Abating GHG Emissions with Dynamic Arrival Times

Incorporating Dynamic Arrival Times after port uncertainties to abate GHG emissions from large container vessels

C.F.Broersma
4309227

Abating GHG Emissions with Dynamic Arrival Times

Incorporating Dynamic Arrival Times after port uncertainties to abate GHG emissions from large container vessels

by

C.F.Broersma
4309227

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on May 20, 2021 at 09:30 AM.

Report number:	2020.MME.8521	
Student number:	4309227	
Project duration:	July, 2020 – May, 2021	
Thesis committee:	Dr. W. W. A. Beelaerts van Blokland,	TU Delft, daily supervisor
	Prof. dr. R. R. Negenborn,	TU Delft, chairman of the committee
	Dr. ir. E. B. H. J. van Hassel,	TU Delft, commitee member

Delft University of Technology

Executive summary

Introduction
The container shipping industry is known for rapid growth over the years, defined as the container revolution. Container liner shipping organisations facilitate trade between all regions globally by deploying vessels in a shipping network. These networks operate so that several fixed ports are visited in a given period of time. This is referred to as a liner service. Several parameters accommodate this service. The number of containers to be discharged or loaded during the port call and the distances at sea between the ports are the two most important ones. Together these parameters determine the network schedule. This schedule is fixed and published months in advance to the involved stakeholders and the cargo customers. Since the container shipping network is part of a larger network, it is favourable for the continuation of the supply chain to maintain this schedule. Although the importance of the continuation is recognised, the industry is not known for a high degree of schedule reliability. This is due to the presence of regular and irregular uncertainties in the network. The consequences and the attention of the shipping' sector activities on climate change are increasing. This is because the shipping sector is held accountable for approximately 3% of the global carbon dioxide emissions. In reaction to the growing concerns regarding climate change, the IMO set several objectives to mitigate the GHG emissions. To comply with these objectives, a list of short-, mid-and long-term candidate measurements are composed by the IMO.

Research
Maritime emission reduction strategies are commonly divided into two main categories: technical and operational. Speed optimisation and port call optimisation are listed as two short term operational measurements. Approximately 90% of the causes for schedule unreliability in a shipping network originate from the port call. Schedule unreliability on its turn leads to waiting time on arrival, increased port turnaround times, and an increased voyage speed to recover the schedule. The voyage speed of a container vessel has a cubic relationship with fuel consumption, and since these vessels consume fossil fuels, this automatically leads to increased GHG emissions. Therefore, it is found that the port call conditions and the voyage efficiency are highly correlated with each other. A frequently applied methodology to optimise a process or service is the Lean Six Sigma Methodology with the corresponding DMADE approach. This approach contains a current and a future state model. The first part of this study, the current state analysis, is performed to identify the causes and effects of port uncertainties. The findings of this first part are used as input for the second part of the research. This second part, the future state, proposes a design to mitigate the effects of port uncertainties on GHG emissions. This approach is translated into the main research question as follows:

> **"What are the causes and effects of port uncertainties in a shipping network, and to what extent is a Dynamic Arrival Time able to mitigate the effects on the GHG emissions?"**

Current state analysis
According to the relationship of the port call variances to the GHG emissions, the first part of this research is dedicated to assessing the port call process and determine the significance and the causes for port call variations. A method to analyse and eventually optimise a process or service is the Lean Six Sigma (LSS) methodology. This methodology comprehends several tools that address uncertainties (waste formation) and reduce the number of defects. A case study for the Maersk mainline vessels in the Port of Rotterdam is performed to analyse the port call process. The complete port call process is considered, so from the End of Sea Passage (EOSP) of the arriving vessel to the Start of Sea Passage (SOSP) of the departing vessel. To measure the performance, three Port Performance Indicators (PPIs) are considered: arrival reliability, turnaround time reliability, and idle time. For the reliability measurements, a scheduled window is compared with an actual window. For 433 large container vessels, the event log data is retrieved, merged and analysed. It is found that these vessels have on-time reliability

of 78.0% and a turnaround time reliability of 42.6% if a four-hour specification limit is applied to the data. The data analysis did not show strong correlations between variables (e.g., container moves or bunker volumes) or critical events executed during the port call. This lead to the conclusion that further qualitative analysis on port uncertainties is required. The variations in the turnaround time reliability are assessed on the TIMWOODS waste types from the Lean methodology. Subsequently, to identify the root causes rather than the symptoms of variations, a Root Cause Analysis (RCA) is performed to the waste assessment. It is found that during the port call process, six main root causes are present.

If these waste types are further assessed for the complete shipping network, it is found that there is additional waste in the form of transportation at sea. This type of waste is defined as the sub-optimal voyage speed during sea transit to the arrival port. A sub-optimal speed results from variations in the network schedule that find their cause mostly (+90%) during the port call process. The sub-optimal voyage speed can be due to a lack of situational awareness of delays and communication, contractual barriers, or commercial incentives (fluctuating cargo value). Furthermore, it is found that most ports operate under a First Come First Serve principle, and the first contact is made at a distance of 30 nautical miles from the port. The consequence is that the vessel might arrive at a time when the vessel is not able to enter the port. In this scenario, the vessel either goes drifting or to anchorage.

Future state design

One way to enhance the voyage efficiency is to identify and communicate variations in the port call process at an early stage utilising a Dynamic Arrival Time (DAT). This DAT differs from the scheduled arrival time so that the vessel's arrival time is adjusted in a Just-in-Time (JIT) arrival. The concept of JIT is part of the Lean methodology and has proven to significant benefits in other industries. The primary effect is that the speed is adjusted over the sea transit to a lower value. Given the relationship between the speed and emissions, it is assumed that incorporating the DAT leads to a reduction of transportation waste, and subsequently, fuel expenditures and emissions. To test this assumption, an Agent-Based Discrete Event Simulation model in Anylogic is programmed. This model can test three different scenarios for a Short Sea Shipping (SSS) network. All three scenarios are tested in three measurement parameters from the current state analysis: waiting time, turnaround time, and fuel consumption and emissions. The first scenario ($j = 1$) represents the ideal situation with no uncertainties in the port call process. Within this base scenario, the schedule is maintained. The second scenario ($j = 2$) applies different port call uncertainties without incorporating the DAT design. The third scenario ($j = 3$) applies the same uncertainties in the network but incorporates the DAT design. The scenarios are indexed on the three measurement parameters. There are two methods to express the reduction potential: only for the delayed vessels or all the vessels. It is found that a fuel and emissions reduction of up to 30.9% is achieved when DAT is implemented to the delayed vessels under irregular uncertainties (low probability, high impact) in the port call process. The port call process with regular uncertainties (high probability, low impact) shows less fuel and emission reduction in the network. Under these conditions, the results show a reduction of emissions up to 9.1%. If all the simulation vessels are taken into account, the effect is respectively 0.5% and 6.1%. This is depicted in Table 6.7.

	$j = 2$	$j = 3$	
		regular uncertainties	*irregular uncertainties*
Fuel consumption [ton]	39291.7	39131.7	36907.7
Reduction [ton]	n/a	160.0	2384.0
Index	100.0	99.5	93.9

Table 1: Effect of Dynamic Arrival Time practices ($j = 3$) on the fuel consumption for all vessels

Incorporating a Dynamic Arrival Time (DAT) leads to two main benefits: increased efficiency of the arrival voyage (by reducing transportation waste) and shorter port turnaround times. Firstly, increased voyage efficiency results from the substitution of waiting time in increased voyage time, consequently lowering fuel consumption and emissions. Secondly, the increased level of predictability positively affects the vessel's turnaround time and the port's overall performance. A reliable prediction of the arrival time leads to efficient planning or rescheduling of the stakeholder's activities. For example, a predictable arrival time leads to improved planning of nautical services on arrival, resulting in less port congestion at the port entrance area. This will converge the shipping network to the first scenario ($j = 1$), where the port variations are reduced. In other words, the port call is optimised. Consequentially, the emissions from the departure transit will also decrease. However, given the Lean methodology's waste analysis, it is found that the complete elimination of all variations in the port call process is impossible. For example, there is always the threat of adverse weather conditions that cause variations in the port turnaround. In May 2019, the MEPC approved amendments where voluntary cooperation between ships and port is encouraged to reduce GHG emissions. Given the development trend of the shipping industry's digitisation, together with the challenge of climate change, it is very likely that the industry will increase the uptake of Dynamic Arrival Time (DAT) practices in daily operations to contribute to the IMO GHG reduction strategy.

Preface

This thesis is the final work to obtain my Master's degree for the Design, Production and Operations track of the Marine Technology from the Delft University of Technology. I want to make use of the opportunity to thank several people who have supported me while I was writing this thesis.

Firstly, I would like to thank Dr W.W.A. Beelaerts van Blokland for guiding me through this project with his enthusiasm and experience. Dr W.W.A Beelaerts van Blokland' knowledge and experience of the airport industry gave interesting insights and directions. Furthermore, I would like to thank you for the guidance and the freedom to explore that you gave me. Also, I would like to express my gratitude to Prof.ir.R.R.Negenborn, my second supervisor from the university and Dr.ir.E.B.H.J. van Hassel, my committee member. I would also like to thank Shahrzad Nikghadam from the TU Delft, who helped me get acquainted with my first simulation experience.

I want to thank all colleagues from Maersk Line who I met during the beginning of my thesis. In particular, I would like to thank Eddo Idzinga for all his time and knowledge. Especially the *Gemba's* we did in the port were very enjoyable. You triggered my interest in container shipping, and I learned a lot from your experience. Additionally, I would like to thank Captain Andreas van der Wurff, Marcel Westhoff, Damian Gonsalves and Frederik Tralls from Maersk Line and APM Terminals for their time.

Lastly, I would like to thank my parents, Brigitte and Andries, my brother Martijn, and my sister Cathleen. Each one of you had a supportive role in this project in its own way. Thanks to all my friends, and in particular Konstantinos, who helped me with his experience writing a thesis and other projects during the Master. And of course, I would like to thank Gijs, who brought me in contact with an employee of Maersk Line.

C.F.Broersma
4309227
Delft, May 2021

List of Figures

List of Tables

Acronyms

ATA Berth Actual Time of Arrival Berth. 32, 33, 37

ATA PBP Actual Time of Arrival Pilot Boarding Place. 32

ATC Cargo Actual Time of Completion Cargo. 34

ATD Berth Actual Time of Departure Berth. 34, 37

ATS Cargo Actual Time of Start Cargo. 33

ATT Average Turnaround Time. 18, 43

BPM Business Process Model. 9, 23, 29, 32, 45, 47, 62

CI Crane Intensity. 31, 34, 49

CMPH Crane Moves per Hour. 34

CRT Current Reality Tree. 51, 54, 56, 77, 81, 86

DAT Dynamic Arrival Time. iv, v, 9, 28, 57–65, 68–70, 77, 79, 81–83, 86, 88

DCSA Digital Container Shipping Association. 58

DMADE Define Measure Analyze Design Evaluate. 57

DMAIC Define Measure Analyze Improve Control. 8

DPMO Defect Per Million Opportunities. 80

DTA Distance To Arrival. 58, 59, 64

EGCS Exhaust Gas Cleaning System. 16

EOSP End of Sea Passage. iii, 32, 35

ETA Estimated Time of Arrival. 56, 59–61, 86

ETA Berth Estimated Time of Arrival Berth. 30, 31, 45, 80, 85

ETA PBP Estimated Time of Arrival Pilot Boarding Place. 30, 31

ETC Bunkers Estimated Time of Completion Bunkers. 31, 34, 62

ETC Cargo Estimated Time of Completion Cargo. 30, 31, 34, 54

ETC Service Estimated Time of Completion Service. 31

ETD Berth Estimated Time of Departure Berth. 30, 31, 34, 45, 55, 80, 85

FC Fuel Consumption. 71

FIFO First In First Out. 27

GHG Green House Gas. iii, ix, xi, 3–9, 13, 15–17, 27, 57, 64, 70, 78, 83, 85, 88

GloMEEP Global Maritime Energy Efficiency Partnership. 23, 34, 58, 73

IAO Idle Time after Operations. ix, 34, 43–45, 69, 88

IAT Inter Arrival Time. 67

IBO Idle Time before Operations. ix, 33, 43–45, 69, 88

IMO International Maritime Organization. iii, 3–6, 11, 13, 16, 23, 58, 73, 85

IQR Inter Quartile Range. 43

ISPS International Ship and Port facility Security code. 48

JIT Just-in-Time. iv, 23, 26–28, 32, 58, 61, 64, 68, 70, 71, 77, 79, 81, 86, 97

KPI Key Performance Indicator. 49, 54

LSCI Liner Shipping Connectivity Index. 4, 11

LSL Lower Specification Limit. 38

LSS Lean Six Sigma. iii, ix, 8, 27–29, 58, 79, 80, 82, 85, 89

NNVA Necessary but Non Value Adding. 47, 48

NTA Nautical Time on Arrival. 32, 88

NTD Nautical Time on Departure. 88

NVA Non Value Adding. 47, 86

OPEX Operational Expenditures. 27

OPS Operations. 88

OTRP On Time Resource Planning. 19, 21, 37

PBP Pilot Boarding Place. 32, 35, 41

PI Performance Indicator. 9, 54

PMPH Port Moves per Hour. 30, 33, 34, 39, 43, 49, 54, 56, 77

POR Port of Rotterdam. 4, 8, 9, 30, 32, 34, 37, 43, 45, 73

PPI Port Performance Indicator. iii, 17–19, 69, 70, 77

RCA Root Cause Analysis. iv, 8, 9, 51

RTA Requested Time of Arrival. 59

RTA Berth Requested Time of Arrival Berth. 31

RTA PBP Requested Time of Arrival Pilot Boarding Place. 31

RTD Berth Requested Time of Departure Berth. 34

SECA Sulfur Emission Control Areas. 16

SOSP Start of Sea Passage. iii, 35

SOT Standard Operating Time. 67

SSS Short Sea Shipping. iv, 28, 66, 69, 70, 73

STS Ship-to-Shore. 17, 32, 49

TAT Turnaround Time. 8, 11, 17–19, 27, 30, 35, 37, 39, 43, 45, 48, 50, 51, 54–57, 61, 64, 70, 73, 77, 81, 82, 85, 86, 88

TEU Twenty Foot Equivalent Unit. 3, 10, 66, 67, 80

TOC Theory of Constraints. 51, 56

TOS Terminal Operating System. 33, 34

TP Thinking Process. 51

TPS Toyota Production System. 21, 47, 49

TTA Time To Arrival. 58, 59, 64

UDE Undesirable Effect. 9, 47, 51, 55

UNCTAD United Nations Conference of Trade and Development. 3, 4, 17–19

USL Upper Specification Limit. 38

VA Virtual Arrival. 28, 47

VHF Very High Frequency. 31, 34

VTS Vessel Traffic Services. 31

WTA Waiting Time on Arrival. 70, 77

Nomenclature

α	Waypoints segments where the delay is known
β	Waypoints segments where the delay is unknown
$\delta_{p,i}$	Additional port time of vessel i
ι	Impact of the delay
ρ	Probability of delay occurrence
σ_b	Buffer between consecutive vessels in the port
$d_{i,wp}$	Distance between waypoints
D	Distance between port of origin and destination
$DFC_{s,a,i}$	Dynamic fuel consumption of vessel i while at anchorage during the sea transit
$DFC_{s,s,i}$	Dynamic fuel consumption of vessel i while sailing during the sea transit
$FC_{s,a,i}$	Fuel consumption of vessel i while at anchorage during the sea transit
$FC_{s,s,i}$	Fuel consumption of vessel i while sailing during the sea transit
$r_{p,i}$	Delay in the port for vessel i caused by vessel $i-1$
$S_{D,i}$	Virtual Arrival voyage speed of vessel i
$S_{d,i}$	Scheduled design voyage speed of vessel i
$t_{a,i}$	Sailing time of vessel i between two consecutive departures
$t_{p,i}$	Port turnaround time of vessel i
$t_{s,a,i}$	Time at anchorage of vessel i during the sea transit time
$t_{s,i}$	Sea transit time of vessel i
$t_{s,s,i}$	Time sailing of vessel i during the sea transit time
$t_{t,i}$	Total time that vessel i spends between two port departures
w	Waypoints along the sea transit

Contents

1

Introduction

Maritime transport is the most important contributor to global trade, with 90% of the total trade by volume carried by water [41]. According to a trade report from the United Nations Conference of Trade and Development (UNCTAD), a trading volume of 11.03 billion ton is facilitated by the shipping industry in 2019. The container shipping industry, which experienced rapid growth in the last decades, facilitates 60% of this form of transportation [101]. Although the movement of goods via shipping is cost, and energy-efficient, the industry is still held accountable for approximately 3% of the global Green House Gas (GHG) emissions [41]. If this number is put into perspective to countries, the shipping industry would be the sixth biggest contributor to Green House Gas (GHG) emissions [67]. The growing demand has led to a significant increase in vessel sizes accompanied by newly experienced complications. As mentioned, the sector emissions are significant, but also on a smaller level, the ports have difficulties handling the much-increased size of vessels. This leads to a high degree of schedule unreliability in the shipping industry [102, 72, 34, 33]). In this Master thesis, I will address the issues facing the largest shipping container handler, Maersk Line, and propose a design to improve the current process. In this first chapter, the different components and structure of this thesis are discussed. Section 1.1 provides background information to the container shipping industry in general. Section 1.2 introduces the GHG emissions and lists the contribution of the shipping industry and the candidate measurement solutions. Section 1.3 introduces the problem in this thesis. This is followed by the research objective in Section 1.4, and the research approach in Section 1.5. Section 1.6 provides a brief introduction to the case study and the organisation Maersk Line. Lastly, the scope of this thesis is defined in Section 1.7.

1.1. Container shipping industry

A container logistic company's service is focused on enabling worldwide trade by deploying vessels in different sailing networks [53]. A vessel route with a given time table is denoted as a service [13]. Services are constantly improved such that cargo transport is cost- and time effective. Each step in the process, from loading containers in port A to unloading containers in port B, is subject to optimisation [13]. The priorities of the customers of the shipping industry are clear: service, reliability, and price [53].

Over the last decades, the optimisations, mostly by increased container vessel carriage capacity in the service of shipping containers, have allowed rapid growth. This growth is also known as the container revolution, in which the industry realised an average annual increase of 8.6% [19] and this trend is not likely to stop [87]. In 1956, the first container ship had a capacity of 58 Twenty Foot Equivalent Unit (TEU). In 2017, ships carried more than 20,000 TEU, and the 2067 forecast predicts vessels with a 50,000 TEU capacity. In 2019, the container shipping industry could be held accountable for 60% of the total world trade by facilitating 811 million TEU. In that same year, Asia and Oceania handled 62% of the containers. As a result of (amongst other) this increased carrying capacity, around 90% of the trade is carried by sea [41].

To allow the significant growth of the container shipping industry, a high degree of optimisation is required. Not only to maintain profitability but also to comply with the regulations set by the International

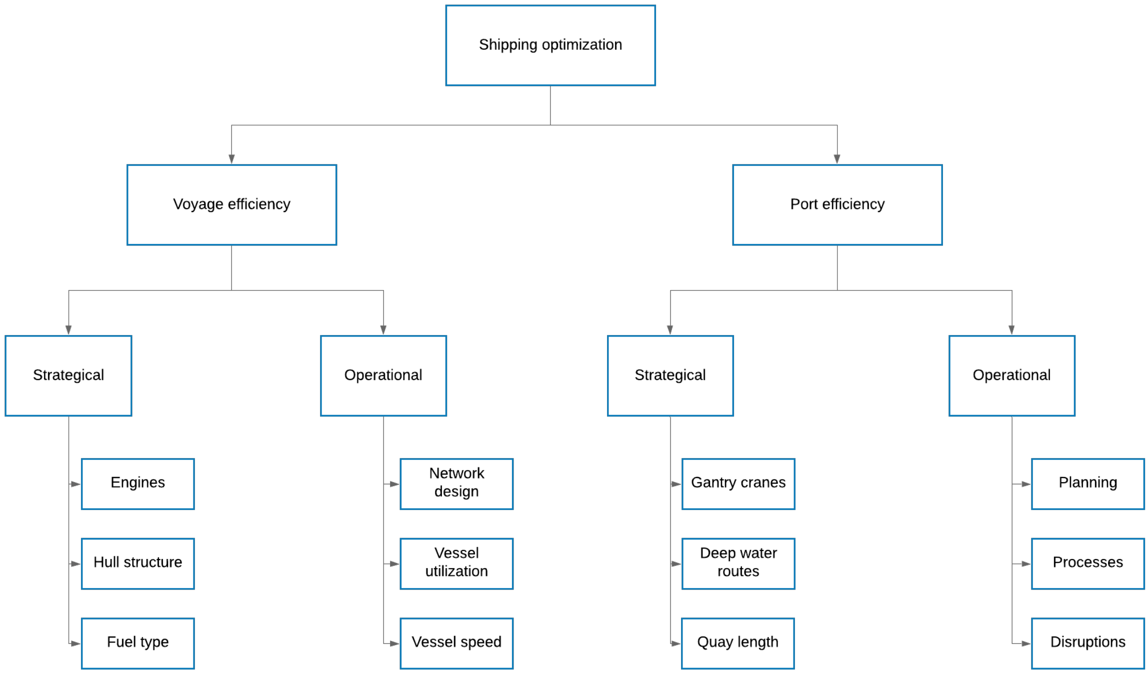


Figure 1.1: Shipping optimisation strategies. Own elaboration.

Maritime Organization (IMO) [41]. The shipping sector's optimisation is divided into two components: voyage- and port efficiency, which consists of two sub-components: strategical and operational decisions (Figure 1.1). For the voyage efficiency, the strategical decisions are long-term decisions such as the type of engines installed, the optimal hull structure for new build vessels, and the type of consumed fuels [51]. The (relatively) short-term decisions are made on the operational level. These aspects comprise decisions on fleet utilization, network design and the maintained vessel speed during the voyage [99].

The UNCTAD developed the index Liner Shipping Connectivity Index (LSCI) to measure the trend in the container industry. Research by the UNCTAD shows that five of the top ten ports are located in China, followed by the Port of Rotterdam (POR) in the sixth place. The index comprises six components: vessel size and capacity and the number of connections, weekly calls, services, and companies. Figure 1.2 depicts the trend of these components where bigger vessels and fewer companies in the industry are found. Furthermore, the liner shipping connectivity index is correlated with the port traffic. The better the LSCI, the higher the port traffic volumes. Continuous challenges for the port accompany this trend. The port's role in shipping optimisation has grown over the years to a multi-modal supply chain hub. On the strategic level, capital-intensive decisions are made regarding the port's capacity by investing in gantry cranes and accessibility by maintaining deep water routes and increasing quay lengths. This allows ports to accommodate the growing vessels and execute the required operations safely and efficiently. On the operational level, port decisions are made to optimise port efficiency, requiring less capital-intensive investments. Examples are planning optimisation, intra-port process optimisation and disruption management [114].

1.2. GHG Emissions

Green House Gas (GHG) are essential for life on earth because, without these gasses, the average temperature would be -18 degrees. However, human activities accelerated the amount of GHG content in the atmosphere by consuming fossil fuels to such an extent that the atmosphere will heat up to a value that has severe consequences to life on earth. In the year 2019, 76% of the carbon dioxide emissions (CO_2) are a cause of fossil fuels combustion and deforestation [112]. Figure 1.3 depicts the

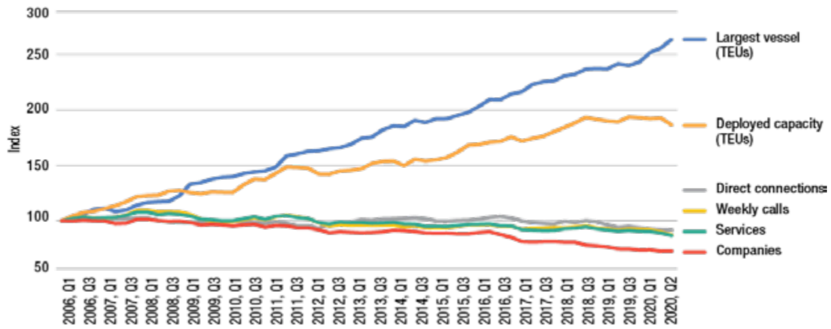


Figure 1.2: Liner Shipping Connectivity Index (LSCI) components [101].

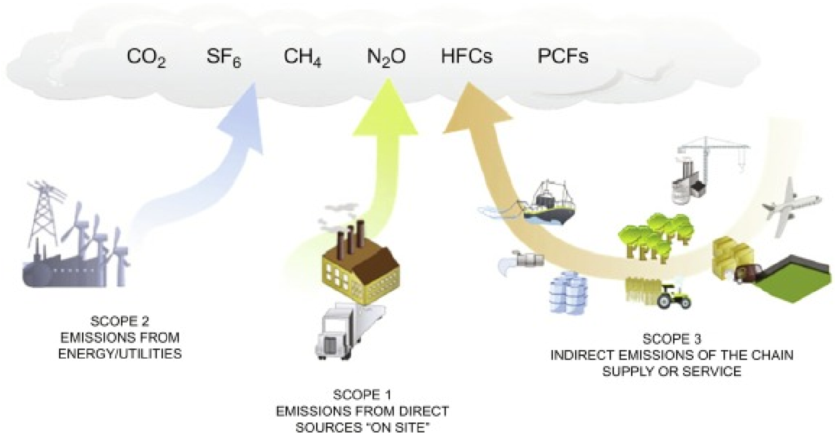


Figure 1.3: Major sources of GHG emissions [112]

industrial activities that have a large impact on the production of GHG emissions.

A sailing vessel consumes fossil fuel in the engine as an energy source. As a result, exhaust gasses are directly emitted into the air. The most relevant gasses are: carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxides (SO_2), and nitrogen oxides (NO_x). Next to these gasses, black carbon (BC) and particulate matter (PM) are formed. The amount of gasses formed during the combustion of fuel is mainly a function of the vessel speed and the type of fuel consumed [6]. Other industries, such as the automotive industry, tend to replace fossil fuels with renewable sources to fulfil the energy demand. However, due to the considerable amount of energy used during a vessel voyage, this is not an option for the shipping industry within the foreseeable future [106]. Table 1.1 provides an overview of the shipping industry's contribution to the global level of GHG emissions.

The container fleet represents a small percentage of the total world commercial fleet but is responsible for 20% of the generated emissions from international shipping in 2007 [79]. The container fleet predominantly consumes Heavy Fuel Oil as fuel type due to the attractiveness of operational costs, reliability and the current refuelling capabilities when it comes to the infrastructure. Heavy Fuel Oil is known for a high carbon rate compared to other fuel types such as Marine Gas Oil, Liquefied Natural Gas or Biofuels [88].

The International Maritime Organization (IMO) is a United Nations specialised agency responsible for the safety and security of shipping and the prevention of atmospheric pollution by ships. The third GHG study of the IMO presented a scenario where the CO_2 emissions could increase by 50-250% by 2050, compared to 2008. In reaction to the environmental concerns, the IMO introduced a provision in Annex VI of the International Convention for the Prevention of Air Pollution from Ships (MARPOL), representing an international policy to mitigate the effects of the shipping industry. The policy contains short-, mid, and long-term emission mitigating measurements imposed on the shipping industry. These

Exhaust Emission	Abbreviation	Shipping contribution on global production [%]	Year of measurement
Particulate matter	PM_x	1-14	2014
Black Carbon	BC	8-13	2015
Carbon oxides	CO_x	3.1	2015
Sulphur oxides	SO_x	10	2018
Nitrogen oxides	NO_x	18-30	2019

Table 1.1: Contribution of the shipping industry to the global emission levels [11]

measurements are intended to reduce the emissions by at least 40% in 2030 and pursuing this to at least 50% in 2050, compared to the numbers from 2008. These measurements are taken to comply with Paris Agreement temperature goals.

The strategy proposed by the IMO addresses the role of the port developments within the short-term measurements. The MEPC 74 resolution adapted in May 2019 encourages the cooperation between the port and shipping sector to contribute to the reduction of GHG emissions. According to the IMO, port optimisation includes several technical, operational, economic and regulatory actions that contribute to their ambitions. For example, the provision of onshore power supply in ports, safe and efficient bunker of low-carbon fuel types, and port optimisation efforts to facilitate just-in-time arrival of ships [33].

Another operational, efficient short-term measurement to abate emissions is the concept of slow-steaming. The practice of slow-steaming gained traction during the economic recession in 2008 when the oil price experienced a rapid increase, and container logistic providers cut costs by reducing the vessel operating speed. In the beginning, there were concerns about the technical consequences to the engine, but these concerns are overcome [37]. In 2010, 70% of the Maersk Line fleet practised slow steaming operations at engine loads below 40%. As a result, two million ton of carbon dioxide was saved that year [47]. This operational measurement is highly effective since the fuel expenditures are accountable for approximately 50-60% of the operational expenditures ([72], [35], [81], [59]). A secondary positive effect is that the vessel's fuel consumption has a cubic relation with the vessel speed [55], and the fuel consumption on its turn has a linear relation to the GHG emissions [78]. The short-term measurement of speed reduction (slow-steaming) can also be found in table 1.2.

Type	Years	Measure	Target
Short-term	2018-2030	New Energy Efficiency Design Index (EEDI) phases	New vessels
		Operational efficiency measures (e.g., SEEMP, operational efficiency standard)	In-service vessels
		Existing fleet improvement program	In-service vessels
		Speed reduction	In-service vessels
		Measures to address methane and VOC emissions	Engines and fugitive emissions
Mid-term	2023 - 2030	Alternative low-carbon and zero-carbon fuels implementation program	In-service vessels/ Fuels / New vessels
		Further operational efficiency measures (e.g., SEEMP, operational efficiency standard)	In-service vessels
		Market-based Measures (MBMs)	In-service vessels/ Fuels
Long-term	2030 +	Development and provision of zero-carbon or fossil-free fuels	In-service vessels/ Fuels / New vessels

Table 1.2: Overview of the IMO GHG reduction strategy [103]

1.3. Problem statement

A container logistic company's service is focused on enabling trade between customers worldwide by deploying vessels in different sailing networks [53]. A vessel sailing within such a network is provided with a time table and is denoted as a vessel service [13]. Ideally, the service schedule adapts to a rather static profile, meaning that the schedule is maintained. This is called schedule or service reliability and is longed for by all stakeholders. For example, it enables the cargo customer to efficiently incorporate the schedule within the rest of the organisations' supply chain. In addition to this, shipping lines can effectively incorporate the practice of slow steaming operations on the tactical level. This has proven to be a highly efficient approach to reduce fuel consumption and GHG emissions [107].

Reality shows that maintaining schedule reliability is often not possible due to various uncertain factors that occur during the execution of the container shipping service [55]. These uncertain factors are categorised into two types. The first type is defined as regular and recurring uncertainties such as congestion in the port's nautical area, varying terminal productivity or moves deviations, and unexpected waiting times due to tidal restrictions [72]. Due to the recurring profile of the regular uncertainties, shipping lines use probabilistic models to absorb the negative effects of using buffers in tactical planning. However, too large buffer times lead to a decrease in port resources utilisation. The second type occurs more occasionally and irregularly and is labelled as disruption events. Examples of disruption events are gantry crane breakdowns, severe weather on route or in the port, and labour strikes [55]. The port uncertainties that lead to schedule unreliability have negative consequences spread over three parts: the arrival leg, the port call, and the departure leg [101]. Examples of the consequences per part of the network are as follows:

- **Arrival voyage**
  - Waiting time on arrival leading to asset (fleet) underutilisation.
  - Drifting and port congestion leading to unsafe situations.
- **Port stay**
  - Increased inventory-holding costs.
  - Under utilisation of port resources (cranes, nautical services).
  - Possible disturbances cascaded to connected supply chains (hinterland, barges, feeders).
- **Departure voyage**
  - Increased vessel speed to the succeeding port to recover the schedule leading to increased energy demand.
  - A possibility of cut and runs or a port skip with customer service deterioration as a consequence.
  - Risk of losing a window in the succeeding port, which on its turn might lead to additional waiting time, and thus, lower asset utilisation.

The lack of consistency in vessel schedules, or service unreliability, is seen by the industry and customers as a major challenge that the industry is faced with [93]. A report from Sea-Intelligence states that the global maritime schedule reliability is 59% in 2011 [91]. Another analysis from Cargo Smart found that more than half of the 10,000 TEU vessel is delayed more than 12 hours, and a quarter of them was delayed more than 24 hours [97]. A report from Drewry states that the average deviation of the actual arrival time compared to the estimated arrival time was 1.9 days in February 2015 [24]. To conclude on the problem statement, service unreliability is translated into additional operational costs [110], cascading time effects through the rest of the supply chain [102], decreased customer experiences, and additional fuel consumption and emissions. According to a report from Notteboom, 90% of the causes for schedule reliability find their origin in the port area [72].

1.4. Research objective

This research assesses what port call optimisation efforts could lead to a reduction of GHG emission from the shipping industry. According to Verhoeven, port call optimisation is a low-hanging fruit that will decarbonise the maritime sector [108]. It is assumed that variations in the port call process lead to (un)expected waiting times, speeding-up and other types of waste in the process with increased GHG emissions. Especially today, the mitigation of these emissions is under wide attention due to the growing concerns regarding climate change. If a vessel can reduce the port TAT, the vessel can use this time to slow down the vessel at sea, resulting in lower fuel consumption. Given that 90% of the causes for schedule reliability originates from the port area [72], it is interesting to open this 'black box' and search for possibilities that contribute to a future scenario where ports are more capable of maintaining schedule reliability. This is also emphasised by Lind et al., who states that "..there is a continuous need for enhanced collaboration and information sharing among actors in the maritime transport sector to optimise the current processes and services, as well as providing innovation opportunities" [90]. Therefore, the port call process is analysed, assessed, and a proposal towards a design that improves the port call is provided.

The research aims to identify the reasons for variations in the port call process and what design improvements lead to better performance. The first objective is to understand the process, identify the stakeholders, and measure the Maersk mainline vessel's performance in the Port of Rotterdam (POR). This is done by deploying a descriptive business process model combined with the Lean Six Sigma (LSS) technique. This technique is a systematic approach towards identifying waste and inefficiencies in a process or service. These waste types are further analysed by making use of the Root Cause Analysis (RCA). Together, these efforts indicate the current state port call process for Maersk mainline vessels in the Port of Rotterdam (POR). Based on these findings, the second objective is to propose a design that contributes to the port call's better performance. This is called the future state where the reduction of GHG emissions are central. This research objective leads to the main research question that is substantiated by five sub-questions. The questions are depicted in Figure 1.4. Each phase column represents what sub-question is answered in what DMADE phase. Together this contributes to the main questions that are listed at the top of the figure. The DMADE phase columns, with corresponding sub-questions, are further elaborated in the research approach.

1.5. Research approach

The Lean Six Sigma (LSS) is a combination of the two most popular quality management tools globally. The Lean methodology addresses waste in a process, where the Six Sigma technique focuses on process improvement [57]. The Define Measure Analyze Improve Control (DMAIC) method is a problem solving tool which is associated within the LSS technique [69]. The business problems and the performance metrics are established in the Define phase. Next, the Measure phase expresses the process's present performance levels in terms of the established metrics. Throughout this study, data from Maersk vessels in the Port of Rotterdam is analysed on a set of performance metrics. In the Analyse phase, the root causes for deviations or defects are qualitatively analysed. These first three phases describe the model in the current, or "as-is" state. The Improve and Control phases are carried out to identify and implement solutions to improve the process into the "what-if" phase [5]. If it is hard to implement the Improve and Control phase, it is chosen to adapt to a Design and Evaluate phase. Within this research, it is chosen to apply the DMADE cycle due to the practical limitations. The latter two phases aim to propose a design that improves the current state in terms of the key metrics that are earlier defined. To conclude, the DMADE cycle is a systematic approach to answer the main research question, and therefore an efficient methodology for this study.

As the previous sections already introduced, the shipping industry is faced with the challenge to mitigate the GHG emissions from their operations. This research is particularly focused on the cooperation of the port and the vessel to take this challenge forward. Therefore, the main research question is:

> **"What are the causes and effects of port uncertainties in a shipping network, and to what extent is a Dynamic Arrival Time able to mitigate the effects on the GHG emissions?"**

1.5.1. DMADE cycle

As described, this research approaches the main research question by deploying the DMADE cycle. The rest of this section describes what sub-question is answered and what techniques or methods are used.

I. Define

The define phase is fundamental for the research since it provides technical background to the demarcated research context. Firstly, the mathematical relationship between the port call and the GHG emissions are described. This is done by defining a container shipping network and analysing the characteristics. This is followed by an assessment of the port in general and the corresponding Performance Indicators (PIs) used in the later phase of this research. Lastly, an assessment of the port and optimisation techniques is provided. The corresponding sub-question that is answered in this phase is:

> **”What is the relationship between port call uncertainties and emissions in a liner network?”**

II. Measure

Based on the assessed literature from the previous phase, the measurement phase aims to provide statistical insights into the port call’s current state. By performing qualitative analysis, the descriptive Business Process Model (BPM) is composed. This is the first deliverable of the research, and this deliverable must lead to the understanding of the process and an overview of the involved stakeholders. The second deliverable is a quantitative analysis that provides insights into the identified Performance Indicator (PI) of Maersk mainline vessels in the Port of Rotterdam. During this phase, the principles of the Six Sigma technique are applied. Six Sigma is a quantitative improvement technique that is explained in the literature study in Section 2.3. This phase aims to understand the port call process and identify and measure potential bottlenecks and inefficiencies by searching for data patterns.

> **”What sub-processes are executed during the port call process and what is the performance of Maersk vessels in the Port of Rotterdam (POR)?”**

III. Analyse

The third phase aims to analyse and assess the gained knowledge from the previous two phases and search for improvement areas. This is done by highlighting the root causes for process variations. The results from the previous two phases are used as input for this phase. First, the cause and effect diagram (fishbone diagram) is created. This is followed by a Root Cause Analysis (RCA). Together these two analytical Six Sigma tools help identify the root causes for Undesirable Effect (UDE) in the system. This leads to the third sub-question:

> **”What are the root causes for port call uncertainties?”**

IV. Design for improvement

The improvement phase’s design is the start of the ”to-be” or ”future” model. The current state and the reasons for variations are used as opportunity areas. Within organisations, the improvement phase is enabled by brainstorming sessions with different departments [64]. This research is limited to proposing a hypothetical design that contributes to improving the port call and the shipping network performance due to practical limitations. The design that is introduced to the network is the concept of a Dynamic Arrival Time. This concept relies on quality data and transparency between stakeholders to improve the vessels voyage efficiency and turnaround time in the port. This section assesses what adaptations to the current state design are required to reach a state where a DAT is efficiently implemented. This leads to the fourth sub-question:

> **”How can Dynamic Arrival Times be implemented in the liner network?”**

V. Evaluate

The last phase evaluates the improvement hypothesis proposed in the design phase using an Agent-Based Discrete Event Simulation model. Using a simulation model, the current state of a network is tested before and after the design improvement from the previous phase. This research aims to seek opportunities that optimise the port call and the network, thereby reducing the GHG emissions from the container industry. This lead to the fifth and final sub-question:

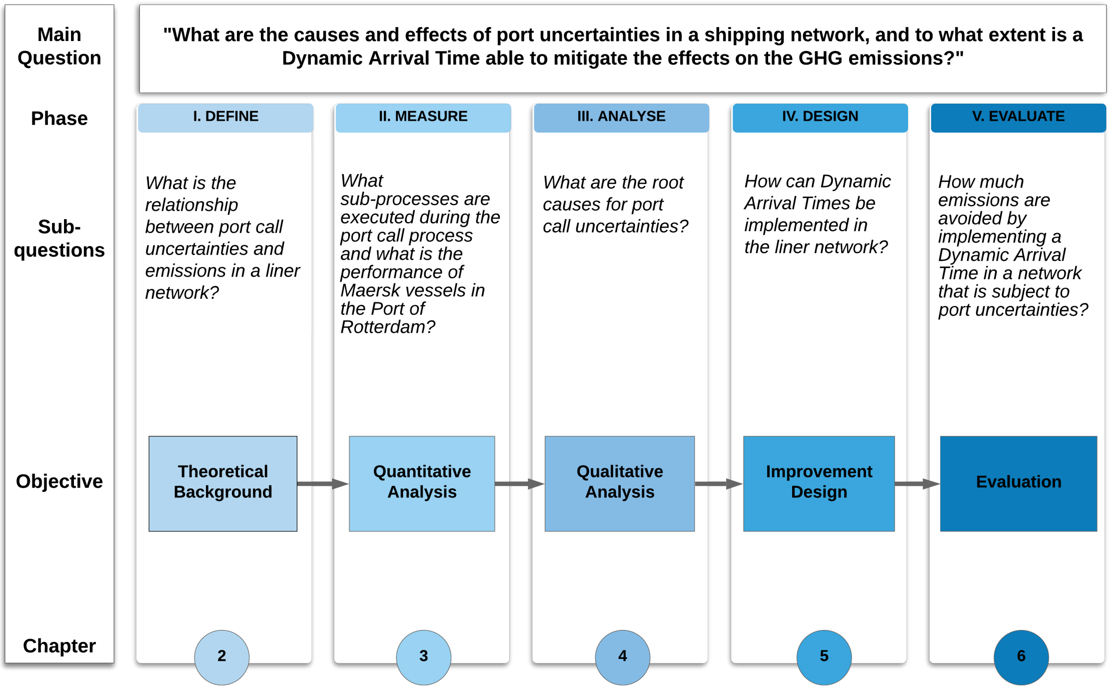


Figure 1.4: Overview of the methodology and corresponding research questions

> **”How much emissions are avoided by implementing a Dynamic Arrival Time in a network that is subject to port uncertainties?”**

The thesis is structured in a way that each chapter contains a phase. After completing all five phases, Chapter 7 reflects on the DMADE cycle before the conclusion Chapter 8.

1.6. Maersk case study

Throughout this research, event log data from A.P. Moller - Maersk (Maersk) is used. Maersk is an integrated container logistics company and member of the A.P. Moller Group. Maersk is currently the largest operator of container vessel globally, and as a pioneer in the maritime industry, they strive to reduce carbon emissions. Maersk aims to serve their customers by connecting and simplifying the supply chain to facilitate global trade so that consuming organisations maintain competitiveness in their market. The organisation's goal is to reach carbon neutrality in the ocean segment by 2050. In the year 2019, the company reduced the carbon efficiency by 5.2%.

This thesis uses port call process data of Maersk mainline vessels in the Port of Rotterdam from the year 2020. The mainline vessel is the organisations largest commercial container vessels that are sailing in the fleet. The vessel can reach up to 400 meters in length with a corresponding container capacity of 20,000 TEU [110].

1.7. Scope

The port is a bi-directional and multi-modal node that is part of a larger supply chain. This makes the port a highly complex logistic system with more than 28 involved stakeholders and numerous processes [74, 94]. Therefore, it is important to determine the scope of this thesis. The upcoming section provides an overview of the choices that are made to define the scope.

1. Vessel selection and case study

The first scope of this thesis is that the vessels under consideration are Maersk mainline vessels within, or approaching, the Port of Rotterdam. The mainline vessels are the biggest (up to 400 meters) in the Maersk Line fleet. The mainline vessels have a considerable impact on the port's performance due to their characteristics regarding size and required port resources. Furthermore, the LSCI shows a trend where these container vessels are growing in the industry (figure 1.2). These vessels require pilots, tugs and linesmen on arrival, and the presence of these vessels on the fairway has a great impact on the smaller vessels. Besides that, the vessels have dedicated quays to berth too. Altogether this highlights the importance and in-elasticity of mainline vessels in the port area and the shipping network. By improving the port call, and corresponding schedule reliability of the mainline vessel, the feeders and barges will also optimise their schedules and port calls.

2. Port operations

Secondly, the port operations under consideration are limited to entering the port, discharging and loading containers, acquiring services, and leaving the berth. The container stacking yard or hinterland operations are not considered since it is assumed that these factors have less influence on the port Turnaround Time (TAT). For this thesis, the relationship between port operations and sea transit is discussed.

3. Fuel and emissions

The last scope is made regarding the type of fuel consumed and the corresponding emissions. The vessels in this thesis are assumed to consume HFO during sailing operations. Green House Gasses (GHG) production and other pollutant emissions are proportional to the amount of HFO burned [46]. The IMO made a list of emissions with the corresponding pollutant emissions ratios (per) [41]. This contains the following emissions:

- carbon dioxide (CO_2)
- sulphur oxide (SO_x)
- methane (CH_4)
- nitrogen oxide (N_2O)
- particulate matter (PM)

2
Technical background

The continuously growing demand for global trade over sea demands a high degree of optimisation in the shipping sector. Not only to maintain profitability but also to comply with the regulations set by the IMO [41]. A promising strategy to optimise the shipping sector lies within the operational measures. Optimising the operational efficiency can be broadly described twofold: voyage and port optimisation (see figure 1.1). Port call optimisation and speed optimisation are both presented as promising strategies to reduce the GHG emissions from the shipping industry [41]. It is assumed that these two strategies consist of a certain synergy. This chapter provides technical background into both strategies and searches for a relationship between them. This answers the first sub-question:

> **"What is the relationship between the port call turnaround and GHG emissions?"**

Firstly, in Section,2.1 technical background information on the container network is provided. Section 2.2 elaborates on the role of the port in this container network. This is followed by a literature study into process optimisation techniques in Section 2.3, and port call modelling techniques in Section 2.4. Subsequently, the available literature on voyage optimisation is assessed. The conclusion on the technical background is provided in Section 2.6. This section provides an answer to the first sub-question from this thesis. Subsequently, an assessment of the literature is performed in Section 2.7 to prevail the literature gap, and, therefore, the importance of this research.

2.1. Container network model

A shipping container network is designed to facilitate trade between different regions overseas. In the strategic and tactical phase, decisions are made regarding the number and sequence of ports to visit, the number of containers to move, and the required time at sea and in the port areas. As a result, a network such as figure 2.1 is composed. Within this network, there are static parameters (e.g., the distance between ports), decision variables (e.g., speed of the vessel) and stochastic variables (e.g., delays at ports).

2.1.1. Time factors

A vessel that operates in a network has two operating stages: time at sea or time in the port. If the vessel completes one service call, the sum of these operating times is equal to the total time that the vessel spends in the network. The time between intermediate departures is expressed with equation 2.1. The time that the vessel is at sea between ports is further described as the summation of the sailing time ($t_{s,s,i}$) and the waiting time at anchorage ($t_{s,w,i}$) (equation 2.2). Ideally, the vessel network is designed and operated in a way that no waiting times are present. However, due to uncertainties during port operations, there is a chance of waiting time at anchorage. It is estimated that a container vessel spends 6% of the time at anchorage waiting due to delays in the port [36]. Shipping lines, together with terminal operators, incorporate buffers between consecutive vessels in the schedule to

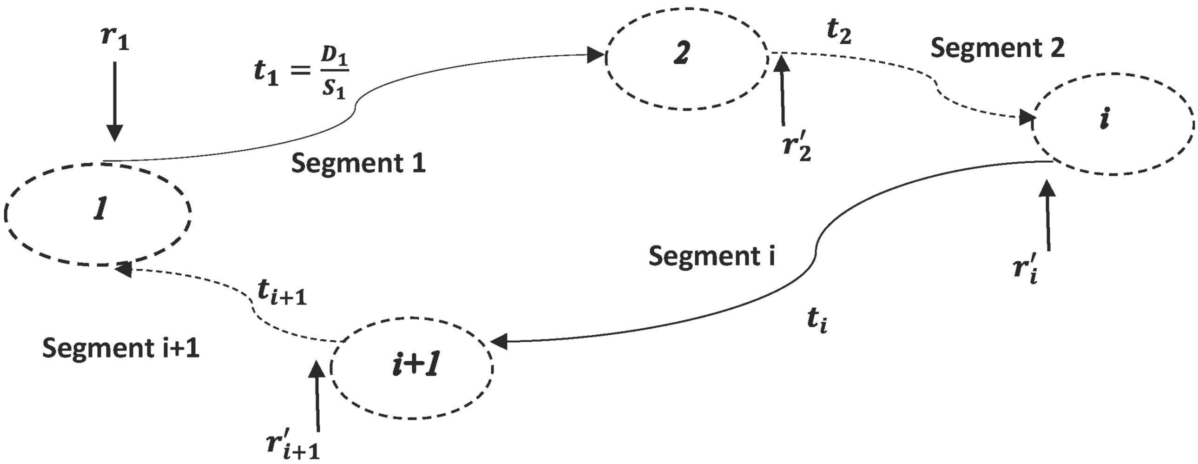


Figure 2.1: Container shipping network [59]

hedge against regular uncertainties [55]. Depending on the significance of the total delay in the port (δ_{p-1}), the buffer (σ_b) can (partially) absorb the delay (r_i) (equation 2.3).

$$t_t = t_s + t_p \tag{2.1}$$

$$t_s = t_{s,s} + t_{s,a} \tag{2.2}$$

$$r_i = \sigma_b + \delta_{p,i-1} \tag{2.3}$$

Waiting time at anchorage as a result of port delays leads to multiple consequences. The direct consequence is schedule unreliability. In the case of schedule unreliability, the vessel cannot sail according to the predefined schedule. Since the vessel is part of a bigger logistic supply chain network, the connected schedules of manufactures, service providers, customer etc., experience schedule reliability as well. Now, if such a connected (downstream) organisation operates under the Lean principles, the inventory is minimised in the process. This way, delays of, e.g., raw materials, directly affect the production rate of such an organisation [15].

To mitigate the consequence of a delay in a port, the vessel captain increases the departure leg's speed to arrive on time in the next port and recover the schedule [72]. A vessel that sails from one port to another covers a distance of a segment (D_i), and together with the schedule speed (S_i), this determines the time that the vessel is sailing at sea ($t_{s,s}$).

$$t_{s,s,i} = \frac{D_i}{S_i} \tag{2.4}$$

This thesis assumes that the vessel experiences anchorage time on arrival due to port uncertainties (delays) at the arrival port. In other words, during the planning phase of the network, there is no presence of scheduled waiting times.

$$t_{s,a,i} = r_i \tag{2.5}$$

By substituting equation 2.4 and 2.5 into equation 2.1, the total time that a vessel spends in between two ports (measured from the departure times) ($t_{t,i}$) is:

$$t_{t,i} = (\frac{D_i}{S_i} + r_i) + t_{p,i} \tag{2.6}$$

Parameters	Abbreviation	Value	SI Unit
Installed Power	P_{inst}	49920	kW
rpm at MCR	n_{MCR}	84	r/min
Propeller diameter	D_{prop}	10	m
Length overall	LOA	366	m
Length perpendiculars	LPP	347	m
Beam	$Beam$	48	m
Molded draught	T_m	16.0	m
Ballast draught	$T_{ballast}$	10.7	m
Depth	D	22.9	m
Sea margin	SM	15%	avg.

Table 2.1: Input parameters for the Hollenbach Model [51].

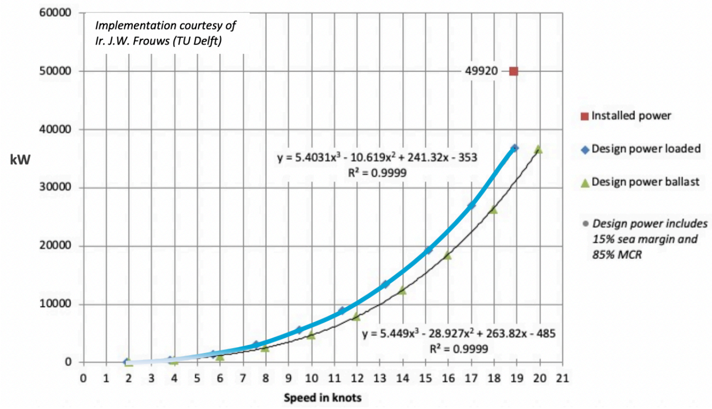


Figure 2.2: Hollenbach model output power-speed curve [51].

2.1.2. Fuel and emissions

The fuel consumed during the sailing time between the ports is calculated as the summation of the fuel consumption during sailing and the fuel consumption during the time at anchorage (equation 2.7). The fuel consumption at sea is further segregated into fuel consumption for the propulsion mechanisms and the auxiliary engines. The auxiliary engine is both used during sailing as well as during anchorage time. It is further assumed that if the vessel is at anchorage, only the auxiliary engines are used. This results in the total fuel consumption as equation 2.8 proposes. This fuel consumption is on its turn a function of the energy consumption ($EC_{prop,s}$), and the specific fuel oil consumption ($SFOC_s$). These two variables are determined by a combination of time, speed, and vessel characteristics. The speed and the vessel (and engine) characteristics determine the power-speed curve. The power is often empirically approximated as a cubic relationship to sailing speed [55]. The calculation provides a specific required power ($P_{prop,s}$) at different levels of speed (S_i). Consequentially, by multiplying this power with the time that the power is required (t_s), the energy consumption ($EC_{prop,s}$) is calculated. Research by Kouzelis proposes a case study where this power-speed relationship is empirically approximated. The research applies the Hollenbach method by deploying a model from Frouws (TU Delft). The input and results from the power-speed relationship are depicted in Table 2.1 and Figure 2.2.

$$FC_s = FC_{s,s,i} + FC_{s,a,i} \tag{2.7}$$

$$FC_s = \left[FC_{prop,s} + FC_{aux,s}\right] + \left[FC_{aux,a}\right] \tag{2.8}$$

$$FC_{prop,s} = EC_{prop,s} \cdot SFOC_s \tag{2.9}$$
$$FC_{aux,s} = FC_{aux,a} = pFC_{prop,s} \cdot FC_{prop,s} \tag{2.10}$$

Where:

$$EC_{prop,s} = P_{prop,s} \cdot t_{s,i} \tag{2.11}$$

and:

$$P_{prop,s} = f(S_i) \tag{2.12}$$
$$P_{prop,s} = 5.4031 \cdot S_i^3 - 10.619 \cdot S_i^2 + 241.32 \cdot S_i - 353 \tag{2.13}$$

The installed main- and auxiliary engines emit exhaust gasses when the combustion of fossil fuels takes place. Besides oxygen, water and vapour, the exhaust gasses contain GHG emissions. As depicted in table 1.1, the shipping industry is responsible for a significant amount of the total GHG

Fuel type	Carbon content	Conversion factor	Price Rotterdam (2020)	Global 20 Ports (2020)
Diesel / Gas Oil	0.875	3.206	$377.50	$425.00
Light Fuel Oil	0.86	3.151		
Heavy Fuel Oil	0.85	3.114	$276.00	$304.50
Liquefied Petroleum Gas (LPG)	0.819	3.000		
	0.827	3.030		
Liquefied Natural Gas (LNG)	0.75	2.750		

Table 2.2: Marine fuel types assessed by carbon content ([2]) and corresponding prices [19])

emissions. With the current growth trend and forecast of the shipping industry, it is not likely that these numbers will decay. In reaction to the growing environmental concerns, the IMO compiled several rules and objectives that strive to reduce the emissions [41]. The most common GHG emissions are particulate matter, black carbon, carbon oxides, sulphur oxides, and nitrogen oxides. The pollutant emissions ratio (per) is defined as the ratio between the pollutant emissions and the specific fuel consumption [96] (equation 2.14). Within the literature, this is often referred to as the conversion factor.

For diesel combustion, the carbon dioxide (CO_2) and sulphur oxide (SO_2), the per values are almost completely determined by the fuel type. The values for nitrogen, black carbon, and particulate matter are less trivial and heavily influenced by the temperature and other conditions at which the fuel's combustion takes place [96]. The chemical composition of fuel consists mainly of hydrocarbons, e.g. $C_{15}H_{32}$. Given the atomic weights of carbon and hydrogen, respectively 12.011 and 1, the carbon mass fraction in fuel is approximately 85%. These hydrocarbons react with oxygen (O_2) with an atomic weight of 15.9994 during the engine's combustion. This results in a total atomic mass of 44 for CO_2. Using the atomic weights, the ratio between CO_2 and carbon is now equal to 44:12 [2]. There is a wide variety of fuel available, where table 2.2 depicts the most commonly used marine fuels. The prices in the table are the average of the period July 2020 till January 2021. With the initiation of the Sulfur Emission Control Areas (SECA), more emphasis is put on the amount of sulphur content in the fuel. The new regulation, which is often referred to as IMO 2020, limits the maximum allowable sulphur content in the fuel outside of the SECA zones to a value of 0.05 mass/mass. Within the SECA zones, this maximum is already at 0.01 mass/mass. Another method to comply with the legislation is by making use of an Exhaust Gas Cleaning System (EGCS). This alternative method filters and captures the exhaust valves' sulphur content before it is released in the air [42].

Within this thesis the fuel carbon content per unit weight of fuel is approximated at 86.4% [20]. This leads to the carbon dioxide emission consumption equation:

$$per = \frac{spe}{sfc} \tag{2.14}$$

$$EC_{CO_2} = (0.8645) \cdot (44/12) \cdot FC_s = 3.17 \cdot FC_s \tag{2.15}$$

Other factors for GHG emissions are obtained from the Third IMO GHG Study. The results are presented in table 2.3.

Emission type	Abbreviation	Content Marine HFO [g/g fuel]	Content Marine MGO/MDO [g/g fuel]
Methane	CH_4	0.00006	0.00006
Nitrogen Oxide	N_2O	0.00016	0.00015
Sulphur oxide	SO_x	0.004908	0.00264
Particulate Matter	PM	0.00699	0.00102

Table 2.3: Marine fuel types assessed by other GHG contents ([41])

2.2. Port model

Now that the relationship between the port TAT and the fuel consumption and emissions is clear, the following section provides an introduction to the port and corresponding elements. This is done through a brief study of the processes that are executed, the corresponding performance measurements and an assessment of schedule reliability.

2.2.1. Definition and function of the port

Traditionally, the port is defined by Paixão et al. as an ”...area made up of infra and superstructures capable of receiving ships and other modes of transport, handling their cargo from ship to shore and vice-versa and capable of providing logistic services that create value-added” [74]. A process is a collection of inter-related events, activities, and decisions points that involve several actors and objects that collectively lead to an outcome of value to at least one customer [26]. Therefore, the port call process is within this thesis defined as the set of events and activities performed to the vessel in the port area to handle the cargo and provide logistic services. The port process is, unlike manufacturing processes, a bi-directional logistic system. Often, the port is referred to as an inter-modal transportation hub. This means that in the port, multiple forms of transportation, such as rail, road, and inland water networks, come together to facilitate the continuous flow of goods [74]. For an incoming mainline vessel, the execution of events and activities in the port area requires collaboration and communication between the vessel crew, agent, terminal, and other parties, including administrative stakeholders such as border control, customs, immigration and port authority [56]. According to a Port Technology report, there are 28 parties involved during a port call process [94].

The multi-stakeholder environment characterises the port call process by a high degree of complexity. According to Paixao et al., the activities are performed in an unorganised way, with high costs and inadequate service, lost opportunities and sub-optimisation of resources [74]. To measure the port performance, the United Nations Conference of Trade and Development (UNCTAD) compiled a list of port PPIs. The following sections provide a short introduction to the operational processes performed during the port call and the port performance measurements proposed by the UNCTAD by utilising the port performance model from Figure 2.3 [61].

2.2.2. Input, controls and resources

As Figure 2.3 depicts, the port model starts with the input variables. The input to the port model is a container vessel with certain parameters and variables. The parameters include all the static information on the vessel, such as the length and the width. Additionally, there are several variables, such as the container load and the demand for port services. Although the figure does not clearly present this, these input parameters and variables lead to a plan. This plan includes several elements such as a stowage and bunker plan, and together these plans lead to laytime. During the execution of this plan (the actual port process), there are controls such as border controls, immigration and security that all parties must comply with. Lastly, for the execution of the plan, there are several resources required. The required resources can be distinguished between tangible (e.g. STS cranes) and intangible resources (e.g. communication systems). Additionally, the port infrastructure (e.g. depth levels), which is also not clearly defined in Figure 2.3, is an important factor determining a port’s competitiveness.

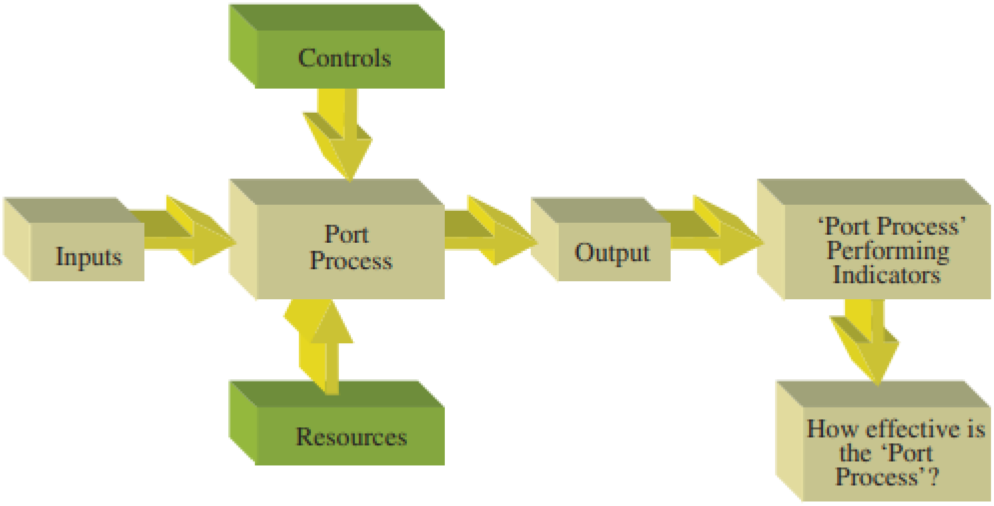


Figure 2.3: Port performance model [61]

2.2.3. Port process

The port call, interchangeably used with the port Turnaround Time (TAT), is when the vessel enters the port, load and unloads the containers, uses the desired services and departs [52]. The time in the port is mostly determined by the number of containers to be discharged and loaded [101]. Often, the time that a vessel is at anchorage outside the port is included in the port TAT [17]. The vessel is either underway (nautical operations) or at berth (berth operations) within the port area. According to a recently published set of standards, the vessel is at berth from the moment that the first line is released on arrival till the last line is released on departure [22]. During the time that the vessel is underway in the port area, the vessel agent might call upon the nautical services provided by the Port Authority, such as a pilot, tugs and linesmen, to enable a safe transition from the port entry to the terminal and vice-versa [65]. In the container industry, this is known as the mooring process on arrival and departure. Once the mooring process is executed, the terminal activates the pre-positioned gantry cranes to commence with the unloading operations. During the execution of the container handling by the gantry cranes, the vessel agent might recall upon additional services such as bunker delivery, stores, maintenance activities, diving activities or other operations such as a crew change. Throughout the execution of the operational processes, the Port Authority imposes the vessel agent with compliance procedures, legislation, customs declarations and other forms of controls. Figure 2.4 provides an example overview of the stakeholder involvement throughout the process [56].

2.2.4. Port Performance Indicators

According to a report from the UNCTAD, PPIs are simply measures of various aspects of the port operations. The indicators should be easy to calculate, simple to understand and provide insights into key areas' operations. The PPIs is used to compare the measured performance with a target and, secondly, to observe trends in the acquired information [99]. Figure 2.3 depicts the port performance model that is proposed by Marlow et al. [61]. The vessel reaches the port performance model's output from figure 2.3 when the vessel leaves the port area and commences with the new sea leg. The output is evaluated based on a set of measurement indicators that describe the efficiency of the process. A frequently used PPI in the container shipping industry is the port Turnaround Time (TAT) [101]. The TAT is a function of the operational efficiency during the execution of the port call process [111]. A port strives for an adequate operational efficiency level to maintain a competitive position towards other ports [65]. The Average Turnaround Time (ATT) of ports worldwide show a strong distribution when the region is considered. The global average of ATT is at 25.5 hours, with East and North Asian ports holding an average of only 17.2 hours against a 64.6 average ATT in South African ports [93]. The port turnaround time divided by the number of resources required to fulfil the tasks is often used to determine the productivity of the port call [98]. Shipping lines aim to minimise the port TAT so that the vessel can operate more revenue-generating voyages in a period of time.

More recent research entails a new approach to measuring port performance by introducing the agile port. An agile port focuses on flexibility and the development of a structure that allows for rapid response to changing circumstances. This allows organisations to maintain their position in a competitive market of continuous and unanticipated changes. Six important observations that address the urge to introduce agile ports are: (1) the growing significance of ports in the economic environment, (2) the increased level of competition between ports, (3) the necessity to include service rather than costs alone, (4) the continuously growing globalisation, (5) the evolution in the transport sector where organisational, technological and commercial aspects grow in importance, and (6) the development of fast communication systems. If a port successfully adapts to the concept of an agile port, the transition from a port as a logistic distribution centre (third generation) to a transport solution provider (fourth generation) is reached. The UNCTAD describes the third generation port development as capital and know-how environments, where the fourth generations rest on a knowledge-based environment. The introduction of agility in a port is substantiated by the concepts of Lean, just-in-time, and process redesign techniques [61]. Incorporating the agile principles into the port gives rise to the On Time Resource Planning (OTRP). Agile ports are further discussed in Section 2.3.2. The OTRP is a PPI that focuses on the planning versus the actual performance of the port call.

The principle of an aircraft TAT at the airport is similar to a vessel TAT in the port. Although there are similarities in the process, the reliability, or OTRP of the airline industry is much higher. A report from the Federal Aviation Administration provides an overview of three major airports in the United States where the OTRP values are almost equal to 90% [29]. The definition of on-time remains arbitrary in the industry. Where one airline accepts one minute as a standard, another airline might use 15 minutes. Nonetheless, there is a mutual understanding that on-time reliability is an essential measure towards customers [38]. A report by Wu and Caves states that the most effective way to improve the OTRP is to incorporate higher buffer times between flight schedules. However, these higher buffer times lead to a higher TAT, which leads to less revenue-generating activities. In other words, there is a trade-off between reliability and the turnaround time [109].

2.2.5. Port uncertainties

The reasons for the schedule unreliability of a shipping network are numerous. This section assesses the available literature on port uncertainties and the role of these uncertainties towards schedule unreliability.

The research by Notteboom classifies the reasons for delays into four types: (1) port/terminal operations including mooring and berthing, (2) port access channel including pilotage and towage, (3) maritime passages such as the Suez or Panama canal, and (4) mechanical failures or bad weather [72]. Wang and Meng (2012) [105] classify the reasons for delays into two categories: uncertainties at sea and in the port. During the voyage at sea, the vessel could be delayed by severe weather (e.g., storm and fog) or sea conditions (e.g., current and tide). In the port area, uncertainties are present during the nautical part (e.g., navigation difficulties) and the berth operations (e.g., quay crane handling efficiency and container handling deviation). According to the report from Notteboom, 90% of the causes for schedule unreliability in the shipping service are disruptions during port operations [72].

A similar approach towards delays is used in the airline industry. Hessburg categorises disruptions into controllable and non-controllable situations. The former disruptions present delays that are out of control of the operator, where the latter type relates to the aeroplane's inherent and systems [38].

Research by Molkenboer focused on the delays during the port's nautical operations and analysed why vessels were delayed on arrival and departure. This study shows that almost 70% of the delays are caused by the assigned tugs not available to assist during mooring on arrival. The remaining 30% is caused by congestion in the port, pilot unavailability, and berth unavailability, respectively, 15%, 8%, and 7%. On departure, 48% of the delays are caused by the unavailability of tugs. The remaining 52% is caused by unfinished terminal operations, unreadiness to depart, pilot unavailability, and congestion, respectively, 27%, 13%, 7%, and 5% [65].

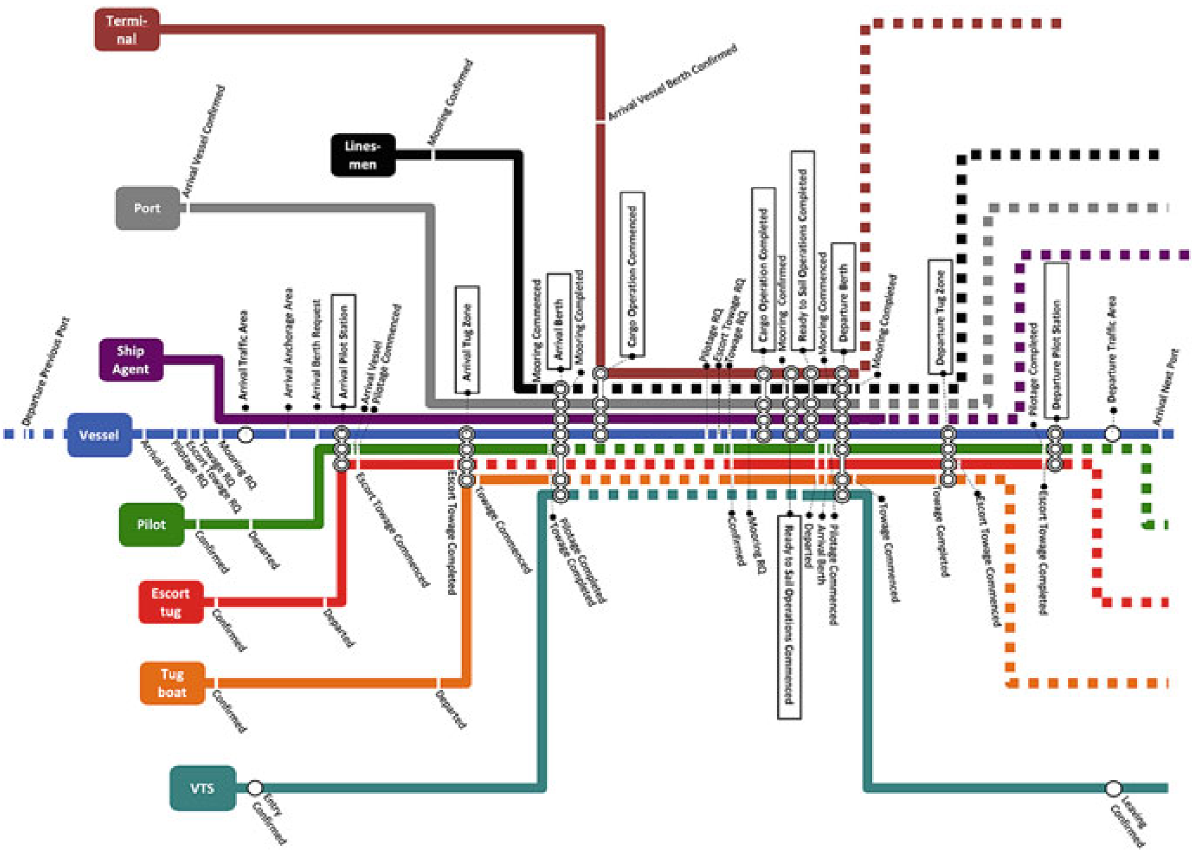


Figure 2.4: Port call process and stakeholders [56]

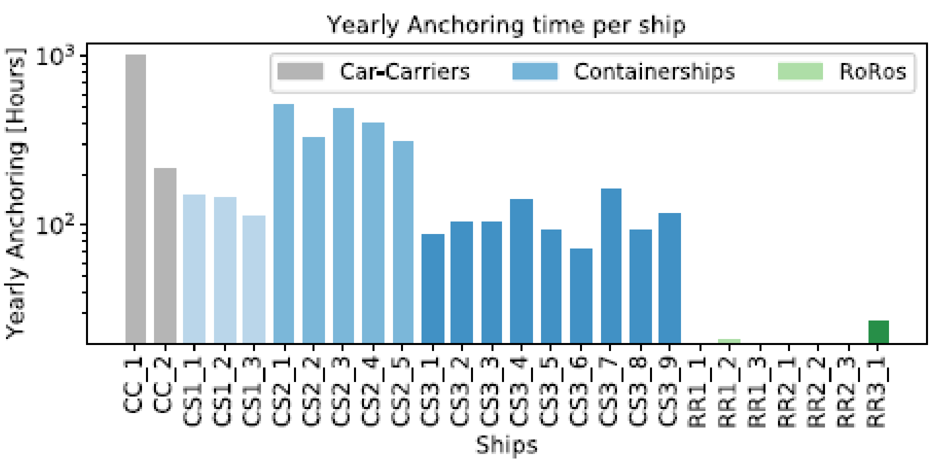


Figure 2.5: Container vessel anchor times [3].

2.3. Port call optimisation

Within the research field, there is a wide variety of literature available to improve (port) processes. This section starts with an assessment of the available process improvement and/or optimisation techniques. The applicability of the techniques to support port call optimisation are tested by assessing research efforts that adopt the specific technique.

2.3.1. Lean Six Sigma

Lean and Six Sigma are two prominent process improvement techniques that are applied in organisations today. Both techniques have a strong customer-driven approach. Next to these techniques, other well-known process improvement techniques are Total Quality Management (TQM), Just-In-Time (JIT), and World Class Manufacturing (WCM).

Lean technique

The Lean technique is a systematic approach to identify and eliminate waste from a process by continuously improving the product or the service at the pull of customer ([57], [50]). The five guiding principles of the Lean technique to eliminate waste in a process are [57]:

- Specify value: defining what activities add value to the process.
- Value stream mapping: a visual representation of the material and information flow.
- Flow: the product or service must move as fast as possible between value-adding activities.
- Pull: the customer demand determines the rate of flow.
- Perfection: process improvement leads to the continuous elimination of waste.

Incorporating Lean techniques within an organisation has been proven to lead to a range of benefits such as reduced customer lead times, reduced time to launch new services, and improved productivity and profit. A study by Leite and Vieira assessed the applicability of the Lean technique to the service sector. The study shows no single solution or model to follow when the Lean methodology is applied to the service sector, but rather a mix of tools and practices that need to be adjusted for the situation. According to this same study, besides the potential gains, applying the Lean technique to the service sector also has limitations. Especially when a process is not well defined and lacks in reporting, a Lean project can offer resistance [54].

Waste assessment

Taiichi Ohno, co-developer of the Toyota Production System (TPS), suggests that 8 types of waste account for up to 95% of the costs in non-Lean manufacturing environments. These types of waste (Muda) are overproduction, waiting, transportation, non-value-added processing, excess inventory, defects, excess motion, and underutilised people [50]. Often, these waste types are referred to as the TIMWOOD waste types. According to Olesen et al., these types of waste are not always applicable to a process, such as a port environment. For example, transportation, defined as a waste type by Ohno, is exactly the ports' core business. So besides Muda, the concepts of Muri and Mura must are introduced. Mura is the Japanese term for inconsistency or the unevenness in operations, and Muri is the Japanese term for unreasonableness or the overburdening of people and resources [73]. According to Youngman, Mura (unevenness) is often the cause for Muda (waste) and Muri (strain). Reducing unevenness is the way to address both of the other issues. Youngman states that if the focus is put on waste reduction, the symptomatic issues are fixed rather than the deeper systematic issues [113]. Figure 2.6 provides a schematic overview of the concepts with the Japanese terms and the translation.

These Japanese concepts are also used within the research field. Olesen et al. suggest that only the concept of Muri and Mura apply to port operations. The research elaborates on this by stating that terminal operators are often paid to hold inventory, and therefore, it is not a waste (Muda) [73]. Paixao et al. use all three concepts by stating that Muri focuses on preparing and planning port processes. At the same time, Mura relates to implementing the resources and proactively eliminates waste within them. The concept of Muri brings forward the On Time Resource Planning (OTRP) metric. Together

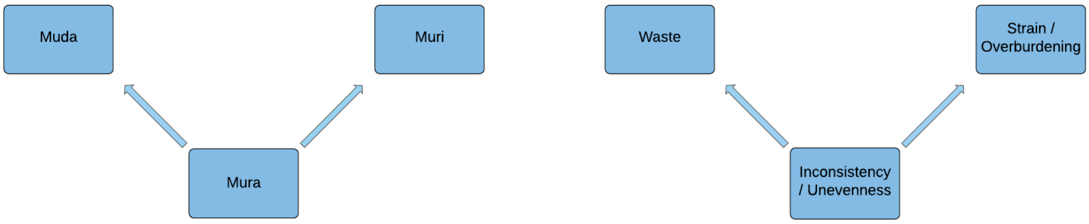


Figure 2.6: Overview of the Mura, Muri, and Muda concepts by Youngman [113]

they focus on these concepts that must lead to improved planning and operations, which leads to a reduction of the Muda (waste). According to Paixao et al., the stochastic demand (unevenness) of port services is the origin of serious bottlenecks (congestion) within the port environment [74].

Six Sigma technique
Next to the Lean technique, a well-known improvement method is the Six Sigma technique. Six Sigma is a technique that is focused on the processes and uses a systematic methodology to improve the process ([64], [69]). According to Pyzdek, Six Sigma is a rigorous, focused, and highly effective implementation technique when quality improvement is aimed for [80]. The technique is based on the principle that no more 3.4 Defects Per Million Opportunities (DPMO) can be present to reach the Six Sigma value. If the value of the defects per million increases, the Six Sigma value decreases [57]. Six Sigma is accomplished by using four principles [80]:

- Eliminate defects: anything that is unacceptable for a consumer must be eliminated.
- Reduce variation: reduction of process variation is key to eliminating defects.
- Data: the important role of data eliminates political influences.
- Voice of the customer: the goal is to serve the customer better, faster and cheaper.

Ung and Chen proposed and applied a systematic quality assurance framework, resting on Six Sigma principles, to determine the quality of the container handling operations. The research conclusion indicates that Six Sigma's adaptation is an appropriate tool to measure and appreciate the customer's voice, i.e., the shipping company. By mapping the process centring times, the process variation can be determined, and unusual trends or patterns in the data can be located. The research does not provide further insights on the improvement and control phase of the DMAIC structure that is maintained [100]. Research by Nooramin et al. uses a similar framework for the optimisation of container terminals. The results of the research show significant reductions regarding congestion. The limitations of the research lie within the control phase. To successfully test the results, a long-range of data is required [83].

To conclude on the two techniques, Lean approaches improvements by banishing non-value activities (waste) while Six Sigma approaches the problem through statistical quality control (variation is waste) [62]. Loyd acknowledges these differences by stating that Lean and Six Sigma have a difference in the tools they use, but there is no conflict in the objective. Therefore, both techniques' amalgamation is acknowledged to be successful and prioritised above a stand-alone [57].

2.3.2. Agile ports
Paixao et al. stipulates on a drawback of incorporating Lean techniques in an organisation, and in special, in the port environment. When a port is operated on a high level of Leanness, the port cannot exploit unexpected customer opportunities by being unable to adapt quickly. A high degree of Leanness is effective when the process is complete, or at least to a high degree, controlled by the owner [74]. Katayama and Bennett added that Lean is characterised by using fewer resource inputs while

increasing the pressure for higher output performance. Altogether, this makes a system less resilient in case of uncertainties [48]. The port is such an uncertain environment, and, thus, it is stated that a complete Lean port is not desired. To overcome this problem, Paixao et al. introduce the concept of agility [74].

Agility is described as the ability ”to cope with demand volatility by allowing changes to be made in an economically viable and timely manner.” [49]. Paixao et al. describe agility as a strategy responsible for strengthening the links between the internal and external business environments [74]. According to Baker, an agile organisation enriches the customer, strives for cooperation to enhance competitiveness, can adapt by redeploying assets and people rapidly, and leverages the impact of people and information [7]. Within this research by Baker, the cooperation to enhance competitiveness is elaborated with an example called ”virtual organisation”. Within such an organisation, a group of independent firms come together (virtual) through the usage of an IT network, intending to exploit a certain market opportunity.

2.3.3. Just-in-time ports

Section 2.3.1 mentioned the types of waste that are present in a non-Lean environment. One of these waste types is waiting and includes waiting for material, information, equipment, tools, etc. This type of waste is not present within a Lean environment, and all resources are provided Just-in-Time (JIT); not too soon, not too late [50]. If the principle of Just-in-Time (JIT) is applied to the port, it stipulates the importance of cargo arriving and departing exactly according to schedule with no tolerance for early or late arrivals or departures. Consequentially, the amount of cargo in the yard area reduces, fewer ships need to wait before berthing, and the service's quality towards the customer increases [74]. According to Moon and Woo, the practice of just-in-time operations reduces the waiting time in the port areas. This is reached by providing a planned service while maintaining the designed voyage speed during the sea transit. Such on-time performance leads to the improved operational efficiency of a liner service [66]. The concept and the potential of JIT are recognised in the literature and the industry. Recently, the Global Maritime Energy Efficiency Partnership (GloMEEP), which is part of the IMO, published the JIT Arrival Guide [33]. An important note from this guide is that the port call's optimisation is a prerequisite for JIT Arrival. The complete list of advantages and disadvantages categorised for different stakeholders is listed in Appendix A.

2.4. Port call modelling

All aforementioned optimisation techniques have an important aspect in common. To improve a process, the user must clearly define the process. Process modelling aims to identify, map, and analyse the ”as-is” process and understand inefficiencies that provide improvement opportunities. This section describes two modelling stages. First, a study is done regarding the available descriptive modelling techniques and the shipping sector application. Secondly, a similar approach is used to analyse the available literature on simulation modelling.

2.4.1. Descriptive modelling

A descriptive model is mainly deployed for documenting, understanding and sense-making of a certain process [92]. Business Process Model (BPM) is a descriptive modelling technique widely applied in the industry and the research field. Several benefits from deploying a BPM are cost reductions, increased operational cycle speed, customer satisfaction and quality improvement [84]. Fyrvik and Uthaung proposed a hierarchical approach to develop an BPM model and is represented with figure 2.7 [32]. The first step is to gather relevant information on the physical process and create a top-process level. The next step is to gather relevant data, which helps to scope to a sub-process(es). The final step of creating a BPM is a detailed level of the role and activities within the sub-process(es). Often, swimlane pools and lanes are applied to structure the role of different actors within the process. Swimlane pools represent a specific entity or a role, where the lanes within that pool specify a sub-partition of the pool [1].

A descriptive model of the port call process is proposed by Lyridis et al. Within this research, a Business Process Model (BPM) modelling technique is proposed to identify and optimise the elements that contribute to the quality of shipping company operations. The research uses a case study for the movement of a container vessel from Madrid to Athens. The data from the sub-processes are used as

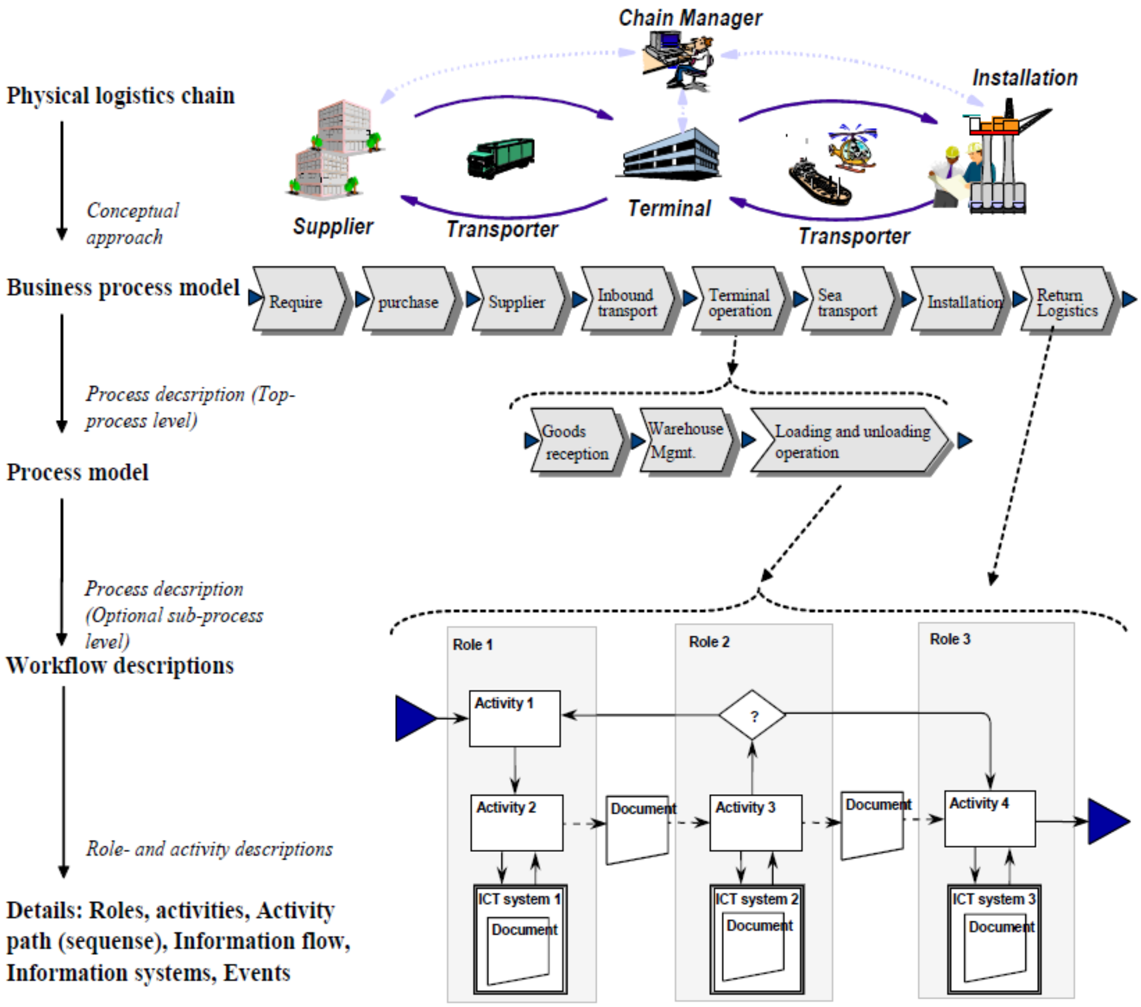
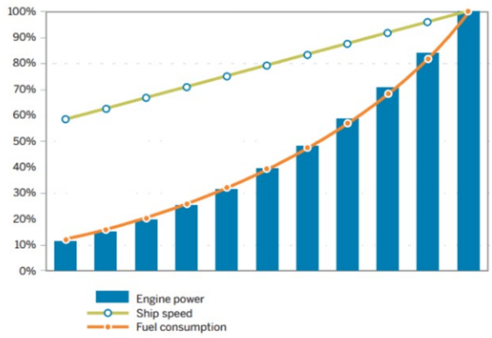
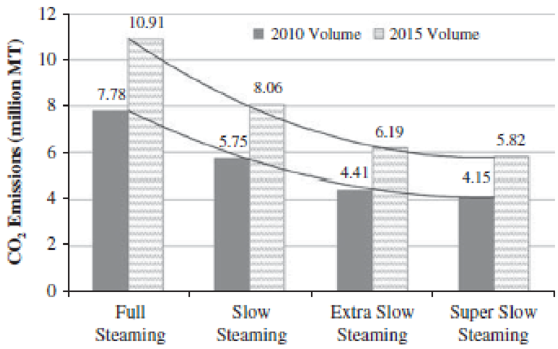


Figure 2.7: Hierarchical approach to process modeling [32]



(a) Relation between speed, power, and fuel consumption [107].



(b) Reduction of CO_2 from reducing the vessel speed [60].

input for the improvement phase. The research suggests that if a web-based communication system is implemented, the port's idle time can be reduced, potentially affecting the cost and time factors [58].

2.4.2. Simulation modelling

Fishwick defined simulation as "... a branch of learning that designs models of actual or theoretical physical systems, executes them on a computer and analyses the output" [30]. Simulation modelling is a way to solve complex real-world systems that are hard to test with experiments. Furthermore, it provides the flexibility to apply random occurrences, such as crane breakdowns, and measure the effects. During the simulation, the takt times can be measured. This takt time is the average time to complete a sub-process. By measuring these takt times, an assumption can be made on the average time necessary to complete a sub-process. This enables to measure and address variations within the sub-processes more precisely [16].

A port simulation model can measure the inventory (vessels) over the sub-processes during the port call. The allocation of human resources and equipment contributes to preview the possible constraints that may affect the port call's performance and devise a set of emergency measures [16]. This can be reflected in the previously mentioned concepts of defining Muri (inconsistency), Mura (strain), and Muda (waste) (see section 2.6). Moon and Woo proposed a Dynamic Liner Service Evaluation Model (DLSEM) to establish a relation between port operations efficiency and the economic and environmental consequences. The model results show that there is indeed a positive correlation between improved port operations and the amount of fuel consumed and CO_2 that is emitted. When the ship's time in the port is reduced by 30%, both the annual fuel consumption and the emissions are reduced by 36.8% [66].

2.5. Voyage optimisation

As Figure 1.1 depicts, the optimisation efforts of a shipping network can be approached by several strategies. The previous sections addressed the role of port optimisation, where the upcoming section continues by assessing voyage optimisation by speed control.

2.5.1. Vessel speed

This section assesses the available literature on this topic to gain more insight into the role of speed to fuel consumption and emissions. It is widely acknowledged that the vessel speed has a significant impact on the operational costs (economic), as well as the emissions (environmental) ([46], [27]). This is due to the cubic relation of the speed with the fuel consumption ([55], [28]). An OOCL vessel data analysis shows that 50% more fuel is consumed per unit of distance if the vessel speed is increased by a couple of knots [53]. It is approximated that fuel consumption accounts for 50-60% of the total operational expenditures. So, a decrease of the vessel speed will have direct impact on the fuel consumption, and therefore the operational expenditures ([72], [35], [81], [59]).

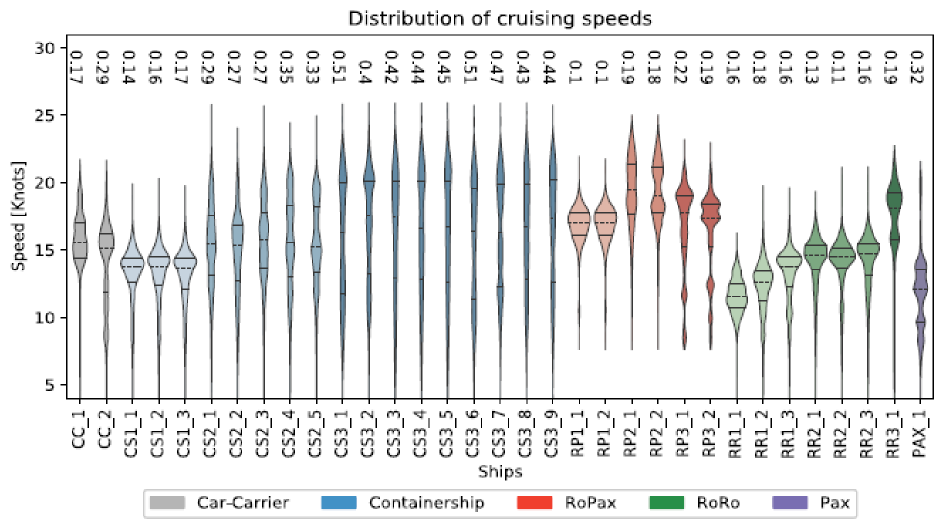


Figure 2.9: Distribution of vessel speed measured over one year [3].

Together with high fuel prices and low freight rates, these assumptions lead to the incorporation of slow steaming in the networks of shipping lines [77]. To maintain the cargo delivery capacity within a service that operates under slow steaming practices, shipping lines must add container vessels to the network. As a result, a secondary positive effect of a reduction of the idle fleet is realised. This makes the complete fleet, and thus the organisation, more cost-effective [60]. Lastly, an argument for incorporating the practice of slow steaming in the planning phase is that it provides shipping lines to recover late departures from ports by increasing the vessel speed. By doing so, the vessel can catch up on the schedule to avoid a late arrival at the next port [59]. A comprehensive list of studies into the positive effects of vessel speed on a shipping company's economic and environmental performance is assumed to have deterministic operations. However, in practice, the vessel speed is partially controlled by the uncertainties during the port operations [55]. This leads to a relatively new practice, called Virtual Arrival.

2.5.2. Virtual Arrival

In section 2.2.5 the port uncertainties are defined as regular and irregular events. Irregular events have a more stochastic profile, and it is hard to hedge against the consequences by applying time buffers in the schedule [55]. As a consequence of the irregular uncertainties, vessels experience waiting times at the port entrance. This lead to the uptake of the Virtual Arrival clause in the industry. The definition of Virtual Arrival by Intertanko is as follows: "Virtual Arrival is a process that involves an agreement to reduce a vessel's speed on the voyage to meet a revised arrival time when there is a known delay at the discharge port" [44]. In contrast to slow-steaming, the uptake of virtual arrival does not extend the transportation time, but it minimises the time at anchorage by maintaining a lower sailing speed [77]. According to Jia et al., a vessels flexibility to reduce the speed depends on the loading condition and the contractual agreement (charter party clauses). Most of the time, these agreements contain a clause that states that the agent must "dispatch at utmost speed". Arjona Aroca et al. measured the fuel and emission savings from JIT Arrival. The research uses a sample of data that contains voyage parameters such as the distance covered, average speed, and waiting times at anchorage. The waiting time on arrival is used to assess to what extent the vessel operator can reduce the voyage speed. The results show that vessel operator can reduce the speed over the arrival leg to 15-23% if the delay is known on departure [3]. Jia et al. performed a similar calculation where a methodology is proposed to measure the fuel consumption reductions by implementing the Virtual Arrival policy. This study shows that by using 50% of the excess port time to slow down during the voyage, the vessel can save 422 tonnes of CO_2 and 6.7 tonnes of SO_x per voyage. This is against a total consumption of 3,886 tonnes of CO_2 and 61 tonnes of SO_x on the original voyage. Given these numbers, a CO_2 and SO_x reduction of respectively 11.4% and 11.0% are obtained. Both of these researches apply the concept under the assumption that all the excess time can be used for slowing down the voyage. The pseudo speed ($v'_{i,j}$)

now becomes:

$$v'_{i,j} = \frac{D_j}{(t_{0,ij} + \Delta t_{i,j})} \tag{2.16}$$

where:

$t_{0,ij}$ = The original sailing time
$\Delta t_{i,j}$ = The shortened port waiting time

According to this formula, the vessel is aware of the excess port time on departure from the previous port. This allows the vessel to slow down over the complete voyage to an optimal speed. This approach results in the highest fuel reduction that is possible. Another take away from Jia et al. is that the lowest feasible sailing speed of a Very Large Crude Carrier (VLCC) is 7 knots [46].

The literature prevails that by implementing Virtual Arrival or Just-in-Time (JIT) policies, the shipping network can significantly reduce the GHG emissions without impacting the transportation time of the voyage. However, according to Poulsen and Sampson, the uptake of virtual arrival in the industry is uncommon. By deploying a qualitative study, it is found that the cargo value is volatile, and being at the right place at the right time outweighs the benefits of cost reductions along the route. Besides that, shipping companies use the anchorage time for resting hours for the crew and time to catch up on maintenance and administrative tasks. Another finding is that the uptake of Virtual Arrival is limited due to a lack of trust in the notification and data accuracy. Since most ports are still operating under a First In First Out (FIFO) policy, being early can be beneficial [77]. Lastly, Rehmatulla and Smith's survey shows a lack of reliable information on the potential costs and savings obstructing Virtual Arrival implementation. According to this, the concept is seldom applied [81].

2.6. Conclusion on the technical background

The first section of this chapter gives information to answer the first sub-question:

"What is the relationship between port call variations and emissions?"

The technical background aims to provide a logical and mathematical relationship between the port Turnaround Time (TAT), the time at sea, and the corresponding container network emissions. An efficient container network's business objective is to schedule vessels that sail between ports in a network so that the demand for logistic services is provided while minimising the Operational Expenditures (OPEX). The OPEX is for 50-60% determined by the fuel consumption. Variations during the port TAT need to be resolved by speeding up to the next port to recover the schedule. It is found that more than 90% of the variations originate from the port area. The speed increase of the vessel behind schedule results in increased fuel consumption due to the third power relationship between the speed and the fuel consumption. Subsequently, the amount of fuel consumed has a proportional relationship to carbon dioxide and sulphur oxide emissions. Additionally, the delayed vessel's variation propagates to the schedules of vessels that are planned close to the delayed vessel.

Given the role and the importance of the port call regarding the rest of the shipping network, a study is done towards port call optimisation or improvement. Lean and Six Sigma are proven to be both effective process improvement techniques. An amalgamation of the techniques could help identify and eliminate bottlenecks and variations in the process and optimise the port TAT. The application of these techniques assesses the process capabilities and identifies if there is waste in the process. Especially in the manufacturing industry, this has proven to be successful, according to the literature. However, the background study prevails that ports differentiate from a manufacturing process due to a constant presence of non-controllable uncertainties in the port. The uncertainties have a stochastic profile which makes a complete Lean port impossible to achieve. Therefore, the concept of agility is introduced to the port environment. Agility enables a port to be responsive to an uncertain scenario by leveraging people and information. If agility is correctly implemented in the port environment, the port can mitigate the negative consequences of a variation in the port TAT. Just-in-Time (JIT) is part of the LSS technique and has the goal to reduce inventory in a process. This thesis assumes that variations in the port call process lead to inventory in two ways: increased port turnaround times and the possible formation of waiting times in anchor areas or drifting vessels.

The quest to arrive JIT introduces the concept of Virtual Arrival (VA). This concept is enabled by effective communication and transparency between the stakeholders in the process. The current research lacks a clear mathematical description, implementation in practice, and proof of the Virtual Arrival concept. Research by Poulsen and Sampson states that although the industry is positive on the concept of Virtual Arrival, the uptake in practice is still rare [77]. This study reconsiders the concept's terminology and states that a Dynamic Arrival Time (DAT) is a more appropriate term.

This research tests the concept of a DAT by using a simulation model. Within the simulation model, the user can model the port call and corresponding port uncertainties. This allows the user to measure the effect of using a DAT to arrive JIT, and consequentially reduce the waiting times, fuel consumption and emissions.

2.7. Knowledge gap

Based on the technical background assessed in this chapter, this latter section addresses the research gap identified accordingly. There are three gaps identified that are discussed per paragraph.

The first research gap that is identified is regarding port optimisation. Previous research into port optimisation focuses on parts of the port call process rather than the complete process. For example, when the focus is put only on the nautical chain [65], or if only a limited number of stakeholders is considered in an improvement project [58]. As a result, improvement efforts lead to silo-optimisation and do not contribute to the overall optimisation of the port call process [9]. Furthermore, the analysed research uses broad terms to describe port uncertainties and are limited to four or five categories [72, 104]. This is unexpected due to the findings that more than 90% of the causes for schedule unreliability originate within the port area [72]. A method to identify and improve a system or process is the Lean Six Sigma (LSS) methodology and is widely applied to the production industry. Although this has proven to be a successful method, the LSS methodology's adaption in the port call process has not been found in the literature. To the authors' knowledge, no research includes all port call aspects and systematically approaches the process by deploying different Lean Six Sigma technique tools.

The second research gap that is identified is regarding the synergy between port call optimisation and voyage efficiency. The candidate measurements express speed optimisation and port call optimisation as two separate goals, where this research aims to synthesise these two optimisation strategies. This research can achieve this synergy since the port call process is taken from a holistic perspective rather than parts of the port call process. By assessing the complete port call process, the port's role in the shipping network is established. Although this increases the scope of the study, it is important to establish this connection. This is because of the challenge regarding the emissions that the industry is faced with.

The third research gap is regarding a relatively new concept initiated in the industry but not yet clearly defined in the literature. This is the concept of using a Dynamic Arrival Time (DAT), or often referred to as Virtual Arrival. According to Simon and Poulsen, insufficient information and experience is the main reason why vessels and ports do not communicate on revised arrival times. This research aims to fill this gap by first providing more information on the concept by addressing both the theoretical and practical challenges. Secondly, the simulation model in Anylogic aims to provide proof of the concept in a Short Sea Shipping (SSS) network. Together this must lead to a better understanding of the concept and more reliable information for policy making and further research.

3
Current state

The previous section described the relation between the port uncertainties and the consumption of fuel and emissions. The conclusion from that section states that port uncertainties (variances during operations) are strongly correlated to fuel and emissions. Besides that, it is proven in that section that the network operates at its best when there are no delays or variances in the port. Port optimisation is therefore assumed to be a successful short-term measurement for the reduction of emissions. Before a system or a process is optimised, the user must be aware of its current state behaviour [80]. Within the DMADE cycle, the measure phase transition is now initiated where this current state is assessed. The measure phase aims to provide answers to the second sub-questions, which is as follows:

> **Which sub-processes are executed during the port call process, and what is the performance of the Maersk vessels in the Port of Rotterdam?**

To answer this question, a descriptive BPM with swimlanes is formed by using the hierarchical approach to process modelling [32]. Following this approach, firstly, a top model is defined, which is then specified into a more detailed model. This model is used to identify the sub-processes (and corresponding events, activities, and roles), and assess the available data. From the information of this descriptive model, an analytical Lean Six Sigma (LSS) model is created. This LSS model retrieves and stores event log data from 433 Maersk mainline vessels in the Port of Rotterdam in 2020 and assesses these vessels' performance.

3.1. Port call process

The port call process is divided into a planning phase and an operational phase [65]. The planning phase estimates timestamps before arrival, where the operational phase retrieves and stores actual data. The planning phase is based on the contractual agreements where the basis for a contract includes a sale of goods (containers), a vessel, and a terminal to handle the goods. More detailed planning is established before arrival, including passage planning and port planning with corresponding time stamps. Most of the time, establishing the timestamps is discussed with the users of the time stamp to ensure availability. Correctly estimating the timestamps is important for scheduling the required and desired services during the port call. The actual time stamps are acquired when the process is executed. For the continuation of the complete network, it is important to minimise the difference between the operational and planning time stamps. In general, this is referred to as reliability and within the shipping network known as schedule reliability [33]. As described in Section 1, the shipping industry is not known for a high degree of schedule reliability.

The first part of this thesis aims to understand the causes for port call uncertainties, where the second part aims to optimise the process to reduce these uncertainties. When process optimisation is aimed for, the first step is to identify the processes by deploying a descriptive model. The first step of the hierarchical approach towards process modelling is the description of the logical chain [32]. This step is described in Section 2.1. The upcoming sections continue with the process description on a more

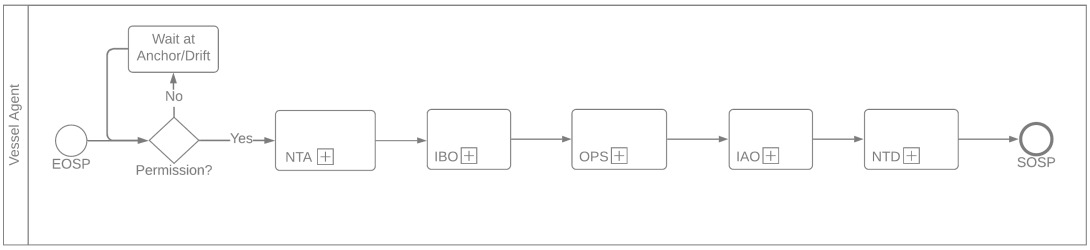


Figure 3.1: Mid-process level

detailed level. According to the hierarchical approach, firstly, the process model is divided into five sub-processes. Together these sub-processes form the mid-process level. These mid-processes are further segregated into more detailed role-and activity diagrams [32]. In addition to this, the information (timestamp data) from the processes are mapped within the sub-processes. Following this approach, this section provides detailed insights into the sequential activities and events executed during the port call process. As depicted in Figure 3.1, the time in the port is segregated into five sub-processes. The vessel's time drifting or at anchorage is not taken into account when the port TAT is considered.

Data systems

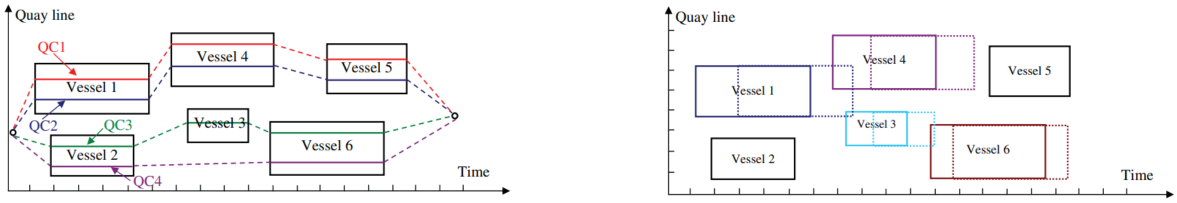
Together the five sub-processes determine the Turnaround Time (TAT) of the vessel in the port. For the sake of clarity, the acquired timestamps throughout the process are converted into the DCSA standards [22] and are summarized in Table 3.1.2. The latter two columns indicate the type of operating system that retrieves and stores the data and whether the data is available for this thesis. The Maersk Ship Performance System (MSPS) is an operating system that measures and tracks the vessels' performance while at sea. The Central Operations Management System (COMS) is used for the port call and functions as a planning and execution system. Besides the port call's actual data, the COMS system also contains data on the schedules based on the network design and the port calls' dynamic schedules. Maersk Line operates these two aforementioned systems. Next to these systems, the Terminal Operating System (TOS) is managed by the terminal. For the Maersk mainline vessels in the Port of Rotterdam (POR) this terminal is one of the APM Terminals.

3.1.1. Planning phase

Three windows are established throughout the planning phase in the chronological order of proforma, scheduled, and requested. Different stakeholders use these windows for different purposes. For example, the bunker supplier requires an Estimated Time of Completion Cargo (ETC Cargo) for their planning of supply vessels, and the Port Authority benefits from an accurate Estimated Time of Arrival Pilot Boarding Place (ETA PBP). The upcoming sections give a brief description of these windows.

Proforma window

As described in Section 3.1, the shipping line forms a contract with the terminal consisting of a couple of elements. One of these elements is the number of containers to be handled during the port call. Based on this number, the terminal provides the shipping line with an estimated Port Moves per Hour (PMPH). The PMPH is the main determinant for the window calculation [101]. The service's proforma window is denoted with an ETA Berth and an ETD Berth. Often, this is called the laytime or lay days. Furthermore, the contract contains clauses such as tariff per container, demurrage and dispatch costs. These two latter costs are formed when the actual laytime is longer or shorter than initially planned. This window is published to the customers months in advance [33]. Customers and downstream stakeholders incorporate these scheduled network times in their supply chains. This makes a reliable proforma versus actual window valuable for the involved stakeholders and customers.



(a) Berth plan with crane allocation [115].

(b) The effect of schedule variances [115].

Figure 3.2: Example of a berth plan with a crane allocation that is subject to variances [115].

Schedule window

Before the execution of the port call process, the vessel agent, terminals, and shipping line determine the schedule window where the ETA Berth, and ETD Berth are internally (peer to peer) communicated. In general, these changes are not communicated to the customers [33], although there are industry initiatives that aim to facilitate more transparency [89]. A schematic overview of a berth plan (schedule window) is depicted in Figure 3.2a. The horizontal axis expresses the time horizon, where the vertical axis represents the quay length. The coloured lines indicate the Crane Intensity (CI) per vessel over time. Together this is referred to as the crane allocation. Based on the ETA Berth an Estimated Time of Arrival Pilot Boarding Place (ETA PBP) is scheduled. The ETA PBP is when the vessel is estimated to arrive at the pilot pick-up point outside of the port area.

As the vessel is alongside at berth, the next considered timestamp is the estimation of the completion of bunkers and services (ETC Bunkers, ETC Service). The vessel agent plans these bunkers and services. During the execution of these services, the estimated time of bunker completion is not shared with the shipping line and the terminal [33]. These bunkers are planned to finish three hours before the Estimated Time of Completion Cargo (ETC Cargo). This is the moment where the terminal estimates to be done with the stowage plan. In general, this is one hour before the ETD Berth. At the end of a labour shift (every 8 hours), an update of the estimation time is provided.

Requested window

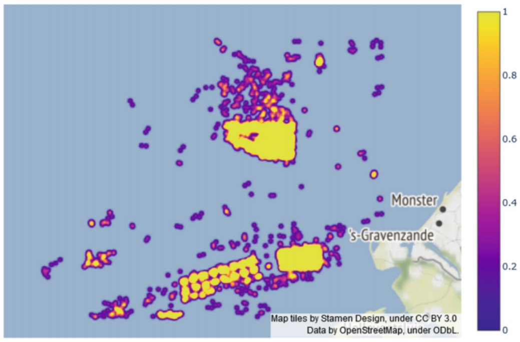
This last window is the most accurate and is used as an agreement on operations. Before arrival, two important time stamps are communicated between the captain, the Port Authority, and the terminal: the Requested Time of Arrival Berth (RTA Berth) and Requested Time of Arrival Pilot Boarding Place (RTA PBP). The RTA PBP is communicated to the vessel via the Very High Frequency (VHF) radio after connecting the Port Authority via the Vessel Traffic Services (VTS). Normally, the first contact moment is within a range of 30 nautical miles from the port. The RTA Berth allows the vessel to slow down at the last part of the voyage. However, contractual agreements could oblige the vessel to maintain a predefined speed. The RTA Berth is communicated between the terminal operator and the vessel (via the agent) via telephone [33].

3.1.2. Operational phase

The operational phase (actual time stamps) might differ from the planning (estimated time stamps). This is caused by regular and irregular events and is referred to as port uncertainties or variances [72]. The effect of uncertainties or variances in the port call process is depicted in Figure 3.2b. The figure depicts a scenario where vessel one is delayed for a certain amount of time. Consequently, this delay affects vessel three, four, and six. Due to the applied buffers in the berth plan, the delay decays over time. Section 3.2 elaborates on the presence and effects of these delays. Before reaching this section, the upcoming sections are dedicated to describing the physical sub-processes executed throughout the port call process on a more detailed level. This is done by segregating the port call process into five sub-processes. The sub-processes are evaluated on the performed activities, the involved stakeholders, and the acquired time stamps throughout the process.

Nautical operations on arrival

Based on the ETA Berth the vessel sails towards the port with a voyage speed that is either determined by the vessel agent or based on the contractual agreement between the carrier and the charterer [33].



(a) Anchorage areas outside the port [31].

(b) A drifting vessel before entering the port [33].

Figure 3.3: Representation of the anchorage areas and a drifting vessel outside the Port of Rotterdam [31, 33].

When the vessel is in close proximity to the port, the vessel agent indicates that the vessel nears the End of Sea Passage (EOSP). This EOSP notification indicates that the vessel is within a certain range from the port and that the vessel is prepared to enter if the berth is available. Before entering the port, the vessel agent must acquire permission from the Port Authority to enter. There is not a standard moment or geographic location where the vessel agent secures this timestamp. If no permission is provided by the Port Authority or the terminal is not available, the vessel can either sail to the anchorage area or start drifting. Frankzeit et al. used the Automated Identification System data to map the port areas [31]. The result of this measurement is depicted within Figure 3.3a. The figure clarifies the geographic locations of the anchorage areas outside the Port of Rotterdam (POR). Figure 3.3b shows an example of a vessel drifting for approximately 12 hours outside the port area before permission to enter is provided [33]. If the vessel arrives Just-in-Time (JIT), the event log shows an EOSP and an ATA PBP time stamp that is within a close time range of each other. If this is not the case, the vessel has chosen to either go to anchorage or start drifting.

After the vessel is granted permission to enter the port, the vessel captain sails to the Pilot Boarding Place (PBP). The PBP is a dedicated geo-fence area outside the Port of Rotterdam (POR) where the pilot is obliged to embark on the vessel. The pilot has the role and responsibility to safely manoeuvre the vessel from the PBP to the terminal on arrival and vice-versa on departure [63]. As the vessel proceeds to the fairway, the pilot determines the number of tugs required to assist the port area's manoeuvring. There are three tugboat companies (KotugSmit, Fairplay, and Svitzer) active in the port area that operate over 40 tugboats. Sometimes, if permission is given by the Port Authority, the vessel is allowed to make use of Shore Based Pilotage. If a vessel length is over 75 meters, the vessel must use linesmen for the berthing process. These linesmen use tenders and portable winches to secure the vessel at the quay [75]. Together the operations of the pilotage, towing, and linesmen operations format the port's nautical services. The BPM of the sub-process of the nautical operations is depicted in Figure 3.4. When the vessel arrives at the berth by attaching the first line, the Actual Time of Arrival Berth (ATA Berth) time stamp is notated. The nautical operation time, often referred to as the Nautical Time on Arrival (NTA), is equal to the time delta between the ATA Berth and the ATA PBP.

Terminal turnaround process

Once all the lines are safely attached and the Harbour Master provides clearance, the gangway is placed on the quay. This allows the pilot the disembark the vessel and the lashing crew to embark on the vessel. The first rows of containers placed on the deck are attached to the deck structure by lashing rods and twistlocks in the container corners. These containers corners are accessible from the lashing bridges between the container rows. The lashing rods and twistlocks are necessary to prevent failures as a function of hazards during sailing (e.g., green water loads and heavy winds) [82]. The lashing crew has the responsibility to unlock the lashing rods to enable container lifting. The containers corners that are not accessible from the lashing bridge are detached from each other by using a gondola cage. According to the stowage plan provided before arrival, the terminal equips some Ship-to-Shore (STS) gantry cranes with a gondola cage. This cage is equipped with several crew members, and by moving between the container stacks, the twistlocks are unlocked. The remaining STS gantry cranes

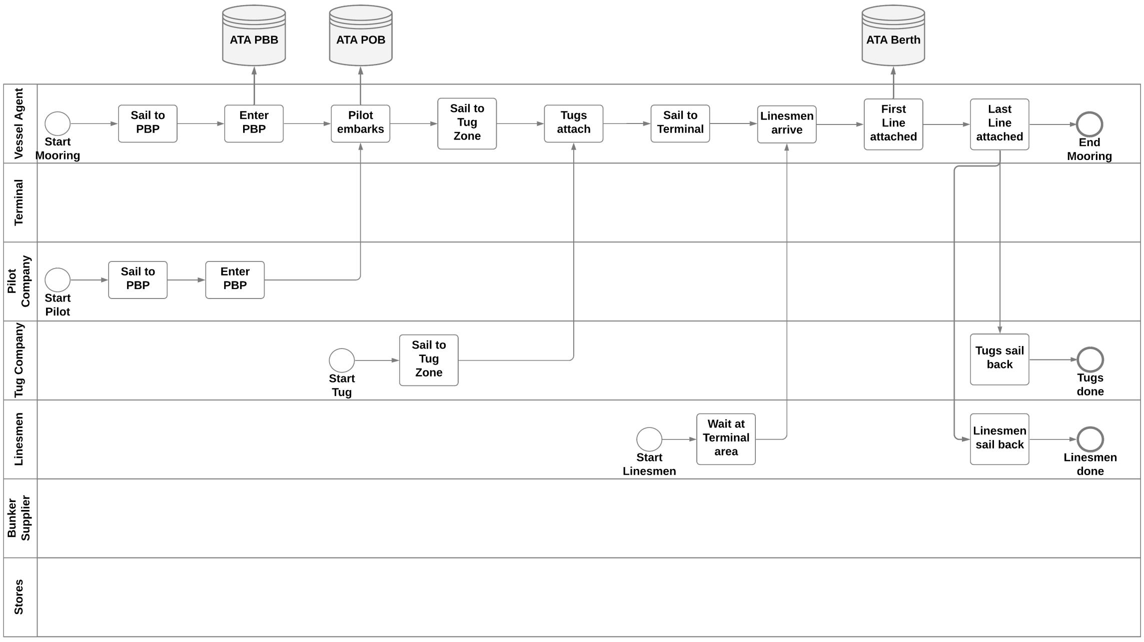


Figure 3.4: Nautical processes on arrival

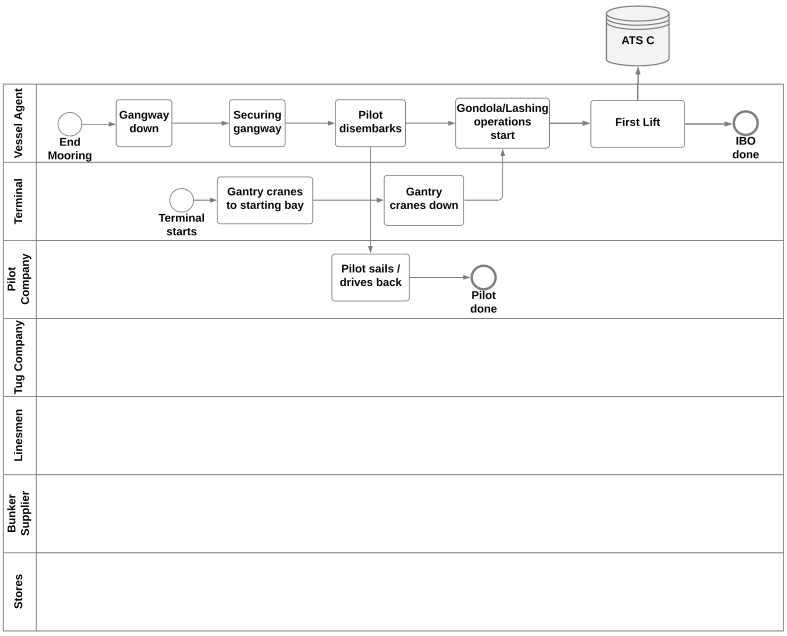


Figure 3.5: Terminal processes before operations

start lifting the containers where twistlocks and lashing rods are already removed. Normally a spreader has the ability to lift a single container. However, sometimes, twin-lift spreaders are used [71]. The moment that the first container is lifted, the terminal reports the first lift in a timestamp format in the Terminal Operating System (TOS). The standardised notation for this timestamp is the Actual Time of Start Cargo (ATS Cargo) [22]. The time delta of the ATS Cargo and the ATA Berth is within this thesis labelled as the Idle Time before Operations (IBO).

Once the first container is lifted, the terminal starts by executing the stowage plan. Under standard operating conditions, the time to complete the operations is mainly determined by the Port Moves per

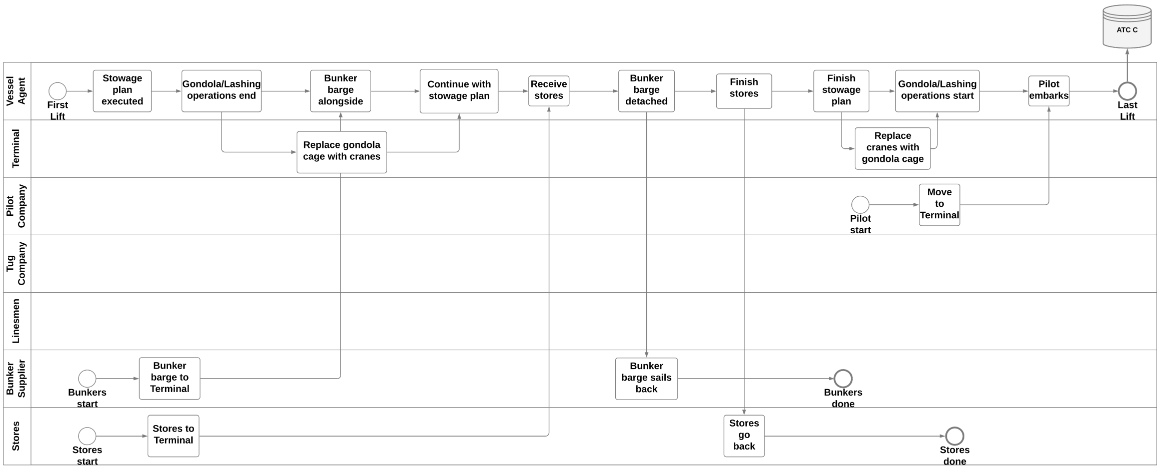


Figure 3.6: Operational processes while the vessel is at berth

Hour (PMPH). The PMPH is on its turn a function of the Crane Moves per Hour (CMPH) multiplied with Crane Intensity (CI). In preparation for the port call, the vessel agent provides the terminal with the vessel's stowage plan. The terminal assigns several cranes to the vessel based on the stowage plan. The total number of containers moves comprises out of the container to be loaded (C_l), discharged (C_d), and shifted (C_s). Together this number of container moves, divided by the PMPH determines the time to complete cargo operations. This is represented by equation 3.1. During the cargo operations, some services, such as the provision of marine bunker fuel supply, are acquired by the vessel. The Port of Rotterdam (POR) is in the top three bunker suppliers worldwide by delivering 9 million cubic meters per year to the vessels [76]. Other services such as stores, repairs, maintenance and crew changes are planned within the cargo operations schedule. Prior communication between the shipping line and terminal must lead to efficient planning of the services within the cargo operation time. The Estimated Time of Completion Bunkers (ETC Bunkers) is when the bunker supplier estimates to complete the service. This timestamp is communicated between the bunker supplier and the vessel (via the agent) by VHF or telephone. According to a report from the GloMEEP, there are numerous reasons for delays in this process, such as swell restrictions, smell limitations on board, and varying pumping rates. However, no communication contains updates on this estimated completion time. The ETC Bunkers together with the ETC Cargo, and other services (repairs, maintenance etc.) determine the ETD Berth. Three hours before the ETC Cargo, the pilot is ordered via the Port Authority. A shorter period of time before this moment, the lashing crew embarks on the vessel to start with the lashing operations. Additionally, the terminal changes some spreaders with the gondola cage to start locking the twistlocks before the last lift [33]. The DCSA standards notate the last lift as Actual Time of Completion Cargo (ATC Cargo) [22]. After the last lift, the shipping crew checks whether the containers are properly stacked and locked. An overview of the cargo operation sub-process is presented with Figure 3.6.

$$\Delta_{ops} = \frac{C_l + C_d + C_s}{PMPH} = \frac{C_l + C_d + C_s}{CMPH \cdot CI} \tag{3.1}$$

Before departure, the agent communicates the ETD Berth to the Port Authority via the telephone or mail. Based on this timestamp, the Port Authority provides the vessel with a Requested Time of Departure Berth (RTD Berth). Changes in the weather conditions might result in a request for additional tugs. After clearance is provided, the tugs attach to the vessel, and the linesmen start detaching the lines. Once the last line is released, the Actual Time of Departure Berth (ATD Berth) time stamp is notated in the Terminal Operating System (TOS). The time delta of ATD Berth and the ATC Cargo is within this thesis labelled as Idle Time after Operations (IAO). This represents the time that is required to leave the berth after the last cargo lift is executed. The sub-process is represented by igure 3.7.

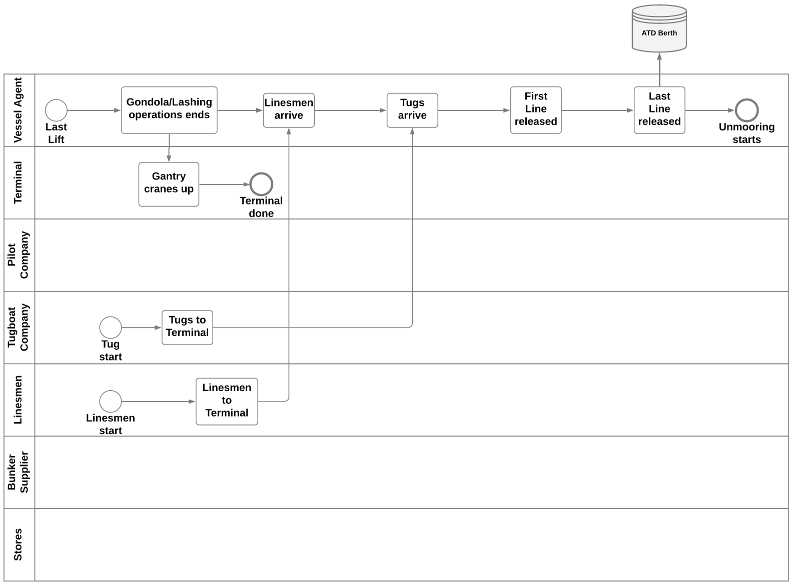


Figure 3.7: Terminal processes after operations

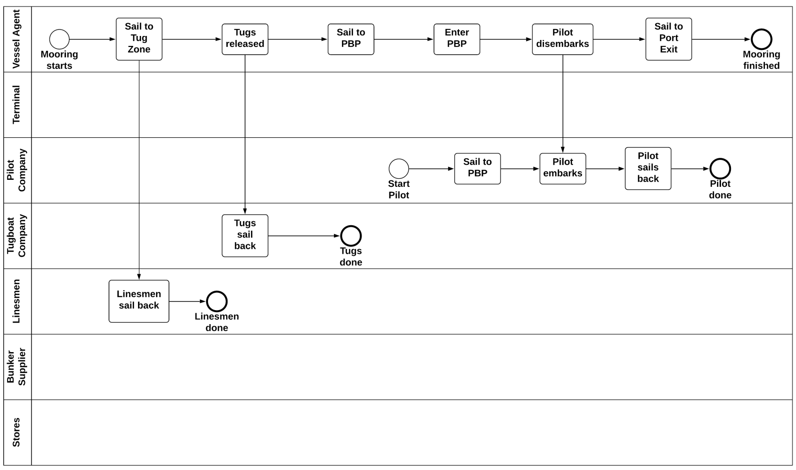


Figure 3.8: Nautical processes on departure

Nautical operations on departure

The nautical operations on departure are comparable to the procedure on arrival. This time the pilot is already on board to safely guide the vessel out of the port. After the tugs detach from the vessel at the fairway, the vessel continues to sail to the Pilot Boarding Place (PBP). This is the same geofence area outside the port as on arrival. The pilot boat meets the pilot within this area, and after that, the pilot is disembarked, the vessel notates the Start of Sea Passage (SOSP). The sub-process is represented by Figure 3.8.

Together these five sub-processes form the port Turnaround Time (TAT). To summarise the port call process, the process starts with the End of Sea Passage (EOSP) and ends with Start of Sea Passage (SOSP). The acquired time stamps throughout the process are presented in Table 3.1.2. As can be seen from the table, the timestamps are retrieved and stored in different information systems. The identified stakeholders from the port call process are depicted in Table 3.2. Savage et al. define stakeholders as those interested in an organisation's actions and can influence it [86]. The stakeholders in this diagram are limited to the physical stakeholders within the scope of this thesis.

Abbreviation	**Description**	**System**	**Owner**
EOSP	End of Sea Passage	MSPS	Shipping Line
ATA PBP	Actual Time of Arrival Pilot Boarding Place	COMS	Shipping Line
POB	Pilot on Board	COMS	Shipping Line
ATA Berth	Actual Time of Arrival at Berth	TOS	Terminal
ATS Cargo	Actual Time of Start Cargo	TOS	Terminal
ATC Cargo	Actual Time of Completion Cargo	TOS	Terminal
ATD Berth	Actual Time of Departure Berth	TOS	Terminal
SOSP	Start of Sea Passage	MSPS	Shipping Line

Table 3.1: Collected timestamps throughout the port call process

Sub-process		**NTA**		**IAO**	**OPS**		**IAO**	**NTD**	
Time stamp	EOSP	ATA PBP	POB	ATA Berth	ATS Cargo	ATC Cargo	ATD Berth	ATA PBP	SOSP
Vessel agent	X	X	X	X	X	X	X	X	X
Terminal operator				X	X	X	X		
Pilot company		X	X	X			X	X	
Tug company		X	X	X			X	X	
Linesmen				X			X		
Bunker supplier					X	X			
Other services					X	X			

Table 3.2: Involvement of stakeholders over the port call process

The aforementioned sections provided an overview of the five sub-processes that are executed during the port call process. The second part of the second sub-questions aims to provide insight into vessels' performance in these five sub-processes.

3.2. Lean Six Sigma port model: Maersk case study

Research by Notteboom states that 93.8% of the causes for schedule unreliability is related to port performance. According to this report, the major source for delays is port congestion and further defined as unexpected waiting times before berthing or starting/loading or discharging [72]. To provide more insights in the port performance, a qualitative study is performed in this section. The previous section provided a detailed descriptive analysis of the port call process by segregating the complete process into five sub-processes. This section aims to measure and map the performance of these sub-processes by performing data analysis. The analysis is performed on 432 vessels entering the Port of Rotterdam (POR) in 2020. The chronological approach to this data analysis is as follows:

- Set measurement objectives and corresponding techniques
- Retrieve, store and merge data from different information sources
- Map and visualise the data
- Reflect on the data analysis

The model requires an Excel download from three sources (MSPS, COMS, and TOS) and are linked with each other by an unique vessel ID. This input is redirected to the MS Access database. Subsequently, the data is used in a Python model to measure and visualise the performance measurement objectives.

3.2.1. Performance measurement objectives and techniques

As the previous section described, the first step is to identify and describe the measurement objectives and corresponding techniques. These performance measurements are based on the assessed literature from Section 2.2.4. The assessed port metrics are on time reliability, turnaround time capability, and idle time (or bottleneck formation).

On time reliability

Reliability is defined as "...the probability that one or more of its links does not fail to function, according to a set of operating variables" [72]. The actual arrival times are measured against the scheduled arrival times to measure the vessels' on time reliability. Within the literature study, this is also introduced by Paixao et al. as the On Time Resource Planning (OTRP) performance measurement [74]. To recall the definitions that are used, the proforma time is the time according to the long-term published schedule, and the scheduled time is the time that is adjusted on the mid and short-term before the port call. Therefore, it is estimated that the proforma window is less reliable than the estimated window. It depends on the level of deviation acceptance (λ) what the on time reliability is. The higher the value of λ, the higher the probability (P) that the vessel arrives on time by definition. The probability that the value for the arrival time deviation is between the acceptance of deviation with an upper limit (λ_u) and a lower limit (λ_l) is equal to:

$$P(\lambda_l \leq X \leq \lambda_u) = \int_{\lambda_u}^{\lambda_l} f(x)\, dx \tag{3.2}$$

Turnaround time capability

The time that a vessel spends in the port area is predominantly determined by the time the vessel is alongside berth [55]. This is in the literature referred to as the terminal TAT, and equal to the time delta of the vessel arrival at the terminal (ATA Berth) and the departure from the terminal (ATD Berth) ([25], [93]). One important note is that the actual process is compared to a scheduled process rather than a standard value. This is different from a repetitive process that is executed during manufacturing compared to its own performance. This is because a port call is not repetitive (or homogeneous) due to the varying number of containers and acquired services. Therefore, the measurement compares the deviation (x_d) in the planning and the turnaround time's actual performance.

The Six Sigma approach contains a method to measure the capability to produce a service that meets the requirements. These measurements are called the process capability indices (C_p and C_{pk}). The requirements are defined by using a Lower Specification Limit (LSL) and an Upper Specification Limit (USL). Equation 3.5 and 3.6 represent the relation between the parameters. The greater the values for C_p and C_{pk}, the more capable the process is of performing according to the quality standards. Within these equations, the standard deviation and the mean values are substituted (equation 3.3 and 3.4).

$$\overline{x_d} = \frac{\sum x_d}{n} \tag{3.3}$$

$$\sigma_d = \frac{\sum(x_d - \overline{x_d})^2}{n-1} \tag{3.4}$$

$$C_p = \frac{USL - LSL}{6 \cdot \sigma_d} \tag{3.5}$$

$$C_{pk} = min\left[\frac{USL - \overline{x_d}}{3 \cdot \sigma_d}, \frac{\overline{x_d} - LSL}{3 \cdot \sigma_d}\right] \tag{3.6}$$

Idle time (bottleneck identification)

The actual data from the event logs is statistically measured to identify bottlenecks. The identification and elimination of bottlenecks in a process is a method that is used in the Lean Six Sigma DMAIC methodology. Bottlenecks obstruct a process or a service from flowing to the next activity and leads to increased cycle times [69]. In the port call process, this is referred to as idle time. Measuring and analysing each sub-processes' duration helps to identify any bottlenecks in the port call process, and if so, in which phase the bottlenecks occur. Section 3.2.5 divided the port call process into five sub-processes. The next section explains how the model retrieves the data from the port call process used in this case study.

3.2.2. Data retrieval

Table 3.1.2 provided an overview of the collected timestamps throughout the process. For this case study, additional time stamps are retrieved to include the planning phase as well. Since different information systems store these timestamps, a Microsoft Access Database is programmed. This is a Database Management System (DBMS) used in combination with a Microsoft Jet Database Engine. Utilising queries, the output from multiple databases is collected and merged into a single source. Every vessel is fitted with a unique vessel ID. This ID is a combination of the voyage code and the vessel code. By merging the inputs, the vessel ID is the link that combines the right event logs.

Planning data			**Operational data**		
Window	Time stamp	System	Window	Time stamp	System
Proforma	ETA Berth	COMS	Actual	ATA PBP	COMS
	ETD Berth	COMS		POB	COMS
Schedule	ETA Berth	COMS		ATA Berth	TOS
	ETD Berth	COMS		ATS Cargo	TOS
				ATC Cargo	TOS
				ATD Berth	TOS

Table 3.3: Overview of the retrieved data from the port call process

λ_l; λ_u $hours$	On time [%]	Not on time [%]
-2; 2	55.2	44.8
-4; 4	78.0	22.0
-6; 6	89.1	10.9
-8; 8	92.6	7.4

Table 3.4: On time arrival reliability for different specification limits

3.2.3. On time reliability

Figure 3.9 a depicts the proforma arrival deviation measurements. The negative values indicate that the vessel arrives ahead of schedule, and the positive value indicates that the vessel experiences a late arrival. Due to the presence of outliers in the data set, the horizontal axis adapts to a wide range. The proforma arrival performance measures to what extent the shipping lines able are to arrive according to the schedule that is planned months in advance. Unsurprisingly there are more outliers in this data set. The schedule arrival data, represent by Figure 3.9 b, gives an indication of the performance measurement in the mid-and short-term. The moment that the scheduled arrival time is locked before the port call determines the arrival time's reliability. To elaborate on this, if a scheduled arrival time is locked 72 hours in advance by the shipping line, there is a higher probability that the vessel does not arrives within the on time limits. On the other hand, locking the scheduled time 24 hours before arrival, the vessel's probability is higher. The cumulative distribution function shows that for a value of $\lambda = 0$, the density is approximately 0.60. This indicates that the ratio of early arrival and late arrival is equal to 60:40. The on time reliability's acquired results are specified for different values where $\lambda_l = \lambda_u$ and presented in Table 3.4.

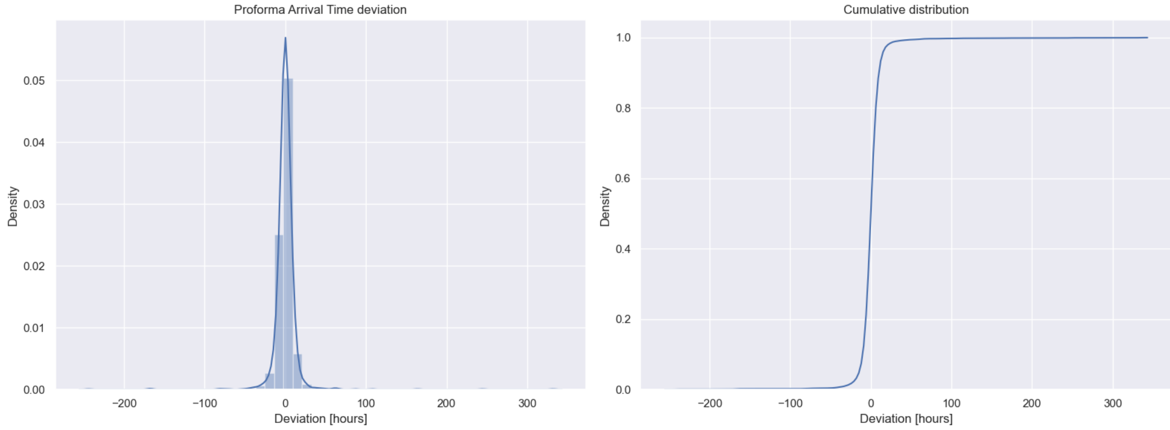
3.2.4. Terminal turnaround reliability

The proforma terminal TAT is estimated by the terminal by considering the PMPH and the number of containers to be discharged and loaded. Section 3.1.2 elaborates on the procedure to determine this time window months in advance. Figure 3.10 shows the relation between the container moves and the TAT. If the data is concentrated around the regression line, the operations performed under consistent conditions, making it easier to define schedules in advance. However, the figure indicates no strong correlation between the container moves and the TAT. The low concentration of data points around the regression line indicates significant deviations in the TAT process.

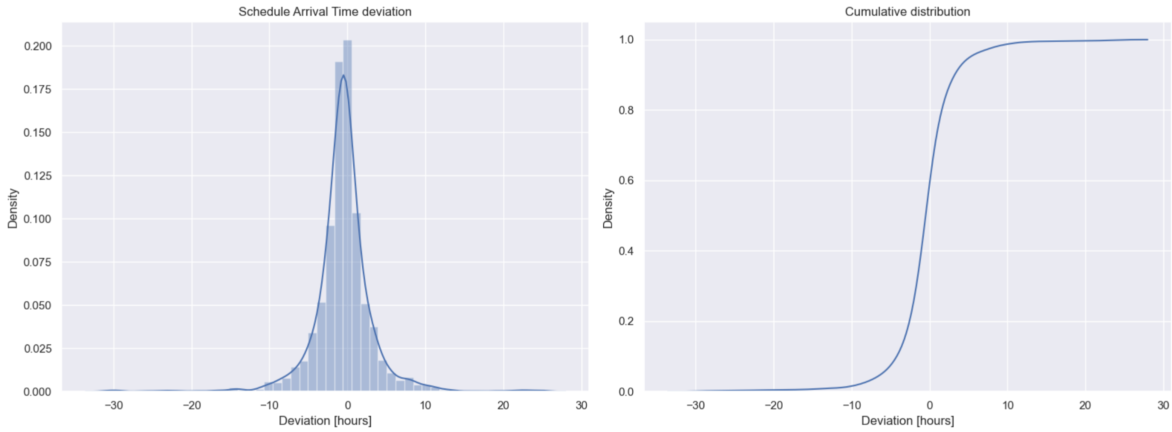
To gain better insights into the reliability of the terminal operations, the proforma TAT is plotted against the actual TAT (figure 3.11). The figure shows significant deviations in the planned TAT and the actual TAT. These deviations are referred to as terminal TAT deviations and further analysed in Chapter 4. Schedule reliability is an important measurement factor to determine the performance of a system [72]. However, the definition of reliability remains arbitrary within the industry [68]. As described, this research proposes the process capability indices (C_p, and C_{pk}) from the Six Sigma technique to measure the capability of the process to produce a service that meets the requirements. The latter column of Table 3.5 shows the percentage of port calls that are not within the range of the specification limits. Depending on the definition of reliability, this measurement technique provides an insightful overview of the terminal TAT performance. The port calls that are not within the limits of the specification are assumed to include a certain type of operational waste in the process. Further elaboration on the waste assessment is done in Chapter 4.

3.2.5. Sub-process measurements

As described, it is important to measure a process on a more granular level to identify bottlenecks. Section 3.1 segregated the complete port call process into five sub-processes. The available data from the two information systems (COMS and TOS) is mapped for these sub-processes within this



(a) Proforma arrival deviation



(b) Schedule arrival deviation

Figure 3.9: Probability and cumulative distribution curves for the proforma and schedule arrival time deviations

$LSL; USL$	C_p	C_{pk}	TAT within limits	TAT outside limits
hours	-	-	[%]	[%]
-2; 2	0.078	0.069	22.9	77.1
-4; 4	0.156	0.146	42.6	57.4
-6; 6	0.233	0.224	59.5	40.5
-8; 8	0.311	0.302	72.8	27.2

Table 3.5: Turnaround process capability indices for different specification limits

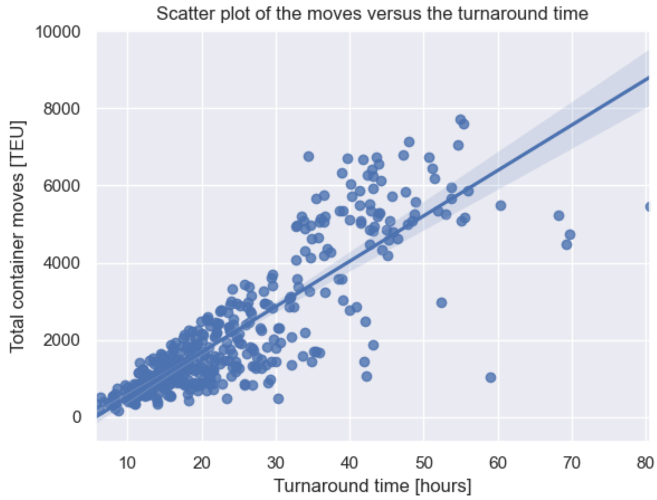


Figure 3.10: Correlation between container moves and the terminal turnaround time

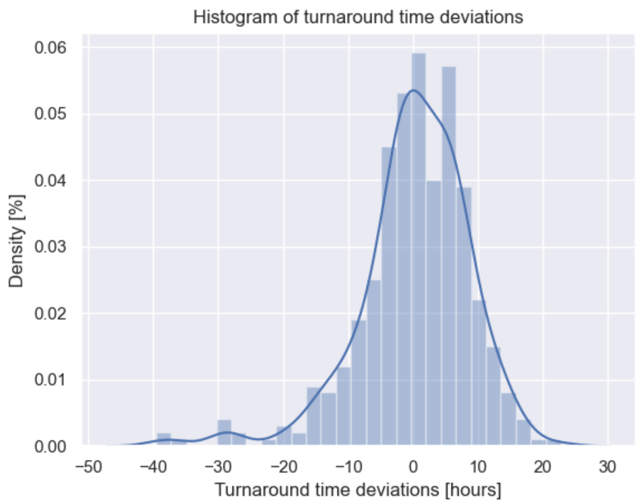


Figure 3.11: Deviations in the proforma and actual turnaround time

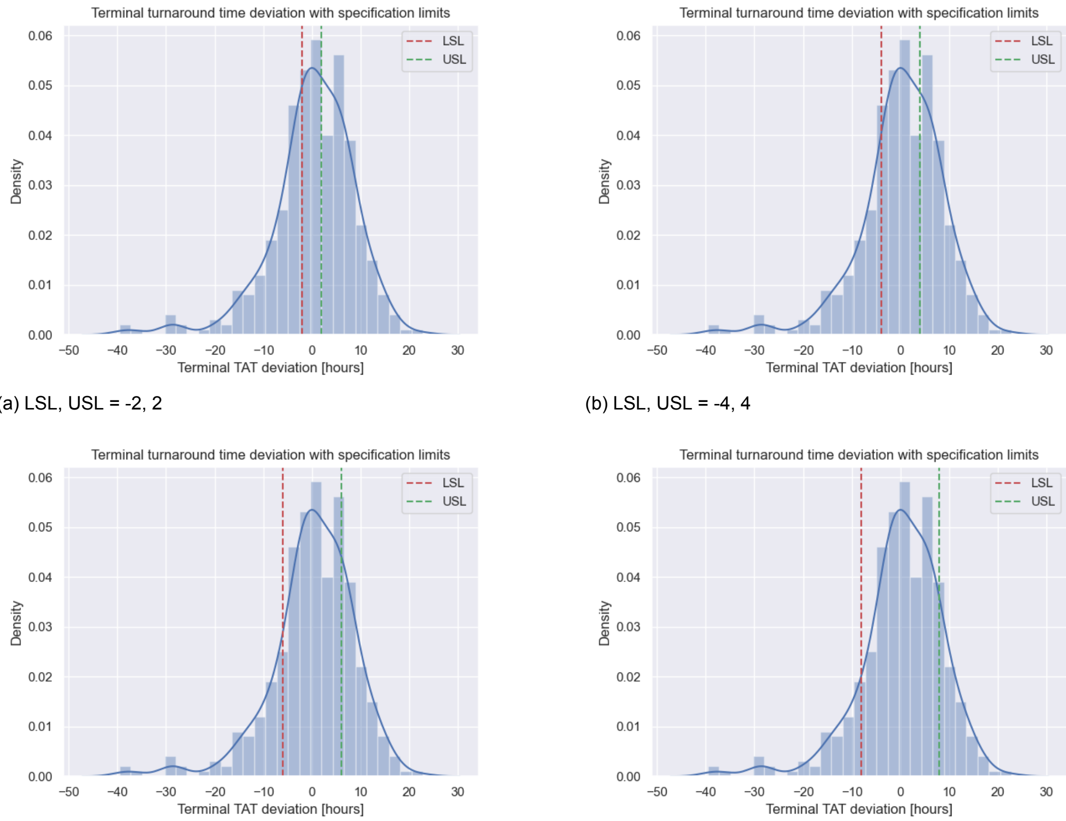
section. The measurement aims to identify if there are data patterns in the performance. The reader can find the quantitative results from the measurement in Table 3.6. The visualisation of the mapped data is depicted in Figure 3.13.

Pilot Time Arrival

The first sub-process that is identified is the Pilot Time Arrival. Within the event log, this is the delta of when the vessel enters the Pilot Boarding Place (PBP) and when the pilot embarks the vessel. These timestamps are manually reported on a paper document. The data indicate that the deviations within this sub-process are limited, and most of the time, equal to zero.

Nautical Time Arrival

The Nautical Time Arrival presents the moment that the pilot enters the vessel until the first line is attached. The vessels under consideration have two destinations within the port. APMT I is the abbreviation for APM Terminal Rotterdam, and APMT II is the abbreviation for APM Terminal Maasvlakte II. Due to the difference in distance to the terminals in the port area, the Nautical Time Arrival for both terminals is analysed separately. The average time from the PBP to APMT I and APMT II are respectively 1.38 hours and 2.22 hours. The difference in distance is the reason for deviation in this sub-process.



(a) LSL, USL = -2, 2

(b) LSL, USL = -4, 4

(c) LSL, USL = -6, 6

(d) LSL, USL = -8, 8

Figure 3.12: Terminal turnaround deviation for different specifications limits

Sub-process	Abbreviation	Mean	Median	Std. dev	Min	25%	50%	75%	Max
Pilot Time Arrival	PTA	0.15	0	0.48	0.00	0.00	0.00	0.05	4.22
Nautical Time Arrival	NTA	1.71	2.03	1.67	0.00	0.0	2.03	2.74	14.13
Idle Time before Operations	IBO	1.71	1.28	2.11	-0.48	0.78	1.28	2.74	23.08
Cargo Operations	OPS	20.73	16.78	12.57	3.28	11.42	16.78	26.77	77.52
Idle Time after Operations	IAO	2.03	1.08	3.10	-22.58	0.77	1.08	1.88	20.92

Table 3.6: Statistical analysis of sub-processes

This is because the Port Authority only permits if the is free from congestion. This is done to avoid manoeuvring the mainline vessel in the port area [33].

Idle Time before Operations
The Idle Time before Operations (IBO) is when the vessel is alongside berth before cargo operations [22]. The data is positively skewed with a value of 5.39 hours and a corresponding mean of 1.71 hours. A data set that shows a high skew is less convenient to predict future values [18]. The positive skew is also represented by the fact that the delta's mean is greater than the median. The cause for a positive skew in the data is large deviations or so-called outliers. The outliers in the data are identified by applying the Inter Quartile Range (IQR) method. This is under the consideration that normal data points appear in high probability regions, while outliers appear in the low probability region [14]. The data set under consideration shows that 36 (8.3%) port calls are represented by a value outside the IQR limits. In general, one hour is incorporated in the scheduling phase for this procedure [33]. The median of 1.28 hours shows that this is too little. The mean of 1.71 is higher and is caused by the outliers. The skewness of the data gives a good indication that there is operational waste in the process.

A data error for the minimum value is noted since it is impossible to perform the first container lift before the vessel is alongside the berth. As Figure 3.5 depicts, one of the operational procedures, before the cargo lifting can start is the practice of gondola and lashing. The time required for these operations is a function of the number of containers that need to be discharged. Figure 3.15 depicts the correlation between IBO and the number of containers discharged during the port call. The left figure represents all the data, where the right figure represents the data that is filtered from outliers. These outliers are statistically determined by identifying the data that shows a value that is exceptionally far from the mainstream data [14]. When the data is analysed, there is no strong correlation found between the number of containers and the idle time before operations. This can also be explained by the prioritisation of the first container lift. This means that the terminal starts with lifting containers before all the twistlocks are removed.

Cargo Operations
The cargo operations are the most time-consuming practice during the port call. Figure 3.10 already depicted the relationship between moves and the TAT. The Average Turnaround Time (ATT) is shown to be equal to a value of 20.73 hours. This is accommodated by an average of 2,214 containers moves per port call and includes the discharge, shifting and loading of containers with respectively 50%, 4.2%, and 45.8%. As a result, the average Port Moves per Hour (PMPH) is equal to a value 106.8. This value is important for the port call process's planning phase since it determines the greater part of the port TAT [55]. When the ATT of the Port of Rotterdam (POR) is compared to the world's averages from Section 2.2.4, the results show an above world's average (25.5 hours) performance.

Idle Time after Operations
The Idle Time after Operations (IAO) is defined as when the vessel is alongside berth after completing the cargo operations [22]. When the IQR is considered, 52 port calls (12%) are outside of the boundaries. This indicates that there is a relatively high number of outliers.

Section 3.7 shows that the loaded containers need to be locked with before departure. Considering this, the number of loaded containers is plotted against the IAO to search for a pattern. The results of the analysis are plotted in figure 3.14. The first observation is the negative value in the unfiltered data. The value of this point is -22.58 hours and might indicate a date insertion error. Again, the analysis does not show a strong correlation between the IAO and the number of loaded containers.

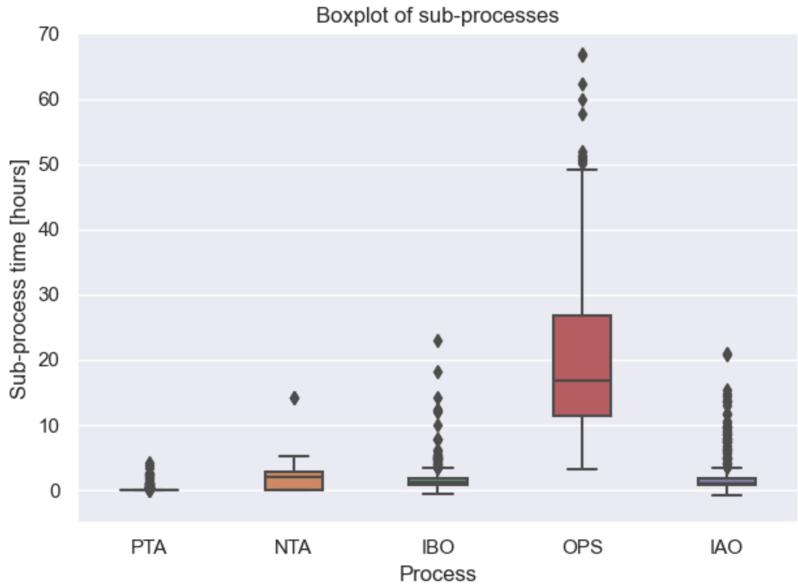


Figure 3.13: Duration of sub-processes

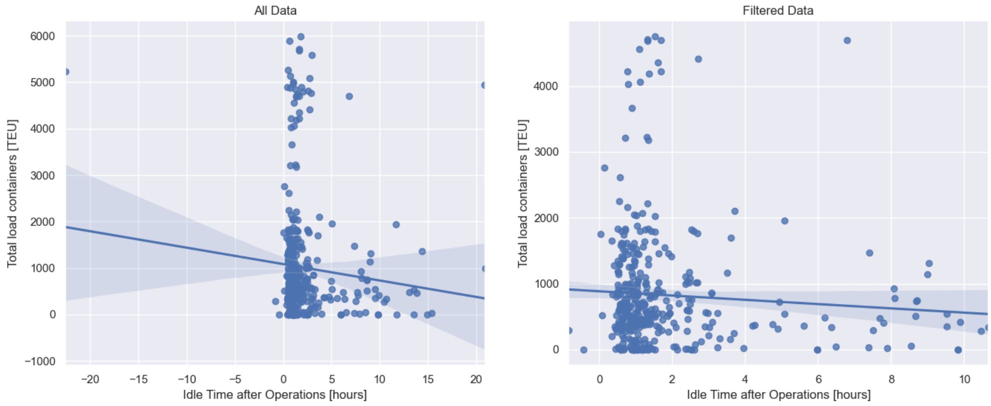


Figure 3.14: Correlation between IAO and number of containers loaded

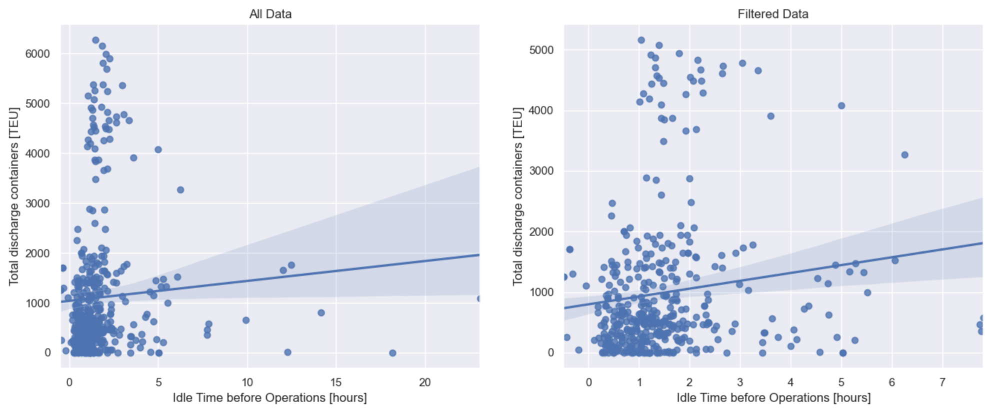


Figure 3.15: Correlation between IBO and number of containers discharged

3.3. Conclusion on the measurement phase

The measurement phase had the goal to provide both understandings and insights into the performance of the process. By deploying a hierarchical BPM model, five sub-processes are identified. Consequentially, these sub-processes are measured on their performance through a qualitative assessment. The most important findings from these two assessments are now briefly discussed in the upcoming section. This provides an answer to the second sub-question of this thesis:

> **Which sub-processes are executed during the port call process, and what is the performance of the Maersk vessel in the Port of Rotterdam?**

The port call process is a sequential process with multiple stakeholders involved throughout the process. Every port call is unique in its own way, and the planning and execution of this process are continuous challenges. The set of variables lead to an ETA Berth and ETD Berth and is called the planned berth window. Involved stakeholders use this window to plan their operations or connect their supply chains (e.g. customers, delivery of services/provisions). Changes in the scheduled window are communicated peer to peer via telephone or email. It is found that the involved stakeholders throughout the process are often not aware of the changes in the schedule. For example, the Port Authority is only notified within a range of 30 nautical miles.

The hierarchical approach segregated the Business Process Model (BPM) into five sub-processes during the operational phase: the nautical processes on arrival and departure, the idle time before and after operations, and the operations of cargo movement itself. Table 3.2 provides an overview of the stakeholder involvement over the port call process. Table 3.3 depicts the data that is stored in the information systems over the port call. Together these two findings provide input for the Lean Six Sigma port model used for the case study. The case study analysed 432 Maersk mainline vessels entering the POR in 2020. There are three performance measurements analysed: (i) on time arrival reliability, (ii) TAT reliability, and (iii) sub-process variations.

The on time arrival assessment shows that early arrival times are measured with a 60 to 40% rate. If an on-time variation allowance of 2 hours is maintained, 55.2% of the vessels are on time at the berth. Since the measurement technique depends on the scheduled window, it is important to consistently lock this estimated time at the same number of hours before arrival. This estimated time is locked in the COMS measurement system, and for a consistent calculation, the user must lock this number 24 hours before arrival.

This is followed by the reliability performance of the terminal turnaround process. Again, the planned berth window is compared to the actual window. When the specifications limits are set to be equal to 4 hours, 42.6% of the port calls is not within these limits. This indicates that the planned TAT from the port call shows considerable variations from the actual TAT. This measurement is limited to terminal TAT and does not include the waiting time on arrival and the nautical services. It is expected that the inclusion of these sub-processes results in higher variations.

Lastly, five sub-processes are identified and measured. The data shows no significant deviations at the pilot pick-up point or the rest of the nautical process. The Idle Time before Operations (IBO), and the IAO measurements show data points with significant deviations that need further analysis. The major time of the port call process is dedicated to cargo operations. Also, within this sub-process, data that shows a strong deviation from the trend indicate operational waste in the process.

The reliability and process capability measurements of the Six Sigma technique are insightful performance measurement techniques. Additionally, retrieving and mapping the data in a more granular way is efficient to identify at what part of the process operational waste occurs. However, the port call process remains stochastic due to the unavoidable presence of irregular uncertainties (e.g. extreme weather conditions). Therefore, the data analysis does not lead to clearly identified correlations but rather indicates operational waste in the process. To provide more insights into the reasons for operational waste, a qualitative study into the root causes for deviations is required.

4 Analysis

This previous section provided insights into the port call process by deploying a BPM and measuring the sub-processes performance using Lean Six Sigma tools. The most important finding from this section is that operational waste is present before and during the port turnaround process. Still, the acquired data is not sufficient for gaining more insights into the reasons. Therefore, the next step focuses on addressing the root cause for these variations [64]. As a result, the third (sub-) research question of this thesis is answered:

What are the root causes for variations during the port call process?

Section 4.1 describes the waste types that are present during the port call process. These types of waste are assumed to be symptoms, referred to as Undesirable Effects (UDEs). Section 4.2 uses this as input to address the underlying causes.

4.1. Waste types

The main purpose of applying lean techniques is to identify and eliminate waste (or non-value-added activities) through continuous improvement [57]. According to Monden, three types of events or operations occur during a time interval: (i) Non Value Adding (NVA), (ii) Necessary but Non Value Adding (NNVA) and (iii) Value Adding (VA). The first type is defined as pure waste and is desired to be eliminated. NNVA contains operations that do not directly add value to the chain but are necessary to continue with the rest of the process. VA operations are all processes that directly contribute to the result [39]. This categorisation is one of the methods to divide operations and finally address waste. The Toyota Production System (TPS) comprises seven waste types. Often, an eighth waste type is added to the list, which leads to the TIMWOOD(S) model:

- **T**ransportation
- **I**nventory
- **M**otion
- **W**aiting
- **O**verprocessing
- **O**verproduction
- **D**efect
- **S**kills

These types are widely popular and initiated by Taiichi Ohno and his team in the 1950s. This evolved into the Lean philosophy [4]. The eight waste types are now briefly discussed using the definitions by Hines et al. [39]. Since these waste types mainly focus on process manufacturing rather than providing a service, each waste type is further assessed on its applicability to the port call process.

Transport
According to Hines et al., transportation of goods is desired to be eliminated as much as possible due to the potential of deterioration and damage. Besides that, energy is required to transport the products. This directly leads to increasing costs during the operations [39]. Olesen et al. already indicated that this type of waste does not apply to the port call process since this is the actual objective of the service [73]. However, the transportation outside of the port call needs further analysis. According to Simon and Poulsen's report, often shipping lines "hurry op to wait" [77]. This type of waste leads to unnecessary high-speed arrivals. As section 2.5.1 described, the speed has a cubic relationship with fuel consumption. Given the research objective of this thesis, this form of waste is crucial to identify and eliminate.

Inventory
Increasing inventory leads to an increased lead time and storage space, resulting in higher costs. Having more inventory than necessary obstructs a steady workflow and hides production-related problems. Stocking inventory could be a consequence of over-purchasing raw materials such as metals, and the potential of accumulating defects increases with the increasing volumes. The user can avoid this by reducing buffers and generating queue systems to prevent overproduction in a manufacturing process [39]. The port call process is composed out of many sequential activities. If these activities do not efficiently follow up on each other, the vessel can not proceed in the process. Therefore, increased inventory leads to an increased port TAT.

Motion
According to the definitions by Hines et al., motion focuses on the unnecessary movement of people or equipment. Unnecessary indicates that it is any movement beyond the minimum required for completing the process step. The mainline vessels entering the port have a dedicated berth area. Therefore, it is assumed that the vessel does not experience any type of motion waste during the port call process. However, smaller vessels such as feeders and barges might experience berth exchanges while in the port. These berth exchanges could result from schedule disruptions from mainline vessels. Due to the intensity of such a change, this is a significant type of waste to these smaller vessels. Additionally, other stakeholders, such as tugs, which move freely in the port, might experience unnecessary motion when operating in the port environment.

Waiting
The time that there is no activity performed that has a Value Adding (VA) or a Necessary but Non Value Adding (NNVA) influence on the process is defined as waiting time. This waiting time can be either people waiting on material and information or equipment found in an idle state. Countermeasures to prevent waiting time include the design of processes to ensure continuous flow or single piece flow, implementing standardisation regarding work instructions and train the employees in a multi-skilled and flexible manner [39]. Waiting time is assumed to be the main type of waste in the port since it directly affects the port TAT. The waiting time is mostly a consequence of another type of waste, inconsistency, or overburdening of resources. However, a sub-waste type is introduced: waiting on information. Missing information or inadequate communication of information leads to waiting time. For example, the authorities (customs) must provide clearance before the vessel is permitted to leave the berth. Next to the customs clearance, certain services must comply with the International Ship and Port facility Security code (ISPS) certification [43]. To conclude, the port call process is an information-intensive process and can lead to serious waiting time if this is not properly assessed.

Overproduction
Overproduction refers to the excess of supply over demand. It is regarded as the most serious and common type of waste according to Hines et al. This type of waste leads to excessive lead and storage time. The quality and productivity decreases by an increase in overproduction. Furthermore, overproduction leads to excessive work-in-progress stock and results in excessive work. Overproduction occurs when the product is produced before the demand or order is processed. This form of waste is tempting when the machines and employees are idle due to a lack of demand. When service providing companies generate overproduction, this could be in the form of cleaning stuff that is already clean enough or providing too much information [39]. Within the port call process, there is no product produced but rather a service provided. Before the port call, the expected time of completion is determined

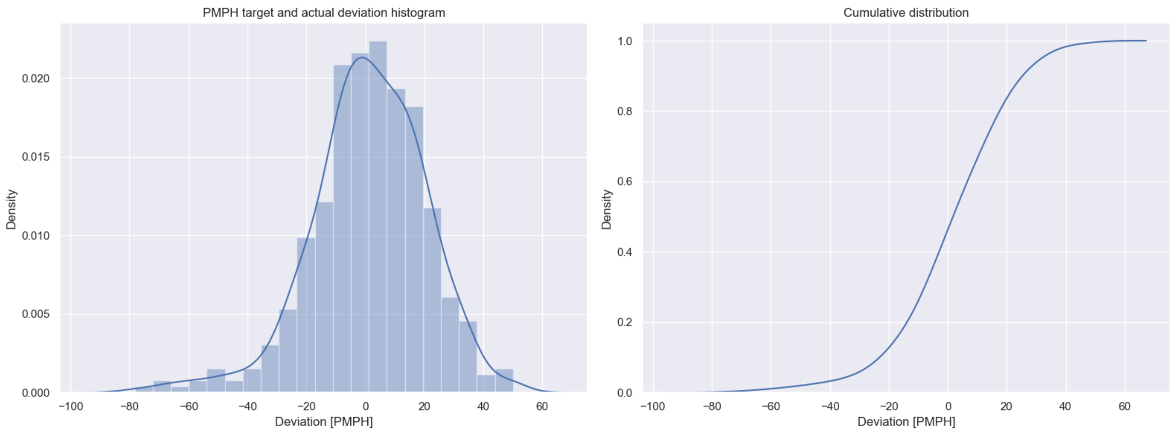


Figure 4.1: Actual versus expected PMPH.

by dividing the expected moves with the expected Port Moves per Hour (PMPH) (see equation 3.1). If the Key Performance Indicator (KPI) of the terminal is to handle the cargo as quickly as possible, this might lead to overproduction. The quay length enables the terminal to handle multiple vessels at a time. If another vessel experiences a negative move deviation, a larger Crane Intensity (CI) becomes available. To reach a maximum value for the KPI, the terminal could decide to reallocate the STS cranes. This results in a value for the PMPH that is larger than was expected in the schedule. Consequentially, the terminal as port call stakeholder is done earlier than expected. Other services such as bunker supplies are operating according to the schedule based on the expected PMPH. To illustrate this problem's significance, the proforma PMPH is plotted against the actual PMPH in Figure 4.1. The results show that a significant PMPH deviation is present when the actual against the target PMPH is measured. The positive values represent a PMPH that is above target. Given the cumulative distribution plot, it is found that more port call processes perform above target. Therefore, in general, the terminal operates on a level of overproduction. In terms of the waste definition, the positive values show an overproduction of the service.

Overprocessing
When overly complex systems perform relatively simple events, the user tends to compensate for the high capital expenditure is over-processing. In other words, inappropriate processing is the usage of complex systems for simple procedures. The ideal situation comprises a machine that can perform its required process and nothing more than that [39]. This type of waste is not in the scope of this thesis.

Defects
A defect is labelled as a product that is not sufficient for use and/or delivery and results in a reproduction or rework of the product. This results in additional costs for the producer and no added value for the customer. To avoid defects, firstly, it must be clear which products and processes generate defects. Secondly, a process must be designed that detect defects during production. Thirdly, the process must be revised by using well-considered improvement implementations. Lastly, using standardised work ensures a consistent process that stimulates defect-free operations [39]. During the execution of lifting and stacking containers, there is a strong presence of potential defects. All containers are attached to another using twistlocks or lashing rods. Inappropriate stacking of the containers leads to recovery work before the vessel is allowed to depart. The vessel crew is responsible for detecting defects by performing a check after the placement of a container. Due to the high stacking rows of the containers, early defect detection can avoid large recovery work. Additionally, the twistlocks and lashing rods can have defects on their own.

Skills
The eighth type of waste is not originally from the Toyota Production System (TPS) but added later. This type of waste focuses on the unused human potential and ingenuity. Often, this type of waste is formed in a system where the management is separated from the rest of the employees. Within these

organisations, the employees are obliged and trained to follow the orders and execute the work as planned. It is stated that excluding the front line workers' expertise and knowledge obstructs efficient improvement projects. This is because these people are the most capable of identifying problems and developing solutions for them. This type of waste is highly relevant for the port call process. The operations that are executed throughout the port call take place in a spatial environment where information is often known by some employees.

4.2. Cause and effect diagram

The idea of process improvements builds upon the action to solve the causes of variation (waste) in a measuring system. A simple graphical method to display the causes for variation is known by multiple names: the Ishikawa diagram, the fishbone diagram, and the cause and effect diagram [80, p. 216]. Within this thesis, the graphical display is referred to as the cause and effect diagram. The measurement phase results indicated that two deviations need further analysis: the arrival and turnaround variations. By measuring the reasons for variations, the design phase's scope is made [64]. Therefore, this assessment aims to validate the reasons for variations in the port call process.

The causes for the TAT deviations are qualitatively tested on the Maersk mainline port call event logs over a period of two months. When the vessel is alongside the berth, four data points are measured, represented by the cause and effect diagram. The waste types in Category C are measured between the moment that the first line is attached until the first container is lifted (idle time before operations). The waste types in Category T provide insight into the reasons for variations while lifting and stacking containers during operations. The latter Category D depicts the potential delay reasons after the last container is lifted until the vessel departs from berth (idle time after operations). This research has chosen to reflect the causes against the TIMWOOD waste types. The waste types are such that they do not add value to the customer. The diagram shows that waiting as waste type is predominantly present in the diagram.

4.3. Discussion on the cause and effect diagram

The cause and effect diagram is an efficient tool to measure the causes for variations in a process systematically. The different data points provide more granularity in the measurement process. However, there is a major drawback that is noted. The usage of such a reporting system for a cause and effect analysis relies on human input.

In the airline industry, a similar approach is used. The disruptions are charged against a specific discipline or organisation that affects the schedule of the network. These causes are reflected in a schedule reliability report. Different airlines use different level of granularity for delay causes. According to Hessburg, this granularity varies from 86 to only a couple of reasons. The report from Hessburg emphasises that these schedule reliability reports are not always a valid index of the real root cause of a delay. This is due to a lack of accuracy that is caused by commercial or managerial incentives. Consequently, these delay reports are the product of creative writing and finger-pointing rather than facts [38]. It is assumed that this problem also applies to the port call process. This waste analysis becomes more accurate by enabling direct communication of reliable information between stakeholders. Ultimately, a complete port call optimisation's shared goal must overcome the individual incentives that lead to silo-optimisation.

4.4. Current Reality Tree

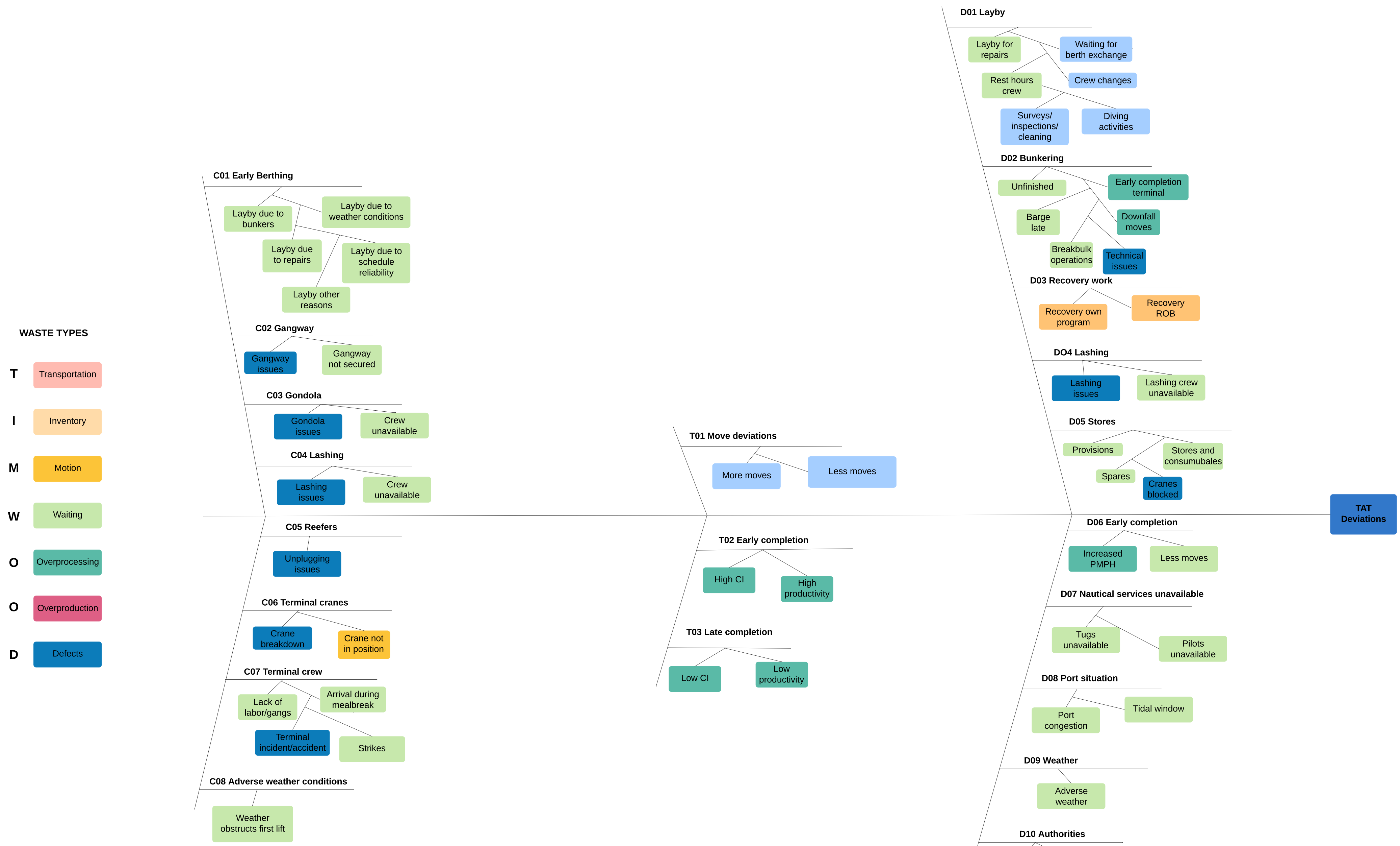
The previous section gives an identification of primary symptoms that lead to variations in the port call process. This section aims to find deeper insights into the reasons for deviations by deploying a Root Cause Analysis (RCA). The RCA is an analytical tool that is part of the Lean Six Sigma method. The RCA is stated to be one of the most powerful tools to assess problems regarding quality, productivity, safety and accidents. Two stages broadly describe the method: identifying the potential cause and the validation of the root cause [5]. The relation between the cause and effect defined by an RCA is proven to be important to design for improvements correctly [40]. In other words, the RCA identifies and analysis causes for operational waste in a system or process.

According to Pareto's law, a small percentage of a group accounts for the largest fraction of the impact. In this context, Pareto proposed the 80-20 rule. This rule helps to focus on several elements in a process rather than a complete process. Therefore, the law is often used to indicate the main contributors to variations in a process. The limitation of this law is that it only applies when no interdependencies are between the system's elements [80]. According to Goldrath, within an organisation, there are numerous interdependencies in a system, and the number of elements that dictate the performance of the system is small. This is known as the Theory of Constraints (TOC). This theory claims that one bottleneck is often the cause for most of the variations in a system. In other words, all symptoms of process variations lead back to a single bottleneck. Solving this bottleneck is often found in small adjustments rather than capital or labour-intensive investments [21].

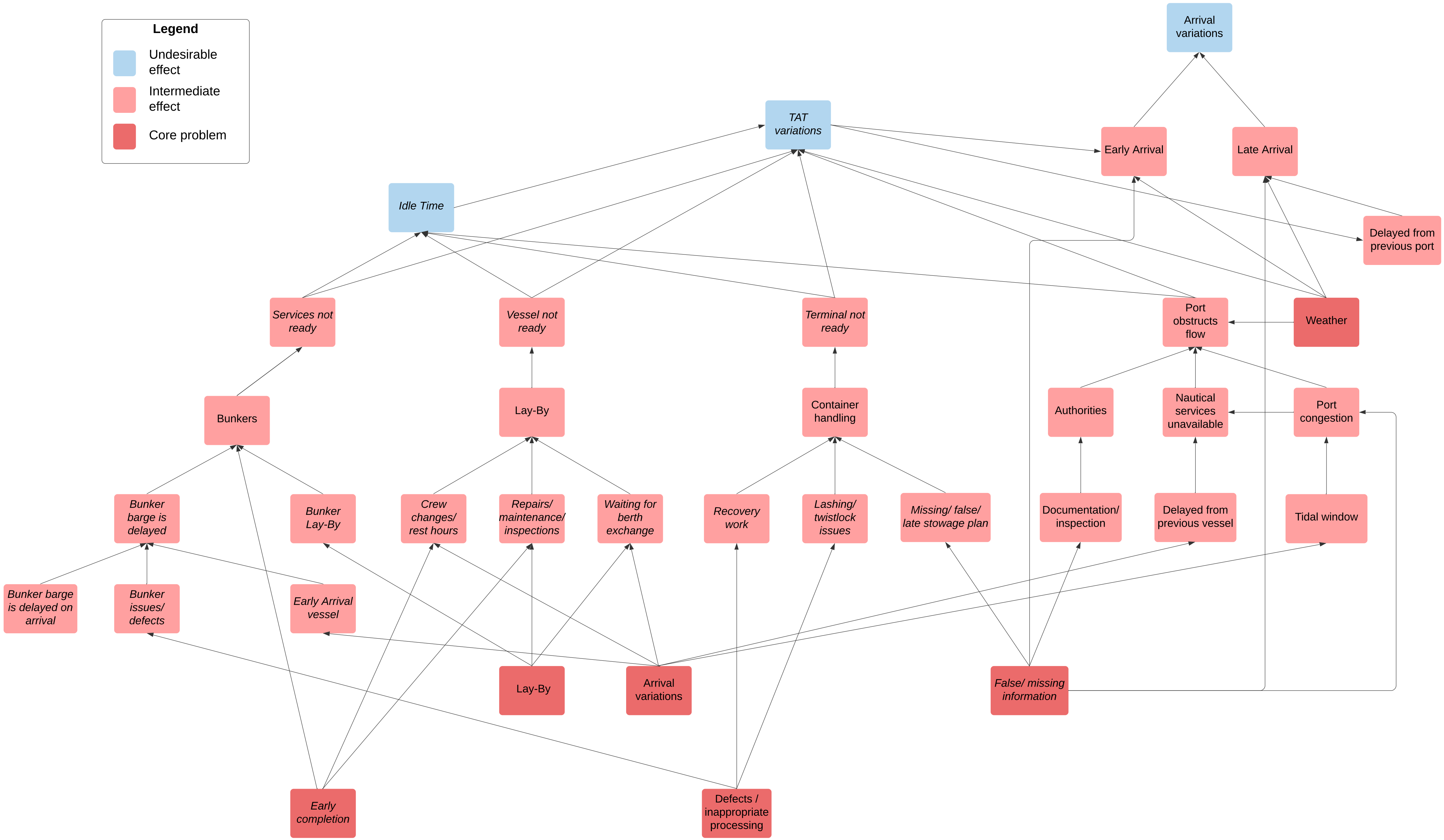
A method to systematically identify the bottleneck (root cause) for a system is the Current Reality Tree (CRT). This tool is a part of the Thinking Process (TP) which develops solutions for common problematic situations [21]. The cause and effect analyses from Section 4.2 are used as input for the CRT. The presence of these symptoms leads to a set of UDEs. According to the definition from the CRT, an UDE is identified by thee requirements:

- It has a negative implication on the performance of the process.
- The problem's presence is there for a longer time (at least several months).
- Previous attempts to sort out the problem did not lead to success.

The CRT that leads to the UDE depicts the path to undesirable outcomes that obstruct a well-performing process. In other words, it tells the user what is going wrong in the process, and what (bottleneck) needs to solve. The application of the methodology focuses on the complete process rather than symptoms [21]. The UDEs assessed in this thesis are increased TAT, and arrival deviation. Additionally, a correlation between these UDEs is searched for in the diagram. The corresponding CRT shows that all UDEs are derived from six root causes. The input of the model is based on the tables from Appendix A.



WASTE TYPES
T
Transportation
I
Inventory
M
Motion
W
Waiting
O
Overprocessing
O
Overproduction
D
Defects
C01 Early Berthing
Layby due to bunkers
Layby due to weather conditions
Layby due to repairs
Layby due to schedule reliability
Layby other reasons
C02 Gangway
Gangway issues
Gangway not secured
C03 Gondola
Gondola issues
Crew unavailable
C04 Lashing
Lashing issues
Crew unavailable
C05 Reefers
Unplugging issues
C06 Terminal cranes
Crane breakdown
Crane not in position
C07 Terminal crew
Lack of labor/gangs
Arrival during mealbreak
Terminal incident/accident
Strikes
C08 Adverse weather conditions
Weather obstructs first lift
T01 Move deviations
More moves
Less moves
T02 Early completion
High CI
High productivity
T03 Late completion
Low CI
Low productivity
D01 Layby
Layby for repairs
Waiting for berth exchange
Rest hours crew
Crew changes
Surveys/ inspections/ cleaning
Diving activities
D02 Bunkering
Unfinished
Early completion terminal
Barge late
Downfall moves
Breakbulk operations
Technical issues
D03 Recovery work
Recovery own program
Recovery ROB
DO4 Lashing
Lashing issues
Lashing crew unavailable
D05 Stores
Provisions
Stores and consumubales
Spares
Cranes blocked
TAT Deviations
D06 Early completion
Increased PMPH
Less moves
D07 Nautical services unavailable
Tugs unavailable
Pilots unavailable
D08 Port situation
Port congestion
Tidal window
D09 Weather
Adverse weather
D10 Authorities
ISPS requirements
Customs


Legend
Undesirable effect
Intermediate effect
Core problem
Arrival variations
TAT variations
Idle Time
Early Arrival
Late Arrival
Delayed from previous port
Services not ready
Vessel not ready
Terminal not ready
Port obstructs flow
Weather
Bunkers
Lay-By
Container handling
Authorities
Nautical services unavailable
Port congestion
Bunker barge is delayed
Bunker Lay-By
Crew changes/ rest hours
Repairs/ maintenance/ inspections
Waiting for berth exchange
Recovery work
Lashing/ twistlock issues
Missing/ false/ late stowage plan
Documentation/ inspection
Delayed from previous vessel
Tidal window
Bunker barge is delayed on arrival
Bunker issues/ defects
Early Arrival vessel
Lay-By
Arrival variations
False/ missing information
Early completion
Defects / inappropriate processing

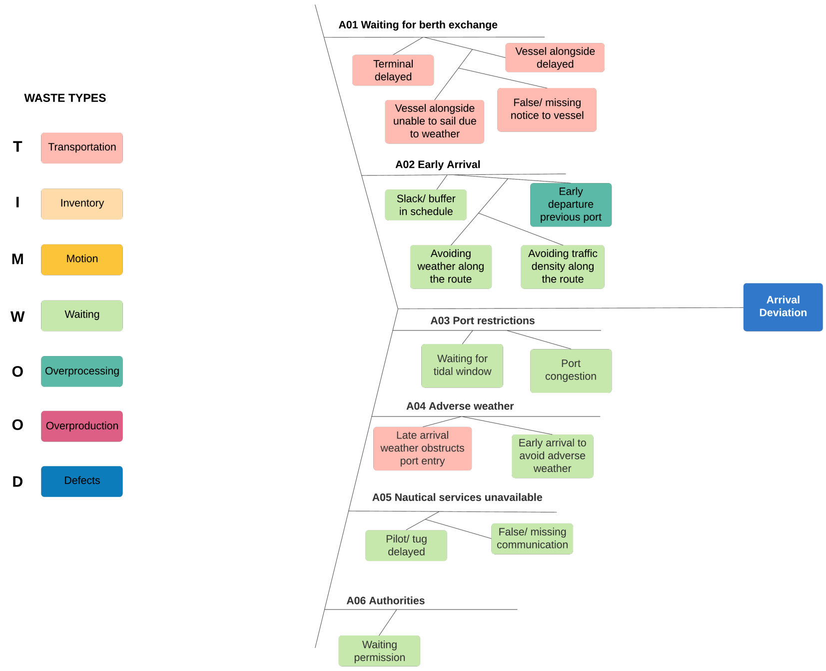


Figure 4.2: Cause and effect diagrams for TAT and arrival deviations

4.5. Discussion on the Current Reality Tree

The statement of Goldrath that all reasons for variances in the process can be lead back to a single element is not reflected by the CRT diagram from this study. As described earlier by Paixao, the port call process is different from manufacturing processes since the owner is not in full control of the process [74]. The weather is such a core problem that it is always present in the container network and can not be controlled. In the port, this can be either wind gusts that obstructs the terminal from lifting containers. Outside the port, swell limitations can obstruct the pilot to embark on the vessel. As the presence of adverse weather, there are numerous reasons for a variation in the port call process, and every port call process is unique in the reason for delay. To scope on the reasons for the delays, six root causes are identified that lead to idle time, variations of the TAT, and arrival deviations.

4.5.1. Idle Time

Idle time is defined as the time that the vessel is alongside berth before and after operations. This time measurement is often considered as KPI or port PIs [22]. The measurement phase indicates that certain port calls show a strong deviation from the average (see Figure 3.13). This indicates that there is a presence of operational waste. However, the formation of this waste needs further clarification. For example, the bunkers are often planned for a certain departure time, close to the ETC Cargo. This value is, in its turn, a function of the PMPH and the number of containers. If one of these variables changes during the port call, there could be idle time forming while the vessel is still on time. It can be discussed if the port operates at that moment at a level of overproduction (waste type). However, if this allows the port to reallocate the cranes to another vessel, it optimises resource allocation.

Other reasons for idle time are planned operations such as repairs, maintenance or additional bunkers after completing operations. It can be the case that there economic or strategic decisions that allow the shipping line to cause idle time after operations. These incentives make it hard to distinguish waste idle time from justified idle time where the justification includes various decisions such as economic or strategic incentives.

4.5.2. Turnaround time variation

In general, it is found that the turnaround time variations are related to at least one of the four intermediate effects, which on its turn, are caused by one of the underlying root causes. This upcoming section uses a bottom-up approach to analyze the diagram.

Early completion

Early completion is earlier defined as overproducing by the TIMWOOD waste type definition. As can be seen from the diagram, early completion is a root cause that leads to waiting time in the process. For example, the terminal can increase productivity and finish earlier than the schedule, but if this jeopardises the crew vessel's resting hours, the vessel cannot sail. This type of overproducing waste leads to TAT variations.

Lay-by

Table 2.2 provides insights into the price differences of marine bunker fuels in the world. It could occur that the price spread is equal to an amount where it is beneficial to lay-by for additional bunkers and increase the speed along the route to the next port. The increased fuel costs along that route segment might be less than the bunker decision's fuel gains. Additionally, a vessel agent might decide in the planning phase to lay-by due to required maintenance or repair activities. These scenarios lead to increased TAT variations. To conclude on this root cause, there is often a financial incentive to a lay-by with increased idle times and turnaround times as a consequence. If this lay-by does not exceed the buffer time with the succeeding vessel, this does not necessarily lead to waiting time for that vessel.

Defects

The types of defects in the port are numerous. Especially during cargo handling, great forces are used to lift, stack, and attach the containers. As described in the waste analysis in Section 4.1, the port can solve defects by redesigning the process or improving the material. An example is the usage of semi- or fully automated twistlocks. The fully automated twistlocks do not require human involvement and would increase the handling time significantly. However, the design of these types are less reliable, and more defects are detected while using them [45]. Improving defects is often a capital intensive strategy [39]. By extending the data waste analysis measurement period, the user will find more information on defects. The user can analyse this information for long-term projects on material improvement.

False/ missing information

False or missing information has consequences on both the port turnaround time and the time at sea. Often, this is referred to as situational unawareness. For example, when the vessel is not aware of an increased TAT of the vessel currently alongside in the port, the intermediate effect is that the upcoming vessel cannot enter the port area. As described earlier, this is referred to as transportation waste. Additionally, missing information leads to port congestion. The first contact moment of the vessel to the Port Authority is at a range of 30 nautical miles [33]. It is interesting to test whether early notification of expected arrival time leads to reduced port congestion. It can be discussed that early completion is a consequence of missing information.

4.5.3. Arrival deviation

As the measurement phase already indicates, the ratio of early to late arrival is equal to 60 and 40%. It is found that a deviation on arrival is both a root cause and an UDE. If the berth is available and the Port Authority grants access, there is a good chance that the vessel enters the port area. However, an early arrival does not necessarily lead to an early departure [95]. This is because it is possible that the bunker or provision services are not able to reschedule and complete before the new Estimated Time of Departure Berth (ETD Berth). Consequentially, the vessel experiences a port TAT that is longer in hours than expected but does not differ from the original departure time. On the other hand, a late arrival also has its consequences. For example, a late arrival can lead to a missed tidal window, amplifying the delay time even more.

False/ missing information

Transportation waste is described as unnecessary high speeds on arrival. The role of false or missing information is a very important root cause for this type of waste. If a vessel at sea is aware of an increased TAT in the port, the captain can adjust the speed to the on time arrival speed. On the other hand, false information of the correct on time arrival can lead to late arrivals.

4.6. Conclusion on the analysis phase

The analysis phase is the last phase of the current state analysis, and the goal is to conclude the causes for variations in the port call process. By doing so, an answer is given to the third sub-question:

What are the root causes for deviations during the port call process?

Three stages form the answer to this question. First, the waste types according to the TIMWOOD model are assessed concerning the port call process. It is found that these eight types of waste are not completely homogeneous with the waste types in the port call process. One important adjustment is the presence of transportation waste on arrival. This type of waste is defined as the unnecessary waiting time on arrival due to a too high speed maintained over that sea leg. In other words, transportation waste indicates that the vessels fuel consumption profile is higher than necessary, leading to a decreased voyage efficiency.

Subsequently, the TIMWOOD waste types are applied to the port call turnaround process by deploying a cause and effect diagram. A set of Maersk mainline vessels entering the Port of Rotterdam is analysed by measuring the performance and waste analysis. Variation in the PMPH performance is assumed to be a significant factor for the deviations in the TAT [93]. The assessment for the idle time before and after operations are more elaborate. The diagram shows, especially after operations, that there are numerous causes for deviations. It is noted that the diagram shows the symptoms rather than the underlying root causes for deviations. To provide deeper insights into the root causes for variations, a CRT diagram is proposed. The results from this study show that some waste types occur more frequently, such as gondola operations on arrival or a bunker lay-by on departure. These waste types are used as input for the CRT diagram. The waste types are all connected to one of the Port Performance Indicators: idle time, TAT variation, and arrival variation. It is found that most of the waste symptoms can be traced back to six root causes: missing information, early completion, lay-by, defects, adverse weather conditions, or arrival variation. Often, this waste is justified with commercial arguments such as increased turnaround times due to bunker operations, or the purchase of goods and services [101].

In the CRT diagram it is found that a deviation on arrival affects the TAT. This is because involved stakeholders plan their services according to the scheduled Estimated Time of Arrival (ETA). Variations from these arrival times lead to conflicts in their own schedules. For example, unexpected arrival times lead to port congestion due to difficulties in planning the nautical services on arrival. This is also in line with the findings of the research by Notteboom [72], and Paixao et. al [16]. The latter research states the stochastic demand (unevenness) of port services lead to further causes such as port congestion (bottlenecks). Therefore, it is found that variations on arrival have a greater chance to further develop into into an even greater variation during the port call process. This is called the cascading effect of a delay. To conclude on this, a deviation on arrival leads to an increased TAT. This leads to the finding that a more reliable and predictable arrival time (after a delay) leads to a shorter TAT.

The root cause of missing information is a typical example of the Theory of Constraints (TOC) by Goldrath. This type of waste is the root cause for bottlenecks that causes variation in a system or process. It is assumed that the solution to this bottleneck is found in a small adjustment rather than a capital intensive investment. These two findings match the criteria of the TOC. This finding concludes that missing information has negative consequences on multiple aspects of the shipping network: increased port turnaround times, inadequate waste assessment, and transportation waste. The first two consequences are focused on the port call. For a Lean improvement project, these two consequences could function as input for the improvement and control phase. Such a project would improve the communication and test (control) this for a longer period of time within an organisation. For this study, the time and resources are limited and therefore, it is chosen to focus primarily on transportation waste. A relatively new concept in the industry is Virtual Arrival. This study assesses this concept and introduces a future state design based on this study. Consequentially, the next two phases of this study (the future state) focus on the role of information sharing between the port and the vessels at sea to reduce transportation waste of container vessels through speed optimisation and a reduction of the Turnaround Time (TAT).

5
Design

The Define Measure Analyze Design Evaluate (DMADE) cycle consists out of two phases: the ”as-is” and the ”what-if” state. The previous sections address the situation by defining, measuring, and analysing the current process. The measure and analysis phase indicates that certain types of operational waste lead to idle time, increased port TAT and variation on arrival. The relation between those variations is that the upcoming vessels cannot enter the port if the vessel alongside experiences an increased TAT. This lead to the assumption that the increased port TAT is the main cause of container shipping’s high anchorage times. As Figure 3.3b depicts, the vessels are often not aware of the increased TAT. This is often the case because the vessel only makes the first contact with the port within a range of 30 nautical miles [33]. As the previous phase concluded, if the vessel arrives at a higher speed than the minimum required speed, this is listed as transportation waste. Within this section, the concept of a Dynamic Arrival Time (DAT) is introduced to avoid this type of transportation waste by assessing the role of early stage delay notification. To successfully implement this concept into practice, adoptions in the current state of the system are required. This leads to the fourth (sub-) research question of this thesis:

”How can Dynamic Arrival Times be implemented in the liner network?”

Section 5.1 proposes a new method to measure the fuel and emissions reductions from a vessel that sails with a DAT. Section 5.2 continues on the concept by proposing an improved design of the port call process. To validate the proposed calculations, a case study is proposed in Section 5.3. Based on this information, an improvement hypothesis is listed. The proposed hypothesis is found in Section 5.4. Lastly, Section 5.5 provides a conclusion on the design phase.

5.1. Dynamic Arrival Time practices in theory

Virtual Arrival is a relatively new concept in the maritime industry. The concept relies on the agreement to reduce the vessel’s voyage speed to meet a revised arrival time when a delay in the port of arrival is known [44]. As discussed in Section 2.7 this study revises the concept by proposing a Dynamic Arrival Time (DAT) concept. The decreased vessel speed leads to an extension of the transit time, and thus, a reduction of the waiting time on arrival (see also equation 5.3). The DAT aims to avoid a scenario where port delays (δ_p) are not known in the port and also not known by the vessel along the route. If an DAT is successfully implemented, the main benefits are:

- Reduction of waiting times on arrival (anchorage time)
- Reduction of fuel consumption
- Reduction of GHG emissions

The industry's actual implementation of Virtual Arrival (or similar concepts) is little to none. According to Poulsen and Sampson, the are four difficulties that obstruct the concept. The GloMEEP adds a fifth challenge to this list:

- Port and terminal logistical challenges.
- Cargo values and savings.
- Lack of trust.
- Unintended consequences of virtual arrival [77].
- Contractual agreements [33].

In addition to this, Wang and Moo state that the main engine has an optimal operating profile at constant speed [104]. Presumably, the captain is not willing to continuously adapt the speed over the voyage.

To overcome these limitations, three adjustments to the current design are proposed. These adjustments are the incorporation of standardisation, waypoints, and delay incorporation. Consequentially, the fuel and emission equation from Section 2.1 are adjusted. The following sections elaborate on how these adjustments can be applied to the current state design.

5.1.1. Standardisation

To collaborate within the port environment, the involved stakeholders must use the same definitions to execute the operations. According to Becha et al., standards are the key to acquiring the benefits of collaboration. According to this research, the definition for a standard is "... an agreement among a business network constituted by actors that share the same common object of interest" [8]. Within this design, the standardised data definitions from the Digital Container Shipping Association (DCSA) are used [22]. DCSA initiates these standards with the aim to create an ecosystem of interoperability across the global supply chain to enable actors to share real time information [23]. This non-profit organisation published the list in 2020 in conjunction with nine member carriers. Furthermore, this list aligns with the definitions used by the International Maritime Organization (IMO) [70].

5.1.2. Waypoints and voyage parameters

The next adjustment that is discussed is the incorporation of waypoints along the route. To recall a shipping network's mathematics, equation 5.1 describes the relationship between the vessel speed, distance, and time. Equation 5.2 depicts the effect of incorporating a buffer (σ_b) between vessels on the waiting time (r_i) of the consecutive vessel. The waypoints (w) that are introduced enable the user to measure at different sea segment stages if there is a delay in the port of arrival identified. If this is the case, a new set of voyage parameters is determined at that waypoint. The voyage parameters include the Distance To Arrival (DTA), Time To Arrival (TTA), and together these parameters determine the Optimum Speed to Arrival (S_{VA}) at that specific waypoint. Equation 5.3 gives a mathematical description of the effect of speed reduction on the waiting time. If a vessel can reduce the speed to a value where the reduction of the vessel speed completely absorbs the port uncertainty, the vessel is sailing Just-in-Time (JIT), and the waiting time at anchorage is eliminated. In other words, the DAT is a method to reduce waiting times by reducing the speed on the sea leg. By doing so, the waste of transportation is eliminated. This is in line with the principle of Lean Six Sigma (LSS) which aims to eliminate all operational waste in a process. The rest of this section elaborates on the algebra used to determine the fuel and emission effectiveness of implementing a DAT.

$$t_{s,s,i} = \frac{D_i}{S_i} \tag{5.1}$$

$$r_i = -\sigma_b + \delta_{p,i-1} \tag{5.2}$$

$$t_{s,s,i} + r_i = \frac{D_i}{S_i} + t_{s,a,i} \tag{5.3}$$

A waypoint is an intermediate reference point along the route that the vessel is sailing. By adding several waypoints along the route, the distance between the waypoints is equal to the total route distance divided over the number of waypoints.

$$d_{i,wp} = \frac{D_i}{w} \tag{5.4}$$

If the vessel is at the port of origin, the number for n is equal to zero. If the vessel arrived at the port of destination, the value is equal to n. The DTA at a specific waypoint n is equal to the total distance D_i subtracted with the distance covered by the previous waypoint segments.

$$DTA_n = D_i - n \cdot d_{i,wp} \tag{5.5}$$

The TTA at a waypoint n is equal to the Estimated Time of Arrival (ETA) in the port of arrival according to the schedule, subtracted with the time that passed to cover the previous waypoint segments. The time that the vessel is underway is equal to the already covered distance, divided by the speed that is maintained over that segment (S_i).

$$TTA_n = ETA_i - \frac{n * d_{i,wp}}{S_i} \tag{5.6}$$

The last voyage parameter that is determined at waypoint n is the vessel speed. This is the speed that needs to be obtained over the upcoming waypoint segments to meet the Requested Time of Arrival (RTA) in the arrival port. This RTA is discussed in the upcoming section. The vessel speed is noted in knots and is bounded with an upper and lower limit. Although the environmental and economic benefits of reducing the vessel speed are recognised, Wärtsilä addresses technical concerns that give rise to a low load range to the main engine. During fuel combustion at a low load range, concerns are lower air flows, poor combustion, cold corrosion, and fouling. To overcome these concerns, the engine manufacturer provided engine upgrade kits and retrofitting solutions. This allows ships to systematically reduce the load range on the engine [107]. It is assumed in this research that the minimum allowable speed for the vessel is equal to 12 knots, and the maximum allowable speed is equal to 22 knots. The maximum allowable speed is determined by making use of the arrival speed data histogram in figure 5.1. The histogram indicates that mainline container vessels (same as from the case study) do not sail above the maximum speed of 22 knots on average. The lower region of the histogram shows arrivals with a speed that is below 12 knots. It is assumed that the calculation of the average speed includes canal- and port transits and drifting operations that are performed under low engine load. These low engine load measurements affect the results and do not show representative values for the average speed. Therefore, it is assumed to maintain the minimum speed of 12 knots that the engine manufacturer provides. Substituting equation 5.5, and 5.6, into equation 5.1 gives the following equation for the vessel's optimal speed at waypoint n.

$$S_{VA,n} = \frac{DTA_n}{TTA_n} = \frac{D_i - n \cdot d_{i,wp}}{ETA_i - \frac{n \cdot d_{i,wp}}{S_i}} \tag{5.7}$$

5.1.3. Delay incorporation

Section 2.1.2 explains the vessel speed's relationship to fuel consumption and emissions by using a static vessel speed. With the implementation of a DAT, the speed is adjusted at the waypoints, and therefore dynamic. The most cost-effective fuel consumption is obtained when the speed is held constant over time [104]. Therefore, the number of speed adjustments is limited to the number of waypoints. If the vessel is not aware of a delay at the arrival port, the speed remains as defined in the schedule (S_i). When the vessel is aware of the delay (r_i), the Estimated Time of Arrival (ETA) from the schedule now becomes the Dynamic Arrival Time. The Distance To Arrival remains the same due to the static behaviour of the waypoints. Subsequently. the speed is reduced to a value where the waiting

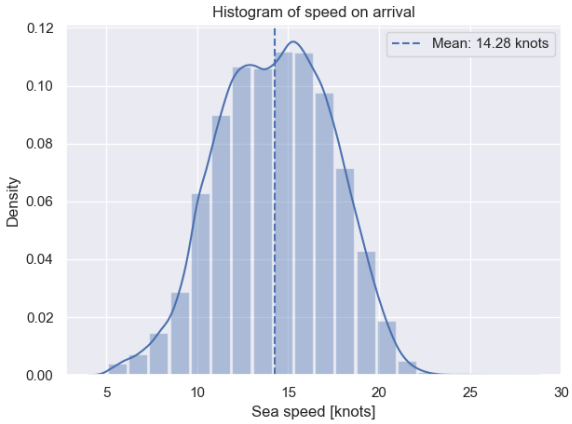


Figure 5.1: Average arrival speed of Maersk mainliner vessel

time at anchorage is minimised. As described in Section 5.1.2, the speed is bounded with a minimum of 12 knots.

$$TTA_n = (ETA_i + r_i) - \frac{n * d_{i,wp}}{S_i} = DAT_i - \frac{n * d_{i,wp}}{S_i} \tag{5.8}$$

The earlier a delay is known by the vessel, the earlier the vessel can reduce the speed, and the greater the effect is on the waiting time. To elaborate on the delay notice's importance, the terms α and β are introduced in this thesis. If the vessel is not aware of the delay, the vessel maintains the speed according to the schedule during that waypoint segment. Now, when the vessel is aware of the delay, the Time To Arrival increases with the positive differential of the DAT and ETA, and the vessel adjusts its speed according to equation 5.7. The higher the value of α, the more time is given to the vessel to reduce the speed. To elaborate on this, the following example is given. If a vessel is aware of a delay at the departure of the origin, the vessel can reduce the speed over all the waypoint segments. As a result, α equals zero, and β equals w. Another scenario is that there are five waypoints ($w = 5$), and the delay notice is given at the second waypoint. This results in $\alpha = 2$, and $\beta = 3$. In other words, the distribution of α and β represents the number of segments where a vessel is aware of the delay or not. The distribution of the values is constrained by the number of waypoints along the route. This leads to the following equation.

$$w = \alpha + \beta \tag{5.9}$$

where:

α = number of waypoints segments where the delay is unknown
β = number of waypoints segments where the delay is known

5.1.4. Dynamic fuel consumption and emissions

The values of α and β are first substituted in the original equations for the time factors (equation 2.4 and 2.5). The revised time equations are thereafter substituted in the fuel consumption equation from section 2.1.2.

$$t_{s,s,i} = \alpha \cdot t_i + \beta \cdot t_D \tag{5.10}$$

$$t_{s,s,i} = \alpha \cdot \frac{d_{i,wp}}{S_d} + \beta \cdot \frac{d_{i,wp}}{S_D} \tag{5.11}$$

$$t_{s,s,a} = (ETA_i + r_i) - t_{s,s,i} \tag{5.12}$$

$$
\begin{aligned}
DFC_{s,s} &= \alpha \cdot DEC_{s,s} \cdot SFOC_d + \beta \cdot DEC_{s,s} \cdot SFOC_D \\
&= \left(\alpha \cdot P_{prop,s}(S_d) \cdot t_d \cdot SFOC_d\right) + \left(\beta \cdot P_{prop,s}(S_D) + t_D \cdot SFOC_D\right)
\end{aligned}
\tag{5.13}
$$

where:

t_d = Sailing time at design speed S_d
t_D = Sailing time at dynamic speed S_D
$SFOC_d$ = Specific fuel oil consumption at design speed S_d
$SFOC_D$ = Specific fuel oil consumption at dynamic speed S_D
$EC_{s,s}$ = Energy consumption of the vessel at sea while sailing
$DFC_{s,s}$ = Dynamic fuel consumption of the vessel at sea while sailing

Under the assumption that $S_D < S_d$, the waiting time at anchorage decreases when the value of β increases. This proves mathematically that a high value of β leads to lower waiting times at anchorage. Ideally, the vessel reduces the speed along the voyage to a value where waiting time at anchorage is eliminated. Consequentially, the speed reduction leads to lower fuel consumption and lower emissions.

To conclude on the algebra of the container network and the implementation of the DAT, several observations are addressed:

- Increased port TAT (might) leads to waiting time on arrival.
- The incorporation of a Dynamic Arrival Time reduces the vessel speed if a port delay is known.
- The fuel consumption is approximated with a third power relation to the vessel speed.
- GHG emissions are proportionally related to fuel consumption.
- The sooner a port delay is notified, the more effective the Dynamic Arrival Time is.
- The Dynamic Arrival Time supportsJust-in-Time (JIT) operations.

5.2. Dynamic Arrival Time incorporation in practice

The previous section proposed several findings from the proposed design with respect to fuel consumption and emissions. This section continues on these findings but focuses on the practical aspects of introducing the design to the port call process and the network. The DAT design basically relies on two principles: situational awareness and real-time communication. Therefore, an improved design focuses on identifying delays within the port environment that on its turn, are communicated to the vessel at sea.

5.2.1. Dynamic Arrival Time calculation

The DAT introduced in equation 5.8 is now further discussed in this section. A graphical representation of the DAT calculation is provided in Figure 5.2. There are five scheduled measurement points throughout the port call. It depends on the scheduled buffer (σ_b) and the value of the delay, caused by a preceding vessel, at a certain point ($\delta_{i-1,j}$) whether the DAT is adjusted or not. If the vessel experiences a total delay that is greater than the buffer, the ETA is replaced with a new DAT (equation 5.14). If the delay is not greater than the buffer, the ETA remains defined as the schedule.

$$
\begin{aligned}
DAT_i = ETA_i + (-\sigma_b + \delta_{i-1,1}) \\
if - \sigma_b < \delta_{i-1,1}
\end{aligned}
\tag{5.14}
$$

The second measurement point is when the first line is attached to the quay. Again, it is measured if the total delay is greater than the buffer.

$$
\begin{aligned}
DAT_i = ETA_i + (-\sigma_b + \delta_{i-1,1} + \delta_{i-1,2}) \\
if - \sigma_b < (\delta_{i-1,1} + \delta_{i-1,2})
\end{aligned}
\tag{5.15}
$$

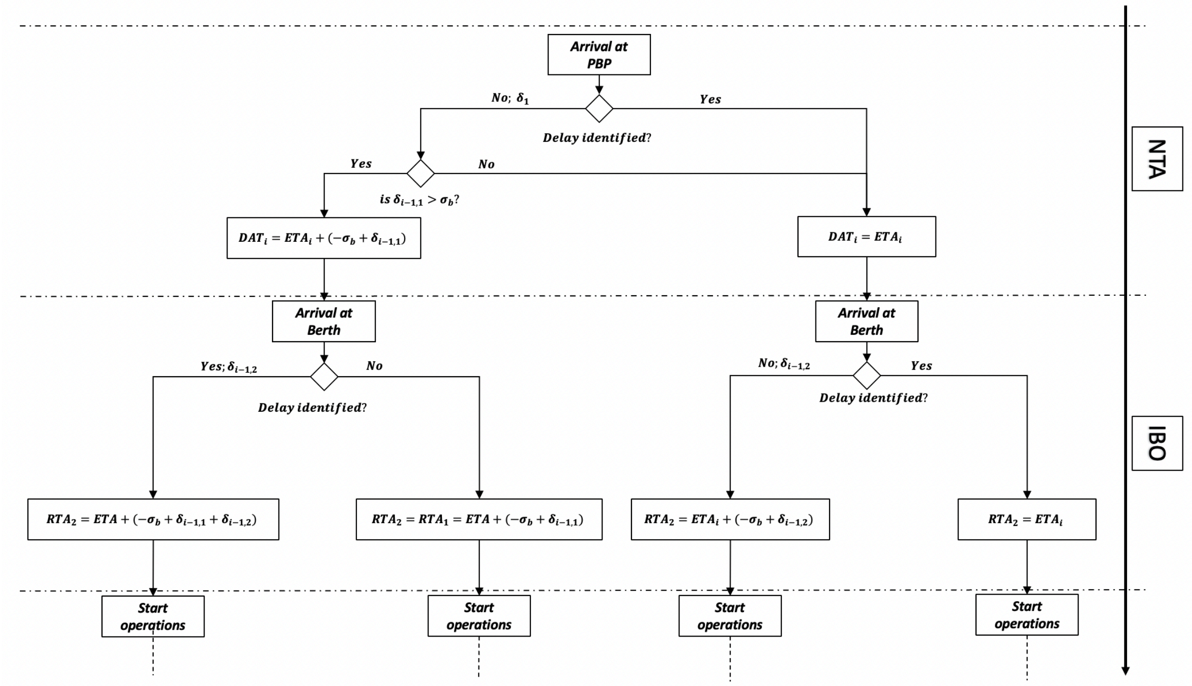


Figure 5.2: Methodology to calculate the DAT through the port call process.

The rest of the port call process continuous with this approach by constantly measuring the scheduled performance against the actual performance in terms of time. As a result, at each of the five measurement points, the total delay is equal to the sum of the delays summed with the delays before that point.

$$r_i = -\sigma_b + \sum_{x=1}^{5} \delta_{i-1,j} \tag{5.16}$$

5.2.2. Port and ship cooperation

The varying DAT from Section 5.2.1 is now implemented in the shipping's network current design. This section elaborates on the required design adjustments to correctly implement the DAT. Figure 5.3 depicts the BPM that realises this.

The design shows a single vessel at sea and a single vessel in the port area. As discussed in Section **??**, the DAT in the port area is calculated after each sub-process. If this value exceeds the buffer time between the consecutive vessels, a revised DAT is communicated to the vessel at sea. This time measurement is assessed at each of the waypoints. The number of waypoints depends on the distance between the two ports. Waypoint j is defined as the waypoint that is in closest proximity to the port of destination. These waypoints' distance depends on the port's geographical situation (e.g., channel speed restrictions). The DAT communicated to the vessel requires an additional assessment from the Port Authority since the Nautical Services need to consent with this planning. It is assumed that port congestion is avoided by incorporating the Nautical Services in an earlier stage of the short-term arrival planning.

The DAT, determined by the vessel alongside, requires a high level of situational awareness. For example, in the current state, the bunker supplier does not update the Estimated Time of Completion Bunkers (ETC Bunkers). By frequently updating the estimated times of completion, the predictability of the DAT becomes more accurate.

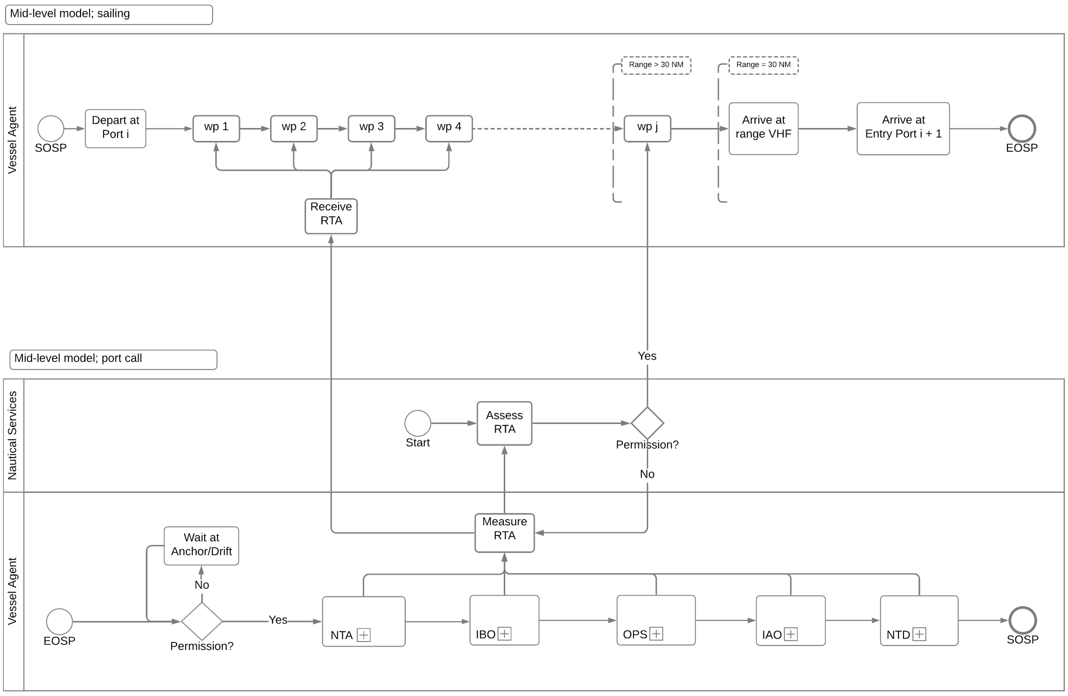


Figure 5.3: Cooperation between the port and the vessel utilising an DTA

5.3. Validation of the Dynamic Arrival Time design

Appendix C illustrates a case study that is performed to prove the mathematics from the DAT design. The case study illustrates the effect of port uncertainties on fuel consumption and CO_2 emissions. To recall an earlier statement (see Section 1.3): in a container network, the vessel speeds up after a delay to the succeeding port to recover the schedule. Three sub-cases are now assessed: no delay ($k = 1$), a delay without a DAT ($k = 2$), and a delay with a DAT ($k = 3$). The input parameters remain the same for all scenarios (see case study input parameters from Table C.1).

For scenario $k = 2$, a delay of 8 hours in the port led to a waiting time on arrival of 6 hours. Furthermore, fuel consumption increases by 14% compared to a scenario without a delay ($k = 1$). The GHG emissions are proportionally related to fuel consumption, and consequentially, these emissions increase with the same percentage. If the DAT is incorporated into the port call process ($k = 3$), different sub-scenarios are measured where the time of notification is taken as an additional variable. If the delay is communicated before departure from the port of origin, the vessel reduces the fuel consumption by approximately 20%. However, to recover the schedule, an increase of 28% in fuel consumption is obtained on the succeeding sea leg. Together these percentages lead to a fuel increase of 4% compared to the scenario $k = 1$. If the delay is communicated in a latter phase at sea, the fuel reduction effect of the DAT decays. A delay notification at the last waypoint results in a reduction on the arrival leg of only 10.3%. If both the arrival and departure leg is considered, this will increase by 9%.

This case study aims to measure the effect of port uncertainties on fuel consumption and the effect of information sharing. It is found that disruptions in the port lead to a significant increase in fuel consumption and corresponding emissions. The Dynamic Arrival Time design is introduced to mitigate these consequences. The sooner a delay is identified in the port and communicated to the vessel, the higher the energy efficiency. In other words, the incorporation of a DAT reduces the transportation waste of a vessel at sea. The case where there is no delay is always the most preferred in terms of fuel consumption and emissions.

5.4. Design hypothesis

The aforementioned sections lead to a hypothesis that is further elaborated in this section. Ultimately this hypothesis is tested through a simulation model. Before testing the hypothesis, explanatory information and expected results are discussed. The hypothesis under consideration is as follows:

- The implementation of a Dynamic Arrival Time design reduces waiting times, fuel costs, and emissions.

The mathematical relationship and the case study in Appendix C already proven to reduce GHG emissions for a single voyage with a delay when a DAT is implemented. The simulation model aims to find a reduction of GHG emissions for a container liner network over a period of time. The evaluation phase proposes a hybrid simulation model that tests these hypothesis for a specified container network. Before testing the hypothesis, the most important findings and conclusions from the design phase are listed in the next section.

5.5. Conclusion on the design phase

The measurement and analysis phase concluded that there is operational waste present both during the turnaround process as well at sea. This waste formation is linked to each other in a way that TAT deviations lead to waiting times on arrival, and these waiting times are in their turn cascaded to the rest of the network. Six root causes were found in the analysis phase (Chapter 4). One of these root causes is missing information. This means that the involved stakeholders are often not involved in the process, leading to unexpected scenarios and corresponding uncertainties. Additionally, there is always the presence of the weather that obstructs the execution of the process. These two phenomena lead to a constant threat of an increased port TAT. Measuring the port progress at several stages enables the port to detect variations at an early stage. This leads to improved situational awareness. Within this thesis, the Dynamic Arrival Time design is introduced. This concept relies on efficient and transparent data sharing to provide JIT arrival and service. Before testing the potential improvement effects, the previous section assessed the prerequisites for implementing the concept. This section concludes the findings of the fourth research question:

"How can Dynamic Arrival Times be implemented in the liner network?"

This question is answered by listing three elements. The first element to incorporate is standardisation on a global level. There are initiatives from the industry that take efforts to propose standardised lists for port call visits. Standardisation has two direct benefits in the communication field: allowance and improvement of digital collaboration. The second element is incorporating a method to calculate variations in the port call process and determine an adjusted arrival time for the succeeding vessels. This is referred to as the Dynamic Arrival Time (DAT). The third element is the inclusion of waypoints. These points along the route are measurement points that avoid the negative consequences of continuous speed adjustments (e.g. overabundance of information or engine limitations). At each of these waypoints, a new set of voyage parameters is determined: Time To Arrival (TTA), Distance To Arrival (DTA) and Optimum Speed to Arrival (S_D). Together these parameters determine the reduced (and dynamic) fuel consumption and emissions.

6 Evaluate

Section 5 proposes a hypothesis regarding the design that is introduced in this thesis. This chapter aims to test this hypothesis. This testing is done by utilising a hybrid Agent-Based Discrete-Event Simulation model (ABDES). The simulation model's goal is to test the effects of uncertainties in the network regarding waiting times on arrival, and the extent to which a Dynamic Arrival Time (DAT) can mitigate the waiting times by reducing the speed of the vessel on the arrival leg, with reduced fuel consumption and emissions as a result. This is translated to the fifth and last sub-question of this thesis:

> **"How much emissions are avoided by implementing a DAT in a network that is subject to port uncertainties?"**

This section starts with a description of the simulation model in Section 6.1. Section 6.2 gives an overview of the results. The model and the results are verified and validated in Section 6.3. Lastly, in Section 6.4 the results are discussed.

6.1. Simulation model

The network that is described in Section 2.1 is programmed in Anylogic. This open-source simulation software operates on Java language and can simulate all three (system dynamics, agent-based, and discrete-event) simulation methods [10]. To simulate a container liner network with a predefined schedule, it is chosen to deploy an Agent-Based Discrete-Event Simulation (ABDES) model. Figure 6.2 presents the workflow of the evaluation phase. The figure represents the methodology to compose a container network, incorporate uncertainties, and measure the performance indicators. The following sections provide a more elaborate description of this methodology.

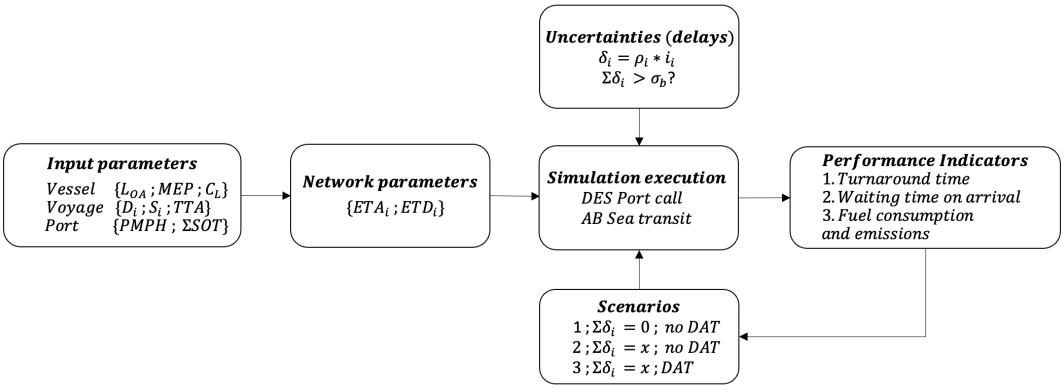


Figure 6.1: Simulation model input parameters, uncertainties, and measurement objectives

	Parameter	Abbreviation	Value	SI Unit
Vessel	Length overall	LOA	366	m
	Beam	B	48	m
	Deadweight	DWT	145,000	t
	Main Engine Power	MEP	89,700	kWh
	Auxiliary Engine Power Factor	$pAEP$	0.22	-
	Specific Oil Fuel Consumption; sailing	$SFOC_s$	160.2	mt/MWh
	Speed range	S_i	9.1-19	knots
	Container capacity	C	13,500	TEU
	Design voyage speed	S	25	knots
Route	Total Distance	D_i	540	Nm
	Number of waypoints on route	w	5	-
	Distance between waypoints	$d_{i,wp}$	108	Nm
	Number of ports in the network	k	4	-
	Schedule network speed	S_i	18	knots
	Buffer	σ_b	4	hours
Port Call	Nautical Time on Arrival (SOT)	NTA_{SOT}	3	hours
	Idle Time before Operations (SOT)	IBO_{SOT}	1	hours
	Idle Time after Operations (SOT)	IAO_{SOT}	1	hours
	Nautical Time on Departure (SOT)	IBO_{SOT}	3	hours
	Port Moves	L_{TEU}	2,200	TEU
	Port Moves Per Hour	$PMPH$	100	TEU/hour

Table 6.1: Simulation input parameters. Partially obtained from Moon and Wang [104, p. 451], and [51]

6.1.1. Input parameters

The simulation model's deterministic input parameters are divided into three categories: vessel-, route-, and port call information. The complete list of deterministic input parameters is found Table 6.1. These parameters present a Short Sea Shipping (SSS) network for mainliner vessels with an average of 2,200 TEU port calls. The distance between the ports are set to be equal to 540 nautical miles, and by incorporating five waypoints, the distance between these waypoints is now 108 nautical miles.

6.1.2. Network parameters

Based on the input parameters from Table 6.1, a network schedule is generated. The network schedule comprises four ports connected through four sea passages (k). The container vessels sail on a fixed rotation schedule where the time in the port and at sea is calculated by making use of the following equations:

	Port A	Port B			Port C			Port D			Port A
$Index$	ETD_A	ETA_B	ETD_B	RTA_B	ETA_C	ETD_C	RTA_C	ETA_D	ETD_D	RTA_D	ETA_A
0	σ_b	34	64	68	94	124	128	154	184	188	214
1	38	68	98	102	128	158	162	188	218	222	248
2	72	102	132	136	162	192	196	222	252	256	282
3	106	136	166	170	196	226	230	256	286	290	316
4	140	170	200	204	230	260	264	290	320	324	350
n	$ETA_B + \sigma_B$	$ETD_A + eq.6.3$	$ETA_B + eq.6.2$	$ETD_B + \sigma_b$	...	...	...	....	...	...	...

Table 6.2: Output network schedule

$$T_{port,schedule} = \Sigma SOT + \frac{L_{TEU}}{PMPH_{port}} + \sigma_b \tag{6.1}$$

$$= NTA_{SOT} + IBO_{SOT} + \frac{L_{TEU}}{PMPH_{port}} + IAO_{SOT} + NTD_{SOT} + \sigma_b \tag{6.2}$$

$$T_{sea,schedule} = \frac{D_i}{S_i} \tag{6.3}$$

$$T_{total,round} = \left[T_{sea} + T_{port}\right] * k \tag{6.4}$$

Based on Formula 6.2 till 6.4 and the input parameters from Table 6.1 a network table is generated. The first five vessels in the network schedule are displayed in Table 6.2. The $n - th$ row depicts the usage of the formulas in the network schedule. The values in the table represent the hours from the start of the simulation. The simulation starts at 01/01/2020 00:00, and the end of the simulation is at 31/12/2020 23:59.

6.1.3. Simulation execution

The amalgamation of the Agent-Based and the Discrete-Event Simulation allows the model to communicate information from the port environment to the vessels (agents). The network is programmed so that the vessel is always in a certain state: either at sea between certain waypoints or in one of the ports. The following sections provide a more detailed description of the simulation.

Network execution

The ABDES model executes the network that is composed of the input parameters (see Table 6.1). The input parameters lead to an initial Inter Arrival Time (IAT) of 34 hours. The container vessel starts at Port A and sails to Port B according to the predefined schedule. After the completion of the sea leg (540 nautical miles), the vessel continues with the port call process (L_{TEU} equals 2,200 TEU). After completion of the Port call process in Port B, the vessel sails to Port C, and so on. Throughout the execution of the model, an event log and database generates and stores information on the different parameters of the vessel, such as the speed (S_i), expected arrival times (ETA_i), and time to arrival (TTA_i).

Port call process

The port call process is programmed as a Discrete-Event Simulation (DES) model. This model's input is derived from the measure phase in the current state analysis in Section 3.2.5. For the port area, the capacity is set to be equal to one. If the port area is occupied by the preceding vessel (agent), the capacity restriction obstructs the vessel from entering the port. In this case, the vessel remains in the anchor area (queue). By entering the port area, the vessel moves from delay to delay block. The delay blocks represent the five sub-processes obtained from the measure phase (see also Equation 6.2). The reader must note that these delay blocks do not represent actual delays, but the Standard Operating Time (SOT) for a sub-process. At each sub-process, there is a probability that the vessel

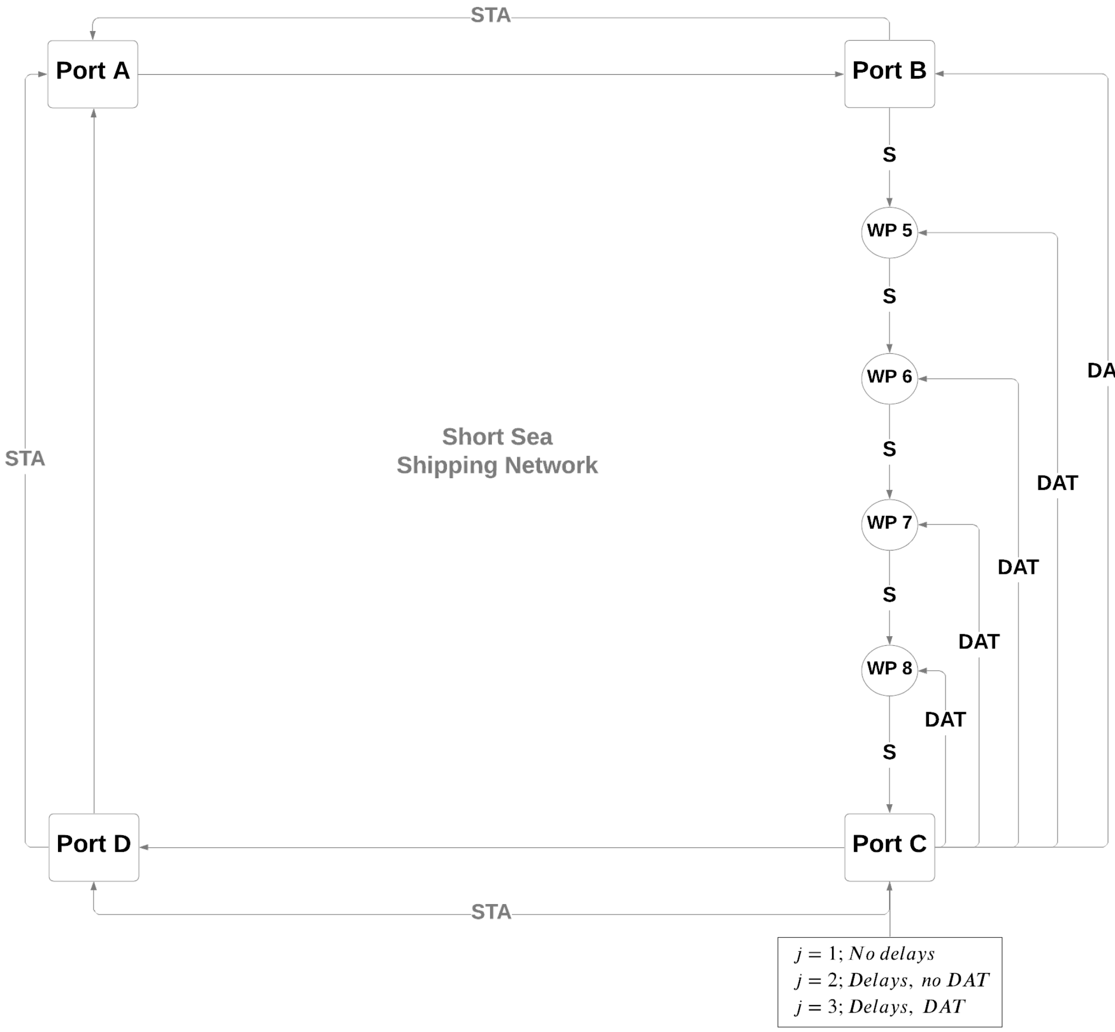


Figure 6.2: Simulation description using waypoints and a DAT.

encounters an additional delay. This is represented by $\delta_{i-1,1}$ till $\delta_{i-1,5}$, and together these delays count up to the total delay $\delta_{i-1,x}$. The simulation model measures at each stage if the delay till that point is greater than the buffer (σ_b). If this is the case, the arrival time of the succeeding vessel is adjusted to the DAT_i.

Sea leg process: delay communication and speed optimization

It is chosen to implement waypoints at which the vessel at sea measures the DAT, rather than continuous updates of arrival times. According to Poulsen, shipping agents and captains are not willing to continuously change the speed of the vessel [77]. The incorporation of the waypoints reduces the effort of speed optimisation to a limited number. The vessel at sea retrieves the Dynamic Arrival Time (DAT) and calculates the JIT speed accordingly. In other words, under the network design speed, the vessel would arrive too early and is encountered with waiting times on arrival. The practice of delay communication allows vessels to slow down to avoid this scenario.

6.1.4. Scenarios

The third block from Figure 6.2 is now further elaborated. This block represents the scenarios that the simulation model executes under different uncertainties (regular and irregular). Section 6.1.3 already mentioned the method to identify and communicate delays to optimise the vessel speed. To measure the effect of this design, three scenarios are tested in a period of a year. The first scenario ($j = 1$) tests

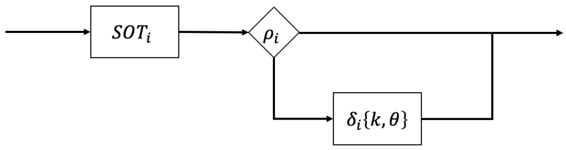


Figure 6.3: Modelling uncertainties at sub-process i using a probability ρ and impact δ

the output variables under a scenario where no uncertainties are present, and the vessel maintains the schedule. The second scenario ($j = 2$) tests a network subject to different uncertainty levels but does not incorporate a DAT notice. The third scenario ($j = 3$) tests the network with the same uncertainty levels as scenario two, but now with a DAT notice.

6.1.5. Uncertainties

As described in section 6.1.3, there are five sub-processes identified. The measure phase indicates that the uncertainties are predominantly present during the IBO and IAO sub-processes. Therefore, it is chosen to apply the uncertainties during these sub-processes. The uncertainties are a function of the probability (likelihood) and the impact.

6.1.6. Port Performance Indicators

Figure 6.2 shows that three output parameters are measured: turnaround time, fuel consumption, and emissions. These are the same PPIs as were found in the measure and analyse phase.

6.1.7. Expected results

The Dynamic Arrival Time (DAT) is used in the simulation model as a method to adjust the speed of the succeeding vessel at sea after a delay is notified in the port of arrival. The cubic relationship between the vessel speed and the fuel consumption of a steaming vessel shows that the practice of slowing down and speeding up do not outweigh each other. Therefore, it is expected that incorporating operational delays leads to an increase in fuel consumption and emissions on the overall. This leads to the expectation that $FC_1 > FC_2, FC_1 > FC_3$, and $FC_2 > FC_3$, or from the greatest to smallest: FC_2 > FC_3 > FC_1 for a complete network. Since the emissions of carbon dioxide and sulphur oxide are proportionally related the fuel consumption, these calculations will follow the same order. However, if the focus is put on arrival leg, the results are different. If the delay in the port is greater, more hours on the arrival leg can be used for the arrival leg. In equation 5.13, a higher t_D, but with a lower S_D, results in a lower $DFC_{s,s}$ due to the third power relationship. Therefore, a higher fuel consumption and emissions is expected at higher port uncertainties. Furthermore, Section 5.1.2 expressed that the earlier a delay is known, the greater the effect of the speed reduction is. A delay is measured in the port after two sub-processes (IBO and IAO). Firstly, the delay must be identified in the port call process, and secondly, the vessel must surpass a waypoint to retrieve the data and adjust the speed accordingly. Section 6.1.4 elaborate on the method to incorporate delays in the port call process. If the delay ($\Sigma\delta_{i-1,x}$) is greater than the buffer (σ_b) at an early stage of the port call process, the vessel surpasses enough waypoints to adjust the speed, and thus leading to a greater reduction effect. This leads the expectation that the simulation results show greater results for irregular events (low probability, high impact). This is because the chance of exceeding the buffer is higher under these conditions.

6.1.8. Model decisions and assumptions

It is chosen to model a SSS network with relatively small uncertainties. This is due to two observations from the literature study. The first observation is that if a delay is communicated in the long term, it is unknown how the situation will develop over the remaining time till arrival. For example, when a long voyage is planned, and a delay is known a couple of days before the port call, there are too many factors for the remaining time to influence the arrival time. Vessel captains often see this insecurity as a reason not to cooperate with dynamic arrival practices [77]. Secondly, it is noted that the simulation of large disruptions in a network involves port skipping and swapping where advanced programming methodologies are required [55]. These disruptive operations, and corresponding decisions, are left out of scope in the model. It is expected that the simulation of this SSS network with relatively small disruptions lead to more accurate results.

6.2. Simulation results

This study's first objective is to measure the effect of operational uncertainties during the port call process on the fuel consumption and emissions of a large container vessel in a shipping network. This is done by testing three scenarios ($j = 1, 2, 3$). The first scenario tests the fuel consumption based on a fixed speed and no uncertainties. The second scenario maintains a fixed speed but applies different levels of uncertainties to the network. The latter scenario applies the same uncertainties as to the second scenario but tests the design implementation as it is described in Section 5. The scenarios are tested for three PPIs: Turnaround Time (TAT), Waiting Time on Arrival (WTA), and Fuel Consumption (FC). The FC is further discussed regarding the GHG emissions. The output parameters are provided with an index number to compare the results. As discussed in Section 6.1.5, the uncertainties applied to the network are a function of a probability (likelihood) and an impact. The magnitude of the uncertainties is depicted in Table 6.6. The results are depicted in Table 6.5 and Table 6.4.

Before analysing the results, an observation is discussed in this paragraph. The simulation results indicate that there is a maximum value for the handling of uncertainties (risk) in the network. In other words, the simulation is not capable of handling outliers (disruptions). These outliers translate themselves into values that are not in line with the expectations after sensitivity analysis (see Section 6.3.2). This is because the simulation cannot handle outliers within the methodology for the DAT calculation. If a delay is identified that is greater than two times the buffer between two consecutive vessels, the model cannot calculate a correct DAT for the second vessel that starts with the sea transit. An elaboration on this is provided in the reflection of the model in Section 7.3. The remaining uncertainties that are compatible for simulation are tested for the different measurement objectives defined in Section 6.1.6. The Turnaround Time (TAT), Waiting Time on Arrival (WTA) and the Fuel Consumption (FC) are now further discussed in this section.

Turnaround Time (TAT)
The combination of a delay quantity (impact) and a probability represent the port call's risk. This is translated into an increased port TAT. The higher the risk of uncertainties, the higher the increased port TAT on average. Scenario $j = 2$ and $j = 3$ are tested for the same risk conditions and thus have the same increase in port TAT. This additional time in the port is compared to scenario $j = 1$, where no uncertainties are present in the network. The increased TAT varies from 2.0-7.3%. The upcoming sections are dedicated to measuring to what extent this increase leads to waiting times and to what extent a DAT can mitigate this. Secondly, the results are reflected against the corresponding fuel consumption and emissions.

Waiting Time on Arrival (WTA)
As Section 2.1 described, there is a relationship between an increased port Turnaround Time (TAT) and increased Waiting Time on Arrival (WTA) in a container shipping network. The simulation results for $j = 2$ and $j = 3$ are compared to each other through an index number. Scenario $j = 3$ shows significant reductions of WTA with indices ranging from 15.4 to 90.7. To recall the definition, the concept of JIT focuses on the complete elimination of waiting time on arrival. Due to the accumulating delay over the port call process, often the buffer is exceeded during the last part of the voyage. At this stage, the vessel has surpassed the latter waypoint, and speed adjustments are not calculated. Consequentially, the network remains with WTA. This is seen for all scenarios under different levels of uncertainty. However, there is a difference noticed between the reduction at higher levels of risk. A high probability and low impact (regular uncertainties) case show a reduction of only 7.1% compared to the low probability and high impact (irregular uncertainties) case, where a reduction of 43.1% is achieved. This can be explained by assessing the role of the time that the delay is exceeded. Since the probability is high, but the impact is low for the first case, the chance that the buffer is exceeded at an early stage is low. The chance that the buffer is exceeded at the second point is greater. However, at that moment, the vessel at sea surpassed the latter waypoint and is not informed of the delay. The other case represents a lower probability but a higher impact. This makes the chance that the buffer is exceeded at the

beginning relatively higher. Since the vessel can now adjust the speed accordingly, the simulation is better capable of arriving JIT. Section 7.3 further reflects on this finding.

Fuel Consumption (FC)
The Fuel Consumption (FC) is calculated by multiplying the specific energy consumption with the time that the vessel sails at this condition. The high probability and low impact results show more speed adjustments but on a small level. This is because there are more port calls where the delay exceeds the buffer with a small amount of time. This is also represented with the speed distribution graph near the design speed of 18 knots (see Figure 6.6a). Given the small differentials in speed, the effect on fuel consumption is also relatively small. For the highest probability ($\rho = 0.8$), a maximum value of 160 metric ton fuel reduction is obtained (9.3% reduction compared to scenario $j = 2$).

On the other hand, if the probability is low but the impact increases, the vessel shows greater speed adjustments. This is depicted in Figure 6.6b with a speed distribution curve that is further shifted from the design speed. Since the simulation is programmed in a way that there are uncertainties before and after the operations, two peaks are formed. The right peak represents a situation with a delay identification and communication at an early sea transit stage. This early notice allows the vessel to adjust the speed over a greater distance and time. Given that there is more time (TTA) and distance (DTA) to adjust the speed, the speed adjustment deviation is small. The left peak depicts a scenario with a late identification and communication of the delay. Hence, there is less time (TTA) and distance (DTA), and the differential of the new speed is now greater. Another observation is that the left peak has a higher density than the right peak. This can be explained with the buffer of four hours that is incorporated in the schedule. The incorporated buffer ($\sigma_b = 4$) is in close range of the delay's impact before and after operations ($k = 3$). Although the probability is low, if both of these delays are formed, the time to cover at the last phase of the transit is suddenly considerable. In other words, a high impact delay at a late stage causes a sudden speed reduction during the last section of the sea transit. For the highest impact ($\delta = 3.0$), a maximum value of 2384 metric ton fuel is obtained (30.6% reduction compared to scenario $j = 2$).

Two assumptions that impact the fuel consumption are discussed in this paragraph. The first assumption is regarding the auxiliary engines. It is assumed that the auxiliary engines require the same amount of energy for sailing and waiting. However, from the technical background study, the auxiliary engines' energy consumption is a function of the energy consumption of the main engine. Therefore, at a lower arrival speed (scenario $j = 3$), the required auxiliary engine power is less than the standard scenario (scenario $j = 2$) at sea. Still, for the waiting time, the energy consumption remains the same for both scenarios. Altogether this leads to lower energy consumption for the third scenario. Secondly, it must be noted that at a lower arrival speed, the SFOC value increases [51]. This results in higher fuel consumption for the third scenario. The effect of both of these assumptions are used to be relatively small and outweigh each other.

6.3. Model verification and validation

According to Sargent, simulation models are increasingly used to solve real world problems and to aid in decision-making. Since decision-makers, and the individuals who are affected by these decisions, rely on these results of the simulation, it is important to measure whether the model and its results are "correct". In the upcoming section the model verification and validation is discussed. Model verification is defined as "...ensuring that the computer program of the computerized model and its implementation are correct". Model validation is defined as "...the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [85]. The purpose (or intended application) of this simulation model is to reduce the speed of the vessel after a delay identification.

There are multiple verification and validation techniques and tests available, where a combination of these techniques and tests are mainly used [85]. The combination of techniques and tests that are used for this thesis is the animation verification, internal verification, parameter variability (or sensitiv-

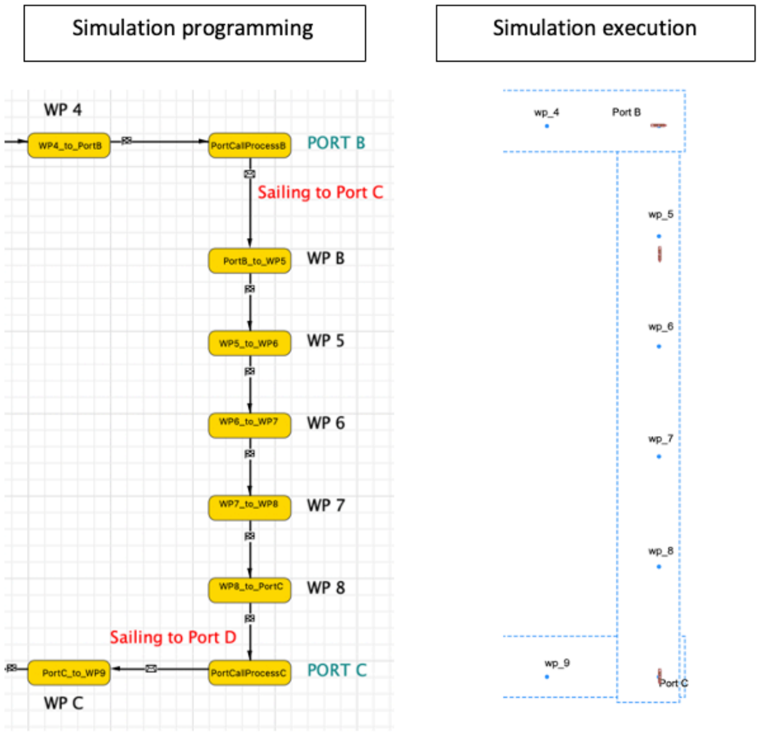


Figure 6.4: Simulation model validation through animation.

ity analysis), event validation, and lastly, the validation by comparing the results against other model results.

6.3.1. Model verification

Animation verification

The first verification technique is a visual technique which is frequently used by the user during the realisation of the conceptual model. The Anylogic software has a built-in visual tool to verify if the vessel sails according to the expectations. Figure 6.4 shows the comparison of the simulation programming, and the execution of the model. This is a simple, yet effective method, to verify if the vessel sails in the ”correct” direction with the ”correct” speed. Furthermore, based on the literature, the speed is bounded and programmed by a lower limit of 12 knots. Considering Figure 6.6a, and Figure 6.6b, the speed parameters are also ”correct”.

Internal verification

Internal validation is performed by executing multiple replications (runs) of the model to determine the (internal) stochastic variability of the model [85]. This simulation is programmed as a deterministic model. This means that the model has no internal randomness, and the same input parameters (uncertainties) are used for different replications of the simulation [10]. For the internal verification of the simulation, the results of replication runs must ensure the same output parameters. The execution of the simulation model, together with the data analysis in Python is a time consuming process, and therefore it is chosen to select two model conditions and replicate the simulation multiple times. The results show that for multiple runs, the same values are obtained. This leads to a successive internal verification.

Parameter variability (sensitivity analysis)

The sensitivity analysis technique consists of changing the input variables and internal variables of the model to determine the effect of the model’s behaviour and output [85]. This sensitivity analysis is already done by testing different uncertainty parameters in Section 6.2. During the execution and analysis phase of these results, the results show that after increasing the impact with more than 3 hours at a probability of 0.2, the dynamic arrival speed (S_D) shows values that are greater than the design speed (S_d). Given the defined purpose of the simulation model (reducing speed), it is no longer ensured that the simulation model works correctly under this condition. This is further discussed in Section 7.3.

The remaining valid parameters (see Table 6.4 and Table 6.5) show a relationship between increased TAT and reduced fuel consumption that is in line with the expectations from Section 6.1.7. This contributes to the verification of the model.

6.3.2. Model validation

A simulation model is developed with a specific purpose, and the validity is determined with respect to that purpose [85]. The purpose of this simulation model is to test what the effect is of incorporating Dynamic Arrival Times on the fuel consumption and emissions in a SSS network. The model uses numerous parameters and variables, including assumptions based on the literature and the data analysis in Section 3.2 (e.g., average number of container moves per call, and average time sailing from port entry to quay). To test whether these assumption lead to a valid output, the upcoming section uses two techniques to test this.

Event validation

The event validation technique is deployed to determine if the "events" of the simulation model are similar to a real world system [85]. The measure phase in Section 3.2.5 assessed event log data from the Maersk Line vessels in the Port of Rotterdam (POR). The idle time data from this section is used as input for the simulation model. To validate the results from the actual data with the simulation data, a comparison is made between the case study data from the measure phase and the simulation data. Table 6.3 depicts this comparison. The results show that the case study data results lie somewhere in between the simulation results. The case study data involves a combination of irregular and regular uncertainties. The simulation model segregates these uncertainties into the two defined uncertainties. This leads to a difference between the case study and the simulation results. This difference is further discussed in Section 7.3.

	Case study data		Simulation data			
			regular uncertainties		irregular uncertainties	
	Mean	St.dev	Mean	St.dev	Mean	St.dev
Idle Time before Operations	1.71	2.11	1.42	1.13	3.34	1.71
Idle Time after Operations	2.03	3.10	1.57	1.23	4.16	2.13

Table 6.3: Simulation model validation through event validation.

Comparison to other models

Lastly, a method to validate simulation results is done by comparing output results with other (valid) models. These can be either analytical, empirical or simulation models [85]. Although the literature on Virtual Arrival is limited, two comparisons are made.

The first comparison is made regarding a research by Jia et.al. This research proposes an empirical approach to measure the potential fuel savings for Very Large Crude Carriers (VLCC) under a Virtual Arrival policy. This is done by using sea voyage and port data from the Automatic Identification System (AIS), and evaluate what the impact on the fuel reduction could be if the excess port time is used as additional sea time. The results indicate that if 50% of the excess waiting time is avoided, an average of 422 tonnes of CO_2 and 6.7 tonnes of SO_x per voyage is saved. Although the approach is different, the outcomes of the results show a same order of magnitude.

The second comparison is made towards a desktop trial by the of the Global Maritime Energy Efficiency Partnership (GloMEEP), which is part of the International Maritime Organization (IMO). This

I = 1.5		Probability ρ											
		0.4			0.5			0.6			0.7		
		TAT	WTA	FC	TAT	WTA	FC	TAT	WTA	FC	TAT	WTA	FC
		hr	hr	mt	hr	hr	mt	hr	hr	mt	hr	hr	mt
j = 1	Value	30.0	0.0	n/a.	30.0	0.0	n/a	30.0	0.0	n/a	30.0	0.0	n/a
	Index	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0	100.0
j = 2	Value	31.1	23.9	860	31.4	28.5	982	31.6	48.3	1351.0	32.2	52.2	1719.0
	Index	103.7	100.0	100.0	104.7	100.0	100.0	105.3	100.0	100.0	107.3	100.0	100.0
j = 3	Value	31.1	15.2	789.5	31.4	19.4	908.5	31.6	33.8	1223.9	32.2	48.5	1559.4
	Index	103.7	63.4	91.8	104.7	67.9	92.5	105.3	70.0.	90.6	107.3	92.9	90.7
	Δ FC	n/a	n/a	70.0	n/a	n/a	74.0	n/a	n/a	127.0	n/a	n/a	160.0
	Δ CO_2	n/a	n/a	222.0	n/a	n/a	234.0	n/a	n/a	402.0	n/a	n/a	507.2
	Δ SO_x	n/a	n/a	4.0	n/a	n/a	4.0	n/a	n/a	7.0	n/a	n/a	7.9
	Δ CH_4	n/a	n/a	4.2E-3	n/a	n/a	4.4E-3	n/a	n/a	7.62E-3	n/a	n/a	9.6E-3
	Δ N_2O	n/a	n/a	0.01	n/a	n/a	0.01	n/a	n/a	0.02	n/a	n/a	0.03
	Δ PM	n/a	n/a	0.49	n/a	n/a	0.52	n/a	n/a	0.88	n/a	n/a	1.12

Table 6.4: Simulation results for different levels of probability at a constant impact level $\delta = 1.5$

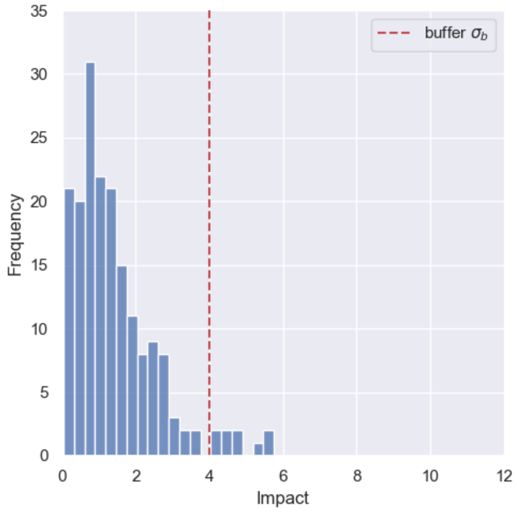
desktop trial compares two scenarios for a vessel that sails from Bremerhaven to Rotterdam. In the trial, a delay of three hours is noticed in the Port of Rotterdam. The first scenario represents a delay notification at the Calling In Point (CIP), and the second scenario incorporates waypoints, where after the seventh waypoint (after seven hours sailing), the vessel is informed on the delay. The CIP is a point which is close to the port, and assumed to be at 30 nautical miles from the port entrance. The results show that a fuel reduction of 23.9% can be achieved if Virtual Arrival with waypoints is incorporated. Although there is no information available on the vessel characteristics, the order of magnitude shows that a validation can be made between the models.

P = 0.2		Impact											
		1.5			2.0			2.5			3.0		
		TAT	WTA	FC	TAT	WTA	FC	TAT	WTA	FC	TAT	WTA	FC
		hr	hr	mt	hr	hr	mt	hr	hr	mt	hr	hr	mt
j = 1	Value	30.0	0.0	n/a	30.0	0.0	n/a	30.0	0.0	n/a	30.0	0.0	n/a
	Index	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0	100.0
j = 2	Value	30.6	2.7	246.0	31.1	54.2	2026.0	31.4	77.1	2241	31.6	81.7	7798.0
	Index	102.0	100.0	100.0	103.7	100.0	100.0	104.7	100.0	100.0	105.3	100.0	100.0
j = 3	Value	30.6	0.4	228.0	31.1	38.8	1440.9	31.4	32.4	1967.6	31.6	46.5	5414.3
	Index	102.0	15.4	92.7	103.7	71.5	71.12	104.7	42.1	87.8	105.3	56.9	69.4
	Δ FC	n/a	n/a	18.0	n/a	n/a	58.5	n/a	n/a	273.0	n/a	n/a	2384.0
	Δ CO_2	n/a	n/a	57.06	n/a	n/a	185.5	n/a	n/a	867.0	n/a	n/a	7556.0
	Δ SO_x	n/a	n/a	1.0	n/a	n/a	2.9	n/a	n/a	14.0	n/a	n/a	119.0
	Δ CH_4	n/a	n/a	1.1E-3	n/a	n/a	3.5E-3	n/a	n/a	0.02	n/a	n/a	0.14
	Δ N_2O	n/a	n/a	2.9E-3	n/a	n/a	9.36E-3	n/a	n/a	0.04	n/a	n/a	0.38
	Δ PM	n/a	n/a	0.13	n/a	n/a	0.41	n/a	n/a	1.91	n/a	n/a	16.7

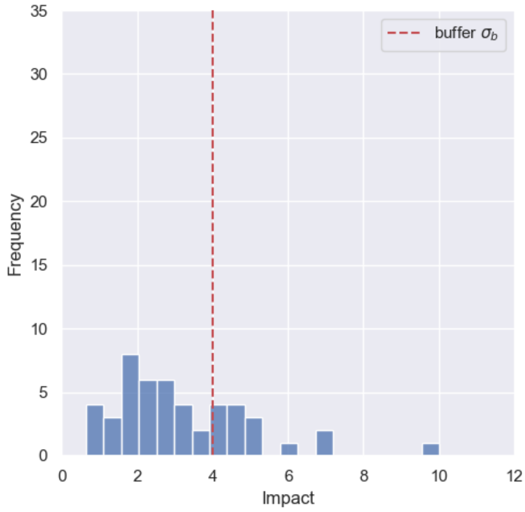
Table 6.5: Simulation results for different levels of impact at a constant probability level $\rho = 0.2$.

		Count	Mean	St.dev	Min	25%	50%	75%	Max
low impact, high probability	Idle Time before Operations	182	1.42	1.13	0.03	0.64	1.11	1.93	5.76
	Idle Time after Operations	177	1.57	1.23	0.03	0.69	1.18	2.28	7.26
high impact, low probability	Idle Time before Operations	45	3.34	1.71	0.87	2.28	3.07	4.23	9.94
	Idle Time after Operations	60	4.16	2.13	0.93	2.24	4.16	5.53	10.3

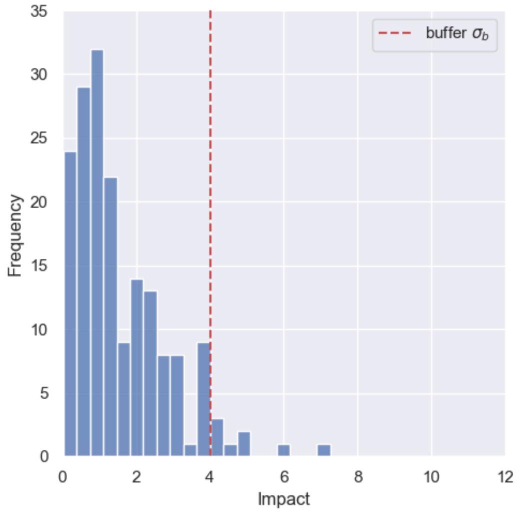
Table 6.6: Statistical analysis for the applied uncertainties



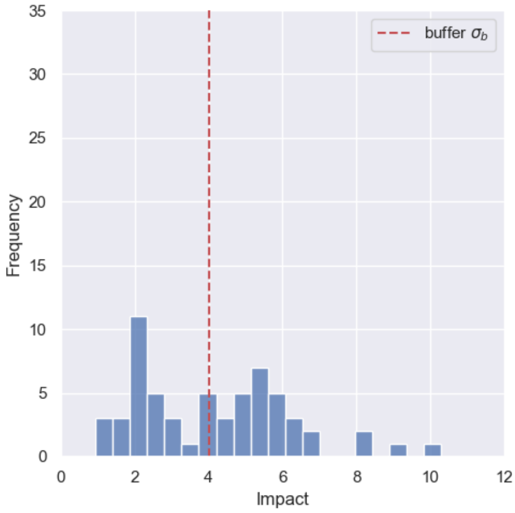
(a) high probability, low impact



(b) low probability, high impact

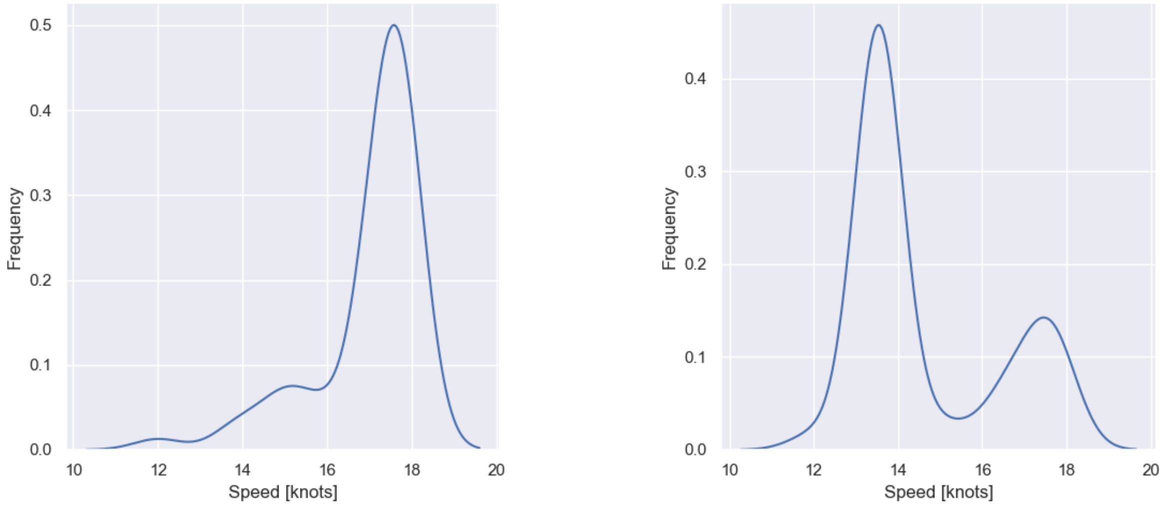


(c) high probability, low impact



(d) low probability, high impact

Figure 6.5: Uncertainties before and after operations



(a) high probability, low impact

(b) low probability, high impact

Figure 6.6: Speed envelop for scenario $j = 3$

6.4. Conclusion on the evaluation phase

The evaluation phase is the last phase of the five phases from the DMADE cycle. Within this phase, the research aims to test the hypothesis from the design phase. The design phase proposed a solution to enhance the voyage efficiency of an arriving vessel after a delay is notified in the port. This phase proposes a simulation to measure this solution in terms of emissions. This lead to the fifth and last sub-question of this research:

> **"How much emissions can be avoided by implementing a Dynamic Arrival Time in a network that is subject to port uncertainties?"**

Before answering this question, a brief overview of the most important assumptions and decisions from the model are discussed. The first assumption is that the port delays are programmed in a way that there are only accumulating delays. The analysis on the port moves (see Figure 4.1) shows that in reality, there is a fluctuation in the PMPH and the number of container moves that result in a shorter port TAT. This would allow the vessel to run in on the delay caused in an earlier phase of the port call process. This is not programmed due to the model's limitation regarding the number of variables and conditions to consider. The second assumption is made regarding the JIT effect that is not considered. In the analysis phase (Section 4), it is found that the magnitude of the delay decays by improving the predictability of the arrival vessels. This assumption is made based on the CRT analysis where (unexpected) arrival deviations result in reduced PPIs. Although this is recognised, the study cannot quantify the effects of predictability on the reduction of operational waste. Hence, the model does not incorporate this calculation. The third and last assumption is made regarding the network. The network that is programmed represents a container network for mainline vessels. Due to these vessels' magnitude, the vessel has dedicated berth areas and has little flexibility in the schedule. This is unlike smaller vessels where rescheduling of quays is done on a more frequent basis. Also, port swapping or skipping is left out of scope due to the unpredictability of these decisions.

There are two conclusions made regarding the results from the simulation. The first observation is towards the Waiting Time on Arrival (WTA). Although the proposed design is incorporated, there is still a significant amount of WTA. This is due to the accumulating delay ($\sigma_{i-1,x}$) over the port call and the waypoints' programming. It is noted that often the delay is identified and communicated when the succeeding vessel has surpassed the latter waypoint. Consequentially, there is no further action to reduce the speed to arrive without a delay (or JIT Arrival). Additional waypoints can be introduced in the last phase of the sea transit to increase the DAT effectiveness. This will further reduce the waiting time on arrival and increase the JIT rate.

	$j = 2$	$j = 3$	
		regular uncertainties	*irregular uncertainties*
Fuel consumption [ton]	39291.7	39131.7	36907.7
Reduction [ton]	n/a	160.0	2384.0
Index	100.0	99.5	93.9

Table 6.7: Effect of Dynamic Arrival Time practices ($j = 3$) on the fuel consumption for all vessels

The second conclusion focuses on fuel consumption and emissions and provides an answer to the fifth sub-question. There are two levels of uncertainties opposed to the network: (i) high probability and low impact (regular), and (ii) low probability and high impact (irregular). For the first level of uncertainties, the buffer is less often, and if so, in a later phase exceeded. Consequentially, the speed differential is small, resulting in less effect on fuel consumption and emissions. The specified scenario shows a reduction of 9.3% compared to a scenario without the design. The second level of uncertainties shows a greater differential when the design is analysed. This level represents a situation where the port call process is subject to higher impact values but less frequently. If the buffer is exceeded at an early stage of the port call process, the vessel can adjust the speed at an earlier sea transit phase. Due to the higher impact of the delays, the design is more effective for irregular uncertainties. Under these uncertainties, a reduction of 30.6% is achieved compared to a scenario without the design. Since fuel consumption is proportionally related to emissions, the same reduction percentages are obtained for the defined GHG emissions. If these reductions are reflected against all the arrival vessels in the network, the results of the design in a Short Sea Shipping are as depicted in Table 6.7.

7 Discussion

This thesis is divided into twofold: a current state analysis of the port call process and a design proposal that reduces GHG emissions by incorporating a Dynamic Arrival Time (DAT). This chapter starts by discussing the synergy of the current state and the future state models in Section 7.1. This is followed by a separate discussion on both models in Section 7.2 and 7.3. Lastly, this chapter discusses the societal and scientific relevance of this thesis in Section 7.4 and 7.5.

7.1. Synergy of the models

Before discussing the two models separately, the synergy between the two models is discussed in this section. Port call optimisation projects are found to be a prerequisite and accelerator for JIT practices and corresponding savings [33]. This is because by improving the awareness of threats and effects, the delay estimation and notification reliability is further improved (see more on this in Section 8.2). A more extensive LSS model, with a collaborative participation degree and more awareness of threats and effects, leads to the improvement of delay notification. On the other hand, utilising an DAT leads to better performance of the port call since it reduces the threat of uncertainties and the cascading effects. Together, the two discussed models lead to an improvement regarding the problem definition: schedule unreliability.

7.2. Reflection on the Lean Six Sigma model

This thesis deployed an amalgamation of the Lean and Six Sigma methodology. These methodologies have proven to lead to significant improvements in manufacturing processes [80]. The adaptation of the techniques in the service industry is more scarce [61]. This section reflects on the adaptation of the Lean Six Sigma methodology to the port call process. This is done by reflecting on several observations from this study.

The first observation is that LSS methodology relies on situational awareness of variances (or so-called waste identification). The port call process is a multi-stakeholder process in a spatial environment. The port call process variations are measured and assessed using quantitative (timestamps) and qualitative information (waste assessment). The quantitative information is stored over multiple information systems, which are not always communicative (see Table 3.1.2). Next to this, the qualitative information on the reasons for variations relies on the effectiveness and willingness of communication between stakeholders in the port environment. The cause and effect diagram shows particular reasons for variations that are communicated via internal communication systems. The quality of the waste assessment is likely to deteriorate due to the number of stakeholders and numerous reasons. Altogether this leads to the first observation that the process's variances are hard to measure due to a lack of accurate information. This obstructs efficient analysis of the waste identification and assessment and diminishes the model's effectiveness in practice.

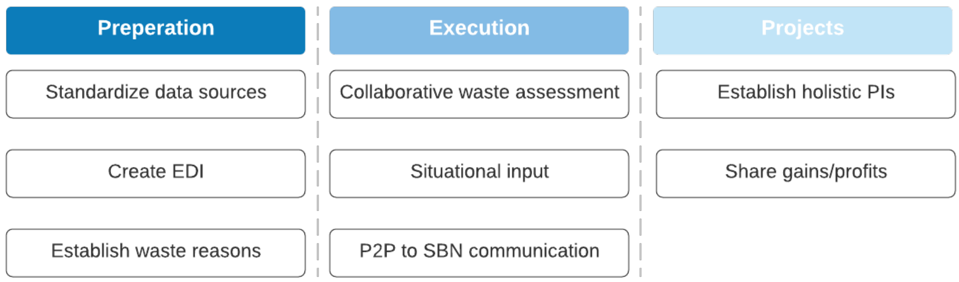


Figure 7.1: Future LSS model

The second observation that is done is regarding the quantitative part of the Lean Six Sigma methodology. It is found that the LSS methodology is only effective when two sorts of cases are considered: a homogeneous process or an accurately planned and well-defined process. The former means that the process has predefined time intervals (cycle times) where a level of granularity and repetitiveness is present. In other words, the same process is expected to have the same time interval that is continuously measured. An example of such a system is the assembly line of products. Such repetitive systems provide clear input for the quality control indicators such as the process capability (c_p) and Defect Per Million Opportunities (DPMO) values [80]. The port call process differs from such a system due to its heterogeneous behaviour. For example, when the sub-process of idle time before operations is considered, the time required for this sub-process largely depends on the number of containers lifted according to the stowage plan. The result is that two port calls with the same cycle time differ from each other when it comes to a waste analysis. For this specific case, it is required to add a variable (container moves) to measure the process capability effectively. Often these variables are stored and protected in internal information systems. More situations (e.g., idle time after operations and container moves) require an additional variable to measure quality control effectively. Next to the limitations of the process's heterogeneity (and missing variables), the Six Sigma measurements' second limitations are found regarding the on time measurements. On time measurement focuses on a planned versus an actual window. The current state port call process includes an ETA Berth and an ETD Berth defined before the port call. Organisational efforts to incorporate more (higher granularity), and enhance the scheduled time stamps (improve focus on scheduling), would allow the LSS model to measure the on time reliability effectively.

To conclude on the LSS, to effectively deploy this model and strive for port optimisation, the user must do several adoptions in practice. The basis of an ideal (future) LSS model relies on transparency, the collaboration between stakeholders, and accurate and granular planning. The LSS model requires input from raw data and quality human input for the waste identification. This is because the input to the model consists of numerous parameters, together with specific port conditions (e.g. the weather, congestion in the port, a smoke fume). An ideal situation where the combination of these two inputs (data and human input) is obtained would be highly effective as a basis for port optimisation. Additionally, a Server Based Network (SBN) would increase the transparency of the port call significantly. Especially in the long term, these adaptations will create interesting improvement opportunity areas on a holistic level. An overview of the future LSS model is provided in Figure 7.1.

7.3. Reflection on the simulation model

The simulation model proposed in this study represents a container network composed of several deterministic input parameters. The vessels present in the network are assumed to have a capacity of 13,500 TEU and a move call of 2,200 TEU during the port call. Container vessels of this magnitude are assumed to have dedicated berth areas with a low degree of rescheduling flexibility. However, there are scenarios where the delay is to such an extent that the network is changed more drastically. For example, port swapping or skipping can take place in the network [55]. Given the self-organising structure of such an event, these cases are left out of the model's scope. Another limitation of the model is that early completion or higher productivity of the terminal is not considered. If a terminal can handle a higher number of containers than expected or the downfall of moves occurs, the vessel can sail early, and the waiting time on arrival is mitigated. The simulation model does not take this effect into account.

The simulation model that introduces and tests the future state design is exposed to different combinations of risk. Either a high probability and low impact risk or a low probability and high impact risk. It is found that the design is more effective regarding emissions when the impact is greater and notified at an early stage. A greater impact is undesired since the vessel must increase the departure speed, with corresponding negative consequences on the fuel. However, early notification on delay is found to be favourable for the reduction potential. Given this observation, one could discuss that adding more waypoints results in higher design effectiveness.

A limitation of the simulation is found regarding the limitations of the uncertainties. Due to a single programmed variable of DAT, the model is not able to deal with greater uncertainties. By programming multiple DATs, different vessels can sail and react to disruptions in the port area. This would allow the simulation model to synchronise multiple networks, where also longer sea transits are analysed.

The latter reflection point is made regarding the secondary benefits of the design that are not integrated with the simulation. The programmed simulation model is a schedule recovery model that only reacts on variances in the port call to arrive JIT. However, it is not considered the effect of this JIT arrival on the port TAT of that same vessel. It is expected that more accurate arrival times affect the port TAT as well. This is substantiated by the Current Reality Tree (CRT) in Chapter 4 where arrival deviation and missing information are labelled as root causes for an increased port TAT. In other words, JIT Arrival leads to fewer port uncertainties and thus shorter turnaround times. This model's limitation is that the positive effect of this improved predictability and arrival accuracy is not taken into account. This is because the study cannot quantify or express the effects of improved predictability on a variation in the TAT.

Table 7.1 depicts four assumptions that have been made during the execution of the simulation. Table 7.2 assesses the models limitations, solutions and corresponding effects on the results.

Assumption	**Consequence**
A constant buffer of four hours is incorporated between consecutive vessels	The buffer between consecutive port calls is important to hedge against small uncertainties—however, a too-large buffer results in the terminal's idle time and less revenue-generating voyages. The buffer between the vessels in the port is difficult to determine, but based on the quantitative study, this value is determined at four hours. A higher buffer would result in less waiting time in the network and less benefits from the DAT design (vice versa for a smaller buffer).
Delays are accumulating	If a delay decays over the port call process, there is a possibility that the delay is lower than the buffer, which makes the DAT redundant. By also implementing possible improvements, lower effects on the fuel and emissions reduction are achieved.
The specific fuel oil consumption is taken as a constant for different speed levels	Incorporating this effect would lead to relatively higher fuel consumption at low engines load.
Effect of longer sea transit and shorter anchorage time on auxiliary engines not taken into account	A longer transit time at a lower energy consumption level of the main engine leads to the lower energy consumption of the auxiliary engines.

Table 7.1: Overview of the simulation assumptions and corresponding consequences.

Limitation	Solution	Effects	
		Positive	*Negative*
Delay programming	Increase frequency by adding waypoints along the sea transit and increase the number of measurement points in the port.	Higher GHG reduction potential	Increases fatigue in real world implementation
Single network	Program multiple sets of voyage parameters (e.g., multiple port calls, multiple DATs etc.)	Better representation of the real world	Complexity model increases
Outlier handling	Include port swapping/skipping decisions	Improves parameter variability	Complexity model increases
Assumption on the input variables	Gather event log data from actual networks and port calls	Improves model validation	Sensitive to data manipulation
JIT effect on TAT not taken into account	Express the effect of arrival predictability on the port TAT mathematically.	Higher GHG reduction potential	Complexity model increases

Table 7.2: Overview of the limitations of the model, the solutions and the corresponding effects

7.4. Societal relevance

Businesses and consumers worldwide rely on the maritime transport network due to the integration and connection of supply chains. It can be said that the increasing globalisation is, for the biggest part, facilitated and accelerated by the growth and developments from the container liners. This makes the improvement of the maritime container transport network reliability highly valuable to society on a large scale. On a smaller scale, the increased predictability of operations in and around the port area improves the daily operations and safety of involved and connected businesses. In addition to this, the consumers of cargo logistic services (both private consumers and organisations) become more aware of their actions' environmental footprint. The commercial sector's growing tendency to set sustainability as a high priority emphasises the importance of a shipping network's continuous improvement. The design state of this thesis, or so-called future state, incorporates a Dynamic Arrival Time (DAT). This design aims to reduce the emissions from the shipping industry through voyage optimisation. To conclude on the societal relevance, this thesis proposes a design that leads to better capacity planning of port resources while simultaneously reducing the operational expenditures of fuel and the environmental effects of harmful emissions.

The Lean Six Sigma port model's findings show that a high degree of collaborative incentives is required to maintain competitiveness. Not only the collaboration efforts throughout the process are important, but collaboration afterwards is equally important. The study proposes a Lean Six Sigma port model that assesses the port call process in a retrospective manner. The model's effectiveness heavily relies on variation (or waste) assessment required after the port call process. If a port call process is not critically reflected in the case of variations, the waste will recur without any improvement perspective. By implementing the LSS model in the port call process while overcoming the model's limitations, the scope for improvement projects on a holistic level of port call optimisation stands out. This is because intensive delay assessment under cooperation will provide insights into the holistic port process bottlenecks rather than individual organisation bottlenecks. For the port stakeholders, this might open the discussion for improvement projects rather than sticking with finger-pointing. Lastly, the introduction of mutually agreed delay reasons in combinations with extensive data analysis contributes to applying thorough data analysis techniques such as machine learning in the port environment to optimise the port call process.

Lastly, the Current Reality Tree shows that arrival deviations have two negative effects: waiting time on arrival (leading to the anchorage and drifting) and port congestion. These two phenomena lead to unsafe situations in a port area since the large vessels have difficulties with manoeuvring. If a Dynamic Arrival Time is used, the predictability of arriving vessels increases. This improves the vessel's coordination and reduces unsafe situations during nautical port operations. Additionally, if the number of vessels for anchorage decreases, there are several other benefits: more space for offshore wind farms, less hull fouling, and less piracy risk. All these secondary benefits lead to a higher level of port performance, and thus, competitiveness.

7.5. Scientific relevance

This thesis is carried out to fulfil the literature gap that is defined in Section 2.7. The literature gap from this section is summarised as follows:

- The Lean Six Sigma methodology was not yet been applied to the port call process.
- Port optimisation for the reduction of GHG is given little attention in the literature.
- The literature on the implementation of dynamic arrival modelling was insufficient.

This study assessed the current literature on optimisation techniques in different industries. It is found that the literature does not include a port call process model that effectively measures and analyses the process. A new type of waste is proposed that differs from the original eight types of waste (TIMWOODS) from the literature. This is the so-called transportation waste throughout the sea leg. Originally, this type of waste is defined as the unnecessary transportation of goods in a manufacturing process. This type of waste definition is irrelevant for the port call process since moving goods (containers) is the main objective. Consequentially, the problem's scope is expanded to a network perspective, and transportation waste is redefined. Within a network, transportation waste is the unnecessary high speed on arrival with waiting times on arrival. According to Poulsen, "we hurry up to wait" [77]. Since the identification and formation of waste is the start of an improvement project in the Lean Six Sigma methodology [80], this transportation waste is used as a starting point for the future model.

According to Rehmatulla and Smith, a lack of information on the potential costs and savings obstructs Virtual Arrival's implementation in both the literature as the industry [81]. This study proposed an elaborate description of the concept and more accurate estimations of the potential savings in fuel consumption and emissions by introducing the DAT. The currently available experiments and research do not use a simulation model but approach it from a retrospective point of view [46, 33]. These calculations use the measured waiting time as additional time that the vessel can use to extend the sea transit over the complete voyage. Within this study, a fuel-saving approximation is used to emphasise the role of the time of notification by utilising a simulation model. Redesigning the current state, and measuring this with a simulation model, was not yet been done in the scientific field.

8

Conclusions and recommendations

8.1. Conclusions

The container shipping industry experienced rapid growth over the last decades, and this trend is not likely to stop. These growth developments make the network less resilient against port uncertainties. These uncertainties are defined as regular and irregular events that cause variations in the port call process. The uncertainties lead to the schedule unreliability of a network. The shipping industry is known for a high degree of schedule reliability, and this is mentioned as one of the biggest challenges for commercial shipping lines. Additionally, the International Maritime Organization (IMO) compiled a list of GHG reduction goals that the shipping industry must comply with in the future. It is found that schedule unreliability leads to increased emissions. Given these observations, this thesis is dedicated to assessing the role and mitigation of uncertainties during the network, particularly to the port call, and reflects these effects against the emissions. This is translated to the main research question:

> **"What are the causes and effects of port uncertainties in a shipping network, and to what extent is a Dynamic Arrival Time able to mitigate the effects on the GHG emissions?"**

This research question is answered using the DMADE approach derived from the Lean Six Sigma (LSS) methodology. This DMADE approach is further segregated in a current state and a future state of the shipping network. The define, measure, and analyse phases propose several tools from the LSS methodology to present a comprehensive overview of the shipping network's current state and the operations during the port call. The second part proposes a design that focuses and contributes to the goals from the IMO to reduce the emissions from the container industry.

This current state model starts with a descriptive elaboration on the operations that are executed and the stakeholders involved during the port call process. This is followed by qualitative performance analysis of Maersk mainliner vessels in the Port of Rotterdam. The latter part of the model assesses qualitatively what types of operational waste occurs in this system. From the current state analysis, it is found that the port TAT is planned on a long-term (proforma) and a short-term (schedule) window. This window is bounded by an Estimated Time of Arrival Berth (ETA Berth) and an ETD Berth. Together these windows are scheduled in a network such that the demand for container transport is fulfilled while maintaining a fuel-efficient speed at sea. The first finding from the literature is regarding the deviations in arrival time or the schedule. These deviations are either peer-to-peer or via telephone communicated between the shipping line and the terminal. The first moment of notice from the vessel to the port operators is only at a range of 30 nautical miles from the port. This leads to unexpected arrival times, leading to unavailability of nautical services and potentially port congestion. Additionally, throughout the port call process execution, five sub-processes are identified that can be segregated from each other by using data elements from different sources in the port environment. The events executed throughout the port call process follow a sequential order and are performed by various stakeholders. During the execution of the sub-processes from the port call, there is little communication between the stakeholders on the expected completion times. This is unexpected since several identified events depend on the expected and actual completion times of preceding events. It is found in the literature that the expected time of completion of bunkers is not communicated to the vessel. Often, such inefficiencies lead to idle time on departure. This first part indicates that certain processes or procedures in a shipping network cause variations and need further assessment. Before assessing these variations qualitatively, a quantitative study is deployed to measure the variances' significance in these processes.

A set of 433 Maersk mainliner vessels are analyzed on three port call measurements: arrival reliability, TAT reliability, and idle time. By applying a specification limit of 2 hours, it is found that 44.8% of the arriving vessel is not on time with a ratio of 60 to 40% of early and late arrival. If the same specifications limits are applied to the TAT reliability, it is found that only 22.9% of the port calls are within the specification limits. This is equal to a value of 0.078 for the process capability index. The latter performance measurement of idle time segregates the complete process in several sub-processes to identify bottlenecks in the system. The data found from the time deltas before and after container lifting operations show many variations that indicate operational waste during these sub-processes. Additional data analyses do not show strong correlations between variables such as container moves and idle time. This indicates that the port call process contains many uncertainties that require a detailed qualitative root cause analysis.

The waste analysis shows that six root causes lead to variations in the port call performance. These root causes are missing information, adverse weather conditions, arrival deviation, early completion, lay-by, and appropriate processing (defects). To apply the Theory of Constraints by Goldrath to this model, the Current Reality Tree is composed. Within the CRT, missing information is the main bottleneck for operational inefficiencies. This root cause leads to variations in the port call TAT, and lead to jeopardised arrival times. This type of root cause is assumed to greatly impact the port call's performance with cascading effect through the rest of the network. Additionally, solving this root cause does not require major capital investment or time but rather a change in mindset and willingness. This is in line with the Theory of Constraints. As the literature indicates, the shipping industry is unwilling to share data between competitors, but this is the major improvement area. Other root causes, such as defects (e.g. twistlocks, lashing rods or cranes), require a high level of capital investments in the material. To conclude the current state analysis, the inadequate usage of information in a shipping network leads to waiting times on arrival and increased turnaround times. In the Lean waste terminology, the waiting times on arrival and increased TAT are Non Value Adding (NVA) to the network and need to be eliminated. Given this finding, together with a technical study on the container network design regarding fuel consumption and emissions, the conclusion is drawn that Virtual Arrival's role needs further assessment in this study.

Following the DMADE approach, two phases are left for the future state model: the design and evaluation phase. The first phase proposes a design expected to contribute to network optimisation (by reducing transportation waste on arrival). Secondly, this design is tested employing a hybrid AB-DES simulation model. The design is reflected against the emissions that shipping lines can reduce by successfully implementing it in the shipping network. Adjustments are made in the current state by incorporating several data measurement points during the port call process. These measurement points proactively measure if there is a delay during the operations that increase the TAT and leads to waiting time on arrival for the next scheduled vessel. If the delay is greater than the buffer that is maintained between consecutive vessels in the port, the arrival time of consecutive vessel is revised from an Estimated Time of Arrival (ETA) to an Dynamic Arrival Time (DAT). This DAT which is higher than the predefined schedule ETA, allows the vessel to adjust the speed to a level where the vessel strives to arrive JIT rather than too early. An important note is that the design does not result in longer sea transits but uses port call data measurement techniques to improve vessels' energy efficiency by arriving JIT in the case of a delay. The concept of a digital and transparent DAT has two direct benefits: reducing the port TAT and reducing emissions. The port TAT is reduced since the involved stakeholders benefit from an improved degree of predictability. For example, a DAT design allows the port to shift from a First Come First Serve principle to a better-synchronised port. This reduces unexpected arrival times and port congestion. Secondly, the emissions are reduced due to the defined relationship between the vessel speed and emissions. Also, secondary benefits of the future state design regarding the network are found. For example, the elimination of waiting times leads to safer operations in the port area due to vessels' continuation (less manoeuvring), less hull fouling, and more space for wind farm projects.

To test the proposed method of delay detection and communication, a simulation model is programmed that reflects a mainliner container network with four ports and four connecting sea legs. The network is executed over a year where uncertainties (variances) are programmed during the port operations. The simulation model tests three scenarios that are exposed to different levels of uncertainties. The simulation aims to provide insights on the effects of uncertainties on emissions and the extent to which the design could reduce emissions. Specific network results show that a dynamic arrival can reduce 30.9% of carbon dioxide emissions.

This research's scope is set in a way that mainliner vessels in the greater seaports are examined. Although this is a great part of the supply chain, many more elements and stakeholders benefit from a higher level of the arrival vessels' predictability. These mainliner vessels load and discharge a high number of containers in the Port of Rotterdam. These individual containers are all part of a greater supply chain with numerous stakeholders. In other words, container vessels are part of a multi-organisation and multi-transportation network. Improving the arrival times' predictability by using transparent communication in this part of the network creates interesting possibilities for many involved stakeholders. Transparency allows the supply chain stakeholders to anticipate changes in the schedule by proactively taking measurements. Often, this is referred to as supply chain visibility and is desired by the downstream stakeholders and customers. Therefore, it can be said that, by utilising a DAT, a more transparent end-to-end supply chain is obtained. This transparent supply chain results in shorter turnaround times and more efficient usage of energy resources. Shorter turnaround times and reduced emissions have numerous advantages on different levels. For example, on the financial level, the profitability increases, and on the value level, the customers experience increases. Additionally, the most important finding is that a more dynamic supply chain is a step towards the industry's challenge regarding the emissions and corresponding climate change.

8.1.1. Summary of sub-research questions

The answer to the main research question is listed in the section above. Each phase of the DMADE cycle is dedicated to answering a sub-question that contributes to answering the main research question. Table 8.1 gives an overview of the sub-questions that are used to answers this main research questions.

DMADE phase	Sub-question	Answer
Define	**SQ 1**: What is the relationship between port call uncertainties and emissions in a liner network?	A container vessel network schedule is composed of the port and sea turnaround. Delays in the port turnaround lead to increased vessel speed to recover the schedule of the network. Increased vessel speed has a third power relationship with fuel consumption, which is proportionally related to GHG emissions. Regarding the IMO regulations for GHG emissions, optimising the port call is an effective strategy.
Measure	**SQ 2**: What sub-processes are executed during the port call process and what is the performance of Maersk Line vessels in the Port of Rotterdam?	During the port call process there are five sub-processes identified which are executed in the chronological order: NTA, IBO, OPS, IAO, NTD. The case study analysed 433 vessels in terms of arrival reliability, TAT variation and idle time formation. It is found that the Idle Time before Operations (IBO) and Idle Time after Operations (IAO) sub-processes show the highest stochastic levels that are accommodated by significant outliers. The case study did not reveal a strong correlation between the retrieved parameters. This concludes that the port call process contains a high degree of stochasticity influenced by the port conditions.
Analyse	**SQ 3**: What are the root causes for port call uncertainties?	A set of six root causes are found that lead to an increase of idle time, port TAT, and a high degree of arrival variations. These root causes are defects, weather, missing information, arrival deviation, early completion, and lay-by. The root cause of missing information and arrival deviation is used as input for the future state model.
Design	**SQ 4**: How can Dynamic Arrival Times be implemented in the liner network?	The implementation of a Dynamic Arrival Time (DAT) is reached by incorporating three elements in the current state: standardisation of data elements, identifying uncertainties, and communication of reliable information.
Evaluate	**SQ 5**: How much GHG emissions are avoided by implementing a Dynamic Arrival Time in a network that is subject to port uncertainties?	To test the effectiveness of the DAT design, a network schedule is composed in Anylogic. This network is tested for different levels of process variation. It is found that a SSS network can save up to 30.9% of emissions for delayed vessels by incorporating a DAT in a shipping network. Furthermore, it is found that the design leads to shorter turnaround times. This reduction of the port TAT will further decrease the emissions throughout the departure transit.

Table 8.1: Overview of the sub-research questions and corresponding answers.

8.2. Recommendations for further research

There are several observations done throughout this study that are listed as recommendations for further research.

Collaboration

The first observation is that the Lean Six Sigma (LSS) model could lead to interesting results regarding port performance and opportunities towards improvements. However, it is found that the model is more effective when a retrospective delay assessment is done in collaboration with the actors that are defined in the stakeholder analysis. This delay assessment requires reliable and transparent data from the involved stakeholders. PortXchange is a digital platform that the Port of Rotterdam develops. This platform combines multiple data sources from the port call process and shares this with the involved and authorised stakeholders [67]. This platform's limitation is that there is no incorporation of waste (variation) post-assessment of the port call. The first practical recommendation would be to improve the data sharing and introduce a collaborative waste assessment procedure. To elaborate, this study highlights the importance of situational awareness in the port call process. It is found that for a successful variation assessment, a combination of data and human input is required. It is found that the biggest bottleneck in the improvement of the port call process and the shipping network is missing information, both data as well as human input. This human input must span over several people and functions in the port ecosystem. Therefore, further research could contribute to a collaborative waste assessment framework after a port call process. The usage of such a comprehensive digital tool over a longer period in practice will effectuate improvement opportunities. Ultimately, after establishing such a collaborative tool, the port can incorporate more advanced systems in the port. For example, the port can assess the role of machine learning for data patterns, or more proactive measurements can be taken (given the important role of on time communication of delays). Together these developments lead to improved predictability and reliability of a container network. Ultimately this brings the industry closer to the most important challenge of emission reductions.

Network expansion

The second observation that leads to a recommendation for further research is regarding the proposed network. As mentioned in the scope in Section 1.7, this study focuses on mainline vessels in a single network. It would be interesting to develop further the model where multiple vessels classes operate in their own network but make use of the same port. To achieve this, each arriving vessel needs to be facilitated with a dedicated Dynamic Arrival Time. Smaller vessels such as feeders and barges are highly dependent on the mainline vessels' arrival times (and corresponding cargo). Developing a model with multiple networks would further optimise transportation waste since the arrival times' predictability increases. Besides that, other downstream supply chains (rail and road) could benefit from this study. As described, the container network is part of a bigger end-to-end supply chain. It would be interesting to measure if truck congestion at the container yard can be avoided by connecting the truck as a stakeholder. A scenario can be tested using a Dynamic Arrival Time to improve the trucks' congestion at the container yard. For example, the port system can redirect trucks to certain waiting areas further away from congestion areas.

Scope expansion

Lastly, it is expected that the Dynamic Arrival Time has more potential in the liquid bulk industry (oil tankers). This is due to the difference in business models between the container and liquid bulk shipping industry. In the bulk industry, the cargo's value is more volatile, making it favourable to "hurry up and wait" during sea legs [77]. It is assumed that the simulation model, together with the mathematical relationships, can be deployed to the liquid bulk industry as well. However, a study in the liquid bulk industry would bring other challenges, such as the cargo's price fluctuation.

Appendices

Appendix A

A qualitative study lead to the identification of causes for idle time and arrival time variations.

Main cause	Sub-cause
A01 Waiting for berth exchange	A01-01 Terminal operations delayed
	A01-02 Vessel currently alongside delayed
	A01-03 Previous vessel not able to sail due to weather conditions
	A01-04 False or missing notice from NEU MAR to vessel
A02 Early Arrival	A02-01 Slack or buffer in the schedule
	A02-02 Early departure previous port
	A02-03 Avoiding adverse weather conditions
	A02-04 Avoiding traffic density on route
A03 Tidal restrictions	A03-01 Vessel waiting for tidal window
A04 Adverse weather conditions	A04-01 Vessel waiting for berth due to adverse weather conditions
A05 Pilot unavailable	A05-01 Pilot delay due to serving previous vessel
	A05-02 Pilot delay due to false/missing communication
A06 Tugs unavailable	A06-01 Tug delay due to serving previous vessel
	A06-02 Tug delay due to false/missing communication
A07 Authorities	A07-01 Waiting for approval of authorities
C01 Early berthing	C01-01 Layby due to weather conditions
	C01-02 Layby due to bunkers
	C01-03 Layby due to repairs
	CO1-04 Layby due to schedule reliability
	C01-05 Layby due to other reasons / request line
C02 Gangway	C02-01 Gangway issues
C03 Gondola	C03-01 Gondola program
	C03-02 Gondola crew not available / delayed
C04 Lashing	C04-01 Lashing issues
	C04-02 Lashing crew not available / delayed
C05 Reefer unplugging	C05-01 Reefer unplugging issues
C06 Crane availability	C06-01 Crane breakdown
	C06-02 Crane not ready/in position
C07 Terminal(crew) issues	C07-01 Lack of labor/gangs terminal staff
	C07-02 Arrival during crew shift change / mealbreak
	C07-03 Terminal incident / accident
	C07-04 Strikes
C08 Adverse weather conditions	C08-01 Adverse weather conditions hamper operations
C09 Other	C08-01 Other issues
D01 Layby	D01-01 Layby for repairs
	D01-02 Layby waiting berth other terminal
	D01-03 Layby for rest hours vessel crew
	D01-04 Layby awaiting crew changes
	D01-05 Layby for diving activities
	D01-06 Layby for vessel surveys/inspections/cleanings
D02 Bunkering	D02-01 Bunker layby
	D02-02 Bunkering after completion due to high terminal productivity
	D02-03 Bunkering after completion due to downfall
	D02-04 Bunkering after completion due to adjusted ETA
	D02-05 Bunker barge late
	D02-06 Bunker delay due to vessel issues
	D02-07 Bunkering got delayed due to breakbulk operation
	D02-08 Bunker delay due to bunker barge technical issues
D03 Recovery work	D03-01 Recovery own program
	D03-02 Recovery ROB
D04 Lashing	D04-01 Lashing or reefer issues
D05 Stores	D05-01 Provisions
	D05-02 Stores and consumables
	D05-03 Spares
	D05-04 Access to vessel store crane blocked
D06 Early completion	D06-01 Early completion due to terminal productivity
D07 Shortage of tugs	D07-01 Tugs not available as ordered
D08 Shortage of pilots	D08-01 Pilots not available as ordered
D09 Traffic congestion	D09-01 Traffic/congestion due to deep draft vessel
	D09-02 Traffic/congestion at adjacent terminals
D10 Tidal restrictions	D10-01 Vessel waiting to sail due to tidal window
D11 Adverse weather conditions	D11-01 Vessel waiting to sail due to adverse weather conditions
D12 Vessel ISPS requirements	D12-01 Vessel delayed due to ISPS requirements
D13 Other	D13-01 Other issues, specify in the comments

Table A.1: Potential causes of idle time formation and arrival deviation

Appendix B

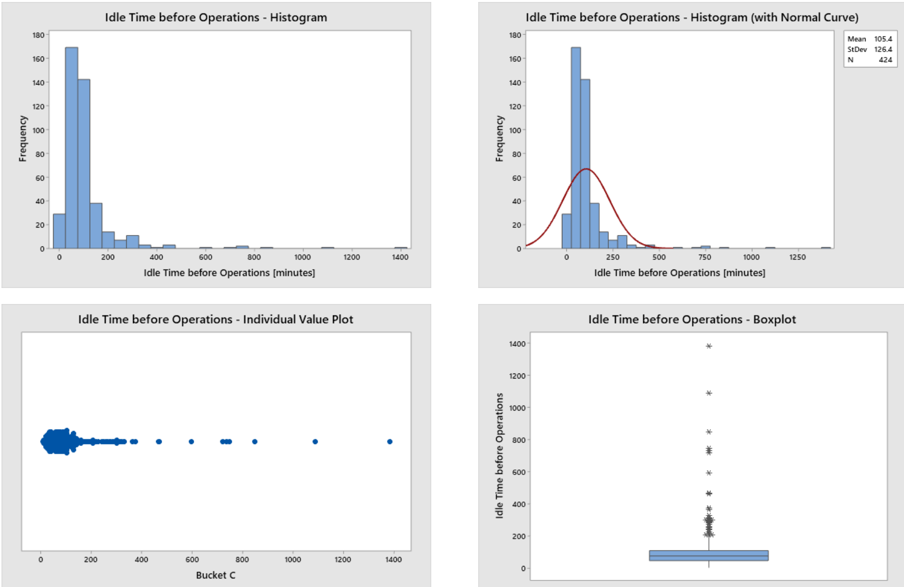


Figure B.1: Idle Time before Operations

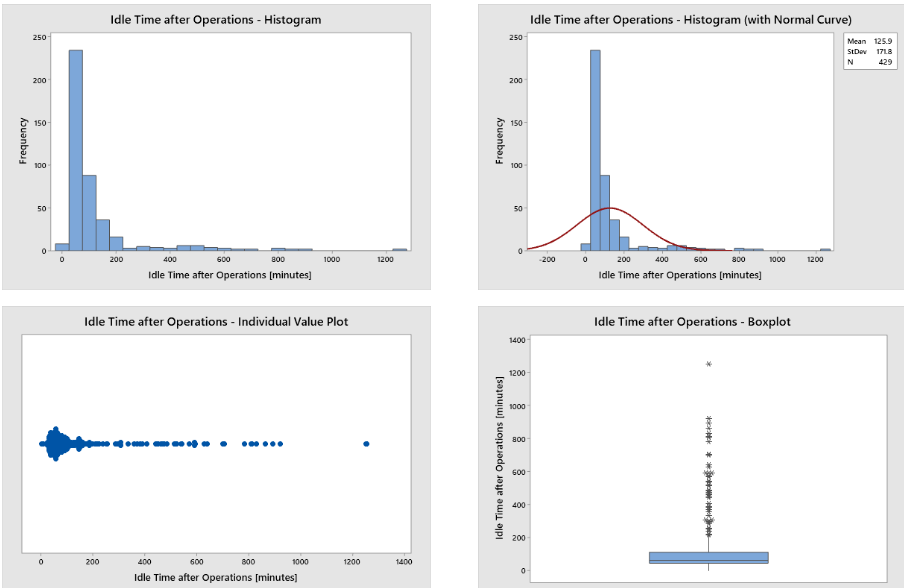


Figure B.2: Idle Time after Operations

Appendix C

C.1. Case study

To illustrate the benefits of incorporating Dynamic Arrival Time practices, this section provides a case study. Case studies are widely applied in the research to gain more insights on processes. According to Bromley, a case study is a “systematic inquiry into an event or a set of related events which aims to describe and explain the phenomenon of interest” [12, p. 302]. In this thesis the case is a vessel sailing from the Port of Algeciras in Spain to the Port of Rotterdam in the Netherlands (see figure C.1). The vessel and route parameters are depicted in table C.1. The engine characteristics and the specific fuel oil consumption are obtained from a research by Moon and Woo [66, p. 451]. It is assumed that a delay in the port of arrival (Rotterdam) results in a late arrival for the vessel that is sailing towards the port. Furthermore, it is assumed that all port resources (cranes, labour etc.) are fully utilised. Consequentially, the vessel encounters a late departure at the Port of Rotterdam that is equal to the experienced port delay on arrival. To recover the schedule, the vessel is assumed to speed up throughout the succeeding sea leg to a speed level which mitigates the delay. As a results, the vessel is according to schedule and Just-in-Time (JIT) in the next port. For the sake of clarity, the next port of destination is the Port of Algeciras.

The case study assesses three scenarios: (I) No delay without DAT, (II) Delay without DAT, and (III) Delay with DAT.

Scenario $k = 1$: No delay without a Dynamic Arrival Time

The first scenario considers a situation where the vessel is sailing on-schedule and no delay is present in the port of arrival. Since the DAT is not incorporated, the standard equation for fuel consumption at sea is used (see equation 2.8). The vessel is on-time and there are no delays, so the waiting time for anchorage is $t_{s,a} = 0$. The speed of the vessel is maintained constant throughout the voyage at the level of the schedule speed from table C.1. The fuel consumption along the route is calculated by making use of the general equation without the DAT (2.8). The results for the fuel consumption and emissions during the arrival and departure leg can be found in table C.2.

The results show that the vessel speed has an average of 20 knots throughout both the sea legs. Given the distance between the ports, the vessel consumes 2,398 ton fuel along the route. Given equation 2.15, this results in a total of 7,602 ton fuel carbon dioxide that is emitted during the operations.

Scenario $k = 2$: Delay without a Dynamic Arrival Time

The second case describes a situation where a delay of 10 hours occurs in the Port of Rotterdam. It is assumed that a buffer of 2 hours is implemented in the schedule between two consecutive vessels in the Port of Rotterdam. According to 2.3 this results is a port uncertainty value (r_i) of 8 hours. Again equation 2.8 is used, but now with a value of $t_{s,a} > 0$. This results in a small increase of fuel consumption on the arrival leg. In order to recover the delay and maintain schedule reliability within the network, the vessel speeds up to the next port of destination. The results of the second scenario can be found in table C.3.

The results show a deviation compared to the results from scenario I. The port delay causes waiting time on arrival that is equal to the port uncertainty. During the waiting time on arrival the vessel makes use of the Auxiliary Engines. This results in an additional fuel consumption of 4 ton fuel while the vessel is at anchorage. A greater deviation is found when the departure leg is considered. The effort that is taken to recover the schedule lead to an increased vessel speed to 22.6 knots. The corresponding fuel and emission consumption is now equal to respectively 1530 ton HFO, and 4,850 ton CO_2. This is equal to a fuel consumption increase of 27.2% along the route back. Due to the proportional relationship between fuel and Carbon Dioxide, the same percentage for the carbon dioxide increase is obtained.

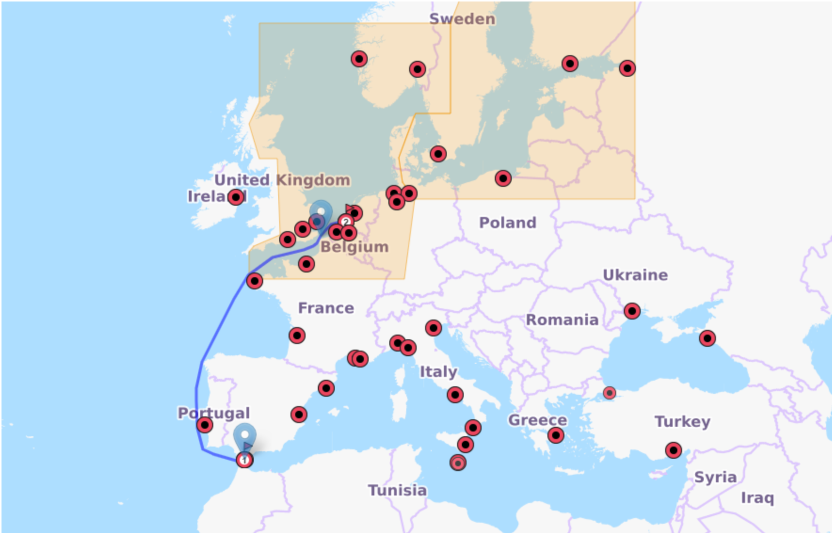


Figure C.1: Nautical route from Algeciras to Rotterdam including SECA zone using SeaRoutes

	Parameter	Abbreviation	Value	SI Unit
Vessel	Main Engine Power	MEP	89,700	kWh
	Auxiliary Engine Power	AEP	16,000	kWh
	Specific Oil Fuel Consumption; sailing	$SFOC_s$	0.375	kg/kWh
	Specific Oil Fuel Consumption; waiting	$SFOC_w$	0.032	kg/kWh
	Container capacity	C	14,000	TEU
	Design voyage speed	S	25	knots
	Schedule speed	S_i	20	knots
Route	Total Distance	D_i	1,392	Nm
	Number of waypoints on route	w	5	-
	Distance between waypoints	$d_{i,wp}$	278.4	Nm

Table C.1: Case study input parameters. Partially obtained from Moon and Wang [104, p. 451]

Parameter	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Unit	*knots*	*knots*	*hours*	*hours*	*hours*	*ton*	*ton*	*ton*	*ton*
Arrival Leg	20.0	20.0	69.6	0,0	69.6	1199	0	1199	3801
Departure Leg	20.0	20.0	69.6	0,0	69.6	1199	0	1199	3801
Total			139.2	0.0	139.2	2398	0	2398	7602

Table C.2: Results case study scenario $k = 1$

Parameter	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Unit	*knots*	*knots*	*hours*	*hours*	*hours*	*ton*	*ton*	*ton*	*ton*
Arrival Leg	20.0	20.0	69.2	8.0	77.6	1199	4	1203	3814
Departure Leg	20.0	22.6	61.2	0.0	61.6	1530	0	1530	4850
Total			131.2	8.0	139.2	2729	4	2733	8664

Table C.3: Results case study scenario $k = 2$

Scenario $k = 3$: Delay with a Dynamic Arrival Time
The last scenario describes the situation where the same delay is encountered as in case II, but now with the incorporation of the DAT design. As equation 5.13 indicates, the amount of fuel consumption at sea is dependent on the values for α and β. These values represent the time that the delay is notified to the vessel agent. To successfully test the effectiveness of Virtual Arrival, the results are iterated for different levels of α and β. These iterations are notated as sub-scenarios. For readability purposes, the results of scenario $k = 3$ are divide over table C.5 and C.6. Before discussing the results in terms of fuel consumption and emissions, the intermediate voyage parameters along the route are depicted with table C.4. Due to the inclusion of waypoints, additional voyage measurements (DTA, TTA, and S_j) are made throughout the route at each waypoint. As table C.1 indicates, 5 waypoints are added along the route, which leads to 5 sub-scenarios.

Parameter	DTA	TTA	S_j	TTA	S_j	TTA	S_j	TTA	S_j	TTA	S_j
Unit	*NM*	*hours*	*knots*	*hours*	*knots*	*hours*	*knots*	*hours*	*knots*	*hours*	*knots*
$at\ w$		$\alpha = 4, \beta = 1$		$\alpha = 3, \beta = 2$		$\alpha = 2, \beta = 3$		$\alpha = 1, \beta = 4$		$\alpha = 0, \beta = 5$	
0	1,392.0	69.6	20.0	69.6	20.0	69.6	20	69.6	20	***77.6***	17.9
1	1,113.6	55.7	20.0	55.7	20.0	55.68	20	***63.7***	17.5	62.1	17.9
2	835,2	41.8	20.0	41.8	20.0	***49.76***	16.8	47.8	17.5	46.6	17.9
3	556,8	27.8	20.0	***35.8***	15.5	33.17	16.8	31.8	17.5	31.0	17.9
4	278,4	***21.9***	13.9	17.9	15.5	16.59	16.8	15.9	17.5	15.5	17.9

Table C.4: Voyage parameters measured per waypoint

First, it is recalled that the higher the value of β, the earlier the delay in the port is noticed and the earlier the vessel is notified. This enables the vessel agent to reduce the speed over the upcoming waypoints. If $\alpha = 0, \beta = 5$, the vessel agent is aware of the delay at the moment of departure in Algeciras. The moment that the vessel is notified with the delay is indicated in the table by means of a bold font. This leads to a reaction of the vessel agent to reduce the speed. For each sub-scenario the speed envelope of the vessel is calculated and depicted in figure C.2. The reduced speed over a waypoint segment leads to a longer sailing time over that segment. The waypoints are static which results in a constant value for each sub-scenario. By substituting the speed in the DAT fuel consumption equation, the total fuel consumption over all the waypoints are determined. Table C.5 and C.6 represents the intermediate values..

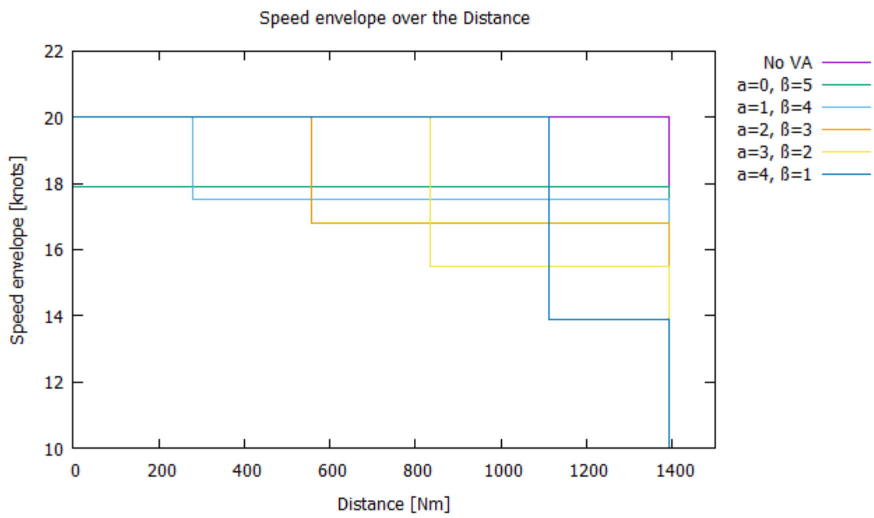


Figure C.2: Speed envelope for different sub scenarios

The results shows that sailing on-schedule is for this case the most preferred solution in terms of fuel consumption and emissions. This case is represented by the index number 100. The Arrival Index shows that significant reductions are achieved by implementing the Virtual Arrival concept. Equation 5.13 already provided a mathematical statement for the relation of α and β. The case study results substantiate this statement with the obtained Arrival Index that decreases as a consequence of an increased β value. The case study assumes that the port operates at a maximum utilisation rate of the port resources. Therefore a deterministic value is taken for the port delay. This results in an increased voyage to 22.6 knots for case II and III to recover the schedule. Within the table this is represented with an increased Departure Index of 127.6. The Total Index shows that by implementing a DAT, the additional fuel and emission consumption is significantly reduced by almost 10% compared to not using a DAT. It must be noted that this is under the assumption that a delay is known and notified to the vessel before the arrival leg commences.

$\alpha = 4, \beta = 1$	w	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Arrival Leg	0;1	20	20.0	13.9	0.0	15.5	240	0.0	240	761
	1;2	20	20.0	13.9	0.0	15.5	240	0.0	240	761
	2;3	20	20.0	13.9	0.0	15.5	240	0.0	240	761
	3;4	20	20.0	13.9	0.0	15.5	240	0.0	240	761
	4;5	20	13.9	21.9	0.0	21.9	127	0.0	127	403
Departure Leg		20	22.6	61.6	0.0	61.6	1530	0.0	1530	4850
Total				193.2	0.0	193.2	2617	0.0	2617	8297

(a) Results case study $k = 3$: $\alpha = 4, \beta = 1$

$\alpha = 3, \beta = 2$	w	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Arrival Leg	0;1	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	1;2	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	2;3	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	3;4	20	15.5	17.9	0.0	17.9	143	0.0	143	455
	4;5	20	15.5	17.9	0.0	17.9	143	0.0	143	455
Departure Leg		20	22.6	61.6	0.0	61.6	1530	0.0	1530	4850
Total				193.2	0.0	193.2	2536	0.0	2536	8039

(b) Results case study $k = 3$: $\alpha = 3, \beta = 2$

$\alpha = 2, \beta = 3$	w	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Arrival Leg	0;1	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	1;2	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	2;3	20	16.8	16.6	0.0	16.6	169	0.0	169	536
	3;4	20	16.8	16.6	0.0	16.6	169	0.0	169	536
	4;5	20	16.8	16.6	0.0	16.6	169	0.0	169	536
Departure Leg		20	22.6	61.6	0.0	61.6	1530	0.0	1530	4850
Total				193.2	0.0	193.2	2517	0.0	2517	7980

(c) Results case study $k = 3$: $\alpha = 2, \beta = 3$

Table C.5: Results case study scenario $k = 3$; part 1

$\alpha = 1, \beta = 4$	w	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Arrival Leg	0;1	20	20.0	13.9	0.0	13.9	240	0.0	240	761
	1;2	20	17.5	15.9	0.0	15.9	183	0.0	183	580
	2;3	20	17.5	15.9	0.0	15.9	183	0.0	183	580
	3;4	20	17.5	15.9	0.0	15.9	183	0.0	183	580
	4;5	20	17.5	15.9	0.0	15.9	183	0.0	183	580
Departure Leg		20	22.6	61.6	0.0	61.6	1530	0.0	1530	4850
Total				193.2	0.0	193.2	2502	0.0	2501	7931

(a) Results case study $k = 3$: $\alpha = 1, \beta = 4$

$\alpha = 0, \beta = 5$	w	S_i	S_j	$t_{s,s}$	$t_{s,a}$	t_s	$FC_{s,s}$	$FC_{s,a}$	FC_s	EC_{CO_2}
Arrival Leg	0;1	20	17.9	15.5	0.0	15.5	193	0.0	193	612
	1;2	20	17.9	15.5	0.0	15.5	193	0.0	193	612
	2;3	20	17.9	15.5	0.0	15.5	193	0.0	193	612
	3;4	20	17.9	15.5	0.0	15.5	193	0.0	193	612
	4;5	20	17.9	15.5	0.0	15.5	193	0.0	193	612
Departure Leg		20	22.6	61.6	0.0	61.6	1530	0.0	1530	4850
Total				193.2	0.0	193.2	2495	0.0	2495	7910

(b) Results case study $k = 3$: $\alpha = 0, \beta = 5$

Table C.6: Results case study scenario $k = 3$; part 2

Bibliography

[1] Gustav Aagesen and John Krogstie. “Bpmn 2.0 for modeling business processes”. In: *Handbook on Business Process Management 1: Introduction, Methods, and Information Systems*. Springer Berlin Heidelberg, Jan. 2015, pp. 219–250. ISBN: 9783642451003. DOI: 10.1007/978-3-642-45100-3{_}10.

[2] Nicoleta Acomi and Ovidiu Cristian Acomi. “The Influence of Different Types of Marine Fuel over the Energy Efficiency Operational Index”. In: *Energy Procedia* 59 (2014). ISSN: 18766102. DOI: 10.1016/j.egypro.2014.10.373.

[3] Jordi Arjona Aroca et al. “Enabling a green just-in-time navigation through stakeholder collaboration”. In: *European Transport Research Review* 12.1 (Dec. 2020). ISSN: 1867-0717. DOI: 10.1186/s12544-020-00417-7.

[4] V. Arumugam, Jiju Antony, and Alex Douglas. “Observation: A Lean tool for improving the effectiveness of Lean Six Sigma”. In: *TQM Journal* 24.3 (2012), pp. 275–287. ISSN: 17542731. DOI: 10.1108/17542731211226781.

[5] Shri Ashok Sarkar, Arup Ranjan Mukhopadhyay, and Sadhan Kumar Ghosh. “Root cause analysis, Lean Six Sigma and test of hypothesis”. In: *The TQM Journal* 25.2 (Feb. 2013). ISSN: 1754-2731. DOI: 10.1108/17542731311299609.

[6] *Assessment of selected alternative fuels and technologies*. Tech. rep. DNV-GL, 2019. URL: https://www.dnvgl.com/maritime/publications/alternative-fuel-assessment-download.html.

[7] John Baker. *Agility and flexibility: what’s the difference?* Tech. rep. Cranfield: Cranfield School of Management, 1996, pp. 2–3.

[8] Becha H. et al. *Standardisation in container shipping is key to boosting economies of scale – importance of data collaboration between shipping lines*. Tech. rep. Smart Maritime Network, May 2020.

[9] H. L. BEENHAKKER. “OPTIMIZATION VERSUS SUBOPTIMIZATION”. In: *International Journal of Production Research* 3.4 (Jan. 1964). ISSN: 0020-7543. DOI: 10.1080/00207546408943064.

[10] Andrei Borshchev and Ilya Grigoryev. *The Big Book of Simulation Modeling: Multimethod Modeling with Anylogic 8*. 2013.

[11] C F Broersma. *Marine Fuel Outlook 2028: Modeling the effect of the IMO legislation on marine fuel demand and price*. Tech. rep. 2020.

[12] Professor D. B. Bromley. “Academic contributions to psychological counselling. 1. A philosophy of science for the study of individual cases”. In: *Counselling Psychology Quarterly* 3.3 (July 1990). ISSN: 0951-5070. DOI: 10.1080/09515079008254261.

[13] Berit Dangaard Brouer, Christian Vad Karsten, and David Pisinger. “Optimization in liner shipping”. In: *Annals of Operations Research* 271.1 (Dec. 2018). ISSN: 0254-5330. DOI: 10.1007/s10479-018-3023-8.

[14] Jason Brownlee. *How to Remove Outliers for Machine Learning*. Apr. 2018. URL: https://machinelearningmastery.com/how-to-use-statistics-to-identify-outliers-in-data/.

[15] Bill Carreira. *Lean Manufacturing That Works : Powerful Tools for Dramatically Reducing Waste and Maximizing Profits*. Saranac Lake, UNITED STATES: AMACOM, 2004. ISBN: 9780814428542. URL: http://ebookcentral.proquest.com/lib/delft/detail.action?docID=243050.

[16] Ana C.Paix□o Casaca. “Simulation and the lean port environment”. In: *Maritime Economics and Logistics* 7.3 (2005), pp. 262–280. ISSN: 1479294X. DOI: 10.1057/palgrave.mel.9100137.

[17] Young-Tae Chang, Younghun Song, and Younghoon Roh. “Assessing greenhouse gas emissions from port vessel operations at the Port of Incheon”. In: *Transportation Research Part D: Transport and Environment* 25 (Dec. 2013). ISSN: 13619209. DOI: 10.1016/j.trd.2013.06.008.

[18] James Chen. *Skewness*. Jan. 2021.

[19] Clarskons. *Clarksons Research Portal*. Dec. 2020. URL: https://www.clarksons.net/Portal/.

[20] James J. Corbett, Haifeng Wang, and James J. Winebrake. “The effectiveness and costs of speed reductions on emissions from international shipping”. In: *Transportation Research Part D: Transport and Environment* 14.8 (Dec. 2009). ISSN: 13619209. DOI: 10.1016/j.trd.2009.08.005.

[21] James Cox III and John Schleier. *Theory of Constraints Handbook*. Vol. 1. McGraw-Hill Professional, 2010.

[22] DCSA. *Standards for a just-in-time port call*. Tech. rep. DCSA, Oct. 2020. URL: https://dcsa.org/wp-content/uploads/2020/10/20201020-DCSA-P6-JIT-Port-Call-Publication-Release1-V1.0-FINAL-1.pdf.

[23] DCSA. *Creating visibility to improve reliability in container shipping*. Tech. rep. Amsterdam, 2021.

[24] Drewry Shipping Consultants. *Annual Container Market Review and Forecast*. Tech. rep. Drewry Shipping Consultants Ltd., 2006.

[25] Cesar Ducruet and Olaf Merk. “Examining container vessel turnaround times across the world”. In: *Port Technology International* 59 (2013).

[26] Marlon Dumas et al. *Fundamentals of Business Process Management*. Springer Berlin Heidelberg, 2013. DOI: 10.1007/978-3-642-33143-5.

[27] Jansper Faber et al. “Regulated Slow Steaming in Maritime Transport”. In: *Transport and Environment and Seas at Risk* (Feb. 2012), pp. 16–17.

[28] Kjetil Fagerholt, Trond A. V. Johnsen, and Haakon Lindstad. “Fleet deployment in liner shipping: a case study”. In: *Maritime Policy & Management* 36.5 (Oct. 2009). ISSN: 0308-8839. DOI: 10.1080/03088830903187143.

[29] Federal Aviation Administration. *ASQP: Airport: Dispatch & Schedule Reliability Report*. 2009.

[30] Paul A Fishwick. *Computer Simulation: The Art and Science of Digital World Construction WHAT IS SIMULATION?* Tech. rep. 1995. URL: http://www.cis.ufl.edu/fishwick/introsim/paper.html.1.

[31] Janna Franzkeit, Hannah Pache, and Carlos Jahn. “Investigation of Vessel Waiting Times Using AIS Data”. In: Apr. 2020, pp. 70–78. ISBN: 978-3-030-44782-3. DOI: 10.1007/978-3-030-44783-0{_}7.

[32] Torkel Fyrvik and Eirik Uthaug. *Process Modelling as Basis for Development and Integration of New Information Systems*. Tech. rep. Rotterdam, 2003.

[33] *GEF-UNDP-IMO GloMEEP Project and the GIA: Just In Time Arrival Guide - Barriers and Potential Solutions*. Tech. rep. 2020.

[34] GloMEEP. *Just In Time Arrival Guide - Barriers and Potential Solutions*. Tech. rep. GEF-UNDP-IMO Glo-MEEP, 2020.

[35] Mihalis M Golias et al. “The berth allocation problem: Optimizing vessel arrival time”. In: *Maritime Economics & Logistics* 11.4 (Dec. 2009). ISSN: 1479-2931. DOI: 10.1057/mel.2009.12.

[36] Anna Gustafsson. *Slow steaming to arrive at the right time*. Feb. 2019. URL: https://www.wartsila.com/insights/article/slow-steaming-to-arrive-at-the-right-time.

[37] Ayudhia P. Gusti and Semin. "The effect of vessel speed on fuel consumption and exhaust gas emissions". In: *American Journal of Engineering and Applied Sciences* 9.4 (2016), pp. 1046–1053. ISSN: 19417039. DOI: 10.3844/ajeassp.2016.1046.1053.

[38] Jack Hessburg. *Flight Disruptions: Evaluating schedule reliability*. 2000. URL: https://www.aviationpros.com/home/article/10388611/flight-disruptions-evaluating-schedule-reliability#:~:text=Schedule%20reliability%2C%20sometimes%20called%20dispatch,for%20a%20given%20airplane%20type..

[39] Peter Hines and Nick Rich. "The seven value stream mapping tools". In: 17.1 (1997), pp. 46–64. ISSN: 0144-3577. DOI: 10.1108/01443579710157989. URL: https://www.leancompetency.org/wp-content/uploads/2015/09/Value-Stream-Mapping-seven-tools.pdf.

[40] L.A.M. Huertas-Quintero et al. "Root cause analysis support for quality improvement in electronics manufacturing". In: *Assembly Automation* 31.1 (2011), pp. 38–46.

[41] International Maritime Organization. "RESOLUTION MEPC.304(72) (adopted on 13 April 2018) INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS". In: 304.April (2018).

[42] International Maritime Organization. *IMO 2020 – cutting sulphur oxide emissions*. 2019.

[43] International Taskforce Port Call Optimization. *A Reliable Port Starts With Reliable Information*. 2018. URL: www.portcalloptimization.org.

[44] INTERTANKO. *Virtual Arrival Optimising Voyage Management and Reducing Vessel Emissions-an Emissions Management Framework*. Tech. rep. 2010. URL: www.ocimf.com.

[45] Hassan Jafari and Khuzestan Province. "Identification and Prioritization of Causes of Halt and Lag in Container Handling Operation". In: *International Journal of Basic Sciences & Applied Research* 2.3 (2013), pp. 345–353. ISSN: 2147-3749. URL: http://www.isicenter.org.

[46] Haiying Jia et al. "Energy efficiency with the application of Virtual Arrival policy". In: *Transportation Research Part D: Transport and Environment* 54 (July 2017). ISSN: 13619209. DOI: 10.1016/j.trd.2017.04.037.

[47] Rasmus Jorgensen. *Slow steaming - the fuel story*. Tech. rep. A.P. Moller - Maersk Group, 2011.

[48] H Katayama and D Bennett. "Agility, adaptability and leanness: a comparison of concepts of a study of practice". In: *International Journal of Production Economics* 60-61.1 (1999), pp. 43–51.

[49] Paul Kidd. *Agile Manufacturing: Forging New Frontiers*. Wokingham, UK: Addison-Wesley, 1994.

[50] Jerry Kilpatrick. "Lean Principles". In: *Utah Manufacturing Extension Partnership* 68 (2003), pp. 1–5.

[51] Konstantinos Kouzelis. *Marine Fuel of the Future: A Decision Support Tool for Shipowners*. Tech. rep. Delft: Delft University of Technology, 2021.

[52] Peter de Langen, Michiel Nidjam, and Martijn van der Horst. "New indicators to measure port performance". In: *Journal of Maritime Research* 4.1 (2007), pp. 23–36.

[53] Chung-Yee Lee, Hau L. Lee, and Jiheng Zhang. "The impact of slow ocean steaming on delivery reliability and fuel consumption". In: *Transportation Research Part E: Logistics and Transportation Review* 76 (Apr. 2015). ISSN: 13665545. DOI: 10.1016/j.tre.2015.02.004.

[54] Higor dos Reis Leite and Guilherme Ernani Vieira. "Lean philosophy and its applications in the service industry: a review of the current knowledge". In: *Production* 25.3 (Feb. 2015). ISSN: 1980-5411. DOI: 10.1590/0103-6513.079012.

[55] Chen Li, Xiangtong Qi, and Chung-Yee Lee. "Disruption Recovery for a Vessel in Liner Shipping". In: *Transportation Science* 49.4 (Nov. 2015). ISSN: 0041-1655. DOI: 10.1287/trsc.2015.0589.

[56] Mikael Lind et al. "Digitalizing the port call process TRANSPORT AND TRADE FACILITATION Series No 1". In: (Feb. 2020).

[57] Nicholas Loyd et al. *APPLICATION OF LEAN ENTERPRISE AND SIX SIGMA AS AN AMALGAMATED IMPROVEMENT STRATEGY*. Tech. rep. 2010.

[58] D. V. Lyridis et al. “Optimizing shipping company operations using business process modelling”. In: *Maritime Policy & Management* 32.4 (Oct. 2005). ISSN: 0308-8839. DOI: 10.1080/03088830500300636.

[59] Ioannis Mallidis et al. “The impact of slow steaming on the carriers’ and shippers’ costs: The case of a global logistics network”. In: *Transportation Research Part E: Logistics and Transportation Review* 111 (Mar. 2018). ISSN: 13665545. DOI: 10.1016/j.tre.2017.12.008.

[60] Michael Maloni, Jomon Aliyas Paul, and David M Gligor. “Slow steaming impacts on ocean carriers and shippers”. In: *Maritime Economics & Logistics* 15.2 (June 2013). ISSN: 1479-2931. DOI: 10.1057/mel.2013.2.

[61] Peter B Marlow and Ana C Paixão Casaca. “Measuring lean ports performance”. In: *International Journal of Transport Management* 1.4 (Jan. 2003). ISSN: 14714051. DOI: 10.1016/j.ijtm.2003.12.002.

[62] J. Marsh and T. Perera. *Lean Six Sigma: Exploring Future Potential and Challenges*. 2011, pp. 37–38.

[63] MI News Network. *Maritime Pilot and His Duties*. Nov. 2019.

[64] Pratima Mishra and Rajiv Kumar Sharma. “A hybrid framework based on SIPOC and Six Sigma DMAIC for improving process dimensions in supply chain network”. In: *International Journal of Quality & Reliability Management* 31.5 (Apr. 2014). ISSN: 0265-671X. DOI: 10.1108/IJQRM-06-2012-0089.

[65] K F Molkenboer. “The critical areas of information sharing for improvement of the efficiency of the nautical chain A Port of Rotterdam case study”. In: (2020).

[66] Daniel Seong-Hyeok Moon and Jong Kyun Woo. “The impact of port operations on efficient ship operation from both economic and environmental perspectives”. In: *Maritime Policy & Management* 41.5 (July 2014). ISSN: 0308-8839. DOI: 10.1080/03088839.2014.931607.

[67] Abishek Nair, Shahmeer Magsi, and Dita Bruijn. *JUST IN TIME SAILING*. Tech. rep. Rotterdam, Feb. 2021.

[68] Rawindaran Nair, Jane Jing Xu, and Robert Mason. “Delivery schedule reliability in the international container liner shipping service: implications for research.” In: *Proceedings of the international forum on shipping: ports and airports*. 2012.

[69] Nikhil Nandakumar, P.G. Saleeshya, and Priya Harikumar. “Bottleneck Identification And Process Improvement By Lean Six Sigma DMAIC Methodology”. In: *Materials Today: Proceedings* 24 (2020). ISSN: 22147853. DOI: 10.1016/j.matpr.2020.04.436.

[70] *New standard data definitions for Just-in-Time port calls*. 2020. URL: https://safety4sea.com/new-standard-data-definitions-for-just-in-time-port-calls/.

[71] Nidec. *An Introductory Guide to Port Cranes and the Application of Variable Speed Drives*. Tech. rep. 2019. URL: https://webcache.googleusercontent.com/search?q=cache:wNdBWZw4zFEJ:https://www.nidec-netherlands.nl/media/2928-an-introductory-guide-to-port-cranes-and-the-application-of-variable-speed-drives-iss1x-0704-0005-01x.pdf+&cd=3&hl=nl&ct=clnk&gl=nl.

[72] Theo E Notteboom. “The Time Factor in Liner Shipping Services”. In: *Maritime Economics & Logistics* 8.1 (Mar. 2006). ISSN: 1479-2931. DOI: 10.1057/palgrave.mel.9100148.

[73] Peter Olesen et al. “Using lean principles to drive operational improvements in intermodal container facilities”. In: *Journal of Facilities Management* 13.3 (July 2015). ISSN: 1472-5967. DOI: 10.1108/JFM-09-2014-0030.

[74] Ana Cristina Paixão and Peter Bernard Marlow. “Fourth generation ports – a question of agility?” In: *International Journal of Physical Distribution & Logistics Management* 33.4 (May 2003). ISSN: 0960-0035. DOI: 10.1108/09600030310478810.

[75] Port of Rotterdam. *Nautical services*. 2019. URL: https://www.portofrotterdam.com/en/doing-business/services/service-range/nautical-services.

[76] Port of Rotterdam. *Rotterdam Bunker Port*. 2020. URL: https://www.portofrotterdam.com/nl/scheepvaart/zeevaart/overig/rotterdam-bunker-port.

[77] René Taudal Poulsen and Helen Sampson. "'Swinging on the anchor': The difficulties in achieving greenhouse gas abatement in shipping via virtual arrival". In: *Transportation Research Part D: Transport and Environment* 73 (Aug. 2019). ISSN: 13619209. DOI: 10.1016/j.trd.2019.07.007.

[78] H. Psaraftis and C. Kontovas. "CO2 emission statistics for the world commercial fleet." In: *WMU Journal of Maritime Affairs* 8 (2009), pp. 1–25.

[79] Harilaos N Psaraftis, Christos A Kontovas, and Nikolaos M P Kakalis. "Speed reduction as an emissions reduction measure for fast ships". In: Athens: International Conference on Fast Sea Transportation, Oct. 2009. URL: https://www.researchgate.net/publication/242094743.

[80] Thomas Pyzdek. *The Six Sigma Handbook: A Complete Guide for Green Belts, Black Belts, and Managers at All Levels*. The McGraw-Hill Companies, 2003.

[81] Nishatabbas Rehmatulla and Tristan Smith. "Barriers to energy efficient and low carbon shipping". In: *Ocean Engineering* 110 (Dec. 2015). ISSN: 00298018. DOI: 10.1016/j.oceaneng.2015.09.030.

[82] *Rules for Classification and Construction I Ship Technology*. Tech. rep. Hamburg: Germanischer Lloyd SE, 2013, pp. 7–16.

[83] Amir Saeed Nooramin, Vahid Reza Ahouei, and Jafar Sayareh. "A Six Sigma framework for marine container terminals". In: *International Journal of Lean Six Sigma* 2.3 (Aug. 2011). ISSN: 2040-4166. DOI: 10.1108/20401461111157196.

[84] Periklis Saragiotis. "Business process management inthe port sector: a literature review". In: *Emerald Insight* (2019).

[85] Robert G. Sargent. "Verification and validation of simulation models". In: *Proceedings of the 2010 Winter Simulation Conference*. IEEE, Dec. 2010. ISBN: 978-1-4244-9866-6. DOI: 10.1109/WSC.2010.5679166.

[86] Grant T. Savage et al. "Strategies for assessing and managing organizational stakeholders". In: *Academy of Management Perspectives* 5.2 (Feb. 1991). ISSN: 1558-9080. DOI: 10.5465/ame.1991.4274682.

[87] Steve Saxon and Matt Stone. *Container shipping: The next 50 years*. Tech. rep. McKinsey & Company, Oct. 2017.

[88] Riley E.J. Schnurr and Tony R. Walker. "Marine Transportation and Energy Use". In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier, 2019. DOI: 10.1016/B978-0-12-409548-9.09270-8.

[89] Todd Scott. *TradeLens: How IBM and Maersk Are Sharing Blockchain to Build a Global Trade Platform*. Nov. 2018.

[90] Sea Traffic Management. *What is Port CDM*. 2016. URL: https://www.onthemosway.eu/wp-content/uploads/2016/04/STM_activity-1.pdf.

[91] Sea-Intelligence. *Global Liner Schedule Reliability Report*. Tech. rep. SeaIntel Maritime Analysis, 2011.

[92] B Silver. *BPMN Method and Style*. 2nd ed. Cody-Cassidy Press, Oct. 2011.

[93] Brian Slack et al. *Ships time in port*. Tech. rep. 1. 2018, pp. 45–62.

[94] Smart Digital Ports. *A Market Analysis for 2020*. Tech. rep. Port Technology, Jan. 2020.

[95] M. Smedts. "Evaluating performance in the transportation chain: the effect of schedule reliability". PhD thesis. 2011.

[96] D Stapersma. "Performance Analysis". In: *Diesel Engines: A fundamental approach to performance analysis, turbocharging, combustion, emissions and heat transfer*. Vol. 1. Delft, 2010. Chap. 2, pp. 66–67.

[97] Peter Tirschwell. *Berth Productivity: The Trends, Outlook and Market Forces Impacting Ship Turnaround Times*. Tech. rep. JOC Group, July 2014.

[98] Jose Tongzon and Wu Heng. "Port privatization, efficiency and competitiveness: Some empirical evidence from container ports (terminals)". In: *Transportation Research Part A: Policy and Practice* 39.5 (June 2005), pp. 405–424. ISSN: 09658564. DOI: 10.1016/j.tra.2005.02.001.

[99] UNCTAD. *Port performance indicators*. Tech. rep. New York: United Nations Conference on Trade and Development, 1976.

[100] S T Ung and Y T Chen. "A practical application of 'Six Sigma' to port operations". In: *Journal of Marine Engineering & Technology* 9.2 (Jan. 2010). ISSN: 2046-4177. DOI: 10.1080/20464177.2010.11020232.

[101] United Nations. *Digitalizing the port call process TRANSPORT AND TRADE FACILITATION Series No 13*. Tech. rep. 2020. URL: https://unctad.org/en/PublicationsLibrary/dtltlb2019d2_en.pdf.

[102] Bert Vernimmen, Wout Dullaert, and Steve Engelen. "Schedule Unreliability in Liner Shipping: Origins and Consequences for the Hinterland Supply Chain". In: *Maritime Economics & Logistics* 9.3 (Sept. 2007). ISSN: 1479-2931. DOI: 10.1057/palgrave.mel.9100182.

[103] Casper Volger. "Alternative fuels on board of carbon-neutral cruise vessels". PhD thesis. 2019.

[104] H Wang et al. "Reduction of GHG emissions from ships. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures." In: (July 2010).

[105] Shuaian Wang and Qiang Meng. "Robust schedule design for liner shipping services". In: *Transportation Research Part E: Logistics and Transportation Review* 48.6 (Nov. 2012). ISSN: 13665545. DOI: 10.1016/j.tre.2012.04.007.

[106] Richard Watson, Henrik Holm, and Mikael Lind. *Green Steaming: A Methodology for Estimating Carbon Emissions Avoided*. Dec. 2015.

[107] Andreas Wiesmann. "Slow steaming-a viable long-term option?" In: *Wartstila Technical Journal* (Feb. 2010).

[108] WPSP. *Port call optimization solutions to reduce emissions start gaining industry traction*. 2020.

[109] Cheng□Lung Wu and Robert E. Caves. "Modelling and optimization of aircraft turnaround time at an airport". In: *Transportation Planning and Technology* 27.1 (Feb. 2004). ISSN: 0308-1060. DOI: 10.1080/0308106042000184454.

[110] A van der Wurff. *Maritime and Ports industry initiative overview*. Tech. rep. Maersk Line, 2016.

[111] Hualong Yang et al. "Sea-Port Operational Efficiency: An Evaluation of Five Asian Ports Using Stochastic Frontier Production Function Model". In: *Journal of Service Science and Management* 04.03 (2011). ISSN: 1940-9893. DOI: 10.4236/jssm.2011.43045.

[112] Kelvin O. Yoro and Michael O. Daramola. "CO2 emission sources, greenhouse gases, and the global warming effect". In: *Advances in Carbon Capture*. Elsevier, 2020. DOI: 10.1016/B978-0-12-819657-1.00001-3.

[113] J Youngman K. *A Guide to Implementing the Theory of Constraints (TOC)*. 2008. URL: http://www.dbrmfg.co.nz/&%20More%20Toyota,%20Kaizen,%20&%20Lean.htm.

[114] Gang Yu and Xiangtong Qi. *Disruption Management*. WORLD SCIENTIFIC, Aug. 2004. ISBN: 978-981-256-017-9. DOI: 10.1142/5632.

[115] Qingcheng Zeng, Zhongzhen Yang, and Xiangpei Hu. "Disruption recovery model for berth and quay crane scheduling in container terminals". In: *Engineering Optimization* 43.9 (Sept. 2011). ISSN: 0305-215X. DOI: 10.1080/0305215X.2010.528411.

Abating GHG Emissions with Dynamic Arrival Times

C.F.Broersma[a], Dr.W.W.A.Beelaerts van Blokland[a], Prof.dr.R.R.Negenborn[a] and Dr.ir.E.B.H.J. van Hassel[b]

[a] Department of Marine and Transport Technology, Delft University of Technology, Mekelweg 5, 2628 CD Delft, The Netherlands
[b] University of Antwerp, Department of Transport and Regional Economics, Prinsstraat 13, B-2000 Antwerp, Belgium

ARTICLE INFO

Keywords:
Maritime industry
Shipping network
GHG reduction strategy
Lean Six Sigma
Dynamic Arrival Time

ABSTRACT

Container liner shipping organisations facilitate trade between all regions globally by deploying vessels in a network with a corresponding sailing schedule. Since the container shipping network is part of a larger network, it is favourable for the continuation of the supply chain to maintain this schedule. Although the importance of the continuation is recognised, the industry is not known for a high degree of schedule reliability. This is due to the presence of regular and irregular uncertainties in the network. It is found that more than 90% of these uncertainties find their origin in the port area. By deploying the LSS methodology, the causes and effects of port uncertainties are further analysed. It is found that the port uncertainties lead to transportation waste at sea in the form of fuel costs and emissions. The shipping sector is held accountable for approximately 3% of the global carbon dioxide emissions. A Dynamic Arrival Time (DAT) design is proposed to recover a schedule after a delay takes place to avoid waiting times and arrive JIT in the port. This differentiates from the current state where a First Come First Serve policy is maintained. An Agent-Based Discrete Event Simulation model in Anylogic is proposed to test the effects of a DAT implementation in a Short Sea Shipping (SSS) network that is subject to regular and irregular port uncertainties. It is found that a fuel and emissions reduction of up to 6.1% is achieved when a DAT is implemented under irregular uncertainties in the network. If the DAT incorporation is tested for regular uncertainties, the effect is equal to a 0.5% reduction in fuel and emissions. Furthermore, it is found that the design leads to a decrease in the port turnaround time due to improved arrival predictability. This improved predictability enables the shipping line (or agent) to recover the schedule and avoid drastic fuel increase during the departure transit. This study's findings are important for the policy-making for shipping companies due to the substantial energy savings that are measured. Furthermore, this study contributes to the MEPC.323(74) resolution, where voluntary cooperation between the port and shipping sectors is encouraged to reduce the GHG emissions from the shipping industry.

1. Introduction

Maritime transport is the most important contributor to global trade, with 90% of the total trade by volume carried by water [21]. According to a trade report from the UNCTAD, a trading volume of 11.03 billion ton is facilitated by the shipping industry in 2019. The container shipping industry, which experienced rapid growth in the last decades, facilitates 60% of this form of transportation [47]. Although the movement of goods via shipping is cost, and energy-efficient, the industry is still held accountable for approximately 3% of the global GHG emissions [21]. If this number is put into perspective to countries, the shipping industry's emissions would be equal to a country such as Germany [32]. The container fleet represents a small percentage of the total world commercial fleet but is responsible for 20% of the generated emissions from international shipping in 2007 [37]. The container fleet predominantly consumes Heavy Fuel Oil as a fuel type due to the attractiveness of operational costs, reliability and the current capabilities of refuelling when it comes to the infrastructure. Heavy Fuel Oil is known for a high carbon rate compared to other fuel types such as Marine Gas Oil, Liquefied Natural Gas or Biofuels [41].

The growing demand has led to a significant increase in vessel sizes accompanied by newly experienced complications. As mentioned, the sector emissions are significant, but also on a smaller level, the ports have difficulties handling the much-increased size of vessels. This leads to a high degree of schedule unreliability in the shipping industry [48, 34, 15, 14]).

To allow the significant growth of the container shipping industry, a high degree of optimisation is required. Not only to maintain profitability but also to comply with the regulations set by the IMO [21]. The shipping sector's optimisation is divided into two components: voyage- and port efficiency, which consists of two sub-components: strategical and operational decisions. For the voyage efficiency, the strategical decisions are long-term decisions such as the type of engines installed, the optimal hull structure for new build vessels, and the type of consumed fuels. The (relatively) short-term decisions are made on the operational level. These aspects comprise decisions on fleet utilisation, network design and the maintained vessel speed during the voyage. Next to the voyage efficiency, there is the port efficiency component. The port's role in shipping optimisation has grown over the years to a multi-modal supply chain hub [35]. On the strategic level of capital, intensive decisions are made regarding the port's capacity by investing in gantry cranes, accessibility by maintaining deep water routes within the port, and increasing quay lengths [52]. This allows ports to facilitate the growing vessels' demand and execute the required operations safely and efficiently. On the operational level, port decisions are made to optimise port efficiency, which requires

ORCID(s):

less capital intensive investments. Examples are planning optimisation, intra-port process optimisation and disruption management [52].

The IMO is a United Nations specialised agency responsible for the safety and security of shipping and the prevention of atmospheric pollution by ships. The third GHG study of the IMO presented a scenario where the CO_2 emissions could increase by 50-250% by 2050, compared to 2008. In reaction to the environmental concerns, the IMO introduced a provision in Annex VI of the International Convention for the Prevention of Air Pollution from Ships (MARPOL), representing an international policy to mitigate the effects of the shipping industry. The policy contains short-, mid-, and long-term emission mitigating measurements imposed on the shipping industry. These measurements are intended to reduce the emissions by at least 40% in 2030 and pursuing this to at least 50% in 2050, compared to the numbers from 2008. These measurements are taken to comply with Paris Agreement temperature goals.

The strategy proposed by the IMO addresses the role of the port developments within the short-term measurements. The MEPC 74 resolution, which is adapted in May 2019, encourages the cooperation between the port and shipping sectors to reduce GHG emissions. According to the IMO, port optimisation includes several technical, operational, economic and regulatory actions that contribute to their ambitions. For example, the provision of onshore power supply in ports, safe and efficient bunker of low-carbon fuel types, and port optimisation efforts to facilitate just-in-time arrival of ships [14].

Another operational, efficient short-term measurement to abate emissions is the concept of slow-steaming. The practice of slow-steaming gained traction during the economic recession in 2008 when the oil price experienced a rapid increase, and container logistic providers cut costs by reducing the vessel operating speed. In the beginning, there were concerns about the technical consequences to the engine, but these concerns are overcome [18]. In 2010, 70% of the Maersk Line fleet practised slow steaming operations at engine loads below 40%. As a result, two million ton of carbon dioxide was saved that year [25]. This operational measurement is highly effective since the fuel expenditures are accountable for approximately 50-60% of the operational expenditures ([34], [16], [39], [31]). A secondary positive effect is that the vessel's fuel consumption has a cubic relation with the vessel speed [29], and the fuel consumption on its turn has a linear relation to the GHG emissions [36].

1.1. Problem statement

A container logistic company's service is focused on enabling trade between customers over the world by deploying vessels in different sailing networks [27]. A vessel sailing within such a network is provided with a time table and is denoted as a vessel service [5]. Ideally, the service schedule adapts to a rather static profile, meaning that the schedule is maintained. This is called schedule or service reliability and is longed for by all stakeholders. For example, it enables the cargo customer to efficiently incorporate the schedule within the rest of the organisations' supply chain [35]. Next to this, shipping lines can effectively incorporate the practice of slow steaming operations on the tactical level. This has proven to be a highly efficient approach to reduce fuel consumption and GHG emissions [50].

Reality shows that maintaining schedule reliability is often not possible due to various uncertain factors that occur during the execution of the container shipping service [29]. These uncertain factors often referred to as disruptions, can be categorised into two types. The first type is defined as regular and recurring uncertainties such as congestion in the port's nautical area, varying terminal productivity or moves deviations, and unexpected waiting times due to tidal restrictions [34]. Due to the recurring profile, shipping lines use probabilistic models to absorb the negative effects by using buffers in tactical planning. However, too large buffer times lead to a decrease in port resources utilisation. The second type occurs more occasionally and irregularly and is labelled as disruption events. Examples of disruption events are gantry crane breakdowns, severe weather on route or in the port, and labour strikes. [29]. The port uncertainties that lead to schedule unreliability have negative consequences spread over three parts of the network: the arrival leg, the port call process, and the departure leg [47]. The most important consequences per part of the network are as follows:

- **Arrival voyage**
  - Waiting time on arrival leading to the asset (fleet) underutilisation.
  - Port congestion leading to jeopardised safety.
- **Port stay**
  - Under utilisation of port resources (cranes, nautical services)
  - Possible disturbances cascaded to connected supply chains (hinterland, barges, feeders).
- **Departure voyage**
  - Increased vessel speed to the succeeding port to recover the schedule leading to increased energy demand.
  - A possibility of cut and runs or a port skip with customer service deterioration as a consequence.
  - Risk of losing a window in the succeeding port, which on its turn might lead to additional waiting time, and thus, lower asset utilisation.

The lack of consistency in vessel schedules, or service unreliability, is seen by the industry and customers as a major challenge that the industry is faced with [43]. A report from Sea-Intelligence states that the global maritime schedule reliability is 59% in 2011 [42]. Another analysis from Cargo Smart found that more than half of the 10,000 TEU vessel is delayed more than 12 hours, and a quarter of them was delayed more than 24 hours [46]. A report from Drewry states that the average deviation of the actual arrival time compared to the estimated arrival time was 1.9 days in February 2015 [12]. To conclude on the problem statement, service unreliability is translated into additional operational costs [51], cascading time effects through the rest of the supply chain [48], decreased customer experiences, and additional fuel consumption and emissions. According to a report from Notteboom, 90% of the causes for schedule reliability find their origin in the port area [34].

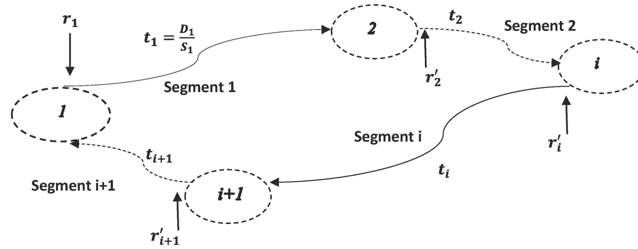


Figure 1: Schematic representation of a container line network [31].

2. Methodology

The literature proposes the Lean Six Sigma (LSS) approach as a frequently used and proven to be an effective methodology for optimisation projects in the product and process industry [28, 7, 45, 35, 8, 38]. The amalgamation of these optimisation theories allows the user to systematically analyse a current state and propose a future state [38]. The DMADE cycle is a derivation from the DMAIC cycle, which is part of the LSS approach [28]. The first three phases establish an overview of the current state, where the latter two phases propose a design implementation or so-called future state. This future state is dedicated to improving the inefficiencies, or so-called waste, from the current state. The DMADE cycle consists out of five phases with the following objective per phase:

1. Define the relationship between the port call and the GHG emissions.
2. Measure the current state of the port call process.
3. Analyse the current state of the port call process.
4. Design the future state.
5. Evaluate the future state.

2.1. Define mathematical relationships

A shipping container network is designed to facilitate trade between different regions overseas. In the strategic and tactical phase, decisions are made regarding the number and sequence of ports to visit, the number of containers to move, and the required time at sea and in the port areas. As a result, a network such as Figure 1 is composed. Within this network, there are static parameters (e.g., the distance between ports), decision variables (e.g., speed of the vessel) and stochastic variables (e.g., delays at ports).

2.1.1. Time factors

A vessel that operates in a network has two operating stages: time at sea or time in the port. If the vessel completes one service call, the sum of these operating times is equal to the total time that the vessel spends in the network. The time between intermediate departures is expressed with equation 1. The time that the vessel is at sea between ports is further described as the summation of the sailing time ($t_{s,s,i}$) and the waiting time at anchorage ($t_{s,a,i}$) (equation 2). Ideally, the vessel network is designed and operated in a way that no waiting times are present. However, due to uncertainties (mostly) originating from port operations, there is a chance of waiting time at anchorage. It is estimated that a container vessel spends 6% of the time at anchorage waiting due to delays in the port [17]. Shipping lines, together with terminal operators, incorporate buffers between consecutive vessels in the schedule to hedge against regular uncertainties [29]. Depending on the significance of the total uncertainty of the vessel in the port (δ_{p-1}), this buffer (σ_b) can (partially) absorb the delay for the succeeding vessel in the port (r_i) (equation 3).

$$t_{t,i} = t_{s,i} + t_{p,i} \tag{1}$$

$$t_{s,i} = t_{s,s,i} + t_{s,a,i} \tag{2}$$

$$r_i = -\sigma_b + \delta_{p,i-1} \tag{3}$$

If the delay is greater than the buffer, it is assumed that the vessel experiences waiting time on arrival. If the waiting time is little, the vessel starts drifting, and if the waiting time is significant, the vessel sails to the anchorage area [14]. Waiting time at anchorage (or during drifting) due to port delays leads to multiple consequences. One of these consequences is schedule unreliability. In the case of schedule unreliability, the vessel cannot sail according to the predefined schedule. Since the vessel is part of a bigger logistic supply chain network, the connected schedules of manufactures, service providers, customer etc., experience schedule unreliability as well. If such a connected (downstream) organisation operates under the Lean principles, the inventory is minimised in the process. This way, delays of, e.g., raw materials, directly affect the production rate of such an organisation [7].

A vessel that sails from one port to another covers a distance of a segment (D_i), and together with the schedule speed (S_i), this determines the time that the vessel (i) is sailing at sea ($t_{s,s,i}$).

$$t_{s,s,i} = \frac{D_i}{S_i} \tag{4}$$

Within this study, it is assumed that the arriving vessel (i) experiences anchorage time on arrival as a result of port uncertainties (delays) at the port of arrival that is caused by a succeeding vessel ($i-1$). In other words, during the planning phase of the network, there is no presence of scheduled waiting times. This leads to the following expression for anchorage time:

$$t_{s,a,i} = r_i \tag{5}$$

By substituting equation 4 and 5 into equation 1, the total time that a vessel spends between the departures of two ports is expressed in equation 6.

$$t_{t,i} = \frac{D_i}{S_i} + r_i + t_{p,i} \tag{6}$$

2.1.2. *Fuel costs and emissions*

The fuel consumed during the sailing time between the ports is calculated as the summation of the fuel consumption during sailing and the fuel consumption during the time at anchorage (equation 7). The fuel consumption at sea is further segregated into fuel consumption for the propulsion mechanisms and the auxiliary engines (equation 8). The auxiliary engine is both used during sailing and during the anchorage time [14]. It is further assumed that if the vessel is at anchorage, only the auxiliary engines are used. This results in the total fuel consumption as equation 8 proposes. This fuel consumption is on its turn a function of the energy consumption ($EC_{prop,s}$), and the specific fuel oil consumption ($SFOC_s$) [26]. These two variable are determined by a combination of time, speed, and vessel characteristics [4]. The speed and the vessel (and engine) characteristics determine the power-speed curve. The power is often empirically approximated as a cubic relationship with respect to sailing speed [29]. The calculation provides a specific required power ($P_{prop,s}$) at different levels of speed (S_i). Consequentially, by multiplying this power with the time that the power is required (t_s), the energy consumption ($EC_{prop,s}$) is calculated. Research by Kouzelis proposes a case study where this power-speed relationship is empirically approximated. The research applies the Hollenbach method by deploying a model from Frouws (TU Delft). The input and results from the power-speed relationship are depicted in Table 2 and Figure 3.

$$FC_s = FC_{s,s} + FC_{s,a} \tag{7}$$

$$FC_s = \left[FC_{prop,s} + FC_{aux,s}\right] + \left[FC_{aux,a}\right] \tag{8}$$

$$FC_{prop,s} = EC_{prop,s} \cdot SFOC_s \tag{9}$$

$$FC_{aux,s} = FC_{aux,a} = pFC_{aux,s} \cdot FC_{prop,s} \tag{10}$$

Parameters	Abbreviation	Value	SI Unit
Installed Power	P_{inst}	49920	kW
rpm at MCR	n_{MCR}	84	r/min
Propeller diameter	D_{prop}	10	m
Length overall	LOA	366	m
Length perpendiculars	LPP	347	m
Beam	$Beam$	48	m
Molded draught	T_m	16.0	m
Ballast draught	$T_{ballast}$	10.7	m
Depth	D	22.9	m
Sea margin	SM	15%	avg.

Figure 2: Input parameters for the Hollenbach Model [26]

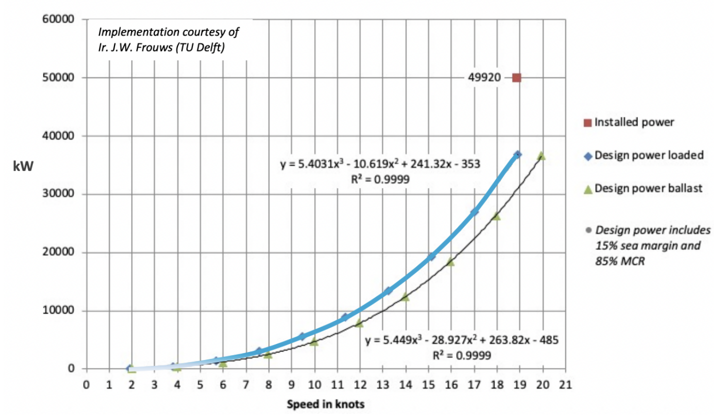


Figure 3: Hollenbach model output power-speed curve [26]

Where:

$$EC_{prop,s} = P_{prop,s} \cdot t_s \tag{11}$$

and:

$$P_{prop,s} = f(S_i) \tag{12}$$

$$P_{prop,s} = 5.4031 \cdot S_i^3 - 10.619 \cdot S_i^2 + 241.32 \cdot S_i - 353 \tag{13}$$

The installed main- and auxiliary engines emit exhaust gasses when the combustion of fossil fuels takes place. Besides oxygen, water and vapour, the exhaust gasses contain GHG emissions. As discussed in the introduction, the shipping industry is responsible for a significant amount (3%) of the total anthropogenic GHG emissions. With the current growth trend and forecast of the shipping industry, it is not likely that these numbers will decay. In reaction to the growing environmental concerns, the IMO compiled several rules and objectives that strive to reduce the emissions [21]. The most common GHG emissions are particulate matter, black carbon, carbon oxides, sulphur oxides, and nitrogen oxides. The pollutant emissions ratio (per) is defined as the ratio between the pollutant emissions and the specific fuel consumption [44]. Within the literature, this is often referred to as the conversion factor (equation 14).

For diesel combustion, the carbon dioxide CO_2 and sulphur oxide SO_x the *per* values are almost completely determined by the fuel type and corresponding characteristics. The values for nitrogen, black carbon, and particulate matter are less trivial and heavily influenced by the temperature and other conditions at which the fuel's combustion takes place [44]. The chemical composition of fuel consists mainly of hydrocarbons, e.g. $C_{15}H_{32}$. Given the atomic weights of carbon and hydrogen, respectively 12.011 and 1, the carbon mass fraction in fuel is approximately 85%. These hydrocarbons react with oxygen (O_2) with an atomic weight of 15.9994 during the engine's combustion. This results in a total atomic mass of 44 for CO_2. Using the atomic weights, the ratio between CO_2 and carbon is now equal to 44:12 [1]. With the initiation of the SECA, more emphasises is put on the amount of sulphur content in the fuel. The new regulation, which is often referred to as IMO 2020, limits the maximum allowable sulphur content in the fuel outside of the SECA zones to a value of 0.005 mass/mass. Within the SECA zones, this maximum is already at 0.001 mass/mass. Another method to comply with the legislation is by making use of an EGCS. This alternative method filters and captures the sulphur content in the exhaust valves before it is released in the air [22]. To conclude on the emissions, the *per* for carbon dioxide and sulphur oxide are equal to respectively 3.2 and 0.005-0.001 mass/mass of fuel used by the engines. As was mentioned earlier in this section, the *per* values for other emissions are less trivial and determined by the conditions during combustion [44].

Within this thesis the fuel carbon content per unit weight of fuel is approximated at 86.4% [9, 24]. This leads to the carbon dioxide emission consumption equation:

$$per = \frac{spe}{sfc} \tag{14}$$

$$EC_{CO_2} = (0.864) \cdot (44/12) \cdot FC_s = 3.17 \cdot FC_s \tag{15}$$

Other factors for GHG emissions are obtained from the Third IMO GHG Study [21]. The results are presented in table 1.

Emission type	Abbreviation	per HFO [g/g fuel]
Carbon dioxide	CO_2	3.17
Sulphur oxide	SO_x	0.05
Methane	CH_4	0.00006
Nitrogen oxide	N_2O	0.00016
Sulphur oxide	SO_x	0.004908
Particulate matter	PM	0.00699

Table 1
Pollutant emissions ratio (per) for different GHG emissions in HFO ([21])

2.2. Current state measurements

2.2.1. On time reliability

Reliability (of a schedule) is defined as "the probability that one or more of its links does not fail to function, according to a set of operating variables" [34]. To measure the vessels' on-time reliability, the actual arrival times (e.g., ATA Berth) are measured against the scheduled arrival times (e.g., ETA Berth). It depends on the level of deviation acceptance (λ) what the on-time reliability is. The higher the value of λ, the higher the probability (P) that the vessel arrives on time according to equation 16. The probability that the value for the arrival time deviation is between the acceptance of deviation with an upper limit (λ_u) and a lower limit (λ_l) is equal to:

$$P(\lambda_l \leq X \leq \lambda_u) = \int_{\lambda_u}^{\lambda_l} f(x)\, dx \tag{16}$$

2.2.2. Turnaround time reliability

The time that a vessel spends in the port area is predominantly determined by the time the vessel is alongside berth [29]. This is in the literature referred to as the terminal TAT, and equal to the time delta of the vessel arrival at the terminal (ATA Berth) and the departure from the terminal (ATD Berth) ([13], [43]). The Six Sigma approach contains a method to measure the capability to produce a service that meets the requirements. These measurements are called the process capability indices (C_p, and C_{pk}). The requirements are defined by using a LSL and an USL. Equation 19 and 20 represent the relation between the parameters. The greater the values for C_p and C_{pk}, the more capable the process is of performing according to the quality standards [38]. Within these equations, the mean (equation 17) and the standard deviation are substituted (equation 18).

$$\overline{x_d} = \frac{\sum x_d}{n} \tag{17}$$

$$\sigma_d = \frac{\sum (x_d - \overline{x_d})^2}{n-1} \tag{18}$$

$$C_p = \frac{USL - LSL}{6 \cdot \sigma_d} \tag{19}$$

$$C_{pk} = min\left[\frac{USL - \overline{x_d}}{3 \cdot \sigma_d}, \frac{\overline{x_d} - LSL}{3 \cdot \sigma_d}\right] \tag{20}$$

2.2.3. Idle time

Idle time is defined as the time that the vessel is alongside berth before and after operations [11]. Bottlenecks are, by definition, operations or activities that obstruct a process or a service from flowing to the next activity and leads to increased cycle times. Consequentially, bottlenecks and idle time are used interchangeably. The identification and elimination of bottlenecks in a process is a method that is used in the Lean Six Sigma DMAIC methodology [33]. Measuring each sub-process's duration helps to identify if there are any bottlenecks in the port call process, and if so, in which phase the bottlenecks occur.

2.3. Current state analysis

2.3.1. Waste evaluation

The main purpose of applying lean techniques is to identify and eliminate waste (or non-value-added activities) through continuous improvement [30, 38, 35]. According to Monden, three types of events or operations occur during a time interval: (i) Non-Value Adding (NVA), (ii) Necessary but Non-Value Adding (NNVA) and (iii) Value Adding (VA). The first type is defined as pure waste and is desired to be eliminated. NNVA contains operations that do not directly add value to the chain but must continue with the rest of the process. VA operations are all processes that directly contribute to the result [19]. This categorisation is one of the methods to divide operations and finally address waste. The Toyota Production System (TPS) comprises seven waste types [38]. Often, an eighth waste type is added to the list, which leads to the TIMWOODS model [19]:

- **T**ransportation
- **I**nventory
- **M**otion
- **W**aiting
- **O**verprocessing
- **O**verproduction
- **D**efect
- **S**kills

2.3.2. Cause and effect analysis

The idea of process improvements builds upon the action to solve the causes of variation (waste) in a measuring system. A simple graphical method to display the causes for variation is known by multiple names: the Ishikawa diagram, the fishbone diagram, and the cause and effect diagram [38, p. 216]. This diagram, which is part of the LSS methodology, aims to categorise the waste types in a schematic overview.

2.3.3. Current reality tree

The RCA is an analytical tool that is also part of the LSS methodology. The RCA is stated to be one of the most powerful tools to assess problems regarding quality, productivity, safety and accidents. Two stages broadly describe the method: identifying the potential cause and the validation of the root cause [2]. The relation between the cause and effect defined by an RCA is proven to be important to correctly design for improvements [20]. In other words, the RCA identifies and analysis root causes for operational waste in a system or process. A method to systematically identify the bottleneck (root cause) for a system is the Current Reality Tree (CRT). This tool is a part of the Thinking Process that develops solutions for common problematic situations [10]. The presence of symptoms leads to a set of Undesirable Effects (UDEs). According to the definition from the CRT, an UDE is identified by thee requirements:

- It has a negative implication on the performance of the process.
- The problem's presence is there for a longer time (at least several months).
- Previous attempts to sort out the problem did not lead to success.

The CRT that leads to the UDE depicts the path to undesirable outcomes that obstruct a well-performing process. In other words, it tells the user what is going wrong in the process, and what (bottleneck) needs to be solved. The application of the methodology focuses on the complete process rather than symptoms [10]. The UDEs that are assessed in this study are increased TAT, and arrival deviation and idle time. Additionally, a correlation between these UDEs is searched for in the diagram.

2.4. Dynamic Arrival Time (DAT) design

A concept which is initiated in the industry is called Virtual Arrival (VA). VA is defined as "...an agreement to reduce a vessel's speed on a voyage to meet a revised arrival time when there is a known delay at the discharge port" [23]. Often, a single static delay is used to test this concept. This study elaborates on this concept by introducing a Dynamic Arrival Time (DAT) to reduce the arrival speed in case of a delay. To test the effects of a dynamic speed adjustment to the fuel consumption and emissions, a DAT design with corresponding mathematical relationships is obtained.

2.4.1. Dynamic voyage parameters

A waypoint is an intermediate reference point along the route that the vessel is sailing. By adding several waypoints (w) along the route, the distance between the waypoints ($d_{i,w}$) is equal to the total route distance (D_i) divided over the number of waypoints.

$$d_{i,w} = \frac{D_i}{w} \tag{21}$$

If the vessel is at the port of origin, the number for n is equal to zero. If the vessel arrived at the port of destination, the value is equal to n. The Distance to Arrival (DTA_n) at a specific waypoint n is equal to the total distance D_i subtracted with the distance covered by the previous waypoint segments.

$$DTA_n = D_i - n \cdot d_{i,wp} \tag{22}$$

According to the schedule, the Time to Arrival (TTA_n) at a waypoint n is equal to the Estimated Time of Arrival (ETA) in the port of arrival, subtracted with the time that the vessel used is underway to cover the previous waypoint segments. The time that the vessel is underway is equal to the already covered distance, divided by the speed that is maintained over that segment (S_i). If the delay of the succeeding vessel in the port of arrival is greater than the buffer, the ETA now becomes a Dynamic Arrival Time (DAT_i), where $DAT_i > ETA_n$.

$$TTA_n = ETA_i - \frac{n * d_{i,wp}}{S_d} \tag{23}$$

$$TTA_n = (ETA_i + r_{i-1}) - \frac{n * d_{i,wp}}{S_d} = DAT_i - \frac{n * d_{i,wp}}{S_d} \tag{24}$$

The last voyage parameter that is determined at waypoint n is the vessel speed. This is the speed that needs to be obtained over the upcoming waypoint segments to meet the DAT_i in the arrival port. Substituting equation 24, and 22 into 4 gives the following equation for the vessel's optimal speed at waypoint n.

$$S_{D,n} = \frac{DTA_n}{TTA_n} = \frac{D_i - n \cdot d_{i,wp}}{DAT_i - \frac{n \cdot d_{i,wp}}{S_i}} \tag{25}$$

2.4.2. Dynamic fuel consumption and emissions

A vessel that sails in a network surpasses the waypoints, where either a delay is known or unknown. To incorporate this in the network, two parameters are proposed: α and β. The values of α and β are constraints by the total number of waypoints (w).

$$w = \alpha + \beta \tag{26}$$

where:

α = waypoints segments where the delay is unknown
β = waypoints segments where the delay is known

Substituting equation 26 into equation 7 results in the dynamic fuel equation 27. In this equation, $S_D < S_d$, and thus, for a higher value of β, a higher value for $DFC_{s,s}$ is obtained.

$$\begin{aligned} DFC_{s,s,i} &= \alpha \cdot DEC_{s,s,i} \cdot SFOC_{d,i} + \\ &\beta \cdot DEC_{s,s,i} \cdot SFOC_{D,i} \\ &= \left(\alpha \cdot P_{prop,s,i}(S_{d,i}) \cdot t_{d,i} \cdot SFOC_{d,i}\right) + \\ &\left(\beta \cdot P_{prop,s,i}(S_{D,i}) + t_{D,i} \cdot SFOC_{D,i}\right) \end{aligned} \tag{27}$$

Substituting the Dynamic Fuel Equation (27) into the equation for the pollutant emissions ratio (14), while using the input from Table 1, the different values for GHG emissions are calculated.

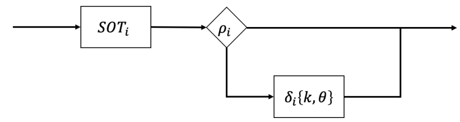


Figure 4: Modelling uncertainties at sub-process i using a probability ρ and impact δ

2.5. Network simulation using a DAT

2.5.1. Model scenarios and uncertainties

To measure this design's effect in a container liner network, three scenarios for different levels of uncertainty are tested in a period of a year. The first scenario ($j = 1$) tests the output variables under a scenario where no uncertainties are present, and the vessel maintains the schedule. The second scenario ($j = 2$) tests a network subject to different uncertainty levels but does not incorporate a DAT. The third scenario ($j = 3$) tests the network with the same uncertainty levels as scenario two, but now with a DAT. Risk, interchangeably used with uncertainties, is defined by the multiplication of a probability and an impact.

$$Risk\ (uncertainty) = Probability * Impact \tag{28}$$

There are five sub-processes identified throughout the port call process [11]. The uncertainties occur during one of these sub-processes.

2.6. Model parameters

Based on the LSS model, several parameters and variables are determined. The input parameters contain vessel, route, and port call parameters. These parameters are deterministic and represent a mainline vessel in a Short Sea Shipping network. An overview of the model parameters is depicted in Table 2.

3. Results

Following the methodology, two models are proposed to measure the current state and a future state. These models are a Lean Six Sigma (LSS) model and a simulation model.

3.1. LSS model

For a number of 433 large container vessels in the Port of Rotterdam (POR), the event logs are analysed. It is found that these vessels have on-time reliability of 78.0% and a turnaround time reliability of 42.6% if a four-hour specification limit is applied to the data. See Table 3 and 4 for the values that correspond to other specification limits (λ_l; λ_u). Additionally, the idle time assessment indicates that the operations before and after the terminal operations show significant data variations. There are no further data correlations found that explain these variations, and therefore, a complementary waste analysis is performed. Following the proposed methodology, a qualitative analysis leads to the identification of six root causes. These root causes lead to the

	Abbreviation	Value	SI Unit
Vessel	LOA	366	m
	B	48	m
	DWT	145,000	t
	MEP	89,700	kWh
	$pAEP$	0.22	-
	$SFOC_s$	160.2	mt/MWh
	S_i	9.1-19	knots
	C	13,500	TEU
	S	25	knots
Route	D_i	540	Nm
	w	5	-
	$d_{i,wp}$	108	Nm
	k	4	-
	S_i	18	knots
	σ_b	4	hours
Port Call	NTA_{SOT}	3	hours
	IBO_{SOT}	1	hours
	IAO_{SOT}	1	hours
	IBO_{SOT}	3	hours
	L_{TEU}	2,200	TEU
	$PMPH$	100	TEU/hour

Table 2
Simulation input parameters. Partially obtained from Moon and Wang [49, p. 451], and [26]

λ_l; λ_u	On-time	Not on-time
hours	[%]	[%]
-2; 2	55.2	44.8
-4; 4	78.0	22.0
-6; 6	89.1	10.9
-8; 8	92.6	7.4

Table 3
On-time arrival reliability for different specification limits

λ_l; λ_u	C_p	C_{pk}	TAT_P	$1 - TAT_P$
hours	-	-	[%]	[%]
-2; 2	0.078	0.069	22.9	77.1
-4; 4	0.156	0.146	42.6	57.4
-6; 6	0.233	0.224	59.5	40.5
-8; 8	0.311	0.302	72.8	27.2

Table 4
Turnaround process capability indices and reliability measures for different specification limits

Sub-process	Mean	Median	Std dev
Pilot Time Arrival	0.15	0	0.48
Nautical Time Arrival	1.71	2.03	1.67
Idle Time before Operations	1.71	1.28	2.11
Cargo Operations	20.73	16.78	12.57
Idle Time after Operations	2.03	1.08	3.10

Table 5
Statistical analysis of sub-processes

formation of idle time and affect the reliability of the port call. The output of this root cause analysis is used as input for the simulation model. These root causes are listed as follows:

- Defects (inappropriate processing)
- Lay-by
- Early completion
- Adverse weather
- False/missing information and communication
- Arrival deviation

3.2. Simulation model

The root cause analysis result indicates that missing information and arrival variations lead to the formation of idle time and increased turnaround time. Just in Time (JIT) is a philosophy that is part of the Lean methodology [38]. The technique, which is more frequently used in the manufacturing industry, calls for the production of what the customer wants and when they want it [6].

A hybrid Agent-Based Discrete Event Simulation (AB-DES) is proposed to test a Dynamic Arrival Time's effectiveness to enhance JIT Arrival in a SSS network that is subject to uncertainties. The model is programmed utilising the open-source software of Anylogic [3]. The simulation model's goal is to test if design adjustments in the current state lead to better JIT performance, and thus, increased voyage efficiency by lowering emissions.

3.3. Turnaround time

The combination of a delay quantity (impact) and a probability represent the port call's risk. This is translated into an increased port TAT. The higher the risk of uncertainties, the higher the increased port TAT on average. Scenario $j = 2$ and $j = 3$ are tested for the same risk conditions and thus have the same increase in port TAT. This additional time in the port is compared to scenario $j = 1$, where no uncertainties are present in the network. The increased TAT varies from 2.0-7.3%.

Regular uncertainties		TAT hr	WTA hr	FC/E mt
$j = 1$	Value	30.0	0.0	n/a
	Index	100.0	0.0	n/a
$j = 2$	Value	32.2	52.2	1719.0
	Index	107.3	100.0	100.0
$j = 3$	Value	32.2	48.5	1559.4
	Index	107.3	92.9	90.7
	ΔFC	n/a	n/a	160.0
	ΔCO_2	n/a	n/a	507.0
	ΔSO_x	n/a	n/a	8.0
	ΔCH_4	n/a	n/a	0.0
	ΔN_2O	n/a	n/a	0.03
	ΔPM	n/a	n/a	1.12

Table 6
Simulation results for irregular uncertainties

Irregular uncertainties		TAT hr	WTA hr	FC/E mt
$j = 1$	Value	30.0	0.0	n/a
	Index	100.0	0.0	n/a
$j = 2$	Value	31.6	81.7	7798.0
	Index	105.3	100.0	100.0
$j = 3$	Value	31.6	46.5	5414.3
	Index	105.3	56.9	69.4
	ΔFC	n/a	n/a	2384.0
	ΔCO_2	n/a	n/a	7556.0
	ΔSO_x	n/a	n/a	119.0
	ΔCH_4	n/a	n/a	0.14
	ΔN_2O	n/a	n/a	0.38
	$\Delta PM.$	n/a	n/a	16.7

Table 7
Simulation results for regular uncertainties

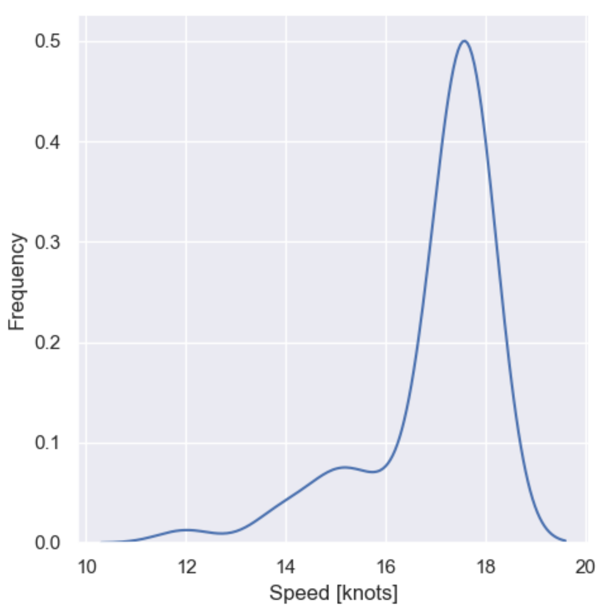


Figure 5: Speed reduction distribution of sea transits with a dynamic speed for regular uncertainties

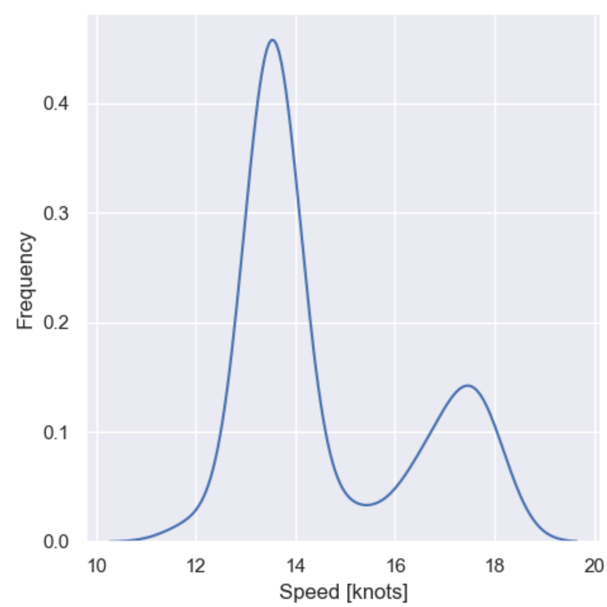


Figure 6: Speed reduction distribution of sea transits with a dynamic speed for irregular uncertainties

3.4. Waiting time

The simulation results for $j = 2$ and $j = 3$ are compared to each other through an index number. Scenario $j = 3$ shows significant reductions of waiting time on arrival with indices ranging from 15.4 to 90.7. To recall the definition, the concept of JIT focuses on the complete elimination of waiting time on arrival. Due to the accumulating delay over the port call process, often the buffer is exceeded during the last part of the voyage. At this stage, the vessel has surpassed the latter waypoint, and speed adjustments are not calculated. Consequentially, the network remains with waiting time on arrival. This is seen for all scenarios under different levels of uncertainty. However, there is a difference noticed between the reduction at higher levels of risk. A high probability and low impact (regular uncertainties) case show a reduction of only 7.1% compared to the low probability and high impact (irregular uncertainties) case. A reduction of 43.1% is achieved.

3.5. Fuel and emissions

The fuel consumption is calculated by multiplying the Specific Energy Consumption (SEC) with the time that the vessel sails at this condition. The high probability and low impact results show more speed adjustments but on a small level. This is because there are more port calls where the delay exceeds the buffer with a small amount of time. This is also represented with the speed distribution graph near the design speed of 18 knots (Figure 5). Given the small differentials in speed, the effect on fuel consumption is also relatively small. For the highest probability ($\rho = 0.8$), a maximum value of 160 metric ton fuel reduction is obtained (9.3% reduction compared to scenario $j = 2$).

On the other hand, if the probability is low but the impact increases, the vessel shows greater speed adjustments. This is depicted in Figure 6 with a speed distribution curve that is further shifted from the design speed. Since the simulation is programmed in a way that there are uncertainties before and after the operations, two peaks are formed. The right peak represents a situation with a delay identification and communication at an early sea transit stage. This early notice allows the vessel to adjust the speed over a greater distance and time. Given that there is more time (TTA) and distance (DTA) to adjust the speed, the speed adjustment deviation is small. The left peak depicts a scenario with a late identification and communication of the delay. Hence, there is less time (TTA) and distance (DTA), and the differential of the new speed is now greater. Another observation is that the left peak has a higher density than the right peak. This can be explained with the buffer of four hours that is incorporated in the schedule. The incorporated buffer ($\sigma_b = 4$) is in close range of the delay's impact before and after operations ($k = 3$). Although the probability is low, if both of these delays are formed, the time to cover at the last phase of the transit is suddenly considerable. In other words, a high impact delay at a late stage causes a sudden speed reduction during the last section of the sea transit. For the highest impact ($\delta = 3.0$), a maximum value of 2384 metric ton fuel is obtained (30.6% reduction compared to scenario $j = 2$).

4. Verification and validation

A simulation model is developed with a specific purpose, and the validity is determined with respect to that purpose [40]. This simulation model aims to test the effect of incorporating a Dynamic Arrival Time on the fuel consumption and emissions in a SSS network. There are multiple verification and validation techniques and tests available, where a combination of these techniques and tests are mainly used [40]. The combination of techniques and tests used for this thesis is animation verification, internal verification, parameter variability (or sensitivity analysis), event validation, and the validation by comparing the results against other model results. The parameter variability verification shows that after increasing the impact with more than 3 hours at a probability of 0.2, the dynamic arrival speed (S_D) shows values that are greater than the design speed (S_d). Given the simulation model's defined purpose (reducing speed), it is no longer ensured that the simulation model works correctly under this condition. The event (of uncertainties) validation shows that the qualitative LSS model results lie somewhere in between the simulation results.

5. Conclusion

This study establishes two models by following the five phases of the DMADE cycle. Firstly, the research deploys several Lean Six Sigma methodology tools to assess the current state of the port call process. The port call process is particularly analysed since more than 90% of the reasons for schedule unreliability originate from the port [34]. A qualitative (measure) and quantitative (analyse) study established a current state model. The current state model results show that there are significant variations when it comes to arrival time compared to the schedule, turnaround times, and subprocesses. By applying a specification limit of 2 hours, it is found that 44.8% of the arriving vessel is not on time with a ratio of 60 to 40% of early and late arrival. If the same specifications limits are applied to the TAT reliability, it is found that only 22.9% of the port calls are within the specification limits. This is equal to a value of 0.078 for the process capability index. The latter performance measurement of idle time segregates the complete process in several sub-processes to identify bottlenecks in the system. The data found from the time deltas before and after container lifting operations show many variations that indicate operational waste during these sub-processes. These variations indicate that the port area is far from Lean. Furthermore, it is found that variations (delays) in the port call might lead to Waiting Time on Arrival (WTA). This WTA can be used to prolong the sea transit leg and thus, reduce emissions. If this is not done correctly, unnecessary levels of fuel are consumed. This is defined as transportation waste, and according to the Lean theory, the objective is to eliminate waste from a system or process [38].

The waste analysis shows that six root causes lead to variations in the port call performance. These root causes are missing information, adverse weather conditions, arrival deviation, early completion, lay-by, and inappropriate processing (defects). To apply the Theory of Constraints by Goldrath to this model, the Current Reality Tree is composed. Within the CRT, missing information is the main bottleneck for operational inefficiencies. This root cause leads to variations in the port call TAT, and lead to jeopardised arrival times. This type of root cause is assumed to greatly impact the port call's performance with cascading effect through the rest of the network. Additionally, solving this root cause does not require major capital investment or time but rather a change in mindset and willingness. This is in line with the Theory of Constraints. As the literature indicates, the shipping industry is unwilling to share data between competitors, but this is found to be the major improvement area. Other root causes, such as defects (e.g. twistlocks, lashing rods or cranes), require a high level of capital investments in the material. To conclude the current state analysis, the in-

	$j = 2$	$j = 3$	
		regular	*irregular*
Fuel consumption [ton]	39291.7	39131.7	36907.7
Reduction	n/a	160.0	2384.0
Index	100.0	99.5	93.9

Table 8
Effect of utilising a DAT ($j = 3$) on the fuel consumption for all vessels

adequate usage of information in a shipping network leads to Waiting Time on Arrival (WTA) and increased Turnaround Time (TAT). In the Lean waste terminology, the WTA and increased TAT are Non-Value-Adding (NVA) to the network and need to be eliminated. Given this finding, together with a technical study on the container network design regarding fuel consumption and emissions, the conclusion is drawn that a Dynamic Arrival Time design can contribute to solving this operational waste.

Following the DMADE approach, two phases are left for the future state model: the design and evaluation phase. The first phase proposes a design that is expected to contribute to network optimisation based on the foregoing phases. Secondly, this design is tested employing an ABDES simulation model. As mentioned in the previous paragraph, the proposed design implements a Dynamic Arrival Time (DAT). This design is reflected against the emissions that can be reduced by successfully implementing this design in the shipping network.

To test the proposed method of delay detection and communication, a simulation model is programmed that reflects a mainline container network with four ports and four connecting sea legs. The network is executed over a year where uncertainties (variances) are programmed during the port operations. The simulation model tests three scenarios that are exposed to different levels of uncertainties. The simulation aims to provide insights on the effects of uncertainties on emissions and to what extent the DAT could contribute to a reduction of the emissions. A specific network results show that using an DAT can lead to a reduction of 30.9% of carbon dioxide emissions. This number only reflects the vessels that are delayed by irregular uncertainties. If all vessels are taken into account for that year, a maximum of 6.9% reduction is achieved for these conditions. If the network is exposed to regular uncertainties, the results show a 9.3% reduction for the delayed vessels, representing a 0.5% reduction for all the vessels. The results are depicted in Table 8.

6. Recommendations

This study aims to contribute to MEPC.323(74) resolution where voluntary cooperation between the port and shipping sector is encouraged to reduce GHG emissions from the shipping industry [14]. This is a continuous improvement process, and the recommendations for further research from this section are proposed to take this challenge forward.

- **Waste evaluation:** establish a collaborative waste assessment framework that incorporates input from the required stakeholders. Such a collaborative model must comprise data flows and human input on delay assessment.
- **Network scheduling:** integrate multiple networks and increase the port capacity with more terminals and berths.
- **Uncertainties:** improve the programming of uncertainties with event log data as input.
- **Simulation:** extent the simulation with DATs for all vessels and ports in a network (rather than a single port) and add more waypoints along the route to improve the last mile accuracy.
- **JIT Effect:** assess and quantify the effect of JIT Arrival on the efficiency of the port call process.
- **Fuel and emissions:** Assess the effect on the fuel consumption and emissions by utilising more accurate engine data.

References

[1] Nicoleta Acomi and Ovidiu Cristian Acomi. “The Influence of Different Types of Marine Fuel over the Energy Efficiency Operational Index”. In: *Energy Procedia* 59 (2014). ISSN: 18766102. DOI: 10.1016/j.egypro.2014.10.373.

[2] Shri Ashok Sarkar, Arup Ranjan Mukhopadhyay, and Sadhan Kumar Ghosh. “Root cause analysis, Lean Six Sigma and test of hypothesis”. In: *The TQM Journal* 25.2 (Feb. 2013). ISSN: 1754-2731. DOI: 10.1108/17542731311299609.

[3] Andrei Borshchev and Ilya Grigoryev. *The Big Book of Simulation Modeling: Multimethod Modeling with Anylogic 8*. 2013.

[4] C F Broersma. *Marine Fuel Outlook 2028: Modeling the effect of the IMO legislation on marine fuel demand and price*. Tech. rep. 2020.

[5] Berit Dangaard Brouer, Christian Vad Karsten, and David Pisinger. “Optimization in liner shipping”. In: *Annals of Operations Research* 271.1 (Dec. 2018). ISSN: 0254-5330. DOI: 10.1007/s10479-018-3023-8.

[6] Cem Canel, Drew Rosen, and Elizabeth A. Anderson. “Just-in-time is not just for manufacturing: a service perspective”. In: *Industrial Management & Data Systems* 100.2 (Mar. 2000). ISSN: 0263-5577. DOI: 10.1108/02635570010286104.

[7] Bill Carreira. *Lean Manufacturing That Works : Powerful Tools for Dramatically Reducing Waste and Maximizing Profits*. Saranac Lake, UNITED STATES: AMACOM, 2004. ISBN: 9780814428542. URL: http://ebookcentral.proquest.com/lib/delft/detail.action?docID=243050.

[8] Ana C.Paixo Casaca. “Simulation and the lean port environment”. In: *Maritime Economics and Logistics* 7.3 (2005), pp. 262–280. ISSN: 1479294X. DOI: 10.1057/palgrave.mel.9100137.

[9] James J. Corbett, Haifeng Wang, and James J. Winebrake. “The effectiveness and costs of speed reductions on emissions from international shipping”. In: *Transportation Research Part D: Transport and Environment* 14.8 (Dec. 2009). ISSN: 13619209. DOI: 10.1016/j.trd.2009.08.005.

[10] James Cox III and John Schleier. *Theory of Constraints Handbook*. Vol. 1. McGraw-Hill Professional, 2010.

[11] DCSA. *Standards for a just-in-time port call*. Tech. rep. DCSA, Oct. 2020. URL: https://dcsa.org/wp-content/uploads/2020/10/20201020-DCSA-P6-JIT-Port-Call-Publication-Release1-V1.0-FINAL-1.pdf.

[12] Drewry Shipping Consultants. *Annual Container Market Review and Forecast*. Tech. rep. Drewry Shipping Consultants Ltd., 2006.

[13] Cesar Ducruet and Olaf Merk. "Examining container vessel turnaround times across the world". In: *Port Technology International* 59 (2013).

[14] *GEF-UNDP-IMO GloMEEP Project and the GIA: Just In Time Arrival Guide - Barriers and Potential Solutions*. Tech. rep. 2020.

[15] GloMEEP. *Just In Time Arrival Guide - Barriers and Potential Solutions*. Tech. rep. GEF-UNDP-IMO Glo-MEEP, 2020.

[16] Mihalis M Golias et al. "The berth allocation problem: Optimizing vessel arrival time". In: *Maritime Economics & Logistics* 11.4 (Dec. 2009). ISSN: 1479-2931. DOI: 10.1057/mel.2009.12.

[17] Anna Gustafsson. *Slow steaming to arrive at the right time*. Feb. 2019. URL: https://www.wartsila.com/insights/article/slow-steaming-to-arrive-at-the-right-time.

[18] Ayudhia P. Gusti and Semin. "The effect of vessel speed on fuel consumption and exhaust gas emissions". In: *American Journal of Engineering and Applied Sciences* 9.4 (2016), pp. 1046–1053. ISSN: 19417039. DOI: 10.3844/ajeassp.2016.1046.1053.

[19] Peter Hines and Nick Rich. "The seven value stream mapping tools". In: 17.1 (1997), pp. 46–64. ISSN: 0144-3577. DOI: 10.1108/01443579710157989. URL: https://www.leancompetency.org/wp-content/uploads/2015/09/Value-Stream-Mapping-seven-tools.pdf.

[20] L.A.M. Huertas-Quintero et al. "Root cause analysis support for quality improvement in electronics manufacturing". In: *Assembly Automation* 31.1 (2011), pp. 38–46.

[21] International Maritime Organization. "RESOLUTION MEPC.304(72) (adopted on 13 April 2018) INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS". In: 304.April (2018).

[22] International Maritime Organization. *IMO 2020 – cutting sulphur oxide emissions*. 2019.

[23] INTERTANKO. *Virtual Arrival Optimising Voyage Management and Reducing Vessel Emissions-an Emissions Management Framework*. Tech. rep. 2010. URL: www.ocimf.com.

[24] Haiying Jia et al. "Energy efficiency with the application of Virtual Arrival policy". In: *Transportation Research Part D: Transport and Environment* 54 (July 2017). ISSN: 13619209. DOI: 10.1016/j.trd.2017.04.037.

[25] Rasmus Jorgensen. *Slow steaming - the fuel story*. Tech. rep. A.P. Moller - Maersk Group, 2011.

[26] Konstantinos Kouzelis. *Marine Fuel of the Future: A Decision Support Tool for Shipowners*. Tech. rep. Delft: Delft University of Technology, 2021.

[27] Chung-Yee Lee, Hau L. Lee, and Jiheng Zhang. "The impact of slow ocean steaming on delivery reliability and fuel consumption". In: *Transportation Research Part E: Logistics and Transportation Review* 76 (Apr. 2015). ISSN: 13665545. DOI: 10.1016/j.tre.2015.02.004.

[28] Higor dos Reis Leite and Guilherme Ernani Vieira. "Lean philosophy and its applications in the service industry: a review of the current knowledge". In: *Production* 25.3 (Feb. 2015). ISSN: 1980-5411. DOI: 10.1590/0103-6513.079012.

[29] Chen Li, Xiangtong Qi, and Chung-Yee Lee. "Disruption Recovery for a Vessel in Liner Shipping". In: *Transportation Science* 49.4 (Nov. 2015). ISSN: 0041-1655. DOI: 10.1287/trsc.2015.0589.

[30] Nicholas Loyd et al. *APPLICATION OF LEAN ENTERPRISE AND SIX SIGMA AS AN AMALGAMATED IMPROVEMENT STRATEGY*. Tech. rep. 2010.

[31] Ioannis Mallidis et al. "The impact of slow steaming on the carriers' and shippers' costs: The case of a global logistics network". In: *Transportation Research Part E: Logistics and Transportation Review* 111 (Mar. 2018). ISSN: 13665545. DOI: 10.1016/j.tre.2017.12.008.

[32] Abishek Nair, Shahmeer Magsi, and Dita Bruijn. *JUST IN TIME SAILING*. Tech. rep. Rotterdam, Feb. 2021.

[33] Nikhil Nandakumar, P.G. Saleeshya, and Priya Harikumar. "Bottleneck Identification And Process Improvement By Lean Six Sigma DMAIC Methodology". In: *Materials Today: Proceedings* 24 (2020). ISSN: 22147853. DOI: 10.1016/j.matpr.2020.04.436.

[34] Theo E Notteboom. "The Time Factor in Liner Shipping Services". In: *Maritime Economics & Logistics* 8.1 (Mar. 2006). ISSN: 1479-2931. DOI: 10.1057/palgrave.mel.9100148.

[35] Ana Cristina Paixão and Peter Bernard Marlow. "Fourth generation ports – a question of agility?" In: *International Journal of Physical Distribution & Logistics Management* 33.4 (May 2003). ISSN: 0960-0035. DOI: 10.1108/09600030310478810.

[36] H. Psaraftis and C. Kontovas. "CO2 emission statistics for the world commercial fleet." In: *WMU Journal of Maritime Affairs* 8 (2009), pp. 1–25.

[37] Harilaos N Psaraftis, Christos A Kontovas, and Nikolaos M P Kakalis. "Speed reduction as an emissions reduction measure for fast ships". In: Athens: International Conference on Fast Sea Transportation, Oct. 2009. URL: https://www.researchgate.net/publication/242094743.

[38] Thomas Pyzdek. *The Six Sigma Handbook: A Complete Guide for Green Belts, Black Belts, and Managers at All Levels*. The McGraw-Hill Companies, 2003.

[39] Nishatabbas Rehmatulla and Tristan Smith. "Barriers to energy efficient and low carbon shipping". In: *Ocean Engineering* 110 (Dec. 2015). ISSN: 00298018. DOI: 10.1016/j.oceaneng.2015.09.030.

[40] Robert G. Sargent. "Verification and validation of simulation models". In: *Proceedings of the 2010 Winter Simulation Conference*. IEEE, Dec. 2010. ISBN: 978-1-4244-9866-6. DOI: 10.1109/WSC.2010.5679166.

[41] Riley E.J. Schnurr and Tony R. Walker. "Marine Transportation and Energy Use". In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier, 2019. DOI: 10.1016/B978-0-12-409548-9.09270-8.

[42] Sea-Intelligence. *Global Liner Schedule Reliability Report*. Tech. rep. SeaIntel Maritime Analysis, 2011.

[43] Brian Slack et al. *Ships time in port*. Tech. rep. 1. 2018, pp. 45–62.

[44] D Stapersma. "Performance Analysis". In: *Diesel Engines: A fundamental approach to performance analysis, turbocharging, combustion, emissions and heat transfer*. Vol. 1. Delft, 2010. Chap. 2, pp. 66–67.

[45] Vijaya Sunder M. "Lean six sigma project management – a stakeholder management perspective". In: *The TQM Journal* 28.1 (Jan. 2016). ISSN: 1754-2731. DOI: 10.1108/TQM-09-2014-0070.

[46] Peter Tirschwell. *Berth Productivity: The Trends, Outlook and Market Forces Impacting Ship Turnaround Times*. Tech. rep. JOC Group, July 2014.

[47] United Nations. *Digitalizing the port call process TRANSPORT AND TRADE FACILITATION Series No 13*. Tech. rep. 2020. URL: https://unctad.org/en/PublicationsLibrary/dtltlb2019d2_en.pdf.

[48] Bert Vernimmen, Wout Dullaert, and Steve Engelen. "Schedule Unreliability in Liner Shipping: Origins and Consequences for the Hinterland Supply Chain". In: *Maritime Economics & Logistics* 9.3 (Sept. 2007). ISSN: 1479-2931. DOI: 10.1057/palgrave.mel.9100182.

[49] H Wang et al. “Reduction of GHG emissions from ships. Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures.” In: (July 2010).

[50] Andreas Wiesmann. “Slow steaming-a viable long-term option?” In: *Wartstila Technical Journal* (Feb. 2010).

[51] A van der Wurff. *Maritime and Ports industry initiative overview*. Tech. rep. Maersk Line, 2016.

[52] Gang Yu and Xiangtong Qi. *Disruption Management*. WORLD SCIENTIFIC, Aug. 2004. ISBN: 978-981-256-017-9. DOI: 10.1142/5632.