do so the popular half-width ratio method was selected. The following paragraph described the method and its application.
Starting from a population of n_0 replications, and thus with n_0 sampled values of an output variable T, the average $\overline{T}$ and an estimation of standard deviation s can be obtained according to the following equations:

$$\overline{T} = \frac{1}{n_0} \sum_{i=1}^{n_0} T_i \tag{7.1}$$

$$s^2 = \frac{1}{n_0 - 1} \sum_{1}^{n_0} \left(T_i - \overline{T}\right) \tag{7.2}$$

Using these values the half width confidence interval for a certain confidence level can be calculated utilising the following equation and the t-student table:

$$h_0 = t_{1-(\alpha/2), n_0 - 1} \frac{s}{\sqrt{n_0}} \tag{7.3}$$

A confidence interval is the mean of an estimate plus and minus the variation in that estimate. This is the range of values in which the estimate is expected to fall between if a simulation is done again, within a certain level of confidence. The half width confidence interval is the absolute value of the variation around the average, and thus it represents an error bound.
In other words, if a half width interval of h_0 is found from n_0 samples of variable T, obtained from n_0 repetitions, with a confidence level of 95%, it is expected that the value of T obtained from repetition $n_0 + 1$ will fall in the interval $[\overline{T} - h_0, \overline{T} - h_0]$ with a confidence level of 95%. This information is of paramount importance when evaluating the outcome of a simulation study, since it gives fundamental insights on the accuracy of the study.
Determining how many repetitions are needed in order to obtain an acceptable (negligible with respect to the specific simulated system) error bound is the ultimate goal of a convergence study.
Since the relation between number and repetitions and the half width can be approximated by a quadratic behavior, the following equation allows to estimate the number of repetitions needed n to obtain the desired half width interval h based on an initial run and repetitions and the consequent half width interval:

$$n = n_0 \left(\frac{h_0}{h}\right)^2 \tag{7.4}$$

By applying this method the number of replications to ensure a 95% confidence interval with an error bound of ± 10000 T on the difference between obtained and generated throughput for simulation

with a generated throughput in the range 0.7-0.9 MT was estimated.
From the initial pilot run with $n_0 = 10$, an error bound of $h_0 = 20377\ T$ was found. Based on this it was estimated that in order to obtain an error bound of ± 10000 T a total of 41 repetitions is needed.
Another issue when dealing with a simulation study is the determination of the warm-up period. According to [9] systems can be divided in terminating (finite horizon) or non-terminating (infinite horizon) ones. In the former, the duration of the simulation is fixed as a natural consequence of the model and its assumptions. The duration can be fixed by specifying a finite length of time to simulate or by limiting the number of entities created or disposed. By definition, a terminating system is one that has a fixed starting condition and an event definition that marks the end of the simulation. The system returns to the fixed initial condition, usually ”empty and idle,” before the system begins operation again. The objective of the simulation of terminating systems is to understand system behavior for a ”typical” fixed duration. An example of a terminating system is a bank that opens at 9: 00 A.M. and closes at 4: 00 P.M. or a ticket booth that remains open until all the tickets are sold or the event begins.
On the other hand, in a non-terminating (infinite horizon) system, the duration is not finite; the system is in perpetual operation. An example of a non-terminating system is an assembly line that operates 24 hours a day, 7 days a week. The objective in simulating a non-terminating system is to understand the long-run, or steady-state, behavior. To study steady-state behavior accurately, the effects of the initial conditions, or transient phase, must be removed from the simulation results.
It is clear then, that when dealing with an infinite horizon system such as the one described in this work, determining the length of the warm-up period becomes essential in order to have trustworthy results.
In [104], a graphic approach to the problem was proposed, called Welch Plot.
Starting from a number R of replications, with $R \geq 5$, let $T_{r,j}$ be the be the j^{th} observation on replication r for $j = 1, 2, ..., n$ where n is the total number of observations per replication and $r = 1, 2, ...R$.
Averages across replications can thus be calculated according to the equation:

$$\overline{T}_j = \frac{1}{R} \sum_{r=1}^{R} T_{r,j} \tag{7.5}$$

After applying smoothing techniques to the series of values obtained, a visual assessment of the convergence of the observed data is possible.
Applying the just described method and selecting a cumulative average as a smoothing technique to 720 observations of the amount of stored materials in the terminal (taken as the best estimator of steady state performance) across the 10 simulations used in the convergence procedure, the Welch Plot reported in Fig. 7.3 was obtained.

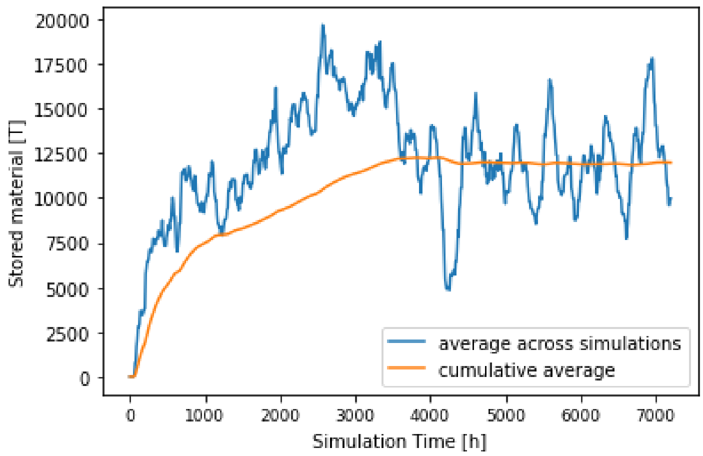

Figure 7.3: Storage levels Welch plot

Observing Fig. 7.3 it can be assessed that the system starts to report steady state related outputs after approximately 4500 hours.
Furthermore, a second method to investigate the warm up period of the system was applied. This

method is based on the analysis of the slope of the function obtained by applying linear regression to the same set of data.
Looking at these values allows to understand the trend in the total amount of material stored in the terminal. In a steady state behaviour, it is expected that the amount stored in the terminal fluctuates around a constant value, without a marked decreasing or increasing pattern. Finding thus a sub-period of the simulation (obtained excluding only data previous to the specific sub-period) in which the stored amount is approximated by a linear regression with slope equal to 0 is deemed to be a valid hint to the start of the steady state behaviour period and thus to the length of the warm-up one.

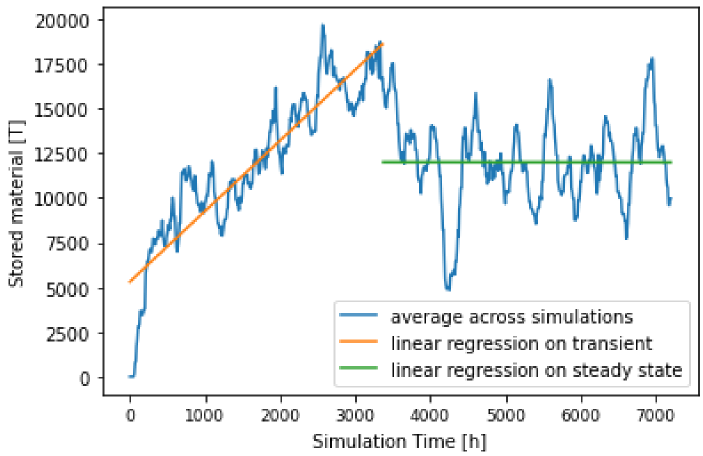

Figure 7.4: Storage levels linear regression approximation

Fig. 7.4 reports the results obtained through this method, showing that it is possible to find a sub-period with the characteristics previously defined already with a starting time of $t = 3500h$.
It is important to underline that correctly individuating the warm-up period of a simulation is essential when the objective of a simulation study is to obtain an estimation of steady state parameters. However, it can sometime be that the simulation study has as objective the better understanding of the transient behaviour of the system. In fact, being the tool presented in this work able to change inputs during the same distribution one of its innovative application could be the study of transients. For example, the change of behaviour of a terminal when the IATs vary because of seasonality could be an interesting study of a transient. In these cases, there is no need to study the warm-up period of the simulation runs while close attention should be given to the accurate modelling of the rate of change of the transient.

7.2.2. Export

The Export Case Study to which the model was applied concerns a wheat export terminal with an average yearly throughput of 3.6 MT between 2007 and 2019, with peaks of 5 MT. The following paragraph summarises the terminal's layout, and it was modelled in this work.

- Quay
  The quay of the terminal is 310 m long and is served by a conveyor gallery 296 m long, according to the terminal operator this makes it possible to unload two carriers of a maximum length of 130 m simultaneously.
- Seaside equipment
  The seaside pieces of equipment available to the terminal are two continuous loaders with rated a capacity of 800 T/h each.
- Conveying lines
  Two 500 m long main conveying lines with 800 T/h capacity respectively connect the storage to the seaside of the terminal.

The layout of the conveying system connecting the landside allows all train and truck unloading stations to unload simultaneously in all the silos composing the storage. The lines interacting with the train stations have a capacity of 800 T/h while the ones serving the truck stations of 400 T/h.

- Storage
  The storage facilities of the terminal consist of 4 silos of 1 kT, 3 silos of 10.6 kT, and 7 silos of 14.3 kT. In the real system, the 4 smaller silos are used as a buffer between the actual storage and the truck stations, since truck arrivals are relatively intermittent. Since this operational policy is not available in the developed tool, the 4 silos were added to the normal storage.
- Landside equipment
  Concerning the Landside, the terminal is provided with 3 truck unloading stations with an average capacity of 200 T/h and 3 train unloading stations with an average capacity of 800 T/h. As already stated each station can serve any of the silos while the other stations are functioning too.

The data made available were the following:

- Seaside arrivals log
  The carriers' arrival log of the terminal was the most important data obtained from this system. The dataset reported arrival times and amounts of each cargo for the years 2016-18. With this data, it was possible to generate distribution for the IATs and the arriving cargoes.
  Furthermore, the operational time of each carrier was reported in this dataset, allowing the generation of loading capacity distributions. However, the operational times reported include stops due to breakdown and other operational reasons, that were thus not taken into consideration in the simulation set-up.

- Landside arrivals data
  Due to the amount of information that would be stored in it due to the enormous amount of trucks and wagons served, no landside arrivals log was available. However, some data about the visiting importing entities was obtainable.
  From these data, it was possible to derive the average size of trucks and wagons arriving at the terminal and their monthly amount, from which their average IAT was derived.
  Furthermore, the yearly modality split amongst rails and roads was obtained from this dataset.

- Operational information
  The terminal provided some operational information as well.
  Very surprisingly, the demurrage costs are not paid by the terminal managing firm and thus a carrier waiting time of 6-8 days is in line with normal operations. On another note, the average dwell time of a parcel in the terminal is 8 days.
  Furthermore, weather downtime is expected to take up to 5% total year time, divided between January and March.

As in the previous case the chosen method to validate the model based on the data provided was to compare the obtained throughput with the generated one while monitoring utilisation KPIs, in particular the average waiting time of carriers.
Furthermore, the terminal energy consumption was compared with the one provided by the terminal. Fig 7.5 and 7.6 show the results of 10 simulation runs, the first based on historical vessels' arrivals from the year 2016-17, the remaining 9 using distributions obtained from the historical data.

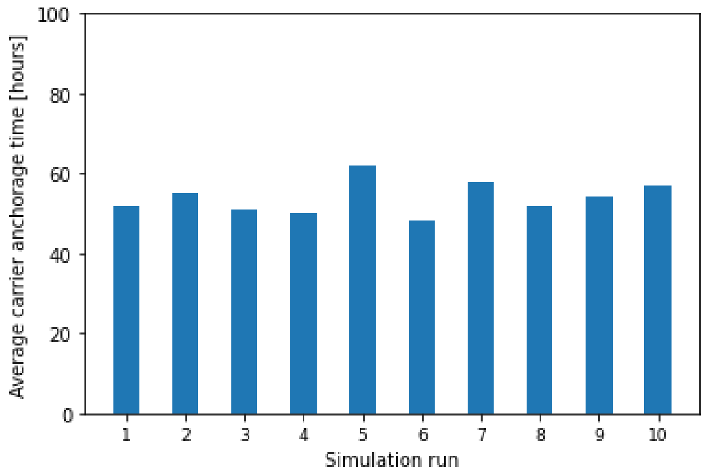

Figure 7.5: Carriers average waiting time

As stated in 5.7.4, carriers' waiting times are not representative of the general terminal performance in the import model, since they mostly depend on the input given by the users about the "campaign time". However, this output can still provide useful information on the performance of the landside sub-system. The fact that the average carriers' waiting time is consistently acceptable among simulations with quite different generated throughputs reflects that the landside sub-system is performing in a proper way. In fact, with the campaign times chosen in the set-up, low carriers' waiting times show that the parcels requested are almost always already completely present in the terminal and the anchorage time imposed on the carriers is due only to the loading process. This information (confirmed by animation checks) proved to be very valuable in the analysis of the throughput data, as explained in the following paragraph.

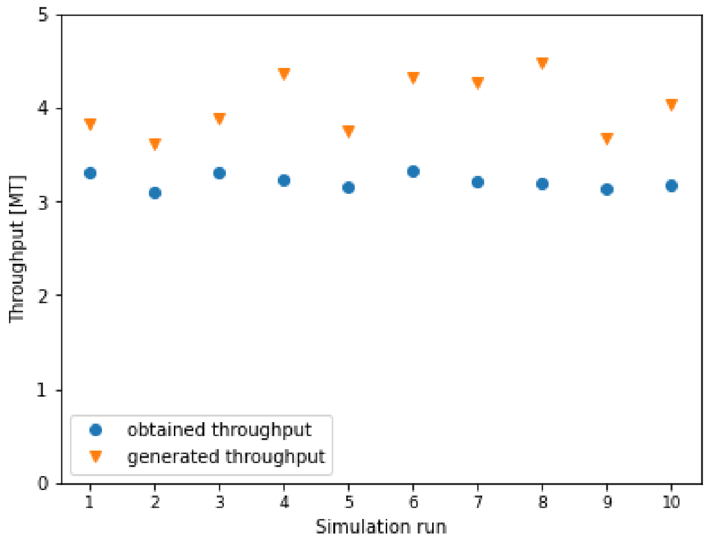

Figure 7.6: Throughput validation results

What is fundamental to analyse in order to understand the terminal performance and during the validation process the model one is the comparison between achieved throughput and generated one. In fact, the difference between these two values represents the amount of cargo that was reneged since not enough space was available in the storage.
Fig **??** shows how the model reports an underperformance of the system in comparison with real-world data, setting the maximum yearly throughput around 3.1 MT. It is important to keep in mind that the

most important data point is the one reported in the simulation run based on the historical data. The performance shown in that specific case is still within the limit proposed in the scope of this project, and the other data points are relatively in line as well. The results obtained are thus still satisfying, even if of lesser quality in comparison with the ones obtained with the import model.
At first glance, the discrepancy just described and thus the lower validness of the export model in comparison with the import was attributed to the complexity of the landside sub-system and the consequent difficulty in capturing it with this generic tool.
In the particular case of the terminal analysed, the real system features various policies to optimise the intake of material from the two different modalities serving the landside. Through the utilisation of buffer bins, direct unloading of trains in the main storage was prioritised in respect of trucks unloading. The material unloaded by trucks is then periodically moved towards the main storage once the buffer bins are completely filled, not hindering the movement of materials from the train stations to the main storage. This simple expedient makes the unloading of both modalities possible at the same time while decreasing the intake time of parcels in comparison with the one obtained in the simulation environment.
However, the previously analysed low anchorage times pointed in another direction. In fact, if the landside sub-system was under-performing as described in the previous paragraph much higher anchorage times would be given as results by the model, due to the fact that the requested parcel was not yet fully present in the terminal at the ship arrival.
For this reason, it is thought that the loading distribution obtained by the terminal data was not fully corrected by the exclusion of breakdowns in the simulation set-up, bringing the simulated system to work with two underperforming fundamental pieces of equipment and thus emptying the storage at a much lower rate than the real system. This entailed that the silos were occupied for longer times and thus not available to allocate incoming parcels. A series of new experiments was thus carried on with modified distributions, more in line with efficiencies commonly assumed in the sector (80%).

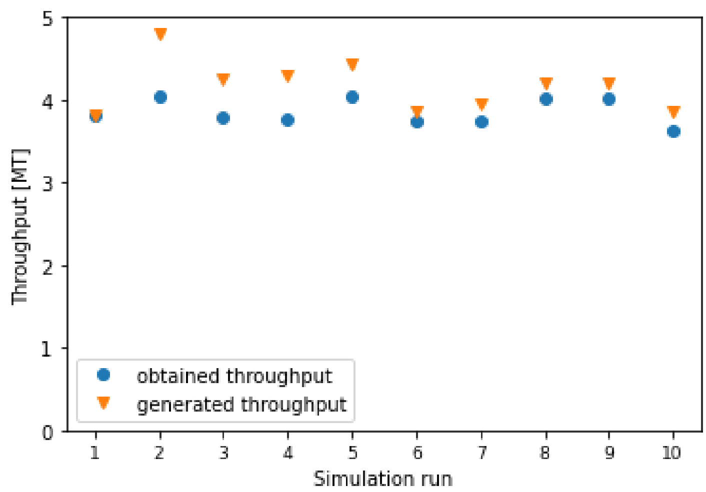

Figure 7.7: Throughput results with improved loading distribution

The results shown in Fig 7.7 support the previously made hypothesis. In particular, the first data point shows how in the the results obtained with the historical data set the obtained throughput coincides with the generated one.

8
Experiments

8.1. Terminal performances

The model was used to carry out a series of experiments on the terminal described in Study Case 1.
In order to understand which of the various resources present in the terminal has the strongest impact on its performance, it was decided to investigate the terminal behaviours varying and their characteristics.
As already stated the terminal can be divided into three different subsystems each of them with its importance for the healthy behaviour of the terminal. Each of them has an installed capacity either for loading, unloading, or storing. The performance of the terminal varying two of these three capacities was investigated.
Two different kinds of variations in the capacity of each of the analysed subsystems were performed, one from a quantitative point of view and one from a flexibility one. In the former, the capacity of each of the servers (unloaders or bins) was changed in value, keeping the number of servers constant. In the latter, the opposite operation was performed, keeping constant the capacity of the whole subsystem but varying the one of the single servers, and thus their number.
In all cases, the routing system was modified to the best of the author's capacity in order to make operations run as smoothly as possible.

8.1.1. Seaside

The first subsystem analysed was the Seaside one, in which the servers are represented by the unloaders.
In the first series of experiments, the capacity of each unloader was multiplied by four different factors, maintaining a fixed throughput.

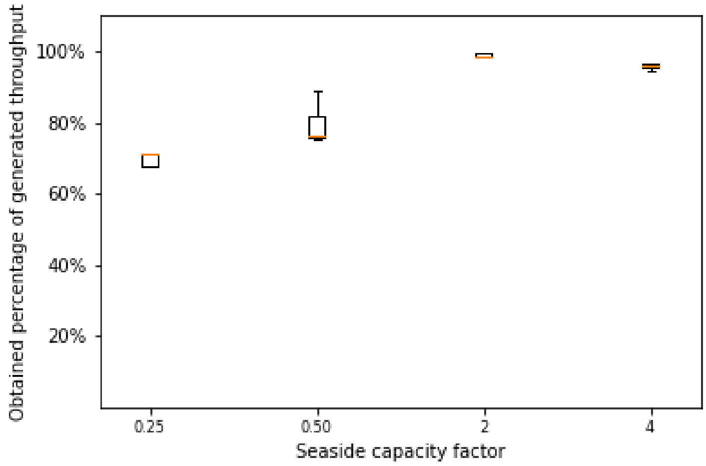

Figure 8.1: Seaside capacity investigation results

The results reported in 8.1 show how a smaller capacity highly affects the terminal performance hindering its capacity to obtain the objective throughput. On the other hand, augmenting the capacity of the unloaders doesn't improve the terminal because of the fixed throughput constraint imposed on the experiments.
In the second series of experiments, four different scenarios were created, selecting the capacities and rated powers of existing pieces of equipment and combining them in order to obtain the capacity of the original system. The specifics are reported in 8.1.

n. unloaders	capacity [T/h]	rated power [kW]	specific consumption [kW/T]
3	800	540 - 500	0.675 - 0.625
2	1600 - 800	855 - 500	0.53 - 0.625
6	400	320	0.8
4	600	500	0.83

Table 8.1: Unloading capacity specifications

Interestingly, Fig. 8.2 shows that the general terminal performance is not altered by this variation in the flexibility of the seaside subsystem. In fact, having the same total installed capacity and having modified the routing system in order to allow operations of each unloader at the same time, the terminal is able to achieve the set throughput.

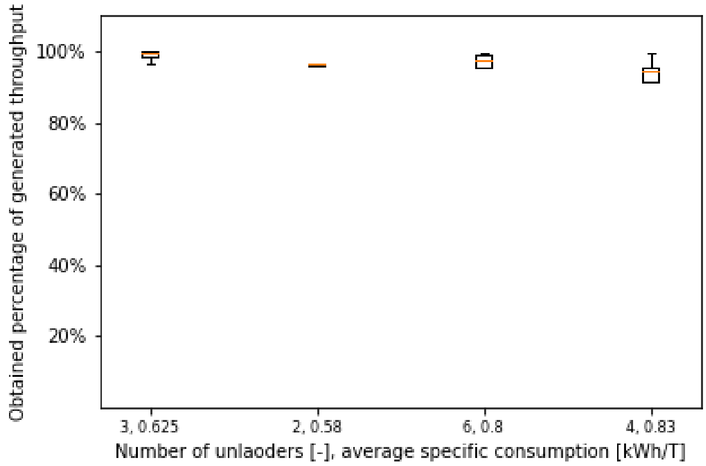

Figure 8.2: Seaside number of servers investigation results

Since not only the capacity but also the rated power and thus the specific consumption of the unloaders was varied, the energy consumption of the terminal in the different scenarios was analysed.

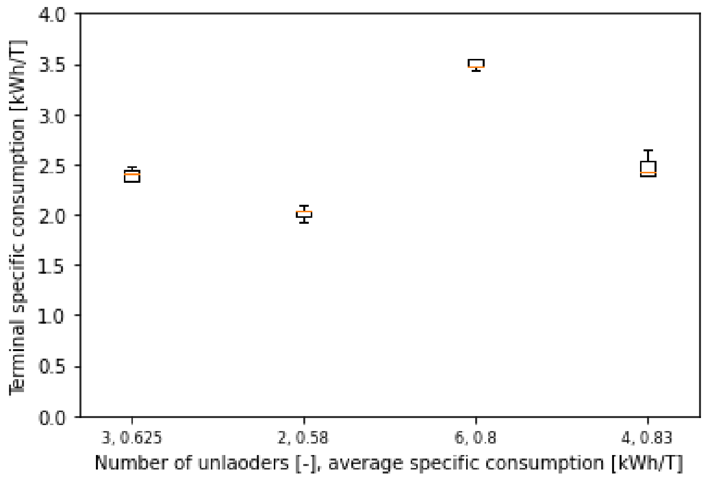

Figure 8.3: Seaside number of servers energy investigation results

As expected, scenarios with a higher average specific consumption lead to a higher amount of energy consumed in order to perform operations. However, the number of unloaders results in an effect on the energy consumption as well. This was attributed to the changes made to the routing system, which, featuring a larger amount of smaller conveyors, has a lower efficiency, leading to higher energy consumption. This explanation is also supported by the results shown in 8.4, showing the percentage of energy used by the unloading system becomes lower when more unloaders are put in place.

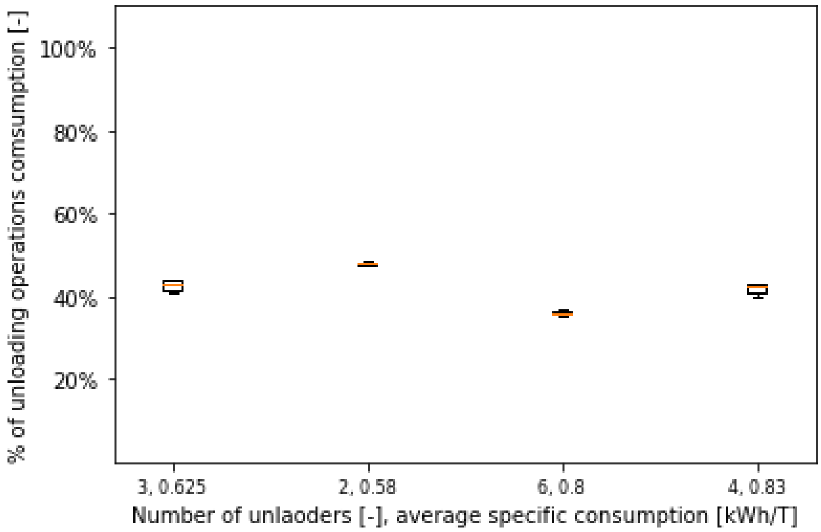

Figure 8.4: Seaside number of servers consumption percentage investigation results

8.1.2. Stockyard

Experiments concerning the stockyard subsystem followed the fashion of the ones performed on the seaside. A first series of scenarios were created by multiplying the capacity of each silo by a factor, thus varying the total capacity of the terminal, and leaving the throughput constant.

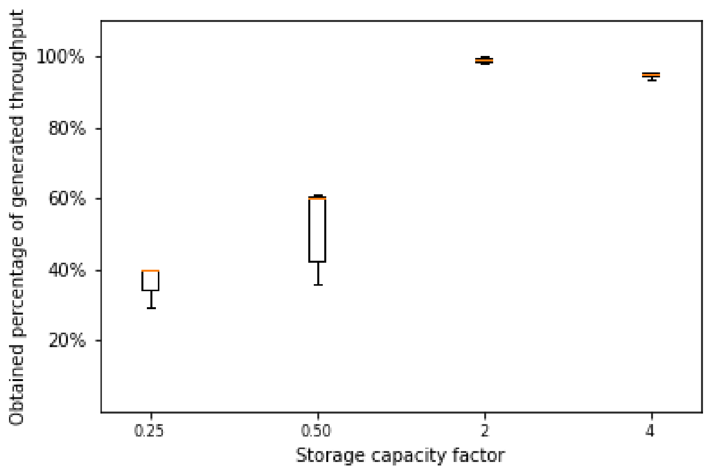

Figure 8.5: Storage capacity investigation results

The results reported in Fig.8.5 show how the reduction of the total capacity of the stockyard has a very high influence on the performance of the terminal, leading to greater disruptions than the one seen in the previous analysis. Again on the other hand, augmenting the stockyard capacity did not achieve any improvement because of the fixed throughput constraint.

In order to create the second series of experiments, the total number of silos in the terminal was modified by multiplying it by four different factors. In order to keep the total capacity constant, the capacity of each bin was multiplied by the inverse of the relative factor.

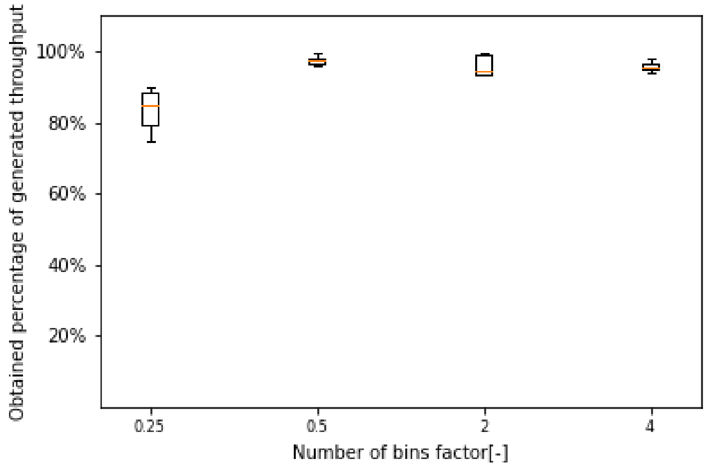

Figure 8.6: Storages number investigation results

Conversely to what was seen in the seaside experiments, if the number of silos inside the terminal is reduced too much while keeping the total capacity constant, operations are relatively hindered. This happened because bins are occupied for longer times by smaller amounts of parcels, not allowing new cargo to be unloaded in the terminal.

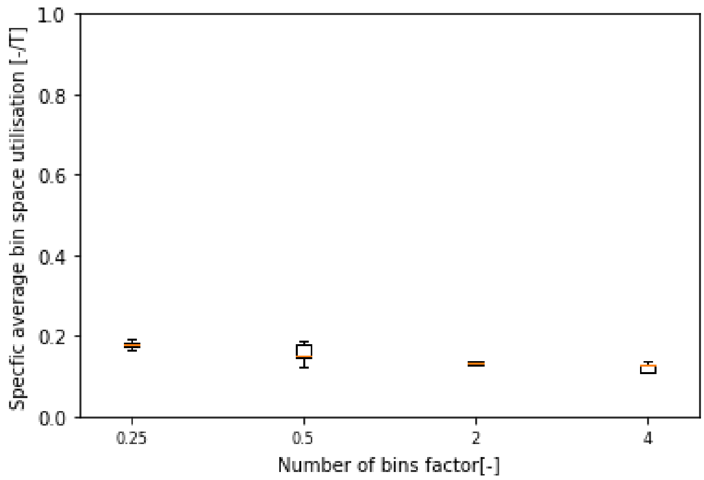

Figure 8.7: Storages number investigation results

To get more insights into these experiments the specific average bin space utilisation (defined in 8.1) was analysed.

$$u = \frac{\sum_s \sum_i \frac{a_{i,s}}{C_s} \frac{\Delta t_{i,s}}{s_t}}{n} \frac{1}{T} \tag{8.1}$$

Where n is the number of silos, $a_{i,s}$ is the amount is silo s in time step i, $\Delta t_{i,s}$ is the duration of time step i of silo s (that varies dynamically based on material movement), C_s is the capacity of silo s, s_t is the total simulation time, and T is the total obtained throughput.
This index permits us to look at the stockyard as one large storage bin and analyse its behaviour. Results shown in Fig.8.7 display how the difference in the size of the bins does not have a great influence on the average amount of material stored in the bins during time. In fact, considering that the value of this index for a silo that is continuously loaded and unloaded at the same rate should be 0.5, the results show that the storage faces longer times in which its utilisation is lower than 50%. In other words, the reason for such a high capacity is only the possibility of handling peaks of stored material when large

carriers arrive, while most of the time the storage is underutilized.
This result shows once more that the reason for such an imposing infrastructure is the decoupling role between modalities of different sizes. It is clear that better coordination (in time and size) between the two branches of the supply chain would lead to the possibility of handling the same throughput with smaller infrastructures.
The slight plummet of the index towards lower values as the number of silos increases is due to the fact that smaller silos are filled up and emptied more often than larger ones, reporting thus in the index a much larger amount of zeros that lower the average.

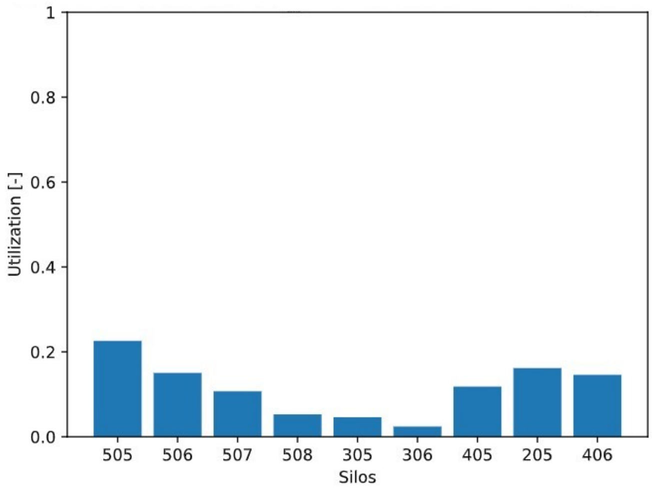

Figure 8.8: Storage capacity investigation results

Fig. 8.8 and 8.9 depict how this index behaves in two of the simulation runs, showing how silos of different sizes behave differently. The smaller silos show more disperse values due to the continuous loading and unloading happening due to their size and number, while the large ones show more regular values since loading and unloading operations lead to complete emptiness more rarely than in the other case.

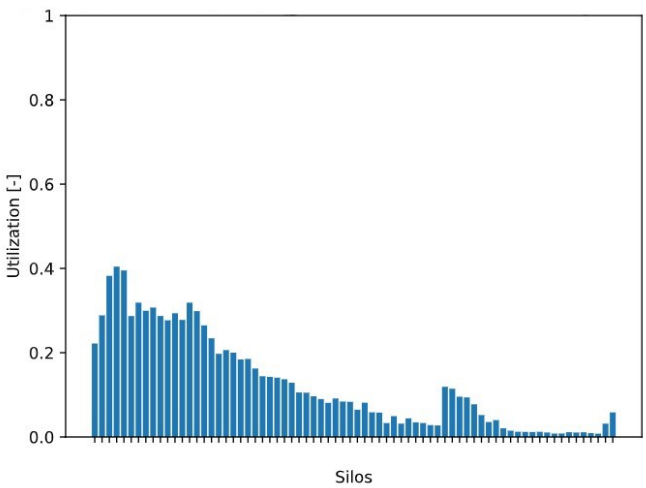

Figure 8.9: Storage capacity investigation results

8.2. Emission reducing operations

To show the capabilities of the model to capture the behaviour of the system when introducing the energy-reducing operations discussed in 4.2, the set-up of Case Study 1 was modified accordingly and tested.

8.2.1. Shore power

Given the berth size of the terminal and the restrictions it imposes on the amount of carriers that can be unloaded at the same time two different possible set-ups were investigated, the first in which only one shore power connection capable of serving both berths was added to the system and the second in which two different shore power connections were added, each one serving one berth.
As suggested in 5.8.1, the data relative to the auxiliary installed power on carriers were taken by [40] based on the carrier's DWT.
Furthermore, the fleet composition was changed along the different simulation runs, varying the number of carriers visiting the terminal equipped to be served by a shore power connection.

$$C_{ratio} = \frac{connection\ time}{berth\ time} \tag{8.2}$$

Given the small number of carriers with a length under 130m, and thus allowing simultaneous operations at the berth, the difference between the two shore power set-ups was unnoticeable. All the carriers allowing shore power connection were served in all the different simulations, with a connection ratio (defined in 8.2) of around 0.98, perfectly in line with the input given regarding shore power connections set-up times.
Other results from this investigation are shown in Fig. 8.10,8.11,8.12 and8.13.

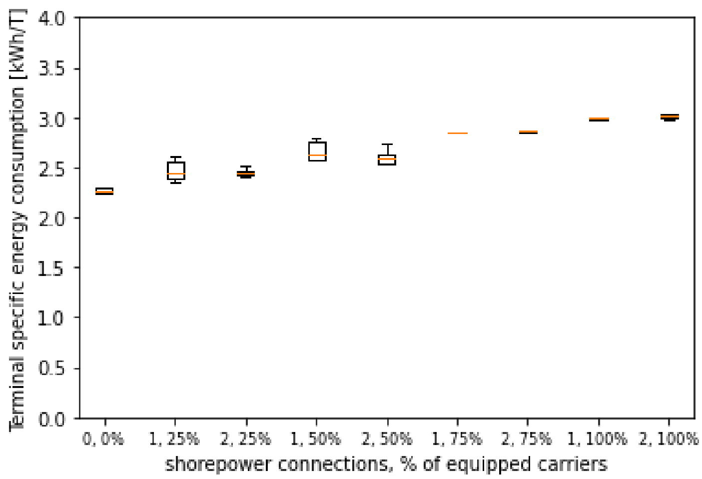

Figure 8.10: Terminal specific energy consumption

Adding the possibility of connecting to the terminal's grid, is it obvious that the terminal energy consumption will increase due to the supply of electricity to the carriers. Fig 8.10 reports the variation of the terminal-specific energy consumption along the different simulation runs, showing the predictable increase of energy consumption at the increase of the percentage of shore power-equipped carriers visiting the terminal.
Furthermore, Fig. 8.11 depicts the share of the total energy consumption of the terminal attributed to shore power connections utilisation. This kind of information is essential to understand what changes will have to happen to the electrical grid of a terminal in order to be able to provide this service to different percentages of the visiting carriers.

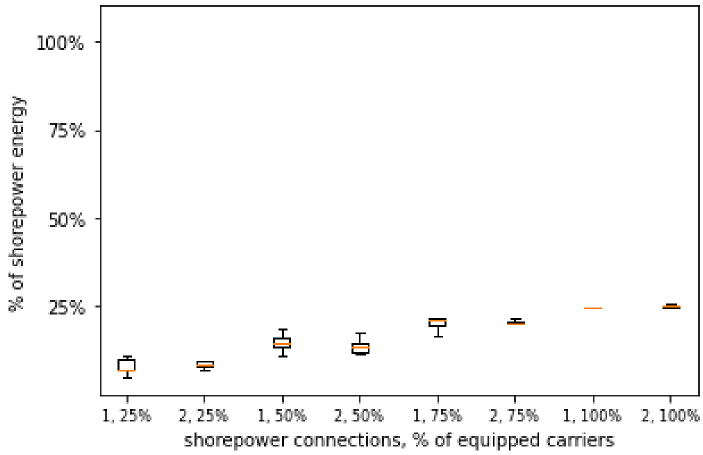

Figure 8.11: Percentage of shore energy consumption

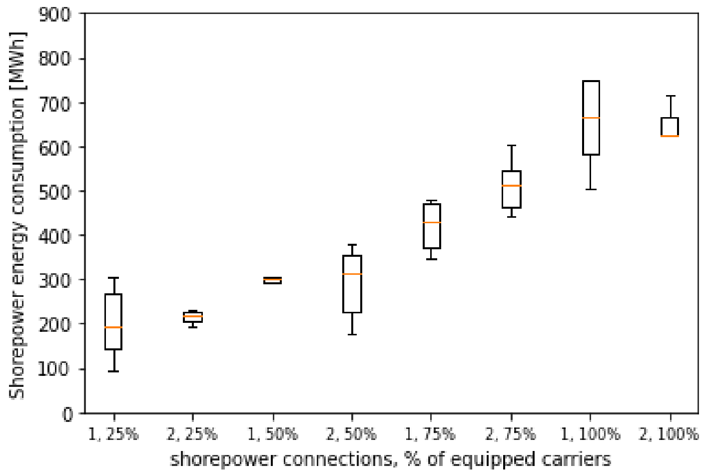

Figure 8.12: Shore energy consumption

Lastly, Fig. 8.12 and 8.13 show quantification of the previously discussed phenomenon. The former gives some specific values to the energy consumption of the shore power process while the latter transposes the energy provided into CO2 emissions relocated to the energy production industry, utilising conversion data from [40].

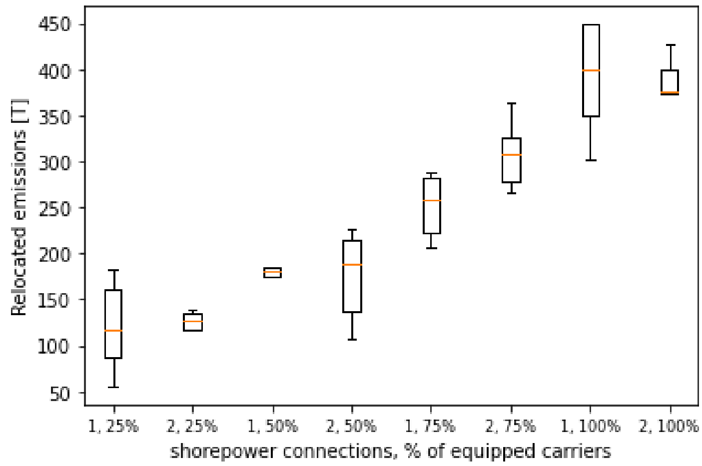

Figure 8.13: CO2 emissions relocation

8.2.2. Wind-assited shipping

To test the effects of wind-assisted carriers visiting the terminal, similar experiments to the one described in the previous sections were carried out.
As stated in 4.2.2, no changes should take place in the terminal in order to be able to serve carriers equipped with wind propulsion technologies, thus the only varying input amongst the different simulation runs was the percentage of wind-assisted carriers visiting the terminal. Furthermore, a hindering coefficient of 0.7 was set to alter the capacity of the unloaders interacting with these ships.

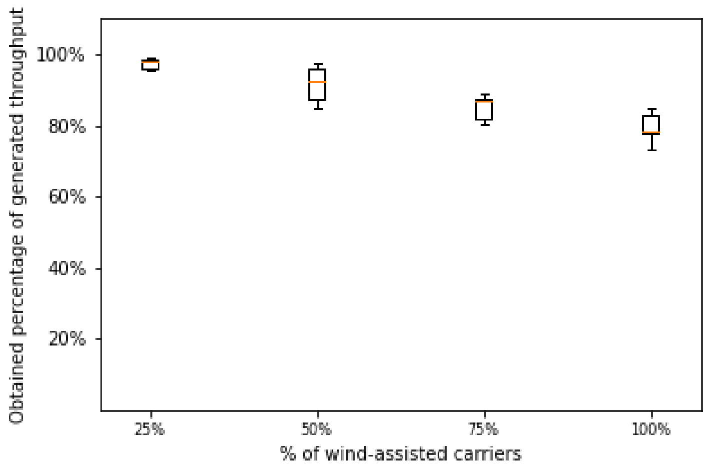

Figure 8.14: Obtained throughput for fleets characterised by different wind-assisted carriers percentage

As expected, the results shown in Fig. 8.14 underline how the service of wind-assisted carriers slows down terminal operations on the seaside, reducing the throughput capacity of the terminal. As stated in 4.2.2

8.3. Common Industrial Practices

As in many other sectors dealing with complex systems, the design of dry bulk terminals is strongly based on common industrial practices. Handbooks such as [103] and [51] provided a huge variety of factors and rules of thumb that are normally applied in this field, obtaining results that are in line with the necessities of the systems.
For example, the total capacity of a terminal is normally set on the common benchmark rules that a

terminal performs a turnover between 12 and 24 times a year (the yearly throughput is between 12 and 24 times the total capacity) and that in order to be able to serve carriers timely a minimum capacity of one and half the DWT of the largest served carrier should be available in the terminal.
However valid these practices could be, in a world in which the efficient allocation of resources becomes every day more important for both economic and environmental reasons, a review and investigation of the most common (and vague) used design rules would surely bring benefits.
As a first small step, in this work, the initial design obtained through static calculations based on these common practices of a terminal commissioned to RHDHV was simulated and its performance was analysed.
The following paragraph summarises the terminal's suggested layout, and how it was obtained.

- Quay
  The length of the maximum carrier that will be served at the terminal amounts to 255m, thus the quay has to be at least of this length. In the simulation, the quay was thus discretised into two berths each of 122.5m each.
- Seaside equipment
  One of the possible equipment selections proposed by RHDHV engineers features two mechanical continuous unloaders with a capacity of 900 T/h each.
- Conveying lines
  Two conveying lines with 900 T/h capacity respectively connect the seaside of the terminal to the storage and landside.
  It is assumed that by proper design of the system, the two main conveying lines are connected to all the terminal's silos not constraining the choice of the line based on the storage destination of the parcel.
- Storage
  The targeted throughput in the first phase of the project amounts to 1.2 MT per year. According to the previously mentioned 12-24 rule, the total storage capacity should amount to 0.5-1MT. Furthermore, in the first phase of the project, the largest servable ship DWT amounts to 45 kT leading to a minimum required storage of 0.67 MT. The storage was thus designed with a capacity of 0.68 MT divided into 12 5000 T and 4 2000 T silos.
- Landside equipment
  Concerning the Landside, the terminal is provided with 4 truck loading stations with an average capacity of 200 T/h. This number is obtained by dividing the yearly throughput by the truck size thus obtaining the yearly number of trucks, and consequently the trucks per day. Multiplying this number by the rule of thumb peak coefficient 1.5, the peak number of trucks is obtained. Using this number and the service and transit time of each truck and dividing it by daily working hours, the needed number of stations is obtained.

Other assumptions about the terminal and the relative rework in order to utilise them in the simulation model are reported in the next paragraph.

- Seaside arrivals
  It was assumed that the arriving carrier could have a DWT of 35 or 45 kT, with the cargo divided into 4 or 5 holds respectively. The methodology described in 5.6.4 was applied to this data, obtaining an average IAT of 297 h, used as the mean for an Eralng II distribution.
- Landside arrivals
  The only assumption made for landside arrivals was the truck size of 35 T. In order to model the dwell time and outtake time of the parcels the distributions from Case Study 1 were used since the yearly throughput is similar.

Fig. 8.8 shows that the terminal designed has a healthy behaviour, being able to achieve the desired throughput in all the simulation runs.

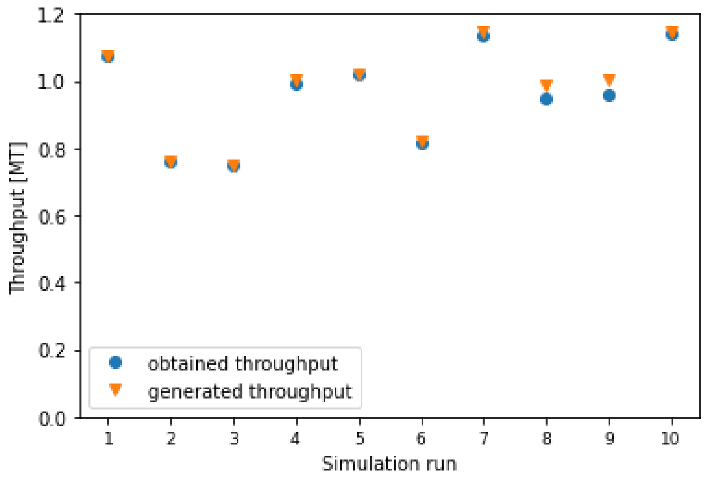

Figure 8.15: Obtained throughput in different simulation runs

As depicted in Fig. 8.16, exceptionally good average waiting times were obtained by the simulated system leading to thinking that the seaside infrastructure was overestimated. However, the considered terminal shares the berth with other stakeholders in the region, making evaluation on this subsystem unsuitable when simulating only the designed system.

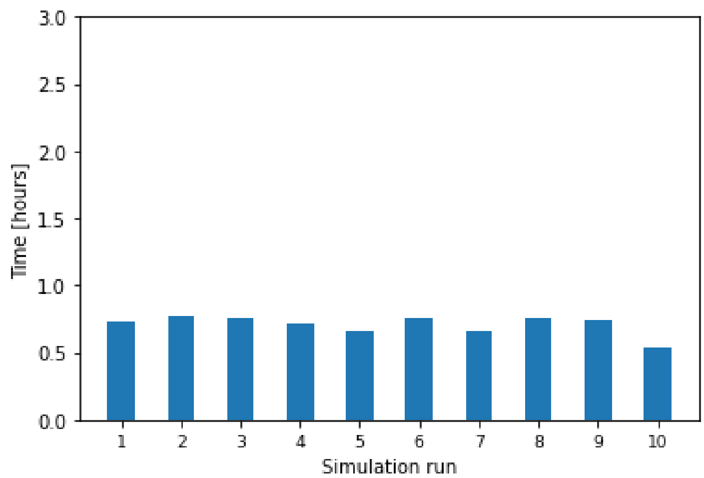

Figure 8.16: Average carrier anchorage time in different simulation runs

Lastly, the values reported in Fig. 8.17 show a satisfactory behaviour of the storage system, characterised by a strong link with the generated and obtained throughput.

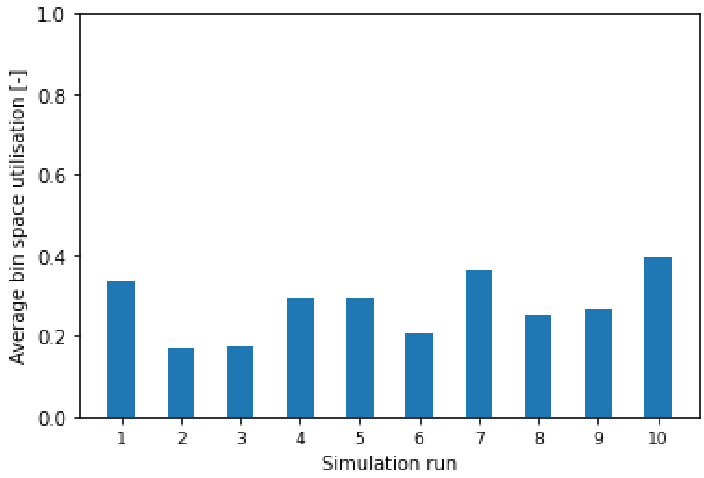

Figure 8.17: Average silo utilisation in different simulation runs

In order to validate or debunk the factors commonly used in the industry previously explained, a series of simulation runs were performed analysing systems in which those rules were not applied.

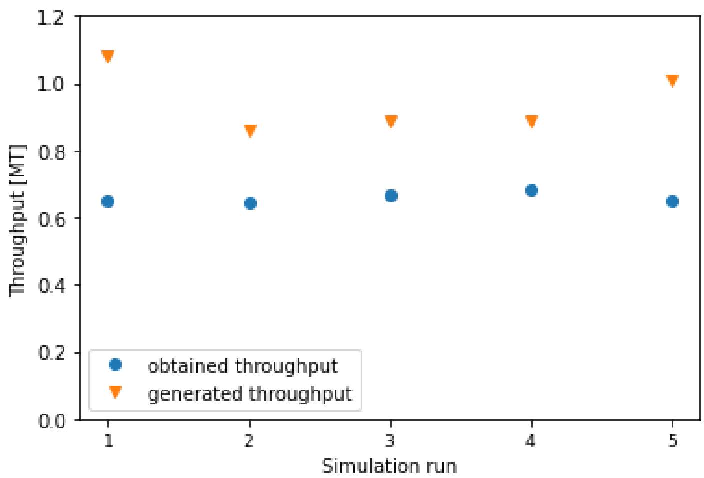

Figure 8.18: Obtained throughput in different simulation runs

Fig. 8.18 features the results obtained without applying the peak factor when calculating the necessary number of landslide stations, leading to 3 stations instead of four. The results show how the system severely under performs with this new setup, being able to reach approximately 50% of the targeted throughput.

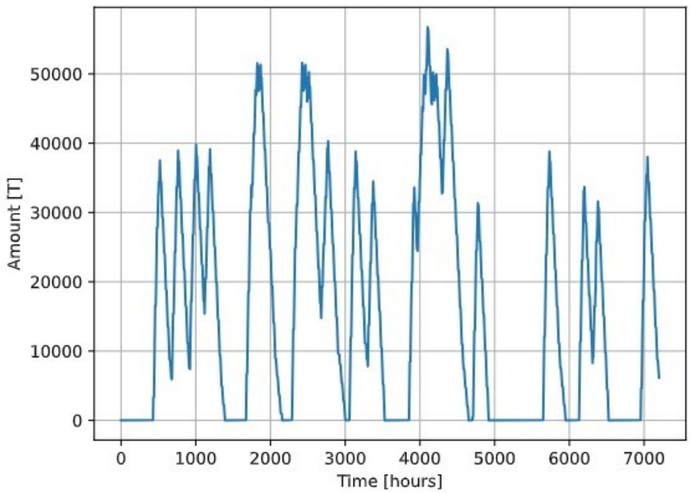

Figure 8.19: Simulation run 7 storage amount

Analysing the amount stored in the terminal along the original simulations it was noted that only in a few occasions during the year the terminal would reach maximum capacity. For this reason another series of simulations was carried out with a total capacity reduced to 0.52 MT.
The results reported in Fig.8.20 shows that, when the generated throughput equal the targeted one, the terminal does face some minor difficulties. Even thought this under performance could be explained by a carrier being served at the moment the simulation was stopped as already suggested in 7.2.1, it was not present in the simulation featuring the designed capacity, showing that the total capacity needed to properly perform is indeed better estimated by the design process conducted using the common industrial practices.

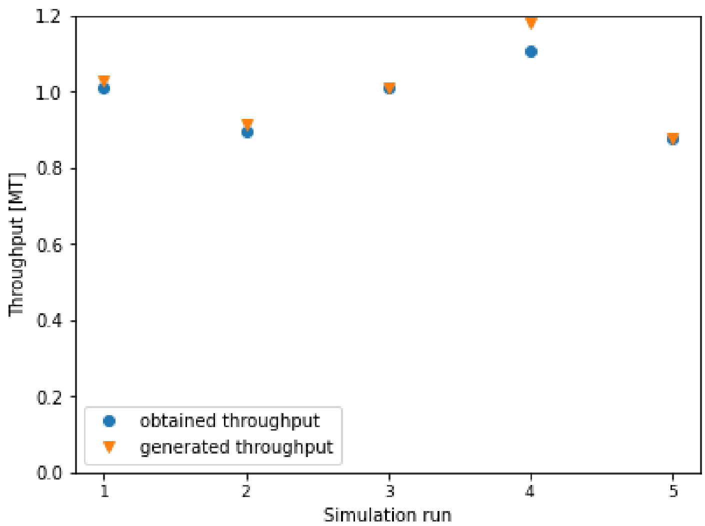

Figure 8.20: Obtained throughput in different simulation runs

These experiments showed how, even if not supported by much scientific proof, the utilisation of peak factors and other coefficients is fundamental to design appropriate systems. This shows that queuing theory and static calculations are able to capture the system behaviour only until a certain degree and thus the results obtained with these methods have to be tweaked in order to reach the targeted design objectives.

9 Conclusion and future work

The current work features the modelling and implementation of a generic DE simulation tool for grain terminals, involving emission-saving operations such as cold ironing and wind-assisted carriers' reception. In order to obtain this final objective, a literature study about simulation in both dry bulk terminals and other cargo terminals was performed, to understand the main challenges and trends of the sector. Furthermore, the operations typical to this system were accurately investigated, described and modelled through two different methodologies, the second of which focuses on the development of generic models and was developed in this work.
Along with the analysis of the normal operations of the system, the gaps for the implementation of GHG emissions-saving procedures and innovations were investigated, identifying the previously mentioned ones.
Verification and validation of the model are included in the work together with an accurate description of the model's working principles. Furthermore, the created tool was applied to different scenarios to gain insights into the analysed system and its behaviours, to understand to what extent the added emissions-saving operations would affect the system and what gains they would produce, and to validate or debunk common industrial practices of the field.
The developed model is able to capture the general behaviour of the system with good approximation while simplifying the simulation setup process, normally very cumbersome. Furthermore, the tool features standardised inputs and outputs, chosen according to the system needs and the common KPIs monitored when evaluating this kind of system. In addition, the model reports outputs concerning the energy consumption of the system, not often included in normal analysis.
The series of experiments carried out showed that the one analysed is a very complex system, acting as a major buffer in a fundamental supply chain. This last function obliges terminals to feature imposing infrastructures, fundamental to face peaks of arrivals but otherwise characterised by low utilisation. Moreover, the importance of seaside and storage capacity was analysed, showing how these two characteristics strongly affect terminal overall performances. The importance of the correct selection of seaside equipment and relative connecting routing system in order to achieve energy efficiency with respect to capacity, specific energy consumption, and number of pieces was underlined by the performed experiments too. Lastly, some quantitative results concerning the implementation of GHG emissions-reducing operations were obtained, showing that OPS could lead to the relocation of a substantial amount of emissions while increasing the energy consumption of the terminal in the range of 5-25% and that the reception of wind-assisted carriers will have relatively high detrimental effects on terminal performances if the considered coefficients are in line with real operations. Lastly, the utilisation of the common industrial practices was validated, showing that the avoidance of the use of the so-called rules of thumb leads to inefficient systems.
From these results it appears clear that smoothing of the supply chain through better coordination between the two different branches would allow terminals for smaller infrastructure and complexity, obtaining more efficient and less environmentally taxing systems. Furthermore, the implementation of shore power connections and wind-assisted carriers' reception would bring major improvements in the marine trade environmental impact, while necessitating great measures and investments to achieve their correct implementation without incurring in hindering the system's performance. With the employ-

ment of both these innovations terminals do not alter their direct environmental impact but allow their clients to reduce theirs. However, the adoption of the first technology would bring direct economic advantages to the terminals, making them energy supplier for the carriers at berth and thus creditable of a payment. On the other hand, the reception of wind-assisted carriers would only be a source of more inefficient operations for the terminal operators, making them major negative stakeholder in the implementation of this revolutionary technology. Attention of policy makers and market regulators will be needed in order to not hinder the commercial development of this new emissions-cutting trend.

However, this study is affected by a series of limitations. As for all simulation model, the results obtained by the one discussed in this work depend heavily on the input data available. If incomplete or inaccurate data is used to develop a simulation set-up, incomplete and inaccurate results will be obtained. Gathering accurate data of such economically and strategically import system is not always straightforward. If the specific data required to run the model is not obtained its performance are fairly hindered, an example of this is the loading distributions mentioned in the validation of the export model. Furthermore, an approximation was made on the density of the materials handled was made, considering all quantities by their weight and by their volume. The difference between the density values of the materials is not vast and thus it should not have led to major mistakes. However, given the amount of material handled, it could have a non-negligible effect on the system's behaviour.

From the environmental point of view, two major limitations were individuated. Firstly, the energy consumption monitoring method implemented in the model is based on a constant rated power value and coefficient. This choice is not in line with the utilisation of equipment capacity distribution and could lead to an overestimation of the consumed energy. Furthermore, the wind-assisted hindering coefficient was chosen in a relatively arbitrary manner, because of the complete lack of data about the operations. This could lead to unreliable results.

Nonetheless, it is believed that this tool could play an important role in the normal engineering process followed by RHDHV engineers, making high-level simulation an embedded and low-cost practice in the design and evaluation of terminals. Furthermore, the possibility of easily simulating the implementation of GHG emissions-saving operations could lead to a larger interest in both the engineers and the clients, enhancing the efforts to reach the energy efficiency needed to meet the current environmental needs.

Based on the work reported in this study many research lines could be followed in order to improve both the developed tool and the understanding of the analysed system. Firstly, the investigation and implementation of different operational policies and the possibility of choosing between them would surely enhance the tool's effectiveness, making it able to simulate different managerial choices done in different situations and thus analyse their effectiveness. Furthermore, embedding an optimised parcel allocation procedure would allow users to get further insight into the correct utilisation of such a fundamental resource for the system. Moreover, better modelling of the power consumption of equipment and the correct calibration of the coefficients used in this process and in the wind-assisted carriers' reception would give the tool more accuracy and adherence to reality when used to analyse those aspects of the system. Lastly, the experiments reported in this work barely scratch the surface of the possible application of this tool to gain better insights into the system performances and the shore power connections in particular. The use of the developed tool to analyse more complex layouts and scenarios would bring important results to better understand how these newly introduced operations would affect the terminal behaviours and what environmental gains could be obtained by their implementation.

Bibliography

[1] Afshin Abadi, Mithun Baphana, and Petros Ioannou. “Simulation models for evaluation of terminal operations and traffic flow on adjacent road network”. In: *IFAC Proceedings Volumes*. Vol. 42. IFAC Secretariat, 2009, pp. 129–134. ISBN: 9783902661500. DOI: `10.3182/20090902-3-US-2007.0091`.

[2] Anas S. Alamoush, Fabio Ballini, and Aykut I. Ölçer. “Ports’ technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review”. In: *Marine Pollution Bulletin* (2020).

[3] Nader R. Ammar and Ibrahim S. Seddiek. “Wind assisted propulsion system onboard ships: case study Flettner rotors”. In: *Ships and Offshore Structures* (2021).

[4] Gregory Atkinson, Hung Nguyen, and Jonathan Binns. “Considerations regarding the use of rigid sails on modern powered ships”. In: *Cogent Engineering* (2018).

[5] Nur Najihah Abu Bakar et al. “Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology”. In: *Renewable and Sustainable Energy Reviews* (2023).

[6] A. G. Progiou E. Bakeas et al. “Air pollutant emissions from Piraeus port: external costs and air quality levels”. In: *Transportation Research Part D: Transport and Environment* (2020).

[7] F. Ballini and R. Bozzo. “Air pollution from ships in ports: The socio-economic benefit of cold-ironing technology”. In: *Research in Transportation Business & Management* (2015).

[8] Fabio Ballini et al. “Health costs and economic impact of wind assisted ship propulsion”. In: *Ocean Engineering* (2017).

[9] Jerry Banks. *HANDBOOK OF SIMULATION*. John Wiley & Sons, 1998.

[10] G R Baunach, E S Wibberley, and B R Wood. “Simulation of a coal transshipment terminal: Batam Island, Idonesia”. In: *Mathematics and Computers in Simulation* 27 (1985), pp. 115–120.

[11] Christiaan De Beukelaer. “Tack to the future: is wind propulsion an ecomodernist or degrowth way to decarbonise maritime cargo transport?” In: *Climate Policy* (2021).

[12] Christian Bierwirth and Frank Meisel. “A follow-up survey of berth allocation and quay crane scheduling problems in container terminals”. In: *European Journal of Operational Research* 244 (3 Aug. 2015), pp. 675–689. ISSN: 03772217. DOI: `10.1016/j.ejor.2014.12.030`.

[13] G. Bordogna et al. “The effects of the aerodynamic interaction on the performance of two Flettner rotors”. In: *Journal of Wind Engineering & Industrial Aerodynamics* (2020).

[14] Evert A. Bouman et al. “State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review”. In: *Transportation Research Part D* (2017).

[15] Christos G. Cassandras and Stéphane Lafortune. *Introduction to Discrete Event Systems*. Kluwer Academic Publishers, 1999.

[16] Manuel Chica, Roberto Rivas Hermann, and Ning Lin. “Adopting different wind-assisted ship propulsion technologies as fleet retrofit: An agent-based modeling approach”. In: *Technological Forecasting & Social Change* (2023).

[17] Todd Chou et al. “A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology”. In: *Sustainability* (2021).

[18] Radu Cimpeanu, Mel T. Devine, and Conor O’Brien. “A simulation model for the management and expansion of extended port terminal operations”. In: *Transportation Research Part E: Logistics and Transportation Review* 98 (Feb. 2017), pp. 105–131. ISSN: 13665545. DOI: `10.1016/j.tre.2016.12.005`.

[19] Radu Cimpeanu et al. “Development and analysis of a port terminal loader model at RUSAL Aughinish”. In: *Simulation Modelling Practice and Theory* 51 (2015), pp. 14–30. ISSN: 1569190X. DOI: 10.1016/j.simpat.2014.11.001.

[20] Systems Modelling Corporation. *Arena*. 2000.

[21] Pablo Cortés et al. “Simulation of freight traffic in the Seville inland port”. In: *Simulation Modelling Practice and Theory* 15 (3 Mar. 2007), pp. 256–271. ISSN: 1569190X. DOI: 10.1016/j.simpat.2006.11.004.

[22] M. Crippa et al. *GHG emissions of all world countries*. Tech. rep. Publications Office of the European Union, 2023.

[23] I. Dafnomilis et al. “Optimal equipment deployment for biomass terminal operations”. In: *Transportation Research Part E: Logistics and Transportation Review* 115 (July 2018), pp. 147–163. ISSN: 13665545. DOI: 10.1016/j.tre.2018.05.001.

[24] Keshav P. Dahal et al. “A port system simulation facility with an optimisation capability”. In: *International Journal of Computational Intelligence and Applications* 3 (4 2003), pp. 395–410.

[25] S. B. Dalsøren et al. “Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports”. In: *Atmospheric Chemistry and Physics* (2009).

[26] Hugo Daniel, Joao Pedro F.Trovao, and David Williams. “Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier”. In: *eTransportation* (2022).

[27] Paul K. Davis. “Generalizing Concepts of Verification, Validation and Accreditation for Military Simulation”. In: *RAND* (1998).

[28] Sureyya Dipsar and Tayfur Altiok. “Control Policies for Material Flow in Bulk-Port Marine Terminals”. In: *SMC’98 Conference Proceedings. 1998 IEEE International Conference on Systems, Man, and Cybernetics* (1998), pp. 3083–3088.

[29] Mark B Duinkerken, Jaap A Ottjes, and Gabriel Lodewijks. “THE APPLICATION OF DISTRIBUTED SIMULATION IN TOMAS: REDESIGNING A COMPLEX TRANSPORTATION MODEL”. In: *Proceedings of the 2002 Winter Simulution Conference*. 2002, pp. 1207–1213.

[30] Sidun Fang and Ruijin Liao. “Optimal Energy-Transport Scheduling for Bulk Seaport Integrated Energy System”. In: *Conference Record - Industrial and Commercial Power Systems Technical Conference* 2022-May (2022). DOI: 10.1109/ICPS54075.2022.9773944.

[31] Xuejun Feng et al. “A simulation-based approach for assessing seaside infrastructure improvement measures for large marine crude oil terminals”. In: *Transportation Research Part E: Logistics and Transportation Review* 142 (Oct. 2020). ISSN: 13665545. DOI: 10.1016/j.tre.2020.102051.

[32] G.S. Fishman and P.J. Kiviat. “The Statistics of Discrete-Event Simulation”. In: *Simulation* (1968).

[33] Food and Agriculture Organization of the United Nations. *Food Loss and Waste Database*. 2024. URL: https://www.fao.org/platform-food-loss-waste/flw-data/en/ (visited on 03/01/2024).

[34] Luca Maria Gambardella, Andrea E Rizzoli, and Marco Zaffalon. “Simulation and Planning of an Intermodal Container Terminal”. In: *Special Issue SIMULATION on Harbour and Maritime Simulation* (1998).

[35] David Gibbs et al. “The role of sea ports in end-to-end maritime transport chain emissions”. In: *Energy Policy* (2014).

[36] Michele Acciaro adn Gordon Wilmsmeier. “Energy efficiency in maritime logistics chains”. In: *Research in Transportation Business & Management* (2015).

[37] CME Group. *Understanding Seasonality in Grains*. 2024. URL: https://www.cmegroup.com/education/courses/introduction-to-grains-and-oilseeds/understanding-seasonality-in-grains.html.

[38] José E. Gutierrez-Romero, Jerónimo Esteve-Pérez, and Blas Zamora. "Implementing Onshore Power Supply from renewable energy sources for requirements of ships at bert". In: *Applied Energy* (2019).

[39] William J. Hall. "Assessment of CO2 and priority pollutant reduction by installation of shoreside power". In: *Resources, Conservation and Recycling* (2009).

[40] IMO. *Fourth IMO GHG Study 2020*. Tech. rep. Internation Maritime Organization, 2020.

[41] Alexander Innes and Jason Monios. "Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen". In: *Transportation Research Part D* (2018).

[42] Raluca Dora Ionescu et al. "Innovative solutions for partable wind turbines, used on ships". In: *Procedia Technology* (2015).

[43] Jonas Jägermeyr et al. "Climate impacts on global agriculture emerge earlier in new generation of climate and crop models". In: *Nat Food* 2 (2021), pp. 873–885.

[44] Shayan Kavakeb et al. "Green vehicle technology to enhance the performance of a European port: A simulation model with a cost-benefit approach". In: *Transportation Research Part C: Emerging Technologies* 60 (Nov. 2015), pp. 169–188. ISSN: 0968090X. DOI: 10.1016/j.trc.2015.08.012.

[45] Yuri Khersonsky, Moni Islam, and Kevin Peterson. "Challenges of Connecting Shipboard Marine Systems to Medium Voltage Shoreside Electrical Power". In: *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS* (2007).

[46] M Kia, E Shayan, and F Ghotb. "Investigation of port capacity under a new approach by computer simulation". In: *Computers and Industrial Engineering* (42 2002), pp. 533–540.

[47] Mariam Kotachi, Ghaith Rabadi, and Mohammad F. Obeid. "Simulation modeling and analysis of complex port operations with multimodal transportation". In: *Procedia Computer Science* 20 (2013), pp. 229–234. ISSN: 18770509. DOI: 10.1016/j.procs.2013.09.266.

[48] Nikolay Kuptsov and Alexander Kuznetsov. "Stochastic Operational Logic for Berths Throughput Modelling of Export Coal Terminal". In: *Lecture Notes on Data Engineering and Communications Technologies* 157 (2023), pp. 46–58. ISSN: 23674520. DOI: 10.1007/978-3-031-24434-6_5.

[49] A.M. Law and W.D. Kelton. *Simulation Modeling and Analysis*. McGraw-Hill, 2000.

[50] R. Leloup et al. "A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimation". In: *Renewable Energy* (2015).

[51] H. Ligteringen and H. Velsink. *Port and terminals*. VSSD, 2012.

[52] Jiahong Lin, Benhe Gao, and Canrong Zhang. "Simulation-based investment planning for Humen Port". In: *Simulation Modelling Practice and Theory* 40 (2014), pp. 161–175. ISSN: 1569190X. DOI: 10.1016/j.simpat.2013.09.009.

[53] Elizabeth Lindstad et al. "Decarbonizing bulk shipping combining ship design and alternative power". In: *Ocean Engineering* (2022).

[54] Ruihua Lu and Jonas W. Ringsberg. "Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the Flettner rotor technology". In: *Ships and Offshore Structures* (2020).

[55] Sarah Mander. "Slow steaming and a new dawn for wind propulsion: A multi-level analysis of two low carbon shipping transitions". In: *Marine Policy* (2017).

[56] A. De Marco et al. "Flettner Rotor Concept for Marine Applications: A Systematic Study". In: *International Journal of Rotating Machinery* (2016).

[57] Yuri Merkuryev et al. "A Modelling and Simulation Methodology for Managing the Riga Harbour Container Terminal". In: *SIMULATION* 71 (2 1998), pp. 84–95.

[58] N. Molders et al. "Influence of ship emissions on air quality and input of contaminants in southern Alaska National Parks and Wilderness Areas during the 2006 tourist season". In: *Atmospheric Environment* (2010).

[59] Adriana Moros-Daza et al. “Greening container terminals: An innovative and cost-effective solution for sustainable reefer container storage”. In: *Journal of Cleaner Production* 466 (Aug. 2024). ISSN: 09596526. DOI: 10.1016/j.jclepro.2024.142664.

[60] P. Naaijen, V. Koster, and R. Dallinga. “On the power savings by an auxiliary kite propulsion system”. In: *International shipbuilding progress* (2006).

[61] United Nations. *Paris Agreement*.

[62] Mihai Neagoe et al. “Exploring the Role of Information Systems in Mitigating Gate Congestion Using Simulation: Theory and Practice at a Bulk Export Terminal Gate”. In: *IFIP Advances in Information and Communication Technology* (2018), pp. 367–374. DOI: 10.1007/978-3-319-99704-9_45ï. URL: https://inria.hal.science/hal-02164888.

[63] Mihai Neagoe et al. “Using discrete-event simulation to compare congestion management initiatives at a port terminal”. In: *Simulation Modelling Practice and Theory* 112 (Nov. 2021). ISSN: 1569190X. DOI: 10.1016/j.simpat.2021.102362.

[64] Mihai ; Neagoe et al. “Exploring congestion impact beyond the bulk cargo terminal gate”. In: *Proceedings of the Hamburg International Conference of Logistics* 26 (2018), pp. 978–981. DOI: 10.15480/882.1808. URL: https://doi.org/10.15480/882.1808https://creativecommons.org/licenses/by-sa/4.0/.

[65] D. Nelissen et al. *Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships*. Tech. rep. CE Delft, 2016.

[66] Mphatso N. Nyanya et al. “Wind and solar assisted ship propulsion optimisation and its application to a bulk carrier”. In: *Sustainable Energy Technologies and Assessments* (2021).

[67] N. Olmer et al. *Greenhouse gas emissions from global shipping, 2013-2015*. Tech. rep. international council on clean transportation, 2017.

[68] J.A. Ottjes and H.P.M. Veeke. “Prototyping in Process Oriented Modeling and Simulation”. In: *Proceeding of the 16th European Simulation Multiconference* (2002).

[69] Jaap A Ottjes, Gabriel Lodewijks, and Dingena L Schott. “BULK TERMINAL MODELLING AND SIMULATION”. In: *5th International Industrial simulation Conference* (2007).

[70] Assia Ait Ouhaman et al. “The storage space allocation problem in a dry bulk terminal: A heuristic solution”. In: *IFAC-PapersOnLine* 53 (2020), pp. 10822–10827. ISSN: 24058963. DOI: 10.1016/j.ifacol.2020.12.2868.

[71] Francesco Parola and Anna Sciomachen. “Intermodal container flows in a port system network: Analysis of possible growths via simulation models”. In: *International Journal of Production Economics* 97 (1 July 2005), pp. 75–88. ISSN: 09255273. DOI: 10.1016/j.ijpe.2004.06.051.

[72] Adnan Pasha and Rajat Rastogi. “A Review of Berth Allocation Problem in Bulk Terminals”. In: *Transportation Research. TPMDC 2022. Lecture Notes in Civil Engineering* 434 (2024), pp. 831–841. ISSN: 23662565. DOI: 10.1007/978-981-99-6090-3_66.

[73] Yun Peng et al. “A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective”. In: *Ocean and Coastal Management* (2019).

[74] René Taudal Poulsen, Stefano Ponte, and Henrik Sornn-Friese. “Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport”. In: *Geoforum* (2018).

[75] Rene Prenc, Dubravko Vucetic, and Aleksandar Cuculic. “High Voltage Shore Connection in Croatia: Network configurations and formation of the connection point to the Utility power grid”. In: *Electric Power Systems Research* (2018).

[76] Heng Ran, Carl-Erik Janson, and Björn Allenström. “Auxiliary Kite Propulsion Contribution to Ship Thrust”. In: *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering* (2013).

[77] *REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC*. 2021. URL: url%7Bhttps://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562%7D.

[78] Nishatabbas Rehmatulla et al. “Wind technologies: Opportunities and barriers to a low carbon shipping industry”. In: *Marine Policy* (2017).

[79] C.A. Robert and M. Dessouky. “An Overview of Object-Oriented Simulation”. In: *Simulation vol:70:6* (1998).

[80] Stewart Robinson. “Simulation Verification, Validation and Confidence: A Tutorial”. In: *Transactions of the Society for Computer Simulation* (1999).

[81] Stewart Robinson. *Simulation: The Practice of Model Development and Use*. John Wiley & Sons, 2004.

[82] Isabelle Rojon and Carel Dieperink. “Blowin’ in the wind? Drivers and barriers for the uptake of wind propulsion in international shipping”. In: *Energy Policy* (2014).

[83] Matthias Schmitz and Reinhard Madlener. “Economic Viability of Kite-Based Wind Energy Powerships with CAES or Hydrogen Storage”. In: *Energy Procedia* (2015).

[84] Marcos Wagner Jesus Servare Junior et al. “A linear relaxation-based heuristic for iron ore stockyard energy planning”. In: *Energies* 13 (19 Oct. 2020). ISSN: 19961073. DOI: 10.3390/en13195232.

[85] Francesc Soriguera, Domenec Espinet, and Francesc Robusté. “Optimization of internal transport cycle in a marine container terminal managed by straddle carriers”. In: *Transportation Research Record* (2033 2007), pp. 21–30. ISSN: 03611981. DOI: 10.3141/2033-04.

[86] L. Styhre et al. “Greenhouse gas emissions from ships in ports e case studies in four continents”. In: *Transportation Research Part D: Transport and Environment* (2017).

[87] Zhuo Sun et al. “MicroPort: A general simulation platform for seaport container terminals”. In: *Advanced Engineering Informatics* 26 (1 Jan. 2012), pp. 80–89. ISSN: 14740346. DOI: 10.1016/j.aei.2011.08.010.

[88] Xinyu Tang, Jian Gang Jin, and Xiaoning Shi. “Stockyard storage space allocation in large iron ore terminals”. In: *Computers and Industrial Engineering* 164 (Feb. 2022). ISSN: 03608352. DOI: 10.1016/j.cie.2021.107911.

[89] Xinyu Tang and Frederik Schulte. “Stockyard Storage Space Allocation in Dry Bulk Terminals Considering Mist Cannons and Energy Expenditure”. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* 14239 LNCS (2023), pp. 154–169. ISSN: 16113349. DOI: 10.1007/978-3-031-43612-3_9.

[90] Fabian Thies and Jonas W. Ringsberg. “Wind-assisted, electric, and pure wind propulsion – the path towards zero-emission RoRo ships”. In: *Ships and Offshore Structures* (2022).

[91] Fabian Tillig and Jonas W. Ringsberg. “Design, operation and analysis of wind-assisted cargo ships”. In: *Ocean Engineering* (2020).

[92] Michael Traut et al. “Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes”. In: *Applied Energy* (2014).

[93] Ernestos Tzannatos. “Cost assessment of ship emission reduction methods at berth: the case of the Port of Piraeus”. In: *Maritime Policy & Management: The flagship journal of international shipping and port research,* (2010).

[94] Unctad. *Review of Maritime Transport 2023*. 2023. URL: https://unctad.org/system/files/official-document/rmt2023_en.pdf.

[95] Department of Economic United Nations and Population Division Social Affairs. *Probabilistic Population Projections based on the World Population Prospects 2022*. 2022. URL: http://population.un.org/wpp/.

[96] H.P.M. Veeke, J.A. Ottjes, and G. Lodewijks. *The Delft systems approach : analysis and design of industrial systems*. Springer-Verlag London Limited, 2008.

[97] T A Van Vianen et al. “Dry Bulk Terminal Characteristics”. In: *BulkSolids India* (2011). URL: http://earth.google.com.

[98] T A Van Vianen et al. “Simulation-based operational control of a dry bulk terminal”. In: *Proceedings of the 2012 IEEE International Conference on Networking, Sensing and Control (ICNSC 2012)* (2012), pp. 73–78.

[99] T. Van Vianen, J. Ottjes, and G. Lodewijks. “Belt conveyor network design using simulation”. In: *Journal of Simulation* 10 (3 2015), pp. 157–165. ISSN: 17477786. DOI: 10.1057/jos.2014.38.

[100] Teus van Vianen, Jaap Ottjes, and Gabriël Lodewijks. “Simulation-based rescheduling of the stacker-reclaimer operation”. In: *Journal of Computational Science* 10 (Sept. 2015), pp. 149–154. ISSN: 18777503. DOI: 10.1016/j.jocs.2014.06.004.

[101] Teus Van Vianen. “Simulation-integrated Design of Dry Bulk Terminals”. PhD thesis. Technische Universiteit Delft, 2015.

[102] Teus Van Vianen, Jaap Ottjes, and Gabriël Lodewijks. “Simulation-based determination of the required stockyard size for dry bulk terminals”. In: *Simulation Modelling Practice and Theory* 42 (Mar. 2014), pp. 119–128. ISSN: 1569190X. DOI: 10.1016/j.simpat.2013.12.010.

[103] The World Association for Waterborne Transport Infrastructure. *DESIGN PRINCIPLES FOR DRY BULK MARINE TERMINALS*. 2018.

[104] P. D. Welch. “A Graphical Approach to the Initial Transient Problem in Steady State Simulation.” In: *10th IMACS World Congress on System Simulation and Scientific Computation* (1983).

[105] Can Wen and Lanbo Zheng. “A Constraint Programming Based Method for Stockyard Management Problem”. In: *International Conference on Internet and Distributed Computing Systems* 9864 (2016), pp. 214–221. DOI: 10.1007/978-3-319-45940-0.

[106] R. Winkel et al. “Shore Side Electricity in Europe: Potential and environmental benefits”. In: *Energy Policy* (2016).

[107] Ziqi Yin et al. “Temporal and spatial evolution of global major grain trade patterns”. In: *Journal of Integrative Agriculture* (2024).

[108] P. E.N.G. Yun et al. “A simulation-based research on carbon emission mitigation strategies for green container terminals”. In: *Ocean Engineering* 163 (Sept. 2018), pp. 288–298. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2018.05.054.

[109] Pengfei Zhang, Joan Lozano, and Yifan Wang. “Using Flettner Rotors and Parafoil as alternative propulsion systems for bulk carriers”. In: *Journal of Cleaner Production* (2021).

[110] Benfei Zhu et al. “Analysis Method of Terminal Throughput Capacity for Coal Export Terminals”. In: *Journal of Waterway, Port, Coastal, and Ocean Engineering* 144 (1 Jan. 2018). ISSN: 0733-950X. DOI: 10.1061/(asce)ww.1943-5460.0000422.

[111] T. Zis et al. “Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports”. In: *Maritime Economics and Logistics* (2014).

[112] Thalis Zis. “Prospects of cold ironing as an emissions reduction option”. In: *Transportation Research Part A* (2019).

[113] Thalis Zis et al. “Payback Period for Emissions Abatement Alternatives: Role of Regulation and Fuel Prices”. In: *Transportation Research Record: Journal of the Transportation Research Board* (2016).

Appendix A: Scientific Research Paper

Generic simulation model for green grain terminal operations

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Abstract

Due to the increasing trade of bulk cargo and the growing attention to efficiency in all steps of its supply chain, a thorough understanding of dry bulk terminal operations is crucial. Existing studies on this subject primarily focus either on the storage space allocation problem, often in conjunction with berth allocation, or on the simulation of this system, usually built for a specific case study. Furthermore, environmental factors have received limited attention in this context, while incorporating environmental considerations into this topic is crucial for sustainable and efficient terminal operations, especially when dealing with such a vastly spread sector as bulk cargo handling.

This work proposes a generic simulation model for grain terminals featuring a storage space allocation heuristic and the option to include cold ironing operations and the reception of wind-assisted carriers. The generic character of the model is obtained by understanding what processes are common to different terminals and to what minimal level of detail they have to be modelled in order to obtain reliable simulation results. Moreover, the model gains further versatility due to its parametric and period-based character.

The model includes the possibility to visualise and investigate the energy consumption of the system, crucial information to face present-day challenges such as the adaptation and enlargement of the electrical grid and the capacity estimation for the installation of new green energy farms.

Additionally, in order to show the genericity of the model and its potential, this study features multiple simulation experiments to investigate different aspects of terminal operational and energetic efficiency, involving the changes in operations caused by the introduction of shore power connections and wind-assisted carriers, a comparison of different unloading technologies, and an attempt to validate the industrial common practices in the field.

Keywords: GHG emissions, grain trade, dry bulk, DES, shore power

Introduction

Dry bulk trade made up for more than 50% of the total marine commerce in 2023 [39], amounting to more than 5 billion tonnes. Among the various dry bulk trades, grain trade is of crucial importance being fundamental for the availability of nourishment for a large portion of both the human and animal population in the present world [43].

It is agreed that the current climate crisis will affect the cultivation of crops around the world [20]. This will lead to changes in grain trade routes and volumes, due to the new climatic conditions of traditionally producing and consuming countries. Another possible outcome will be an important decrease in the amount of grain harvested around the world, making efficient transport without losses, that in some cases can account up to 60% of the harvested quantities [14], of paramount importance. Furthermore, the predicted world population growth [40] will definitely influence the food trade, not only intensifying the trade but also forcing society to find new solutions to meet the population's needs.

Given these reasons, it is evident that a deeper understanding of the grain supply chain is crucial. The implementation of more effective methodologies to address the issues affecting it is essential to tackle the current challenges facing the world with the proper means. By doing so, the efficiency and resilience of this field can be enhanced, ultimately contributing to global food security and sustainability.

In every dry bulk supply chain, an essential element is commonly recognised in the marine terminals, acting as buffers between different modalities characterised by different schedules, sizes and logistical issues. The presence of the terminal thus allows different branches of the chain to behave in relatively decoupled manners with less detrimental effects on each other. For this reason, terminal operations can be quite complex and are nowadays unthinkable without effective and efficient use of information technology and appropriate optimization and operations research methods, commonly used by terminal managers face operational decisions such as scheduling and planning or by engineers during designing and revamping projects.

One of the most used methods by the latter group is Discrete Event Simulation (DES). DES modeling involves simulating real-world operations within a controlled computer environment. This method offers a logical and quantitative approach to enhance understanding of the outcomes resulting from different proposals. A DES model is built by treating each physical item as a discrete entity, characterized by its distinct set of defined properties or attributes. These entities simulate the operational activities that constitute the processes being analysed. Activities have finite execution times, introducing delays to the modelled system. Both these delays and other process times can be stochastic in nature, and various methods are normally used to generate randomly induced delays based on data and operational rules specific to each process or piece of equipment. The combination of logical and random events aims to reflect the most likely operational environment.

However, as agreed by many experts in the field [34], producing a simulation model from scratch can be a very cumbersome and long process, even if using a commercial simulation software. Thus, a generic tool featuring the standardised operations of a terminal could revolutionize the way simulations are developed allowing an integration of simulations into static calculations during the initial phases of projects, enabling quick analysis of multiple situations.

In this context, not enough attention to energy consumption and environmental issues has been put into terminal operations optimization. However, new laws taking effect in the near future are expected to change radically the way port operations are led, especially in Europe. For example, ports will be obliged to guarantee shore power connections to container and passenger ships starting from 2030 [29], and dry bulk is expected to follow shortly after.

In this work, a generic DES model for grain terminals is described. The model is meant to approach the system in a generic way so that it could be applied to the great majority of terminals with minor modifications. In this model, the option to simulate shore power supply and the arrival and service of wind-assisted carriers is included. Furthermore, the model is able to collect energy consumption data from the simulation run, valuable information for energy transition-related problems such as grid expansions and sizing of new renewable energy farms.

Furthermore, in most recent studies a detachment between coefficients and industrial common practices suggested in classical handbooks such as [15] and the reality of the terminals has been underlined [41]. Understanding, where reality lies and thus which coefficient to utilize when designing a new terminal or evaluating the efficiency of an already existing one becomes a crucial issue. This problem claims even more attention in a time in which precise design becomes of paramount importance in order to meet environmental goals and approximation coefficients are looked upon as wasteful.

A attempt to evaluate the validity of the commonly used industry practices and a consequent discussion is presented. Finally, a comparison of the influence of different unloading technologies on the energy consumption of the terminal is provided.

The organization of the work is described below. Section 1 proposes a literature review of dry bulk terminals simulation-related works. Section 2 provides a thorough description of the generalised operations taking place in grain terminals, underlining the similarities and differences between import and export systems and individuating the gaps for the implementation of emissions-saving operations. Section 4 describes the design of various experiments set up, together with the consequent results. Lastly, Section 5 presents the conclusions about the whole model and the developed experiments together with future research lines.

1. Literature Review

It is interesting to mention that almost no study dealing with grain terminal simulation was found. This shows the lack of research in this direction. However, many studies were carried out on iron ore and coal terminal simulation, probably because of the larger dimension of the trade and the higher economic interests in it. The differences between these systems are not small in reality, still, they remain similar from a modelling point of view, thus a literature review of this kind was deemed satisfying as a first approach to the field.

The first application of DES to a dry bulk terminal environment was found in [5]. In this work, a feasibility study for an expansion of an Indonesian coal is described. The focus of the simulation was the ship arrival patterns and the consequent loading and unloading

operations. Only the large ore carriers' inter-arrival times were generated through a distribution while the smaller ships' arrivals were simulated based on the travelling times to the served customers.
On the other hand, in [13] DES model was used to test different storing strategies in an iron ore terminal connected with a mine. The need for the ore to dry was taken into account, making it an interesting case to compare with similar grain terminal operations.
Amongst many other models developed for different specific cases, in [11] the design of a dry bulk terminal DES general tool is discussed, featuring both a port equipment library and optimization capabilities. A Genetic Algorithm was implemented to solve the optimization problem, focused on the design and scheduling of operations.
In [28] a new approach to the system was proposed. This new modelling path consisted in schematising the terminal as a job shop made of different equipment line groups and transport jobs. Each equipment line consists of various pieces of equipment with different characteristics and results available only if all of them are. Different equipment assignment options were evaluated together with several breakdown behaviours.
A whole doctorate thesis[41] was dedicated to developing a complex DES tool for dry bulk design and study and applying it and its variants in multiple investigations. The main objective of the project was to provide port planners with a useful tool during the design process. The model featured different dedicated modules to simulate only the seaside, the landside, the stockyard, and the routing system.
A new discrete event simulation model for the analysis of the unloading operations in an alumina refinery was introduced in [9]. The model took into account both deterministic and stochastic processes including tidal constraints. Furthermore, a heuristic queue sorting mechanism based on cost reduction was developed and integrated into the simulation. In [8] the model was improved and the scope enlarged, taking into account the transport and storage operations, maintenance activities and unloading hatch sequences, a detail often not taken into account in these models but that can affect loading and unloading times.
In [44] a simulation model was implemented to identify terminal throughput capacity. An interesting characteristic of this model was the attempt to connect train arrivals to the ship arrival plans, as usually happens in reality.
As one can see most of the models are clearly focused on the seaside of the terminal, because of the economic importance of the shipping industry. Furthermore, it seems to be commonly agreed that badly planned seaside operations typically have more detrimental effects on terminal operations than inefficient landside planning. However, it has been seen that this lack of attention to landside planning can lead to serious disruptions in the supply chain. For these reasons, in [24] a discrete event simulation was applied to a wood chip export terminal to investigate congestion on the terminal's landside. The model analysed the effects of the variations of the terminal's configuration, the application of a terminal appointment system and the implementation of a gate automation technology in four different truck arrival frequency scenarios. By taking into account different products and truck sizes it was found that the introduction of an appointment system reduces turnaround times by approximately 20% while adding unloading capacity obtains a relatively small improvement. Furthermore, in [26] more possible improvements were proposed in terminal management to avoid gate congestion and in [25] a similar model was applied to study them with an additional view on environmental issues.
Table 1 reports a comparison of the described works with the present one under a series of specifications. As one can grasp from the diagram, a relatively large attention to the production of generic models is present in the field. However, the generic models were developed based on a case study or adapted by it, without precise initial attention to develop such a tool. Oftentimes, simulation of such a system is not approached as a problem on its own but mostly as a tool to demonstrate or prove the validness of results obtained in other ways. The possibility of simulating different policies or scenarios in a computer environment without a real-world implementation is indeed the main advantage and objective of simulation. Still, in order to obtain reliable results the topic itself should deserve more attention and dedicated research, without being a sidekick in works dedicated to other matters.
It is interesting to point out the difference made between the two parameters "Terminal" and "Storage" in the classification of the works. With "Terminal" the modelling and simulation of the stockyard operations was meant. On the other hand, with "Storage" the possibility of setting a maximum capacity for the storage area was indicated. In fact, a relatively common practice found in these works was to leave no maximum constraint to the storage space capacity (and thus describe the whole storage as one infinitely large bin). By running simulations in this fashion, the maximum capacity needed under a series of determined factors (equipment fleet, throughput, etc.) can be easily

estimated. However, it is clear that a certain detail in the simulation of stockyard operations is lost.
Furthermore, with the exception of Dipsar's [13] and Zhu's [44] works, no example of a model able to simulate the whole system was found, with a major interest in the seaside subsystem, for reasons that were already stated.
The literature review carried out highlighted a significant gap in research specifically focused on grain terminal simulation, despite the critical role these terminals play in global trade. While numerous studies have been conducted on iron ore and coal terminals, the unique challenges and requirements of grain terminals remain underexplored. Existing research primarily addresses specific case studies or focuses on particular aspects such as storage space allocation and equipment selection, often neglecting environmental considerations. Furthermore, other than case-specific and problem-specific research, most of the works found focused on only a portion of the terminal, not trying to grasp the complexity of the balancing of relatively uncoordinated supply and demand that takes place in such a system.
From the studies reported, two key insights emerged that shaped this work. First, the complex system can be effectively managed by subdividing it into smaller subsystems, specifically seaside, storage, and landside. Additionally, classifying the various simulation components based on the intelligence required for their operations proved essential.

2. System description

Dry bulk terminals often represent the bottleneck in the supply chain of raw materials due to their intrinsic nature. In fact, being the connection between two or more modalities, their operations can become very complex. This section aims to briefly describe the typical layout, characteristics and operations of a general dry bulk terminal, and grain terminal specifically. For a more in-depth and technical description, the reader is advised to check [15].

2.1. Terminal structure

In contrast with containerized transportation terminals, dry bulk terminals are designed to handle different grades of a specific product or a group of very similar products in a loose form and without any containment, hence bulk.
Based on the kind of material(s) handled, terminals can be generally divided into mined ores terminals, processed minerals terminals, and organic products terminals.
Mined ores terminals (e.g. iron ore, coal) handle mineral products shipped in their natural state without any chemical or concentrating process.
Processed minerals terminals handle mined ores that have been subjected to physical or chemical processes to produce a product ready for use or content-rich mineral for direct feed to an industrial process for the production of metal.
Organic product terminals handle foodstuff or other organic products that are suitable for transport by sea in loose bulk form. Some examples are the various kinds of grains, sugar and wood chips. Generally speaking, these materials are chemically stable but biologically active and do not present a high risk of hazard from that point of view, although self-heating and explosion hazards have to be kept into account.
Another division that is usually made amongst terminals is their purpose, leading to the individuation of import terminals and export terminals. In fact, as a consequence of the material-specific nature of the terminals, it is very logical that the flow direction of the material is specific to the system too. Furthermore, the complexity of operations is quite mitigated by such a practice.
Import terminals are located in regions or locations in need of determined raw materials. They are usually single-product terminals with high to moderate throughput, even though multi-product import terminals exist where volumes are lower and asset utilisation favours a more flexible facility servicing more than one product.
Unloading operations require smaller wave (current)-induced vessel motions in comparison with loading ones, as the equipment makes direct contact with the product. Import terminals are thus located in protected harbours or naturally sheltered calm waters.
Furthermore, import terminals generally have higher rated equipment and storage capacities than export terminals with similar throughput. This is explained by the fact that import terminals have less decisional power on the arrival of carriers and of the landside logistics and thus higher capacities allow terminals to be able to almost always handle ships in relatively quick times.
On the other hand, export terminals are built in regions with high availability of raw materials but without a comparable amount of demand. Export terminals' location is thus dictated by the proximity to the product source.

Table 1: Comparison of dry bulk terminal simulation works with the present work

Work	Generic	Seaside	Terminal	Storage	Landside	Alt. Operations	Energy
Baunach et al. [5]		√	√				
Dipsar et al. [13]		√	√	√	√		
Dahal et al. [11]	√	√	√				
Ottjes et al. [28]	√	√	√	√			
van Vianen [41]	√	√	√	√			
Cimpeanu et al. [9]		√					
Cimpeanu et al. [8]		√	√	√			
Zhu et al. [44]	√	√	√	√	√		
Neagoe et al. [24]				√	√	√	
Neagoe et al. [26]				√	√	√	
Neagoe et al. [25]				√	√	√	√
This work	√	√	√	√	√	√	√

Export terminals are usually single product terminals linked with one or multiple production facilities. The terminal can be operated or owned by the facility itself and thus operations run more smoothly than in import terminals since options to regulate the flow of material to the terminal's stockyard are available. This explains the lower storage and equipment capacity generally installed in export terminals.
Regardless of the purpose and the material handled by a terminal, its operations are divided into three sections: seaside operations, stockyard operations, and landside operations.

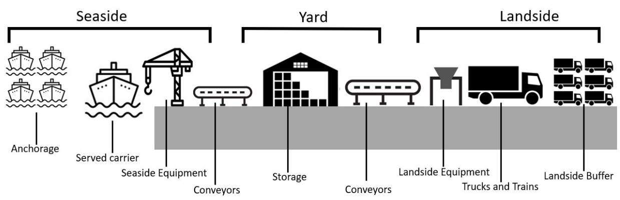

Figure 1: Diagram of the different subsystems

2.2. *Seaside operations*

Seaside operations consist of various steps involving berths, ships, and seaside equipment. After arriving at the port a ship is sent to anchorage, an open sea zone where carriers can wait their turn to be served. As soon as its turn has come, the ship is pointed to a specific berth based on capacity, drought or material restrictions. Travel to berth and berthing operations take place in which the ship is secured to the berth and made ready to (un)load products.

Interaction with ships during these operations can be a difficult and dangerous procedure for various reasons. One of them is the ship balance. Since the cargo makes up for a large percentage of a fully loaded ship weight, its draft varies largely during (un)loading operations. For this reason, (de)ballasting operations have to take place, during, before or after (un)loading. Furthermore, the balance of the ship is influenced by the positioning of the carried materials as well. Therefore, a specific hold order has to be followed during (un)loading operations usually determined by the ship's captain. These two crucial operations make the sea-side process a relatively cumbersome one. Furthermore, both the unloading and loading capacity of the equipment varies greatly during the filling or emptying of a hold depending on the quantity of material still present in the hold itself. Additional equipment can be needed in the ending phase of both operations to level up the created pile or to clean up the hold.
Once a ship is completely (un)loaded and other administrative procedures are taken care of, the ship unberthing operations can begin and after that, the carrier can sail away and leave the port as a new vessel starts the berthing process.
Vessel arrival process and distribution depend greatly on the kind of terminal, materials handled, and contracts standing with clients. Many studies have been carried out to fully model and predict such patterns, obtaining the best results with an Erlang distribution, with the shape parameters depending on the planning ability of the terminal [15]. Erlang-II was found best suited for small terminals with low planning and prediction capabilities, while Erlang-VIII is a good fit to model the arrivals of carriers in larger terminals where the

supply chain is better controlled [15].
Furthermore, seaside operations are influenced by different environmental constraints such as high tides, rain, and strong winds that impair the normal procedure of operations.
Finally, it is crucial to understand that charting contracts usually entail clauses regarding demurrage (fines that the terminal has to pay for vessels' delays) and despatch (fines paid to the terminal by clients if the terminal is able to service a ship before the agreed terms), thus timely seaside operations are essential for the economic performance of a terminal.

2.3. Stockyard operations

Yard operations consist of all the procedures taking place inside the stockyard of the terminal. These comprise not only the movement of material from the seaside and from the landside to the stockyard and vice versa, but internal rearrangements as well. Furthermore, drying, blending and recirculation of products are usually counted as yard operations. Planning of movements and coordination with land and seaside is crucial in order to optimize yard operations. Furthermore, sampling and weighing of materials is normally performed at the moment the product enters the yard.
The horizontal movements of material that happen thus inside the terminal are usually entrusted to two different kinds of equipment: conveyors and vehicles.
Conveyors are efficient pieces of equipment with relatively low operational costs and high efficiency. They rely on electrical motors for their functioning making them a perfect choice from an environmental point of view. However, the capital costs and installation times linked with this kind of technology are relatively high. Furthermore, due to the inherent nature of fixed equipment, they have some major flexibility limits during operations.
On the other hand, wheeled vehicles can be used as a connection between the yard and the seaside of the terminal. This option has very low capital costs in comparison with a conveyor system but the operational costs are usually quite higher due to the necessity of drivers. Vehicles are thus generally used in an initial phase of operations or in a temporary terminal, where the construction of a conveyor system is not deemed profitable.
In the particular case of grain handling terminals, conveyors are usually preferred if capital is available, making the terminal more efficient and the operations environmentally friendly.
Since the yard can basically be looked at as a storage, one of the main problems faced when managing one is the parcel allocation problem. When a cargo arrives at the terminal both from the landside or the seaside it usually has to be stored for a certain period of time constrained by contracts and fines. Since the sizes of the parcels handled cause their allocation or relocation to take up to some days, their optimal positioning in the stockyard becomes of crucial importance.
Another problem arising in the yard system is the routing one. While in a container terminal finding an optimal solution to the parcel allocation problem could be a great step towards an operational improvement, that is not the case in a dry bulk terminal. In fact, routes do not consist of roads or passages travelled via wheeled equipment but in most cases of fixed conveying systems that occupy the whole path. It is thus a way less flexible system that requires a higher level of planning and most importantly a precise definition of the required functionality during the design phase of the terminal.
Optimally solving the routing problem thus consists of finding the best solution to bring the parcel in the destined location taking into account the limited number of routes and equipment available.
It is clear that only finding a common solution to these problems actually proposes a new operational plan for yard management, while taken singularly they become scientifically and mathematically interesting issues but without real application. Therefore, these two problems or part of them are usually combined in different fashions, often adding other operations and a variety of constraints and objective functions.

2.4. Landside operations

Landside operations consist of the interaction of the terminal with the hinterland logistic system taking care of the redistribution or supply of product. This process can be seen as a mirroring one of the seaside one, with the due differences. Given the sizes of the vehicles, the amount of trucks or railcars involved in such a process is way higher than the ships berthing on the seaside. This brings to a different level of complexity and thus approach to entering, registering and weighing procedures. Usually, a series of weighbridges is utilised to gain information about trucks and trains weight when entering and leaving the terminal.
Again because of the large amount of vehicles that take part to this process, the arrival pattern is normally quite hard to predict and control. Different policies are envisioned in contracts with clients, featuring

maximum days of possible layover in the terminal and fines in case of an extended stay of the product. In the case of export terminals, the situation can be a bit different since the terminal is often at least partially operated together with the supplying facility.
Furthermore, landside operations often deal with the cargo split into different terrestrial modalities: trucks and trains. Managing these two different kinds of operations characterised by different necessities and constraints can become a difficult challenge if not addressed with the right amount of preparation.
Another crucial activity that happens on the landside of an export terminal, particularly in organic products ones, is cargo sampling. In fact, in export terminals, every single truck and wagon is sampled in order to check that the material entering the terminal fulfils the requirements of the specific batch. As cargo capacities of ships are way larger than the ones featured by landside modalities, the number of entities entering the terminal on the landside is quite higher than on the seaside. This operation (even if not involving large and costly pieces of equipment) requires thus a high amount of workforce, time and preparation or a series of automated probing stations.
The main problems on the landside of a dry bulk terminal derive from the fact that the number of entities interacting with this part of the system is much higher than the seaside, due to the sizes of the single entity. In fact a relatively large truck can carry up to 40 T of material and a wagon up to 150 T, various orders of magnitude smaller than the amount that can be stored in a carrier. Thus, even if the actual unloading time per vehicle is quite low, all the rest of the operations that accompany this process, and the fact parking space for trucks is often underestimated, make congestion on the terminal land side quite common.
Adding to the problem is the lower costs associated with this logistic chain and thus the smaller attention given to solving the related issues in comparison with the seaside ones. In fact a fleet of trucks operating a reclaiming campaign has a relatively small cost in comparison with the figures featured in vessels chartering contracts.

2.5. *Seasonality*

Grain production is inherently seasonal, closely tied to nature's rhythms. Each specific grain has its own planting, growth, and harvest period depending on its characteristics and the ones of the land where it is cultivated. This seasonality clearly extends to trade, with demand and prices fluctuating throughout the year due to the dynamics between so so-called "Old Crop" and "New Crop" [17].
During the planting months, the source of grain that is available for sale or purchase by end users is from the crops that were harvested during the previous harvest season ("Old Crop"). On the other hand, during the harvest months, the newly harvested crop comes to market and supply is higher ("New Crop").
From a trade perspective, for each commodity, one new crop month futures delivery month is defined while the remaining 11 are designated as old crop months. During the old-crop months, when supply is typically lower, grain tends to be priced higher with prices growing over the course of the other old-crop trading months. When a new crop is harvested, there is once again a higher level of supply. This is why many of the grain markets tend to reflect their lowest seasonal prices during the new crop trading month.
These variations in prices and thus amounts traded significantly impact operations, as the volume of cargoes and ships required changes over the year, leading to a system that is constantly in variation.
As an example, in 2 we report data from the USA wheat trade.
Some of the features described in the previous paragraph are recognisable in the data such as the high peak of both import and export from the beginning of summer until early fall (both for the northern and the southern hemisphere). However, it is important to remember that grain trade cannot be simplified to a simple supply-demand balance. In the current globalised world, many different players and factors such as economy and politics have a great influence on this kind of matter, making it very difficult to establish a fixed pattern.

Figure 2: USA wheat trade overview

In order to obtain reliable results from a simulation model input data are of paramount importance. In the case of a terminal, the carriers' arrival times are the main input data, representing the arrival rate of the entities that flow through the system.
Numerous studies have been conducted on the matter as shown in [15], common practice is to use the Erlang distribution to represent the carriers' IAT since it has been seen that they fit relatively well to real times. However, by using whatever sort of distribution along the whole year the seasonal behaviour of the system is lost.
The link between terminal throughput, carriers' IAT and seasonality is almost never explicitly discussed. Since terminal throughput is one of the most accessible and determining pieces of information about this kind of system, establishing a connection between these two input becomes a crucial matter.

2.6. *External factors*

A terminal is not a completely closed system and thus its operations strongly depend on many external factors. In this work, it was deemed an "external factor" whatever event (even if planned) obliges operations to deviate from the most efficient (physical or temporal) path, without taking into account other operations in this list. According to this definition, the external factors having an influence on the analysed system were summarised in:

- Weather
  Since the terminal is an open-air system not all operations can proceed in all kinds of weather. In particular, loading and unloading operations on the seaside always suffer hard weather such as intense wind, rain, and snow. When one of these conditions takes place, operations are usually suspended and start again once the situation allows it.
  As with the seasonality of the supply, weather strongly depends on the time of the year and the location of the terminal.
- Non-working time
  As in almost every industrial system, there are not only machines working in the terminal but people too. Shift work, holidays, and periodic closures are essential to ensure continuous operation and workers well-being.
  Holidays and periodic closures provide workers with necessary rest, reducing fatigue and preventing burnout, which in turn enhances productivity and safety.
- Maintenance
  Maintenance in industrial systems is essential for ensuring the smooth and efficient operation of machinery and processes. Regular maintenance helps to identify and address potential issues before they lead to breakdowns, thereby minimizing downtime and costly repairs. Furthermore, it extends the lifespan of equipment, ensuring that it operates at optimal performance levels, and it contributes to workplace safety by preventing accidents caused by equipment failures.
- Breakdown
  Even if periodic maintenance and checks are performed flawlessly, breakdowns in industrial systems are inevitable and even if are commonly taken as setbacks and a loss of resources and time, they serve as critical indicators of system weaknesses, highlighting areas that require immediate attention and improvement and ensuring that minor issues are addressed before they escalate into major problems.
- Tides
  Oftentimes, ports are located in protected stretches of coast with peculiar characteristics. However, not always is possible to satisfy all the desirable conditions either for economical, environmental or technical restrictions.
  One of the most frequent limitations a port encounters is the draft of the channel, not always deep enough to allow large carriers to enter or leave the port at all times.
  In these cases, monitoring tide windows and patterns becomes crucial for the optimal functioning of the terminal.

Along with the possibility to incorporate various input distributions, the ability to model external factors is a fundamental strength of simulation compared to static calculations. By dynamically simulating events such as weather conditions, equipment breakdowns, and maintenance schedules, simulations provide a more realistic and adaptable representation of terminal operations. This flexibility allows for a deeper understanding of system behaviour under different scenarios, leading to more informed decision-making and optimized performance.

2.7. *Environmental friendly operations*

Maritime transportation play a large role the challenge of limiting the rise in global average temperature

to below 2°C outlined in the Paris Agreement [23]. In fact, according to [10] transportation accounted for 20% of global CO2 emissions in 2022, and [19] reports that shipping was responsible for 2.89% of global anthropogenic greenhouse gas (GHG) emissions in 2018.
In this scenario, ports, even if accounting for a small portion of shipping emissions, are a hotspot for pollution due to significant anthropogenic inputs, primarily from their high fossil fuel consumption and the inevitable emissions due to concentrated maritime transport [12].
Nevertheless, local air pollutants continue to be the primary concern for port authorities while reductions in greenhouse gas emissions occur incidentally [31].
Studies on the reduction and mitigation of GHG emissions in ports are widely spread, showing the importance of this topic both from an academic point of view and from a societal one.
In particular, [1] is a brilliant example of a review of this field. In order to understand how to introduce the option to simulate green operations in the developed tool this work was analysed and compared with the simulated system.
At the actual state, grain terminals are already quite electrified and thus the amount of operations that could change the environmental impact of a terminal is quite limited. Many of the energy management measures suggested in [1] could cut the amount of emissions in grain terminals, still the great majority involve policies that are not reproduced in the model or fall out of the tool's generic character. Thus the focus was shifted to the measures affecting terminals's clients that would still involve the terminal, the so-called Ship-port Interface Measures [1].
The following aspects/technologies were thus found in line with the scope of this work:

- Energy Usage Inventory
  Creating an energy usage inventory is the initial crucial step in the port's emission reduction strategy. However, very few terminals actually keep track of energy consumption on individual equipment level but merely check the total energy consumption of the system in order to estimate and justify OPEX.
  The results of the inventory offer an analysis to identify effective and appropriate measures, implement GHG reduction strategies, track and benchmark emissions, and ultimately position the port at the forefront of sustainability.

- OPS
  Onshore Power Supply (OPS) refers to the practice of providing a connection to the local grid to carriers berthed at the port. This allows the ships to completely shut down their engines and thus do not consume any fossil fuel during their stay. OPS technology and operations are further explained in Section 2.7.1

- Wind assisted shipping
  In recent years the trend of propelling ships by using wind power has become popular again. The practice of retrofitting ships with sails or other kinds of equipment in order to harvest wind power is one of the most promising ones in cutting shipping emissions. Further details and what this technology entails for a terminal are discussed in 2.7.2

2.7.1. Shorepower

In 2009, [12] discovered that 5% of fuel consumption from ships occurs while they are at berth. Additionally, [19] indicates that an average of 16% of CO2 emissions happen when ships are either at berth or anchorage. From a port perspective, [37] notes that emissions from ships at berth can account for up to 50% of total ship emissions in port areas.
It is evident that greenhouse gas emissions could be significantly improved with the widespread adoption of shore power. Since the first commercial shore power system for cargo ships was installed in the port of Gothenburg, Sweden, in 2000, its use has been growing globally.
When ships are berthed, they typically use onboard diesel auxiliary engines to generate electrical power for essential operations like lighting, ventilation, pumps, cranes, and other equipment. These auxiliary engines are necessary because the main engines are usually shut down while at berth, in fact during cruising ships generate electrical power using generators attached to the main engine shafts.
Auxiliary engines, which can run on various fuels, are connected to electrical generators and ships usually dispose of multiple units, with the total installed capacity usually exceeding the average load required, so that not all engines operate simultaneously. However, the use of low-quality fuel and the power demands of ships mean that auxiliary engines emit significant amounts of pollution and greenhouse gases.

Pollutant	World Wide Reduction[46]	UK Reduction [18]
GHG emissions	48% - 70%	-
CO2 emissions	3% - 60%	91.6%
SO2 emissions	40% - 60%	75.6%
NOx emissions	57% - 70%	45.8%
CO emissions	-	24.5%
BC emissions	57% - 70%	-

Table 2: Reduction in emissions using shore power

Shore power (also called Onshore Power Supply (OPS), Shoreside Power (SP), Shore Side Electricity (SSE), and Cold Ironing (CI)) replaces the use of onboard auxiliary engines by connecting ships to a shoreside power supply while they are berthed. Although this does not completely eliminate emissions from docked ships it significantly reduces atmospheric emissions from ships at berth.
Many quantitative studies have been carried on to analyse the possible benefits of the utilisation of shore power connections. The results obtained by [46] and [18] are reported in Table 2

Although the effects reported are clearly positive, it is important to remember that the use of OPS does not eliminate greenhouse gas and priority pollutant emissions, but merely outsources them to the power generation industry. In fact, the GHG emission reduction capability of shore power is impressive mainly because of the inefficiency of generating electricity from diesel engines, the low grade of fuel used to power auxiliary engines onboard ships, and the lack of any post-combustion pollution control systems on many ships. It is thus important to consider that the energy production mix present in a determined region has a strong influence on the actual effectiveness of this technology. The fact that in some countries electricity from the grid has higher CO2 emissions than electricity from onboard auxiliary engines and that there are transmission and energy conversion losses associated with CI (2% and 8%, respectively) must be included when evaluating the application of SP. In not-so-rare cases, the implementation of shore power could actually bring an increase in CO2 emissions instead of a decrease ([18],[45]).
Still, the other main outsourcing realised through OPS is geographical. CI implementation is in fact able to move the pollutant emissions from populated areas such as the port regions to more remote areas where power plants are usually located. Therefore SSE would lower emissions' explicit damages such as health impacts in those regions [42].

The technological aspects of an OPS system are out of the scope of this work, and the reader is recommended to consult [3], [30], and [32] to gain further insights on the topic.
From an operational point of view, the most interesting characteristics of an SSE system are whether or not it is mobile and how many berths it can provide with a power connection simultaneously or not.
Furthermore, another important characteristic of an OPS connection is its Cable Management System. In fact, CMS can vary from very simple appliances to more complex ones. The most important CMS characteristic is the range of a berth it can cover. So-called "fixed" CMS are cheaper options for terminals, imposing stronger constraints on ship berthing. On the other hand, mobile CMS require higher investments but do not alter berthing operations since they can reposition themselves in order to make connections more favourable.

2.7.2. *Wind-assisted shipping*

Wind propulsion for ships, an ancient technology, has made a comeback as part of efforts to decarbonize the shipping industry.
Nowadays, a wide range of wind propulsion devices are being developed with the primary purpose of cutting down on fuel usage and thus decreasing air pollution emissions. These technologies can exploit wind either in a complementary set-up with conventional power sources such as batteries [38], hydrogen [36] fossil fuel [21] (wind-assisted ship propulsion technologies (WPTs)) or as the primary source of propulsion when the conventional engine is used only exceptionally [6]. Following technological advancements in the 1980s, wind propulsion adaptation as a retrofit for existing ships to help reduce fuel consumption has been preferred to a role as the main propulsion method [2]. Hybridization, in which wind propulsion assists the main traditional fossil fuel running engines which serve to ensure the schedule is maintained, is thus seen as crucial for the broader adoption of wind propulsion technologies in shipping fleets [22].
Many studies have been carried out to investigate the environmental and economic advantages obtainable with the application of this technology. However, since the adoption of technologies of this type is still in the early stages and depends on a wide range of variables results are still a bit controversial and do not always point in the same direction [4].
Still in [7] the following advantages of this technology are summarised:

- 10–40% improvement in the EEOI (Energy Efficiency Operational Indicators)
- 1–50% CO2 emission reduction
- 2–60% fuel saving; particularly suitable for high sea shipping
- No infrastructure required
- Proven technology from long-term development
- High cost-effectiveness (negative marginal abatement cost)

Various wind propulsion technologies have been developed, each operating slightly differently. However, they all share the common goal of providing propulsion power as wind speed increases, thereby reducing voyage time and fuel consumption [4]. Different authors have grouped them in several categories, based on their functioning ([22],[35],[7].
It is important to mention that researchers have pointed out the importance of the type of vessel when it comes to the financial and environmental benefits to be gained, with particular reference to ocean-going low-speed bulk carriers and oil tankers. In fact, this kind of vessel has a wider capacity to easily accommodate additional wind propulsion structures on deck [27].
However, tankers face stricter safety regulations compared to other cargo ship types, complicating the installation of permanent wind propulsion devices. As a result, tankers are not well-suited for WASP devices. Bulk carriers, with design speeds below 15 knots, appear to be more suitable. Additionally, cargo ships are costly to build and have a lifespan of 25–30 years, with WASP ships being even more expensive than traditional cargo ships. Therefore, retrofitting existing vessels with wind propulsion devices is a more cost-effective and quicker option to increase the number of wind-assisted sailing vessels [4].
Given these facts, it is safe to presume that in the coming years, this technology will be applied in this shipping sector. Investigating its operational risks and performance is thus of paramount importance, especially for what concerns the interactions and possible interferences with port infrastructure [33].

3. Methodology and model structure

This section gives a brief overview of the methodology applied during the development of this work and the model obtained through its use.

3.1. Generic model approach

As already stated one of the main goals of this work was to produce a model that would be generic.
Tow different concepts were found to be represented in the word generic. On one side versatility (or flexibility) and thus the ability to be simply applied to different scenarios and situations was clearly deemed to be part of this broader concept. On the other, generality was also found to fit quite well under certain circumstances. A generic model should thus be flexible and versatile enough to be able to adapt itself to the variety of scenarios it could be applied. Still, it should have some general characteristics that remain consistent, usually the ones characterising the group of systems the model will be used to simulate.
The genericness of the model was thus expressed in five different aspects of a simulation model and each of them was solved through the implementations and model characteristics described:

- Resources
  One of the first issues that comes to mind when applying the same model to multiple scenarios is the obvious fact that the scenario will be different. In particular, the resources part of the actual system will be different in numbers and characteristics. It thus becomes an essential characteristic of a generic model to not rely on specific elements of the system but give the user the possibility to vary them and their characteristic at will. To address this challenge, a parameterized approach was applied. This method involves categorizing the typical resources used in a grain terminal and translating them into simulation agent classes. Each class is defined by a series of specific characteristics that detail its features and capabilities within the system.
  Users have the flexibility to select the number of different resources available in the system and thus tailor the simulation to their specific needs and scenarios.
- Inputs
  Another difference between the scenarios that the user could be willing to simulate with a generic tool resides in the inputs the system receives from the environment and are thus not part of the system itself. It is clear that the capability to variate the system inputs becomes essential in a generic model, giving the possibility to compare the simulated performance of the same system in different

conditions or of the same system in the same conditions.
Furthermore, quite some effort was spent on the time flexibility needed in a generic model. In fact, oftentimes inputs need to change not only from one scenario to another, but inside the same scenario too (and thus simulation run). Another important feature of a generic tool was thus individuated in the possibility to not only vary the system inputs scenario by scenario but to be able to vary them and their rate of change inside the same scenario.
In line with this thought, a period-based approach was implemented allowing users to specify different distributions for the various inputs required for a simulation, such as weather distributions and inter-arrival time distributions. Furthermore, users are given the ability to specify the number of periods into which the simulation time is divided for each variable input. This allows users to have different distributions not only for different inputs but also for the same inputs in different periods of the simulation, choosing a different period length and thus the rate of change for each one of them.

- Policies
  Systems can differ not only for inputs and resources but for policies too.
  To some extent, a policy could be seen as a specific type of external input. However, three main differences were individuated between these two aspects of a system which made it more logical to categorise them into two different groups. Firstly, a policy is something that does not come from the outside environment (such as weather, or carrier's arrival). Secondly, policies are not intrinsic characteristics of the system but can be varied without having to change the physical nature of the system (such as equipment capacity, breakdown rate, and storage layout). Thirdly and most importantly, policies are the outcomes of managerial or operational decisions made by terminals' operators concerning the way the terminal faces different situations. Classical examples of a policy are the order in which carriers are served or the way parcels are allocated inside the terminal's storage.
  Because of the inherent difficulty in making the modelling of different policies easily modifiable by users, it was deemed reasonable that in this case the generic model should steer more towards the general side. Understanding what policies are the most commonly used in the specific field and integrating into the tool should be a fundamental part of the model development.
  In this specific work, a comprehensive study of the common policies used in the field was conducted. From this study, the most popular and fitting policies for a generic simulation model were selected. The chosen policies aim to balance the need for a broad application with the practical requirements of specific scenarios. By focusing on widely applicable policies, the model ensures a robust framework that can be adapted to various situations without compromising on the core principles.

- Objectives
  Normally, a simulation model is built to explore a specific characteristic of a system. However, a generic model should at least try to be able to cover multiple objectives and be reliable for different kinds of studies. In order to achieve this, a thorough review of the most common objectives of simulation studies in the specific field and a consequent validation is taken as best practice. Furthermore, overall attention to all the taken assumptions and how they could affect all the activities taking place in the model would surely help in achieving this desirable multi-objectivity.
  Concerning this specific work, two different ways of utilisation of the model were defined, which lead respectively to two different objectives: operations investigation and inputs investigation.
  The former, defined as the main objective of the model, entails applying fixed inputs to a varying system in order to gain operational insights into it. In this scenario, the resources and their characteristics should be varied and their performances monitored. This kind of experimentation is particularly useful during design or redesign projects in order to understand the behaviour of the system before actual changes or investments are made. An example of this kind of application is storage dimensioning.
  The second kind of experimentation deals with the investigation of an existent terminal, whose layout is not challenged. By fixing the system, the user can test its performances in different situations, either to monitor its performances under other circumstances than the real ones or to gain better insights into the system itself. Varying the arriving amount of materials to an existing terminal is an example of this kind of utilisation.

- Outputs
  The last aspect analysed is the model outputs.

Such as the objectives, the outputs of a simulation model are highly variable and strongly depend on the former.
However, some common ground can always be found inside the specific field. The idea is thus to keep the model more towards its ”general” character than its ”versatile” one with respect to this element.
Just as with the policies, a review of the most common outputs of interest in the field is advised and an automatised generation of easily understandable plots and graphs featuring them should be embedded in the tool. Still, the possibility to access relatively raw output data should be left to the user in order to extract factors and indices of his likes. in this work, a series of standard outputs were defined and an automatic generation of plots reporting them was embedded in the simulation tool.

3.2. Model structure

The model was further structured following two different axes, one vertical and one horizontal that allowed to categorise each component present in the system based on two characteristics.
The horizontal axis, and thus categorisation, was chosen based on the many examples seen in Section 1 and the operational characteristic of the single component, leading to a division of the model into three different sub-models: seaside, landside and stockyard.
The division was made only from a formal point of view, all the three sub-models are actually part of one single simulation model, running on the same simulation clock, without the need of any special communication between the three. Still, grouping the different agents into different operational sets made the activities, interactions, and information flows easier to schematise, helping to clearly state which components interacted with each other and which couldn’t.
The other axis was strongly inspired by [16], in which the components are categorised by their intelligence.
In this work three different levels of intelligence were defined:

- Allocator/Manager
  The Allocators are at the highest level of intelligence and they represent the local control function of the PROPER model, translating requirements of the environment external to their sub-system into operational tasks to assign to components of lower intelligence. Their role is to make operational decisions based on the current state of the terminal such as allocating resources and tasks to operators or components. In other words, the Allocators represent the policies implemented by the terminal manager and trigger the other agents to start, interrupt or stop a process.

- Operator
  The Operators represent the core of the terminal, carrying out the actual operations and representing the higher level of the transformation function of their sub-system. Still, Operators have some decisional capabilities and can switch from one process to another based on their states or the states of the components they are interacting with, without the intervention of an Allocator. Furthermore, being the main agent of changes in the terminal state, are the principal triggers of Allocators’ activities.

- Component
  The Components are the lowest rank of the terminal in terms of intelligence and represent the lower level of the transformation function of their sub-system. They can either have no processes and just represent a terminal entity with specific characteristics that change or are changed over time or they can have a process that simulates some sort of operational activities. Still, the process is set, and once triggered is not stopped, interrupted or changed by the component itself but only by the intervention of an Allocator or an Operator.

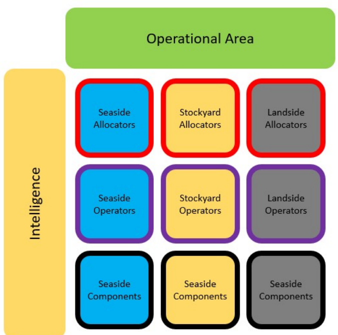

Figure 3: Model structure diagram

The following Sections give a brief overview of the model functioning and its most interesting features. Both an import and an export model were developed in this work, for the sake of brevity only the description of the import model is reported here.

3.2.1. Seaside

Carriers IAT are sampled by a dedicated distribution and used to generate the carriers' calls. At the call moment, carriers activate the parcel allocator that will apply a heuristic to find a favourable position to allocate the carrier cargoes. After their call, carriers take a certain amount of time, again sampled from a dedicated distribution, to reach the anchorage. Once at anchorage, carriers request a berth. A berth is found according to different parameters, most importantly a carrier is allocated to a berth only if one of its cargoes has already been fully assigned to the storage. After obtaining a berth, the carrier triggers the search for a shore power connection (if equipped with shore power technology) and one or more unloaders. Once the unloaders are found, the needed routing to connect each of them to the first of the assigned storage positions is looked for. Meanwhile, the ship requests use of the channel. If the channel is free to use, the carrier proceeds to transit in. After the transit time, the carrier arrives at the berth where berthing and bureaucratic operations can take place. If the unloader and the routing are already in place at this moment, unloading operations can start and won't stop until the carrier is empty. Once the carrier is completely empty, post-operational procedure and unberthing can take place and the channel use is requested once more. Once the channel is free, the carrier is allowed to transit out and leave the system.

3.2.2. Stockyard

In the model, stockyard operations are of secondary importance, since no real operations happen in the stockyard itself since the moving of materials is mostly dictated by Allocators and Operators belonging to the other two sub-systems. However, handling the different cargoes inside the system is a very complex procedure since many different batches of the same cargo are often flowing through it and the amount of every single one of them determines different decisions and behaviours.

As soon as a parcel is allocated, the different storing locations and relative stored amounts are generated and stored.

Once the unloading operations begin, a copy of cargo is generated to keep track of the amount flowing inside the terminal and oversee the unloading operations. The initial amount of a stored parcel is set to 0, the increase of this number and the decrease of the original amount model the flow of material from the carriers to the storage on a high level.

Furthermore, for each storage destination, an additional stored cargo is generated to keep track of the exact amount stored in the specific bin. These "lower level" stored parcels are generated with a starting amount of 0 as well and a total amount equal to the specific allocated amount, the comparison of these two numbers models the flow of material from the carriers to the storage on a lower level, involving the specific destination bin.

Furthermore, for both the high-level and low-level cargoes an available amount is used to manage operations. This variable represents the amount of the parcel present in the terminal not yet allocated to any loading bin, essential since allocation on actual transport happens at different times due to operational delays and unforeseen circumstances.

Unloading operations take amounts from the cargo and move it to both parcels and stored cargo simultaneously. As soon as the first mass-step of a parcel arrives inside the storage, a parcel-dedicated outtake manager is generated and triggered.

3.2.3. Landside

Once the first mass-step of a parcel arrives at the assigned storage location, its dwell time starts running. Once the parcel dwell time has elapsed trucks and trains to collect the material are generated and arrive at the terminal and a portion of the material is moved to the loading bins serving the landside stations.

From a landside modality point of view, once arrived at the terminal, trucks and trains are queued in the parking and in the marshalling yard respectively. As soon as a station handling the requested material is available the modality is served and then sent to the scales to be checked, always simulating service times and movements through dedicated distributions. Once weighted, the modality is free to leave the terminal.

3.2.4. Shore power

Shore power connection operations differ for many factors depending on the technology used. Depending both on the physical connection and the electrical toponomy of the system a shore power connection can be able to serve one or multiple berths, and more in particular a specific section of a berth or the whole berth.

Both these limitations can be modelled, using the berth modelling developed in this work. Shore power connections are in fact linked to one or more berths.

Being modelled berths able to describe either a whole physical berth or only a portion of it, cold ironing devices can be associated to either of them. However, berthing restrictions due to the shore power connection positioning are not part of this model, since the only discriminant taken into consideration is if the berthing ship is using or not the specific portion of the berth. If this is the case, the ship is eligible to be connected.
The flexibility obtained with this approach allows the user to simulate different fleets of shore power connections, varying both by number and technology. The latter is described by their capability of covering one or more berths, or portions of it.

3.2.5. Wind-assisted carriers' reception

A significant concern with adopting wind-assisted carriers is their potential interaction and interference with port infrastructure. While new wind-assisted carriers can be designed to avoid these issues, retrofitted ones might face challenges where the addition of wind propulsion devices hinders normal port operations.
For bulk carriers, the primary concern is that loading and unloading operations could be severely impacted by the placement of rotors or masts. The model addresses technologies that significantly alter the carrier's layout, potentially slowing down these operations and reducing the terminal's loading or unloading capacity.
The model allows users to set a distribution for the percentage of carriers arriving at the terminal with these problematic retrofits. These carriers will apply a hindering factor to the capacity of the seaside equipment serving them, reducing it and thus simulating the real-world difficulties associated with such retrofits.

3.2.6. Energy monitoring

One of the natural outputs of an industrial system simulation model is the working times of each machine involved in the process. By knowing their rated power and an efficiency factor, it becomes straightforward to estimate their energy consumption. Although the procedure is simple, many terminals do not monitor this, and during design phases, energy consumption is often calculated in even simpler ways. It was thought that even a small improvement, such as obtaining working times through simulation instead of static calculations, could enhance the overall understanding of the system.
This approach relies on the user providing accurate data about power consumption, which is not always easy to find. However, it is expected that the rated power for the equipment can be located, and [19] offers useful data to estimate the installed power of ships based on their tonnage. In fact, the ship's rated power dictates the amount of energy consumed by shore power connections.

4. Experiments

In order to showcase its capabilities, the model was used to carry out a series of experiments on an import terminal with a yearly throughput of approximately 1 MT in the years 2017-2021.
The following paragraph summarises the terminal's layout, and how it was modelled in this work.

- Quay
  The quay of the terminal is 290 m long, making thus possible to unload two carriers of 130 m simultaneously.
- Seaside equipment
  The seaside pieces of equipment available to the terminal are a mechanical unloader with a rated capacity of 1200 T/h and two pneumatic unloaders with rated a capacity of 600 T/h each.
  Policy-wise, priority is given to the mechanical unloader being the one with the highest capacity.
- Conveying lines
  Two 2.5 km long main conveying lines with 1200 T/h and 600 T/h capacity respectively connect the seaside of the terminal to the storage and landside. This layout imposes a strict constraint on unloading operations, allowing only two unloaders at a time to work on served carriers.
- Storage
  The storage facilities of the terminal consist of 24 silos with a 2200 T capacity and 12 silos with a 400 T capacity.
- Landside equipment
  Concerning the Landside, the terminal is provided with 7 truck loading stations with an average capacity of 200 T/h and 7 loading bins with a respective capacity of 540 T.

The data made available were the following:

- Arrivals log
  The carriers' arrival log of the terminal was the most important data obtained from this system. The dataset reported arrival times, types of cargo, amounts of each cargo and length of every ship for four years. With this data, it was possible to generate distribution for the IATs and the arriving cargoes.

- Storage log
  Another important dataset was the storage log, reporting the amount of material entering and leaving the terminal daily.
  For this data, it was possible to generate type-specific dwell time distributions and size-specific outtake time distributions.

- Operational information
  The terminal provided some operational information as well.
  The terminal is normally open from 6:45 to 22:30 and maintenance operations take place during closing times. Furthermore, the weather downtime was estimated at 5% of the total year equally distributed between January and March. Lastly, breakdowns and operational disturbances were reported to take up to 10-15% of the working hours.

4.1. Terminal performances

In order to understand which of the various resources present in the terminal has the strongest impact on its performance, it was decided to investigate the terminal behaviours varying and their characteristics.
As already stated the terminal can be divided into three different subsystems each of them with its importance for the healthy behaviour of the terminal. Each of them has an installed capacity either for loading, unloading, or storing. The performance of the terminal varying two of these three capacities was investigated.
Two different kinds of variations in the capacity of each of the analysed subsystems were performed, one from a quantitative point of view and one from a flexibility one. In the former, the capacity of each of the servers (unloaders or bins) was changed in value, keeping the number of servers constant. In the latter, the opposite operation was performed, keeping constant the capacity of the whole subsystem but varying the one of the single servers, and thus their number.
In all cases, the routing system was modified to the best of the author's capacity in order to make operations run as smoothly as possible.

4.1.1. Seaside

The first subsystem analysed was the Seaside one, in which the servers are represented by the unloaders.
In the first series of experiments, the capacity of each unloader was multiplied by four different factors, maintaining a fixed throughput.

n. unloaders	capacity[T/h]	specific consumption[kW/T]
3	800	0.675 - 0.625
2	1600 - 800	0.53 - 0.625
6	400	0.8
4	600	0.83

Table 3: Unloading capacity specifications

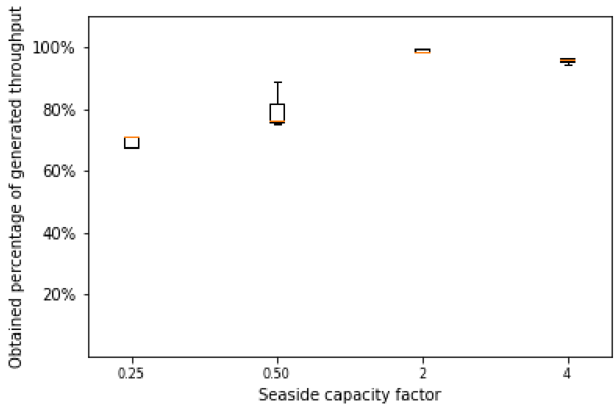

Figure 4: Seaside capacity investigation results

The results reported in 4 show how a smaller capacity highly affects the terminal performance hindering its capacity to obtain the objective throughput. On the other hand, augmenting the capacity of the unloaders doesn't improve the terminal because of the fixed throughput constraint imposed on the experiments.
In the second series of experiments, four different scenarios were created, selecting the capacities and rated powers of existing pieces of equipment and combining them in order to obtain the capacity of the original system. The specifics are reported in 3.

Interestingly, the general terminal performance is not altered by this variation in the flexibility of the seaside subsystem. In fact, having the same total installed capacity and having modified the routing system in order to allow operations of each unloader at the same time, the terminal is able to achieve the set throughput. Since not only the capacity but also the rated power and thus the specific consumption of the unloaders was varied, the energy consumption of the terminal in the different scenarios was analysed.

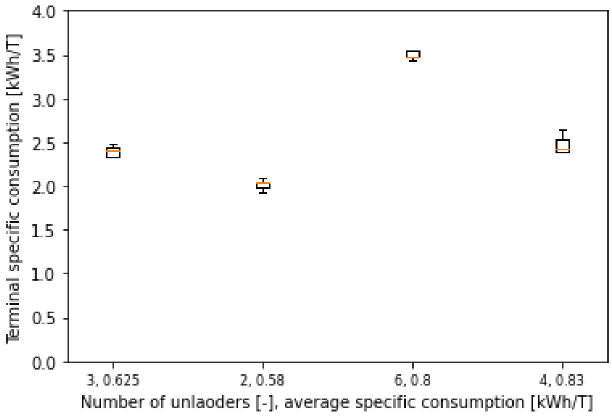

Figure 5: Seaside number of servers energy investigation results

Fig. 5 shows that, as expected, scenarios with a higher average specific consumption lead to a higher amount of energy consumed in order to perform operations. However, the number of unloaders results in an effect on the energy consumption as well. This was attributed to the changes made to the routing system, which, featuring a larger amount of smaller conveyors, has a lower efficiency, leading to higher energy consumption. This explanation is also supported by the results shown in 6, showing the percentage of energy used by the unloading system becomes lower when more unloaders are put in place.

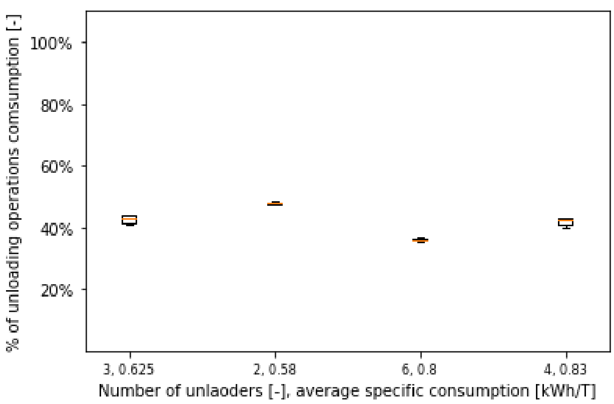

Figure 6: Seaside number of servers consumption percentage investigation results

4.1.2. Stockyard

Experiments concerning the stockyard subsystem followed the fashion of the ones performed on the seaside. A first series of scenarios were created by multiplying the capacity of each silo by a factor, thus varying the total capacity of the terminal, and leaving the throughput constant.

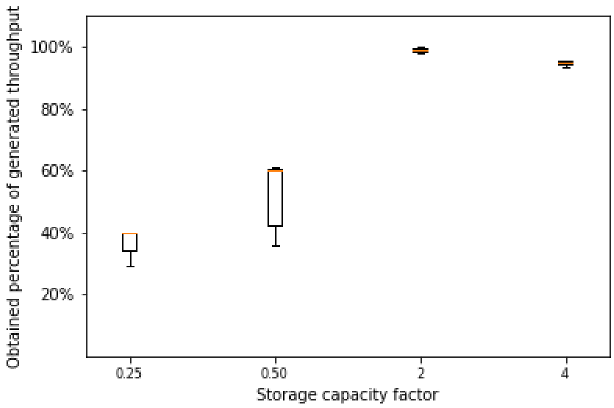

Figure 7: Storage capacity investigation results

The results reported in Fig.7 show how the reduction of the total capacity of the stockyard has a very high influence on the performance of the terminal, leading to greater disruptions than the one seen in the previous analysis. Again on the other hand, augmenting the stockyard capacity did not achieve any improvement because of the fixed throughput constraint.
In order to create the second series of experiments, the total number of silos in the terminal was modified by multiplying it by four different factors. In order to keep the total capacity constant, the capacity of each bin was multiplied by the inverse of the relative factor.

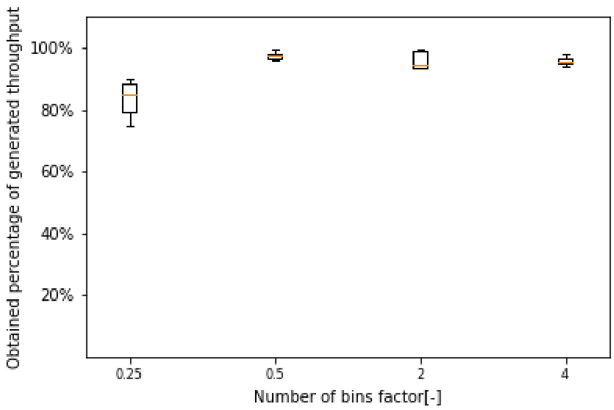

Figure 8: Storages number investigation results

Conversely to what was seen in the seaside experiments, if the number of silos inside the terminal is reduced too much while keeping the total capacity constant, operations are relatively hindered. This happened because bins are occupied for longer times by smaller amounts of parcels, not allowing new cargo to be unloaded in the terminal.

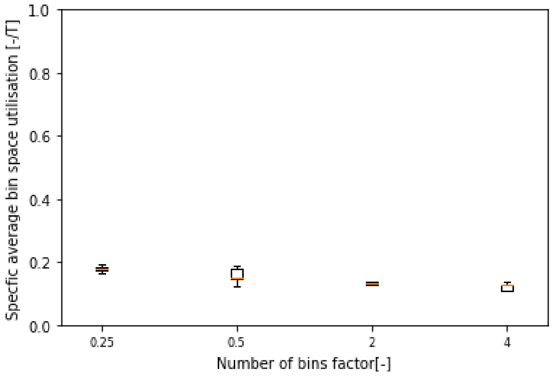

Figure 9: Storages number investigation results

To get more insights into these experiments the specific average bin space utilisation (defined in 1) was analysed.

$$u = \frac{\sum_s \sum_i \frac{a_{i,s}}{C_s} \frac{\Delta t_{i,s}}{s_t}}{n} \frac{1}{T} \quad (1)$$

Where n is the number of silos, $a_{i,s}$ is the amount is silo s in time step i, $\Delta t_{i,s}$ is the duration of time step i of silo s (that varies dynamically based on material movement), C_s is the capacity of silo s, s_t is the total simulation time, and T is the total obtained throughput. This index permits us to look at the stockyard as one large storage bin and analyse its behaviour. Results shown in Fig.9 display how the difference in the size of the bins does not have a great influence on the average amount of material stored in the bins during time. In fact, considering that the value of this index for a silo that is continuously loaded and unloaded at the same rate should be 0.5, the results show that the storage faces longer times in which its utilisation is lower than 50%. In other words, the reason for such a high capacity is only the possibility of handling peaks of stored material when large carriers arrive, while most of the time the storage is underutilized.
This result shows once more that the reason for such an imposing infrastructure is the decoupling role between modalities of different sizes. It is clear that better coordination (in time and size) between the two branches of the supply chain would lead to the possibility of handling the same throughput with smaller infrastructures.
The slight plummet of the index towards lower values as the number of silos increases is due to the fact that smaller silos are filled up and emptied more often than larger ones, reporting thus in the index a much larger amount of zeros that lower the average.

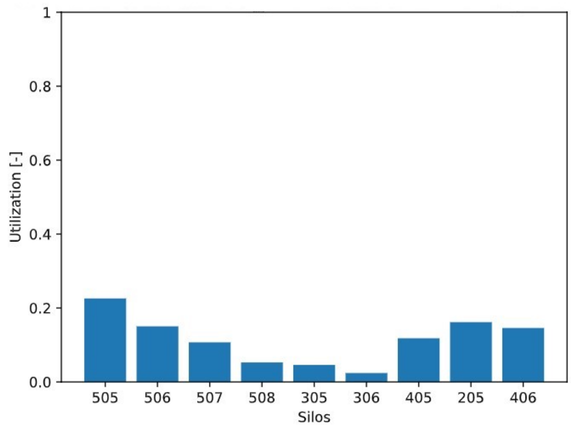

Figure 10: Storage capacity investigation results

Fig. 10 and 11 depict how this index behaves in two of the simulation runs, showing how silos of different sizes behave differently. The smaller silos show more disperse values due to the continuous loading and unloading happening due to their size and number, while the large ones show more regular values since loading and unloading operations lead to complete emptiness more rarely than in the other case.

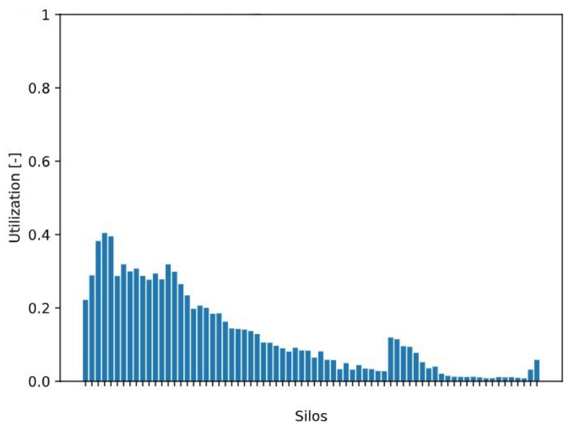

Figure 11: Storage capacity investigation results

4.2. *Emission reducing operations*

To show the capabilities of the model to capture the behaviour of the system when introducing the energy-reducing operations discussed in 2.7, the set-up of Case Study 1 was modified accordingly and tested.

4.2.1. *Shore power*

Given the berth size of the terminal and the restrictions it imposes on the amount of carriers that can be unloaded at the same time two different possible set-ups were investigated, the first in which only one shore power connection capable of serving both berths was added to the system and the second in which two different shore power connections were added, each one serving one berth.
Furthermore, the fleet composition was changed along the different simulation runs, varying the number of carriers visiting the terminal equipped to be served by a shore power connection.

$$C_{ratio} = \frac{connection\ time}{berth\ time} \tag{2}$$

Given the small number of carriers with a length under 130m, and thus allowing simultaneous operations at the berth, the difference between the two shore power set-ups was unnoticeable. All the carriers allowing shore power connection were served in all the different simulations, with a connection ratio (defined in 2) of around 0.98, perfectly in line with the input given regarding shore power connections set-up times.

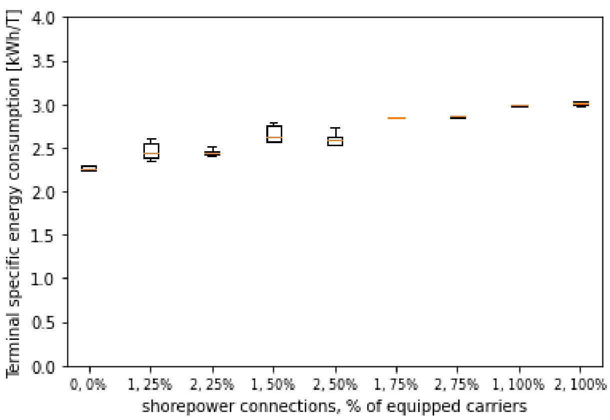

Figure 12: Terminal specific energy consumption

Adding the possibility of connecting to the terminal's grid, is it obvious that the terminal energy consumption will increase due to the supply of electricity to the carriers. Fig 12 reports the variation of the terminal-specific energy consumption along the different simulation runs, showing the predictable increase of energy consumption at the increase of the percentage of shore power-equipped carriers visiting the terminal.

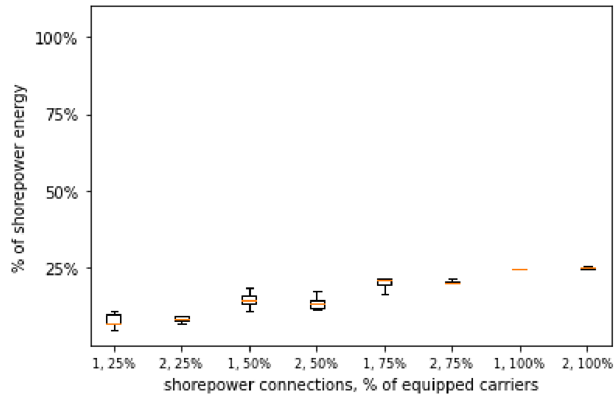

Figure 13: Percentage of shore energy consumption

Lastly, Fig. 14 shows quantification of the previously discussed phenomenon. The former gives some specific values to the energy consumption of the shore power process while the latter transposes the energy provided into CO2 emissions relocated to the energy production industry, utilising conversion data from [19].

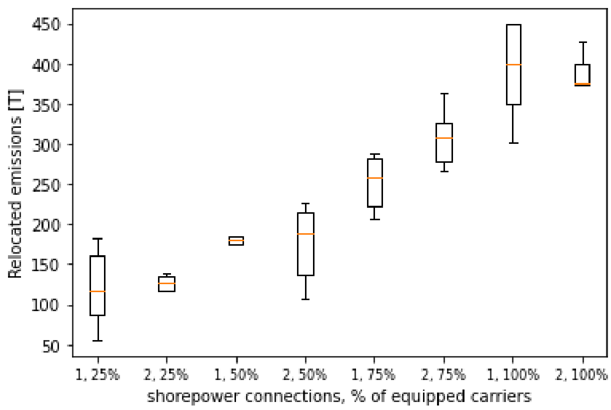

Figure 14: CO2 emissions relocation

4.2.2. *Wind-assited shipping*

To test the effects of wind-assisted carriers visiting the terminal, similar experiments to the one described in the previous sections were carried out.
As stated in 2.7.2, no changes should take place in the

terminal in order to be able to serve carriers equipped with wind propulsion technologies, thus the only varying input amongst the different simulation runs was the percentage of wind-assisted carriers visiting the terminal. Furthermore, a hindering coefficient of 0.7 was set to alter the capacity of the unloaders interacting with these ships.

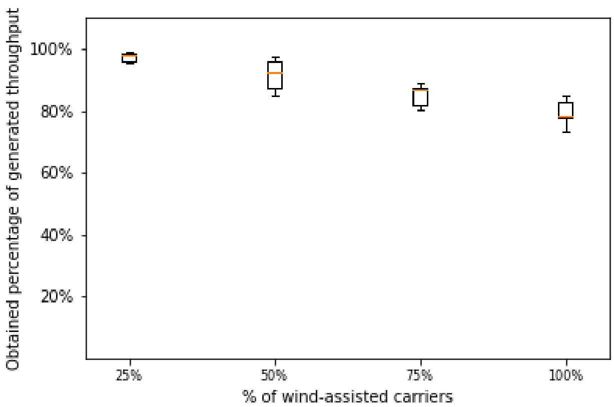

Figure 15: Obtained throughput for fleets characterised by different wind-assisted carriers percentage

As expected, the results shown in Fig. 15 underline how the service of wind-assisted carriers slows down terminal operations on the seaside, reducing the throughput capacity of the terminal. As stated in 2.7.2

4.3. Common Industrial Practices

As in many other sectors dealing with complex systems, the design of dry bulk terminals is strongly based on common industrial practices. Handbooks such as [15] provided a huge variety of factors and rules of thumb that are normally applied in this field, obtaining results that are in line with the necessities of the systems.
For example, the total capacity of a terminal is normally set on the common benchmark rules that a terminal performs a turnover between 12 and 24 times a year (the yearly throughput is between 12 and 24 times the total capacity) and that in order to be able to serve carriers timely a minimum capacity of one and half the DWT of the largest served carrier should be available in the terminal.
However valid these practices could be, in a world in which the efficient allocation of resources becomes every day more important for both economic and environmental reasons, a review and investigation of the most common (and vague) used design rules would surely bring benefits.
As a first small step, in this work, the initial design obtained through static calculations based on these common practices of a terminal commissioned to the engineering consultancy company Royal HaskoningDHV was simulated and its performance was analysed.
The following paragraph summarises the terminal's suggested layout, and how it was obtained.

- Quay
  The length of the maximum carrier that will be served at the terminal amounts to 255m, the quay was thus discretised into two berths each of 122.5m each.
- Seaside equipment
  One of the possible equipment selections proposed by Royal HaskoningDHV engineers features two mechanical continuous unloaders with a capacity of 900 T/h each.
- Conveying lines
  Two conveying lines with 900 T/h capacity respectively connect the seaside of the terminal to the storage and landside.
- Storage
  According to the previously metioned rules of thumbs, the storage was designed with a capacity of 0.68 MT divided into 12 5000 T and 4 2000 T silos.
- Landside equipment
  Concerning the Landside, the terminal was designed with 4 truck loading stations with an average capacity of 200 T/h. This number is obtained by dividing the yearly throughput by the truck size thus obtaining the yearly number of trucks, and consequently the trucks per day. Multiplying this number by the rule of thumb peak coefficient 1.5, the peak number of trucks is obtained. Using this number and the service and transit time of each truck and dividing it by daily working hours, the needed number of stations is obtained.

Fig. 10 shows that the terminal designed has a healthy behaviour, being able to achieve the desired throughput in all the simulation runs.

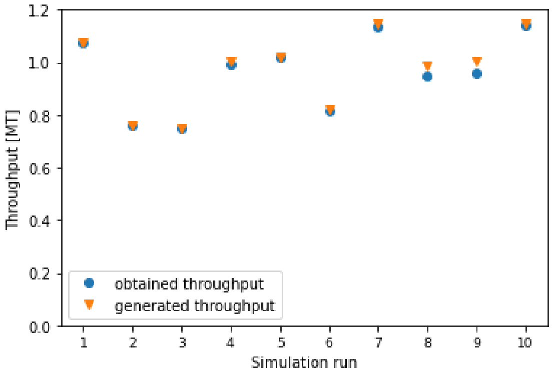

Figure 16: Obtained throughput in different simulation runs

Furthermore, the values reported in Fig. 17 show a satisfactory behaviour of the storage system, characterised by a strong link with the generated and obtained throughput.

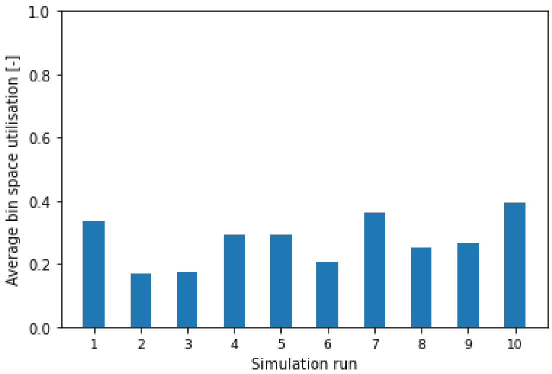

Figure 17: Average silo utilisation in different simulation runs

In order to validate or debunk the factors commonly used in the industry previously explained, a series of simulation runs were performed analysing systems in which those rules were not applied.
Fig. 18 features the results obtained without applying the peak factor when calculating the necessary number of landslide stations, leading to 3 stations instead of four. The results show how the system severely under performs with this new setup, being able to reach approximately 50% of the targeted throughput.

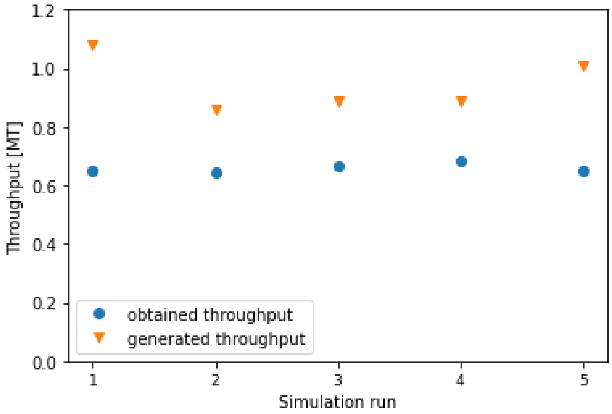

Figure 18: Obtained throughput in different simulation runs

Analysing the amount stored in the terminal along the original simulations it was noted that only in a few occasions during the year the terminal would reach maximum capacity. For this reason another series of simulations was carried out with a total capacity reduced to 0.52 MT.
The results reported in Fig.19 shows that, when the generated throughput equal the targeted one, the terminal does face some minor difficulties, showing that the total capacity needed to properly perform is indeed better estimated by the design process conducted using the common industrial practices.

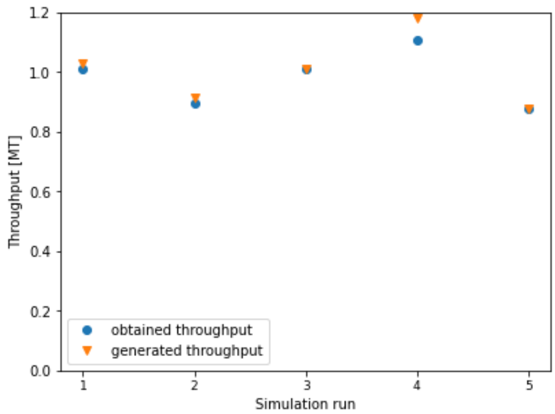

Figure 19: Obtained throughput in different simulation runs

These experiments showed how, even if not supported by much scientific proof, the utilisation of peak factors and other coefficients is fundamental to design appropriate systems. This shows that queuing theory and static calculations are able to capture the system behaviour only until a certain degree and thus the results obtained with these methods have to be tweaked in order to reach the targeted design objectives.

5. Conclusions and outlook

The current work features the modelling and implementation of a generic DE simulation tool for grain terminals, involving emission-saving operations such as cold ironing and wind-assisted carriers' reception. In order to obtain this final objective, a literature study about simulation in both dry bulk terminals and other cargo terminals was performed, to understand the main challenges and trends of the sector. Furthermore, the operations typical to this system were investigated, described and modelled through two different methodologies, the second of which focuses on the development of generic models and was developed in this work.

Along with the analysis of the normal operations of the system, the gaps for the implementation of GHG emissions-saving procedures and innovations were investigated, identifying the previously mentioned ones.

The created tool was applied to different scenarios to gain insights into the analysed system and its behaviours, to understand to what extent the added emissions-saving operations would affect the system and what gains they would produce, and to validate or debunk common industrial practices of the field.

The developed model is able to capture the general behaviour of the system with good approximation while simplifying the simulation setup process, normally very cumbersome. Furthermore, the tool features standardised inputs and outputs, chosen according to the system needs and the common KPIs monitored when evaluating this kind of system. In addition, the model reports outputs concerning the energy consumption of the system, not often included in normal analysis.

The series of experiments carried out showed that the one analysed is a very complex system, acting as a major buffer in a fundamental supply chain. This last function obliges terminals to feature imposing infrastructures, fundamental to face peaks of arrivals but otherwise characterised by low utilisation. Moreover, the importance of seaside and storage capacity was analysed, showing how these two characteristics strongly affect terminal overall performances. The importance of the correct selection of seaside equipment and relative connecting routing system in order to achieve energy efficiency with respect to capacity, specific energy consumption, and number of pieces was underlined by the performed experiments too. Lastly, some quantitative results concerning the implementation of GHG emissions-reducing operations were obtained, showing that OPS could lead to the relocation of a substantial amount of emissions while increasing the energy consumption of the terminal in the range of 5-25% and that the reception of wind-assisted carriers will have relatively high detrimental effects on terminal performances if the considered coefficients are in line with real operations. Lastly, the utilisation of the common industrial practices was validated, showing that the avoidance of the use of the so-called rules of thumb leads to inefficient systems.

From these results it appears clear that smoothing of the supply chain through better coordination between the two different branches would allow terminals for smaller infrastructure and complexity, obtaining more efficient and less environmentally taxing systems. Furthermore, the implementation of shore power connections and wind-assisted carriers' reception would bring major improvements in the marine trade environmental impact, while necessitating great measures and investments to achieve their correct implementation without incurring in hindering the system's performance. With the employment of both these innovations terminals do not alter their direct environmental impact but allow their clients to reduce theirs. However, the adoption of the first technology would bring direct economic advantages to the terminals, making them energy supplier for the carriers at berth and thus creditable of a payment. On the other hand, the reception of wind-assisted carriers would only be a source of more inefficient operations for the terminal operators, making them major negative stakeholder in the implementation of this revolutionary technology. Attention of policy makers and market regulators will be needed in order to not hinder the commercial development of this new emissions-cutting trend.

However, this study is affected by a series of limitations. As for all simulation model, the results obtained by the one discussed in this work depend heavily on the input data available. If incomplete or inaccurate data is used to develop a simulation set-up, incomplete and inaccurate results will be obtained. Gathering accurate data of such economically and strategically import system is not always straightforward. If the specific data required to run the model is not obtained its performance are fairly hindered, an example of this is the loading distributions mentioned in the validation of the export model. Furthermore, an approximation was made on the density of the materials handled was made, considering all quantities by their weight and by their volume. The difference between the density values of the materials is not vast and thus it should not have led to major mistakes. However, given the amount of material handled, it could have a non-negligible effect on the system's behaviour.

From the environmental point of view, two major limitations were individuated. Firstly, the energy consumption monitoring method implemented in the model is based on a constant rated power value and coefficient. This choice is not in line with the utilisation of equipment capacity distribution and could lead to an overestimation of the consumed energy. Furthermore, the wind-assisted hindering coefficient was chosen in a relatively arbitrary manner, because of the complete lack of data about the operations. This could lead to unreliable results.

Nonetheless, it is believed that this tool could play an important role in the normal engineering process followed by RHDHV engineers, making high-level simulation an embedded and low-cost practice in the design and evaluation of terminals. Furthermore, the possibility of easily simulating the implementation of GHG emissions-saving operations could lead to a larger interest in both the engineers and the clients, enhancing the efforts to reach the energy efficiency needed to meet the current environmental needs.

Based on the work reported in this study many research lines could be followed in order to improve both the developed tool and the understanding of the analysed system. Firstly, the investigation and implementation of different operational policies and the possibility of choosing between them would surely enhance the tool's effectiveness, making it able to simulate different managerial choices done in different situations and thus analyse their effectiveness. Furthermore, embedding an optimised parcel allocation procedure would allow users to get further insight into the correct utilisation of such a fundamental resource for the system. Moreover, better modelling of the power consumption of equipment and the correct calibration of the coefficients used in this process and in the wind-assisted carriers' reception would give the tool more accuracy and adherence to reality when used to analyse those aspects of the system. Lastly, the experiments reported in this work barely scratch the surface of the possible application of this tool to gain better insights into the system performances and the shore power connections in particular. The use of the developed tool to analyse more complex layouts and scenarios would bring important results to better understand how these newly introduced operations would affect the terminal behaviours and what environmental gains could be obtained by their implementation.

References

[1] Alamoush, A. S., Ballini, F., and Ölçer, A. I. (2020). Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review. *Marine Pollution Bulletin*.

[2] Atkinson, G., Nguyen, H., and Binns, J. (2018). Considerations regarding the use of rigid sails on modern powered ships. *Cogent Engineering*.

[3] Bakar, N. N. A., Bazmohammadi, N., Vasquez, J. C., and Guerrero, J. M. (2023). Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology. *Renewable and Sustainable Energy Reviews*.

[4] Ballini, F., Olçer, A. I., Brandt, J., and Neumann, D. (2017). Health costs and economic impact of wind assisted ship propulsion. *Ocean Engineering*.

[5] Baunach, G. R., Wibberley, E. S., and Wood, B. R. (1985). Simulation of a coal transshipment terminal: Batam island, idonesia. *Mathematics and Computers in Simulation*, 27:115–120.

[6] Beukelaer, C. D. (2021). Tack to the future: is wind propulsion an ecomodernist or degrowth way to decarbonise maritime cargo transport? *Climate Policy*.

[7] Chou, T., Kosmas, V., Acciaro, M., and Renken, K. (2021). A comeback of wind power in shipping: An economic and operational review on the wind-assisted ship propulsion technology. *Sustainability*.

[8] Cimpeanu, R., Devine, M. T., and O'Brien, C. (2017). A simulation model for the management and expansion of extended port terminal operations. *Transportation Research Part E: Logistics and Transportation Review*, 98:105–131.

[9] Cimpeanu, R., Devine, M. T., Tocher, D., and Clune, L. (2015). Development and analysis of a port terminal loader model at rusal aughinish. *Simulation Modelling Practice and Theory*, 51:14–30.

[10] Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Martin, A. R., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Melo, J. B. D., adn A. Branco, D. O., San-Miguel, J., and Vignati, E. (2023). Ghg emissions of all world countries. Technical report, Publications Office of the European Union.

[11] Dahal, K. P., Galloway, S. J., Burt, G. M., McDonald, J. R., and Hopkins, I. (2003). A port system simulation facility with an optimisation capability. *International Journal of Computational Intelligence and Applications*, 3:395–410.

[12] Dalsøren, S. B., Eide, M. S., Endresen, O., Mjelde, A., Gravir, G., and Isaksen, I. S. A. (2009). Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports. *Atmospheric Chemistry and Physics*.

[13] Dipsar, S. and Altiok, T. (1998). Control policies for material flow in bulk-port marine terminals. *SMC'98 Conference Proceedings. 1998 IEEE International Conference on Systems, Man, and Cybernetics*, pages 3083–3088.

[14] Food and of the United Nations, A. O. (2024). Food loss and waste database.

[15] for Waterborne Transport Infrastructure, T. W. A. (2018). Design principles for dry bulk marine terminals.

[16] Gambardella, L. M., Rizzoli, A. E., and Zaffalon, M. (1998). Simulation and planning of an intermodal container terminal. *Special Issue SIMULATION on Harbour and Maritime Simulation*.

[17] Group, C. (2024). Understanding seasonality in grains.

[18] Hall, W. J. (2009). Assessment of co2 and priority pollutant reduction by installation of shoreside power. *Resources, Conservation and Recycling*.

[19] IMO (2020). Fourth imo ghg study 2020. Technical report, Internation Maritime Organization.

[20] Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J. A., Fuchs, K., Guarin, J. R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A. K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E. J., Okada, M., Phillips, M., Porter, C., Rabin, S. S., Scheer, C., Schneider, J. M., Schyns, J. F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., and Rosenzweig, C. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat Food*, 2:873–885.

[21] Lindstad, E., Polic, D., Rialland, A., Sandaas, I., and Stokke, T. (2022). Decarbonizing bulk shipping combining ship design and alternative power. *Ocean Engineering*.

[22] Mander, S. (2017). Slow steaming and a new dawn for wind propulsion: A multi-level analysis of two low carbon shipping transitions. *Marine Policy*.

[23] Nations, U. (2015). Paris agreement.

[24] Neagoe, M. ., Mohammad Sadegh, . T., Nguyen, H.-O. ., Hvolby, H.-H. ., and Turner, P. A. (2018a). Exploring congestion impact beyond the bulk cargo terminal gate. *Proceedings of the Hamburg International Conference of Logistics*, 26:978–981.

[25] Neagoe, M., Hvolby, H. H., Taskhiri, M. S., and Turner, P. (2021). Using discrete-event simulation to compare congestion management initiatives at a port terminal. *Simulation Modelling Practice and Theory*, 112.

[26] Neagoe, M., Taskhiri, M. S., Nguyen, H.-O., and Turner, P. (2018b). Exploring the role of information systems in mitigating gate congestion using simulation: Theory and practice at a bulk export terminal gate. *IFIP Advances in Information and Communication Technology*, pages 367–374.

[27] Nyanya, M. N., Vu, H. B., Schonborn, A., and Olçer, A. I. (2021). Wind and solar assisted ship propulsion optimisation and its application to a bulk carrier. *Sustainable Energy Technologies and Assessments*.

[28] Ottjes, J. A., Lodewijks, G., and Schott, D. L. (2007). Bulk terminal modelling and simulation. *5th International Industrial simulation Conference*.

[29] Parliament, E. (2021). Regulation of the european parliament and of the council on the use of renewable and low-carbon fuels in maritime transport and amending directive 2009/16/ec.

[30] Peng, Y., Li, X., Wang, W., Wei, Z., Bing, X., and Song, X. (2019). A method for determining the allocation strategy of onshore power supply from a green container terminal perspective. *Ocean and Coastal Management*.

[31] Poulsen, R. T., Ponte, S., and Sornn-Friese, H. (2018). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum*.

[32] Prenc, R., Vucetic, D., and Cuculic, A. (2018). High voltage shore connection in croatia: Network configurations and formation of the connection point to the utility power grid. *Electric Power Systems Research*.

[33] Rehmatulla, N., Parker, S., Smith, T., and Stulgis, V. (2017). Wind technologies: Opportunities and barriers to a low carbon shipping industry. *Marine Policy*.

[34] Robinson, S. (2004). *Simulation: The Practice of Model Development and Use*. John Wiley & Sons.

[35] Rojon, I. and Dieperink, C. (2014). Blowin' in the wind? drivers and barriers for the uptake of wind propulsion in international shipping. *Energy Policy*.

[36] Schmitz, M. and Madlener, R. (2015). Economic viability of kite-based wind energy powerships with caes or hydrogen storage. *Energy Procedia*.

[37] Styhre, L., Winnes, H., anf J. Lee, J. B., and Le-Griffin, H. (2017). Greenhouse gas emissions from ships in ports e case studies in four continents. *Transportation Research Part D: Transport and Environment*.

[38] Thies, F. and Ringsberg, J. W. (2022). Wind-assisted, electric, and pure wind propulsion – the path towards zero-emission roro ships. *Ships and Offshore Structures*.

[39] Unctad (2023). Review of maritime transport 2023.

[40] United Nations, D. o. E. and Social Affairs, P. D. (2022). Probabilistic population projections based on the world population prospects 2022.

[41] Vianen, T. V. (2015). *Simulation-integrated Design of Dry Bulk Terminals*. PhD thesis, Technische Universiteit Delft.

[42] Winkel, R., Weddige, U., Johnsen, D., Hoen, V., and Papaefthimiou, S. (2016). Shore side electricity in europe: Potential and environmental benefits. *Energy Policy*.

[43] Yin, Z., Hu, J., Zhang, J., Zhou, X., Li, L., and Wu, J. (2024). Temporal and spatial evolution of global major grain trade patterns. *Journal of Integrative Agriculture*.

[44] Zhu, B., Zhou, Q., Tian, Y., and Chen, K. (2018). Analysis method of terminal throughput capacity for coal export terminals. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 144.

[45] Zis, T., Angeloudis, P., Bell, M. G., and Psarafti, H. N. (2016). Payback period for emissions abatement alternatives: Role of regulation and fuel prices. *Transportation Research Record: Journal of the Transportation Research Board*.

[46] Zis, T., North, R., Angeloudis, P., Ochieng, W. Y., and Bell, M. G. H. (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics and Logistics*.