Integration of port approach in the port call

Using information sharing and Virtual Arrival for the reduction of vessel emissions

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SAAB

TU Delft

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by

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Abstract

In 2018, the International Maritime Organisation (IMO) adopted a strategy to reduce the emission of greenhouse gasses of maritime shipping in the near future. The IMO is the international governing body for maritime shipping standards. This strategy aims to reduce the carbon emissions of global shipping by 50% in 2050 compared to 2008. It furthermore aims to phase out emissions of greenhouse gasses (GHG's) entirely in the long term. Next to this, the IMO also wants to ensure that the total emissions peak before 2025 and steadily decrease until 2050 (International Maritime Organisation, 2018).
This reduction brings a significant impact on the global emission of greenhouse gasses, because the maritime shipping industry emits an amount of around 1 billion tons of CO_2 in 2018. Global shipping is responsible for 75% of this total. To put this into perspective, this is around 2.9% of the total human emission of CO_2 that year International Maritime Organisation (2018).
Furthermore, the international shipping industry also has an effect on local air quality surrounding ports, because the ship's engines work as generators during berthing or anchoring, depositing other greenhouse gasses. Locally deposited pollution can be found in the form of nitrogen oxides (NO_x) and sulphur oxides (SO_x) (Stapersma, 2010). Arjona Aroca et al. (2020) estimated based on data obtained from port calls in the Mediterranean that ships produce around 15% of their emissions while in port.

Information-sharing between actors in the port call has been deemed an integrator for coordination and a way to optimize the port call process and reduce emissions (Lind et al., 2015). The research question underlying this work is therefore:

"How can increased information-sharing reduce emissions of sea-going vessels in the port call process?"

It was found that with the concept of coordination from supply chain management and intelligent control of large infrastructures a preliminary model can be constructed in which the operational optimization of the port call through information-sharing can be related to logistics synchronization as well as the creation of operational plans. The overview of this model is given in figure 1. This model assumes that for port call optimization, the challenge lies in creating suitable information-sharing concepts and strategies which deliver the context and process visibility. A sound operational plan is determined based on the system goals and sets the actions to obtain those goals. This plan is in turn determined by the way logistics are synchronized over the port call process which also sets the boundaries for the operational plans. Lastly, the logistics synchronization determines the information needs underlying the information-sharing in the system.
Concepts that relate to port call optimization are the virtual arrival concepts and optimal scheduling of vessel movements (Abou Kasm et al., 2021) (Jia et al., 2017a) as well as Port Collaborative Decision Making (Lind et al., 2015). This research sets out to combine these optimization methods for the reduction of emissions for sea-going vessels by assessing these concepts in an integrated way. Such integration of these concepts, relating to the

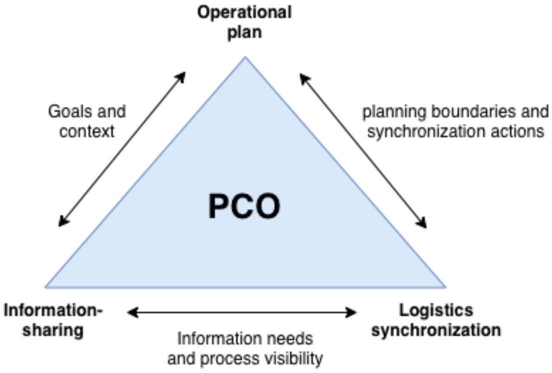

Figure 1: value drivers for port call optimization

coordination statement made by Lind et al. (2015), can be done in the light of intelligent control of transport systems as proposed in Negenborn and Hellendoorn (2010). This way of approaching port call optimization has not been found in literature yet. The research first focuses on the control structure to be implemented based on a system and stakeholder analysis. Secondly, an optimal controller is designed with the use of Linear Programming and theory on rolling-horizon scheduling. This optimal control strategy is then tested by simulating port calls for a case study of Darwin Port, Australia with different approaches to the rolling horizon scheduling.

This thesis proposes a single-agent control structure for vessel movement scheduling and vessel inflow regulation, based on the analysis that the Harbour Master is the main point of planning for vessel movements in port. The single-agent control structure was deemed feasible to handle the vessel arrival problems in reasonable time and with profitable results for emission reduction. Measurement inputs for the vessel operations scheduling comes from the proposed PortCDM concepts as described in Lind et al. (2015) and AIS data of approaching vessels. The system can be controlled by postponing or advancing vessel movements in time to ensure optimal resource use. Secondly, approaching vessels can be advised to decrease their speed as per the virtual arrival concept developed in literature. An overview of the control structure including actuation of the system and measurements is given in figure 2

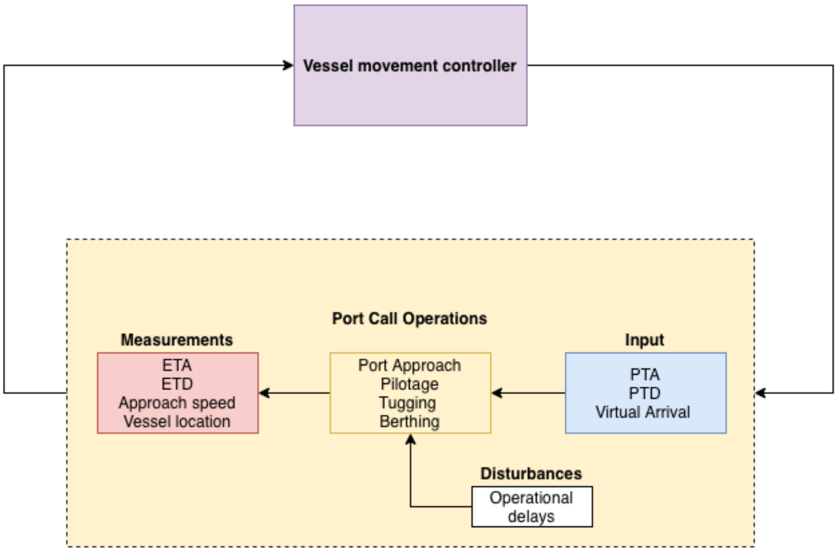

Figure 2: Control structure for vessel movements in the port call process

The design of the vessel movement controller is based on the rolling horizon approach found in intelligent control of transport systems. This approach has already yielded profitable results in aircraft arrival scheduling (Glomb et al., 2022). Focusing on resource availability in the port call, a Mixed-Integer Linear Program (MILP) designed by Abou Kasm et al. (2021) is adapted to be used for a rolling-horizon scheduling strategy. The MILP scheduling model is rewritten to cope with the rolling horizon approach by the selection of subsets of vessels in the planning horizon. Furthermore, constraints regarding vessel speeds are implemented with regards to the Virtual Arrival approach.

The intelligent control concept presented is tested with regards to emission reduction by creating a Discrete Event Simulation model of Darwin Port, Australia. Three experiments are performed, a base case in which no virtual arrival and optimal scheduling are present. Vessels arrive at port and are helped in a First Come, First Serve manner. Secondly, the impact of optimal control is researched with regards to the length of the scheduling horizon and the control period, or rescheduling period. The first experiment assumes a short horizon of 24 hr with a control period of 1 hr. The second experiment takes on a planning horizon of 48 hrs where the control period is 5 hrs. The virtual arrival approach is designed around the way point approach from Broersma (2021), where the first way point where virtual arrival takes action is 500 NM from the port and the distance between way points is 100 NM. The outcomes of the experiments are shown in table 1.

Table 1: Comparison of average emissions per vessel between experiments

Emissions (Tonnes)	FCFS	$T_c = 1$, $\lvert T\rvert = 24$	$T_c = 5$, $\lvert T\rvert = 48$
Avg. fuel use	45.96	38.38	38.74
CO_2	144.77	120.90	124.68
SO_2	0.45	0.38	0.39
NO_2	1.03	0.86	0.88

It was shown that for both scheduling horizons and control periods the rolling-horizon scheduling model yields a reduction of 16.5% of emissions for the average vessels in the simulation. However, this reduction comes at the price of an 8% increase in the average time spent by vessels in their port call. From first point of approach until the departure of the vessel.

The answer to the main research question is that information-sharing about processes in the port call can help reduce emissions if it is combined with other optimization concepts already described in literature. The combination of those concepts, virtual arrival and vessel movement optimization used together with information-sharing can lead to a decrease of 16.5% of average emissions by vessels in their approach and port call. Further research is necessary to determine the impact of the rolling horizon scheduling approach with decreased control periods and longer time horizons. To do so, other solution approaches to the MILP-model should be formulated. Secondly, the use of more elaborate control structures as proposed by Negenborn and Hellendoorn (2010) can help to better model the interactions between actors in the port to come to better and more easily accepted results. Lastly, the research on scheduling optimization can be extended by taking into account environmental factors such as tide and currents on the optimal scheduling of vessels with regards to emission reduction.

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Preface

Rotterdam, April 2022

The thesis before you is written to obtain the master degree in Mechanical Engineering at TU Delft. My combined studies at the faculties of Technology, Policy and Management and Mechanical, Maritime and Materials Engineering together with a lifelong interest in "bootjes" have brought me to the topic of optimization in the port call. It is my belief that process optimization goes a long way in reduction of the impact of manufacturing and transport with regards to sustainability. It does, however, ask for a shift in paradigm which I hope to have contributed to with this research.

I would like to thank Arnoud Vernimmen for taking the time to hear my proposal for research and introducing me to SAAB Technologies B.V. to start the research. Richard Jonker at SAAB Maritime Traffic Management has been my guide in the field throughout this project, advising me on the ins and outs of the port call process and keeping check on the professional validity of this research. His interest for my personal well-being during this project has helped me to keep a steady pace.

For the scientific guidance I want to thank dr. Beelaerts van Blokland. His guidance in creating the preliminary model and structuring my thoughts has been very helpful. The enthusiasm with which he approached my research has been a great motivator together with his ability to let me be free in the creative process. I would also like to express my gratitude towards prof. dr. Negenborn and dr. ir. van Hassel as members of my graduation committee.

I wish you a pleasant read,

Job Willem Lokin

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Chapter 1

Introduction

In 2018, the International Maritime Organisation (IMO) adopted a strategy to reduce the emission of greenhouse gasses of maritime shipping in the near future. The IMO is the international governing body for maritime shipping standards. This strategy aims to reduce the carbon emissions of global shipping by 50% in 2050 compared to 2008. It furthermore aims to phase out emissions of greenhouse gasses (GHG's) entirely in the long term. Next to this, the IMO also wants to ensure that the total emissions peak before 2025 and steadily decrease until 2050 (International Maritime Organisation, 2018).

This reduction entails a significant impact on the global emission of greenhouse gasses, because the maritime shipping industry emits an amount of around 1 billion tons of $C0_2$ in 2018. Global shipping is responsible for 75% of this total. To put this into perspective, this is around 2.9% of the total human emission of $C0_2$ that year.

Furthermore, the international shipping industry has a more local effect on air quality surrounding ports, because the ship's engines work as generators during berthing or anchoring, depositing other greenhouse gasses such as nitrogen oxides (NO_x) and sulphur oxides (SO_x) (Stapersma, 2010). Arjona Aroca et al. (2020) estimated based on data obtained from port calls in the Mediterranean that ships produce around 15% of their emissions while in port.

This chapter will first discuss the view on optimization of port operations through several standpoints. Secondly, the problem statement rising from these perspectives is discussed. Lastly, the research objective and approach at the base of this study will be presented to the reader.

1.1 Shipping efficiency optimization

For reducing the emissions of the maritime shipping industry, several solutions exist. An overview of the areas of improvement in shipping was given by Broersma (2021) in figure 1.1. In optimization of the voyage, a problem occurs with the strategical solutions. In the past decade, the prices of maritime shipping have significantly dropped. The result of this is that container shipping order books are very small in comparison to the fleet capacity. The majority of operational ships was built in the last decade, ordered just before the financial crisis. This means that their replacement will not occur soon, and new technologies will be adopted too late to reach the agreed goals of the IMO in 2030. Strategic innovations in port efficiency are being implemented, such as the use of electric Automatic Guided Vehicles and the use of shore power instead of generators for ship operations. However, the low-hanging fruit is in the optimization of either voyage operations or port operations (WSPS, 2020).

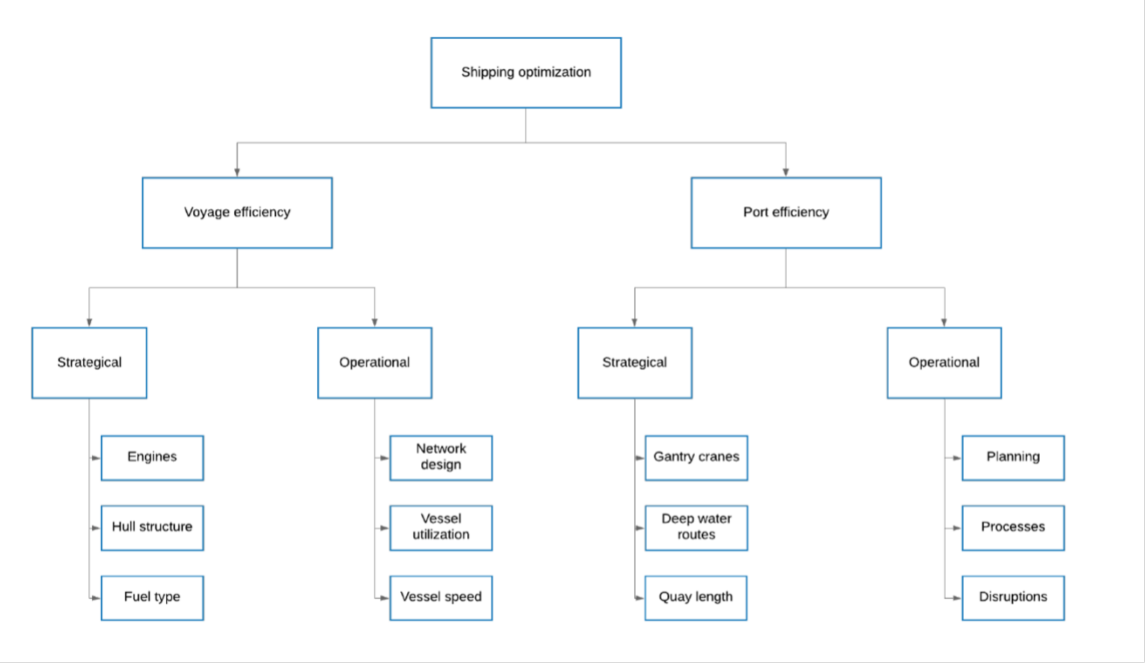


Figure 1.1: Solution areas for efficiency optimization in the maritime shipping industry (Broersma, 2021)

1.1.1 Operations optimization

Research into voyage optimization is ample and is mainly focused on vessel speed optimization for the reduction of GHG's. An example of this is virtual arrival. 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 (OCIMF, 2011). Technical problems arise with the sharing of information to update sea-going ships on delays, but the main hurdle exists in the way contracts are drafted (GloMEEP, 2018). Secondly, in light of port operations, much research is done regarding optimization of terminal operations and berth allocation problems (Wijma, 2018).

1.1.2 Port call optimization

The IMO and its subsidiary GloMeep have coined the concept of just-in-time shipping. This concept tries to overcome waiting times for incoming ships at the port by communicating information about delays and berth availability well in advance of the ship's arrival. This way sea-going ships can reduce their speed, which reduces the fuel consumption underway quadratic to the speed reduction (Broersma, 2021), to arrive at the port of call when berth and service providers are ready to start operations. However, with the just-in-time concept in mind, the operations of the nautical chain containing tugs, pilots, linesmen and other service providers are equally important. Investigations have been done into, among others, optimal tug resting locations in the Port of Rotterdam (Kaljouw, 2019), but remain limited in comparison to terminal optimization research.

1.2 Information-sharing in the port call

A notion already stated by GloMEEP (2018) is that there is a lack of information sharing among actors in the port. The quality of information-sharing is also under par. This makes the concept of just-in-time shipping hard to implement. If port actors do not share

information about their processes, time schedules for berthed ships cannot be updated. This in turn means that sea-going vessels cannot be advised to reduce speed if necessary. Broersma (2021) also found in an extensive qualitative and quantitative research of the port call process that lack of information lays at the base of what he calls transportation waste, this is the unnecessary waiting time upon arrival of a ship due to high speeds maintained during the voyage leading to a higher than necessary fuel consumption.
Regarding the nautical chain this problem lies, according to research performed by Molkenboer (2020) in Port of Rotterdam, in the fact that there should be information protocols to ensure that planning departments of all involved actors are up to date with real-time operations and that information is distributed correctly among port service providers. The influence of information-sharing was researched quantitatively by Wijma (2018) and Arjona Aroca et al. (2020). Wijma (2018) estimated the influence of information-sharing in Port of Rotterdam and found that increased data-sharing could lead to a decrease of 35% of the emissions at anchorage. Arjona Aroca et al. (2020) estimated that emissions can be reduced by 23% if JIT shipping is in place and that waiting times in ports can be reduced by 10%.

The importance of information-sharing between port actors and visiting vessels for the optimization is made clear in these studies. The next section gives an insight into a concept that improves information-sharing.

1.2.1 (Port) Collaborative Decision Making

Currently, information-sharing in ports is mainly done through IT systems such as Port Community Systems, Single-Window and Port Management Information systems. The goal of these systems is mainly to reduce the number of bilateral communications by port actors (Van Baalen et al., 2008). Their work relates to the use of standardized message formats and centralizing all information in the community. It avoids retyping of data and reduces processing costs and physical documents. It could even provide real-time information. A schematic overview is shown in figure 1.2.

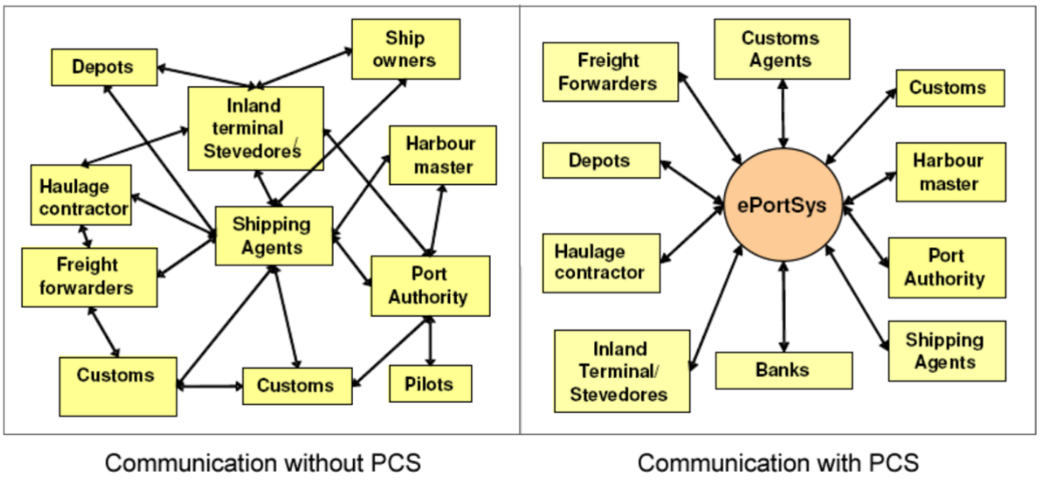


Figure 1.2: Working of Port Community Systems (Van Baalen et al., 2008)

However, both Van Baalen et al. (2008) and Lind et al. (2015) conclude that these systems are merely used for administrative purposes and thus not used for information-sharing about port operations in light of just-in-time shipping. Increased or improved information-sharing, though, can never be the goal, it is a means to optimize a system or process

(Lee and Whang, 2000). The call in literature is therefore to append coordination and collaboration schemes to the existing information technology in ports based on improved information-sharing (Van Baalen et al., 2008) (Wijma, 2018) (Lind et al., 2015). Such schemes have shown in supply chain environments to aid the optimization of production processes in the manufacturing business through, among others, information-sharing (Lee and Whang, 2000),(Lotfi et al., 2013).

Such a collaborative concept, first developed in the aviation industry, called Collaborative Decision Making, is currently discussed in literature about port call optimization (Lind et al., 2015). This concept is focused on a system with shared resources that cannot be used when they are occupied by other participants in the system. The goal of CDM is to provide actors with information (through information-sharing) to allow for close monitoring of interlinked events to help stakeholders make informed decisions on the deployment of resources and capacity (Verkerk, 2018). Based on a "milestone approach", the path of an aircraft is divided into sixteen key events in the handling of a visiting aeroplane from inbound activities. Whenever a delay is obtained, the downstream milestones are delayed. This in turn triggers planning systems at the airport, so that for instance take-off sequences can be altered to optimize runway capacity. The relation to the just-in-time shipping concept can readily be seen.

This concept, in turn, was brought to the maritime industry in the Sea Traffic Management project performed in the Baltic over the last decade. A group of researchers and industry partners have started a living lab to create several optimization techniques to improve shipping efficiency. Port Collaborative Decision Making was deemed the integrator of all these techniques (Lind et al., 2015). The aim is to create situational awareness among actors involved in the port call. By using standardized messages relating to important events in the port call process, like the milestones in ACDM, actors in the port can update their operations based on information from others.

1.3 Problem Statement

As described, port call optimization is a means to reach the goals set by the IMO regarding emissions in 2030. This effort is a joint investment between port operations stakeholders, governing bodies such as the port authority and shipping liners. In the ideal situation, vessels arrive at the designated arrival time with all nautical services ready and berth available. In reality, however, this is not the case. Research has shown that around 45% of container vessels at two large Rotterdam terminals does not arrive within 2 hrs from the scheduled arrival time. It was found that these variations are a great benefactor to port congestion (Broersma, 2021).

In case of congestion, the capacity of nautical services is not enough to handle ships leading to extra delays in the port call process. A root cause analysis showed that the two most important benefactors of delays in the vessel arrival and departure procedure are unavailability of tugs and pilots (Molkenboer, 2020). As expected, these delays cascade over all subsequent ships until the capacity issues are resolved.

At the base of these delays lays a lack of information-sharing and collaboration in planning between the partners in the services related to a port call (Lind et al., 2015), (Broersma, 2021), (Molkenboer, 2020). The wish for better information-sharing in the port call process is therefore clear, but due to the complexity of the port this is not a straightforward case. An overview of all actors involved in the port call as well as their coupling points was made by Lind et al. (2015).

All these actors have preferences regarding data-sharing regimes, their own optimized resource allocation and planning as well as issues regarding competitive advantages. To optimize the port call process, a sensible information-sharing strategy should be devised

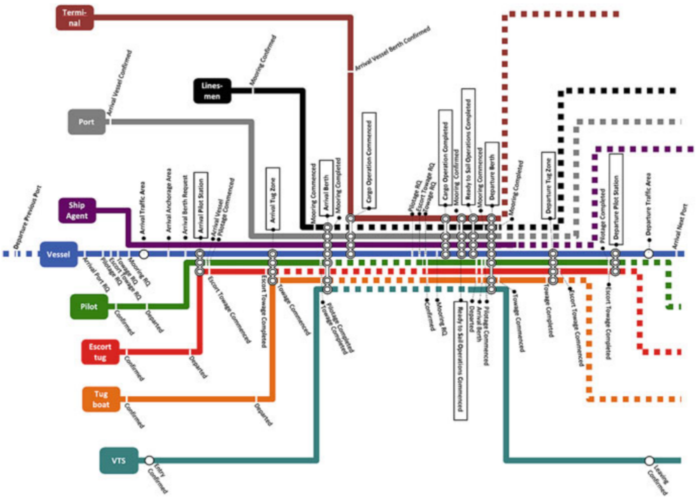


Figure 1.3: Overview of all actors and their relations in the port call process (Lind et al., 2015)

aimed at tackling the problems stated in the beginning of this section. A start has been made by defining standardized message formats and the research of the port call process. However, information-sharing should be used to improve the operations in the port call. Based on information-sharing a coordinated planning effort can help to overcome the problems that arise during periods of port congestion in planning of the port call operations. With this knowledge, the question rises of how information-sharing in this complex environment can be used to create such a coordinated planning effort to optimize the port call process.

1.3.1 SAAB Maritime Traffic Management

SAAB Maritime Traffic Management (MTM) delivers maritime traffic control systems as well as port management systems around the world. SAAB MTM aims at creating solutions that address changing environments, improve safety, efficiency and security and wants to enhance customer capabilities through smarter solutions.
In light of this, the company is eager to create a system that can aid the coordination for the decision-making effort in port operations. Currently, their port management system is focused on capture and sharing of data-points for port operations such as vessel ETA's, fairway entry permissions and applications for service providers. SAAB wants to know if there exists an opportunity to use these data-points in their management systems to coordinate the operations of service providers in ports to optimize performance relating to emissions and efficiency or what effort should be made to extend the operational data captured in their management program.

1.3.2 Main research question

Relating to the earlier stated notion that information-sharing is not a goal but a means to an end, this study aims to research possible ways to use information-sharing as a means for improved coordination and efficiency in the port call process. It is important to quantitatively assess the impact of such coordination on the port call process in terms of waiting times and the emission of GHG's to assess the societal impact of this coordination. The main research question of this thesis is therefore:

"How can increased information-sharing reduce emissions of sea-going vessels in the port call process?"

1.3.3 Scope

The scope of the project is set at the port operations focusing on nautical operations. This means that operations by tugs, linesmen and pilots are included in this study as well as the approaches of sea-going vessels. Broersma (2021) and Molkenboer (2020) both note that the main source of delays through missed information is in this part of maritime operations.

1.4 Research objective

This section will discuss the underlying research approach and objectives for this study. First the knowledge gap is described as was found in the literature review from chapter 2. Secondly, the research approach to answer the main research question is discussed.

1.4.1 Knowledge gap

The current gap in knowledge existing on port call optimization is that on the one hand information-sharing systems have been devised and deemed as an integrator for coordination in the port call process (Lind et al., 2015), but it is, on the other hand, unclear how this should be harnessed . Secondly, the Virtual Arrival concept gives a way to actuate the system based on approach speeds on incoming vessels and is able to reduce vessel emissions during the voyage based on increased information sharing (Broersma, 2021). Thirdly, literature on other infrastructure optimization shows that creating coordination through real-time control can lead to better performance of the controlled system (Negenborn and Hellendoorn, 2010), but this concept has not been applied to the arrival of vessels. Lastly, optimization in vessel arrival has been apparent in literature but is mainly focused on geographic constraints on fairways and creating schedules that optimize fairway use or optimal allocation of tugs and pilots, but vessel arrival scheduling based on resource availability has not been researched much in literature and research on the influence of real-time updates of those scheduling solutions on vessel emissions has also not been found. The question that remains in literature is how these valid concepts on port call optimization can be integrated to create a vessel arrival process that on the one hand takes into account the constraints on resource use in the port and on the other makes use of improved information-sharing between port call actors to create a vessel arrival procedure that reduces the emissions of vessels during their port call.

1.4.2 Research approach

To answer the main research question, the following research approach is designed. From the knowledge gap relating to the literature review in chapter 2, it was found that several optimization concepts have been devised for the port call process. In other infrastructure networks the use of control techniques have shown to be able to increase performance without large investments (Negenborn and Hellendoorn, 2010). Main problems with inefficiencies in the port call lie with problematic resource use for vessel operations and uncertain arrival times of sea-going vessels (Molkenboer, 2020), (Broersma, 2021). This research will thus propose such a control structure for vessel operations in the port call. This is done by assessing the port call as a system in chapter 3, relating to control goals, measurements of the system and ways to actuate it as well as discussing possible control structures. In chapter 4, a prediction model and solution approach are proposed for optimization of the port call process. Chapter 5 and 6 will focus on testing the implementation of such a control structure by first describing a simulation model that can be used to test the control system, after this several experiments will be performed to asses the impact of a controller on the port call. Lastly, the impact of the concept as researched in the experiments will be discussed in chapters 7 and 8. The underlying research questions to answer the main research question are:

Part 1: Problem identification & motivation

1. *How can information-sharing be used for optimization of the port call process?*

Part 2: Solution conceptualization

2. *How can a control structure for vessel operations in the port call be designed?*

3. *How can a controller for vessel operations in the port call be designed?*

Part 3: Solution testing

4. *How can the impact of a controller for vessel scheduling be tested?*

5. *What is the effect of intelligent control of vessel operations on the emissions of vessels in the port call?*

An overview of the contents of this thesis is shown below.

Section	Chapter	Sub-research question	Methodology
Problem identification & motivation	1 Introduction		
	2 Literature review	*How can information-sharing be used for optimization of the port call process?*	Literature review
Solution conceptualization	3 Requirements for intelligent port call	*How can a control structure for vessel operations in the port call be designed?*	System & stakeholder analysis
	4 Controller design	*How can a controller for vessel operations in the port call be designed?*	Linear Programming
Concept testing	5 Simulation model - case study	*How can the impact of an controller for vessel scheduling be tested?*	Discrete Event Modelling
	6 Experiments & results	*What is the effect of intelligent control of vessel operations on the emissions of vessels in the port call?*	Model Simulation
Evaluation	7 Discussion		Reflection on outcomes and methodology
	8 Conclusion		

Chapter 2

Literature review

This chapter will discuss the literature review performed to answer the first sub-question posed in section 1.4.2. First, inefficiencies in the port call process are discussed as well as optimization of the port call process. Secondly, the influence of information-sharing on performance of the port call process is discussed. Thirdly, coordination and optimization concepts for port call optimization are presented as well as the system and control approach discussed by Negenborn and Hellendoorn (2010). Based on the literature review a preliminary model relating to port call optimization and information-sharing is presented.

2.1 Port Call

The port call can be defined as *"All activities prior, during or after the (physical) turnaround process. The port call is initiated when a port is informed for the first time about the arrival of a vessel steaming to the port."* (Lind et al., 2015). The activities that occur during the port call have been researched by Mašović (2019) and the International Taskforce Port Call Optimization (2020). Figure 2.1 shows the involved parties in the port call process. Figure 2.2 shows a more elaborate process model of the port call including a timeline and service requests (a larger version can be found in appendix E).

What becomes clear from these figures is that the port call process involves many actors performing different operations on the vessel calling in port. Secondly, from figure 2.2 the amount of shared timestamps related to the port call becomes visible. To understand the port call process first the actors in the port call and their operations are discussed shortly based on actor analyses made by Mašović (2019), Molkenboer (2020) and Wijma (2018). In the second part the related information-points are discussed.

2.1.1 Port call stakeholders

The first and most important actor in the port call is the *captain* of the arriving vessel. The captain is the highest ranking officer on board of the vessel and responsible for the well-being of the ship and its sailors. The captain has full authority over decisions made on board.

The captain communicates with the port through a *vessel agent*. The main tasks of the vessel agent are administrative and comprise of notifying a port upon arrival of the vessel as well as establishing connections with terminal operators and requesting vessel services on behalf of the captain. Other tasks are handling local customs for the vessel crew and supervisions of cargo operations.

A third actor in the port call process is the *Harbour Master*, the harbour master division is a large division in the port responsible for safe operations and passage of vessels. Vessels make their arrival known at least 24 hours before arrival and are granted clearance by the

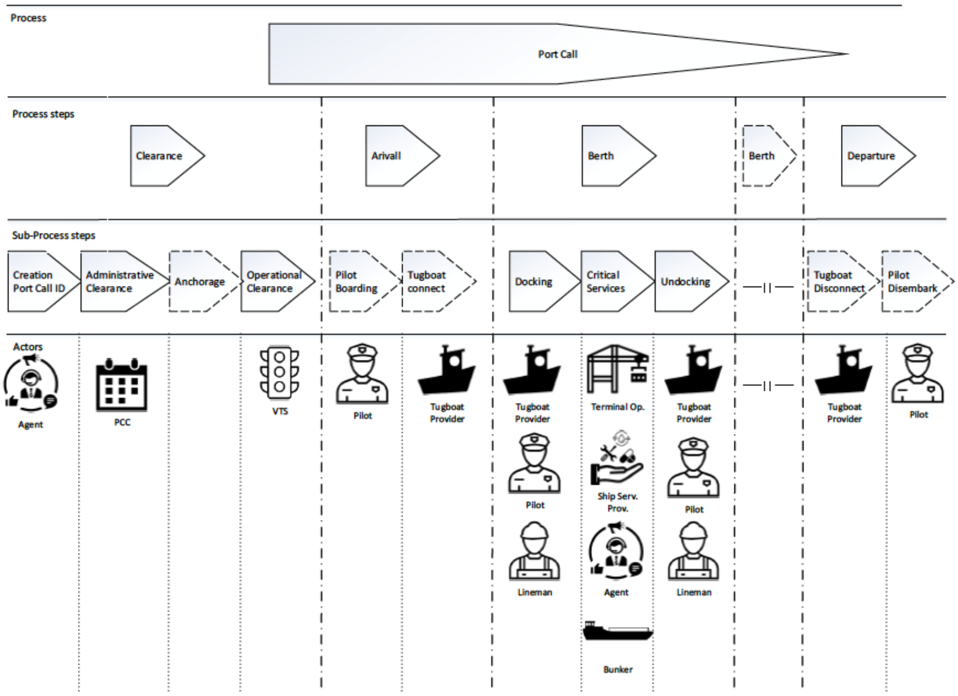


Figure 2.1: Involved stakeholders in the port call (Mašović, 2019)

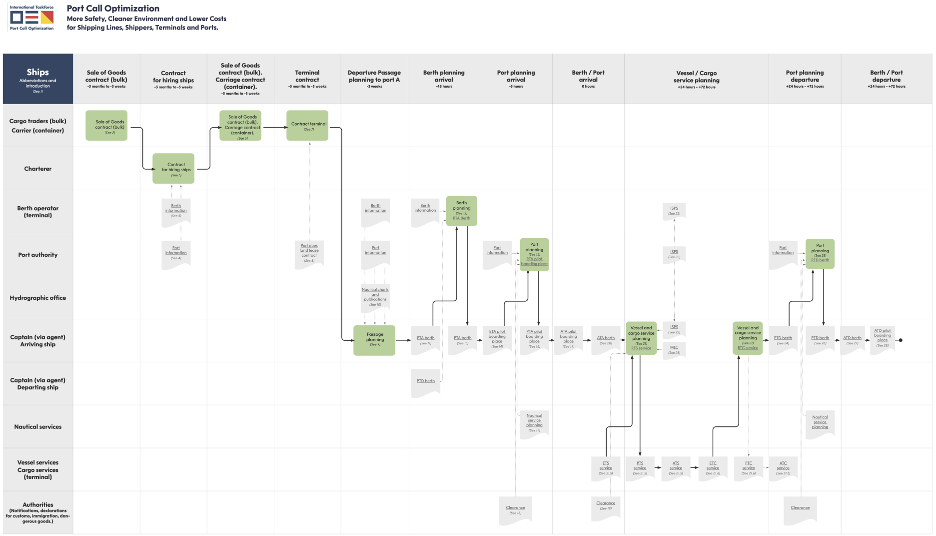


Figure 2.2: Port call process (International Taskforce Port Call Optimization, 2020)

harbour master based on conditional constraints such as tide and weather. The Vessel Traffic Services inside the Harbour Master division is responsible for traffic control in the fairways and operational processing of the arriving or departing vessels.

Another group of actors related to the port call are the *nautical services*, these services are used for safe manoeuvring around the port and consist out of pilot services, tugs and linesmen. Pilots are ordered based on requirements by the port operators and safely navigate vessels through the port. Based on the same requirements tugs are ordered for manoeuvring. Lastly, linesmen are used to dock ships at berth. They have a responsibility of securing all vessels during all weather conditions at every moment of the day.

The *terminal operator* is responsible for the cargo loading and unloading. The terminal operator supports transshipment of for instance dry and liquid bulk goods or containers. The terminals collect the goods for storage or transshipment to and from the hinterland. Lastly, *vessel services* are used for vessel maintenance, provisioning and bunkering. They are not critical to the turnaround process of a vessels, but they support vessels with important services. An overview of all actors is given in table 2.1.

Actor	**Relation to the port call**
Captain	Responsible for vessel and crew well being and in command of all decision
Vessel agent	Administrative liaison for vessel in port call
Harbour master	Port authority responsible for port traffic and safety
Nautical Services	Organizations that assist in the safe fairway passage and docking of arriving and departing vessels
Terminal operator	Organization responsible for cargo loading and unloading
Vessel services	Organizations that provide vessels with auxiliary needs such as bunkering, provisions and maintenance

Table 2.1: Actors in the port call

2.1.2 Information points

As becomes clear from figure 2.2, the port call process involves important time-stamps to reach an agreement of when certain operations are performed during the port call. This part will discuss these points and their importance, described in a port call document from the International Taskforce Port Call Optimization (2020).

Upon arrival of a vessel, the vessel agent will announce an Estimated Time of Arrival (ETA) to the port of call. During the voyage, the updates of vessel ETA will increase and become more reliable. Based on this ETA, the terminal operator will review its operations and berth availability to create a Requested Time of Arrival (RTA), which indicates the moment a vessel can come alongside berth for cargo operations. After the vessel agent has accepted the RTA it becomes the Planned Time of Arrival (PTA).
After agreement on PTA, an ETA is send out by the vessel agent for pilot boarding according to local regulations. This ETA is revised by the port authority according to local regulations about tide and fairway use, availability of nautical service and other administrative clearances. After doing so, a Requested Time of Arrival Pilot Boarding Place (RTA PBP) is sent out to the vessel. After acceptance by the vessel, this becomes a planned time of arrival (PTA PBP).In the agreement upon these timestamps, an important factor is that nautical services such as tugs have a lead time before which a PTA should be agreed up. This lead time ranges from 2-3 hours up to 6 hours for pilots and in some cases 24 hours for tug services.
Upon execution of operations, the planned times turn into Actual Times of Arrival. This

is important in shipping contracts where costs for operations are shared between parties based on the state of the ship.

For vessels services and cargo operations, Estimated Times of Start and Completion (ETS/ETC) will be sent out to the vessel. By planning the sequence of operations and relating to other factors such as departure windows or crew rest hours the vessel will send a Requested Time of Start/Completion. If this is agreed upon by the service provider it becomes the Planned TS/C.

Upon departure, the vessel agent notifies the port authority with an Estimated Time of Departure, ordering nautical services as needed. Again with the appropriate lead time.

Molkenboer (2020), made an elaborate overview using BPMN charts to visually described the process and communications based on these time-stamps between the actors in the port call process.

2.1.3 Inefficiencies in the port call

Tackling inefficiencies in the port call is a good way to reduce greenhouse gas emissions by the maritime shipping industry, because in contrast to lower vessel speeds during the voyage, they do not result in higher transport cargo times and can also decrease costs of shipment. Cost savings are calculated at 75 USD per ton of $C0_2$ emitted an the total reduction of $C0_2$ could reach 60 million tons for international shipping (Poulsen and Sampson, 2020).

The port call process knows three situations where idle time of ships occur, namely during anchoring, manoeuvring and at berth (Poulsen and Sampson, 2020). Due to optimal design speeds of sea-going vessel, captains choose to keep a constant speed during a voyage. Together with the fact that most ports operate on a first come, first serve base, this leads to vessel arriving at a port before it can be handled at the terminal. This in turn means that the vessel must wait at a designated anchoring area outside the port. During anchoring, the ship is idle while still producing emissions to keep the systems on board running. Broersma (2021) calls this transportation waste, the vessels speed was not set to arrive at the moment in time that port operations are ready to receive the vessel. Therefore, there exists a lack of efficiency in the voyage prior to arrival. However, Poulsen and Sampson (2020) conclude that there are financial incentives for cargo owners to have vessels anchoring at port used as *floating storage* and does not see a great deal of improvement in measures reducing anchoring time.

The other two situations are not widely researched in literature (Poulsen and Sampson, 2020). Molkenboer (2020) found that delays in the nautical chain occur mainly due to capacity problems with tug or pilot services or when services are unavailable due to tardiness at a previous assignment. These findings are also backed by Poulsen and Sampson (2020) in a research on delay of tanker vessels. They also include congestion in the fairway and the delay of linesmen as factor for inefficiency during manoeuvring in the port. Broersma (2021) found that unreliable ETA's of vessels lead to cascading delays in port operations. Lastly, Johnson and Styhre (2015) conclude that idle times in ports can be attributed to working hours of crews, late arrival of pilots and the early arrival before stevedoring can commences.

2.1.4 Port call optimization

In optimizing the port call relating to the inefficiencies above, several research areas exist. Much research has gone into the berth allocation problems that exists at terminals (Du et al., 2011). The focus is to optimally use berth availability at terminals through mathematical modelling. The aim of these optimizations is to increase the use of berths to decrease waiting times, emissions and costs for customers.

Secondly, the use of Virtual Arrival schemes are used to align vessel arrival with port readiness. 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 (OCIMF, 2011). These studies relate to creating a system for calculation of optimal voyage speeds under vessel constraints to meet a revised ETA. Such research was performed by Broersma (2021) and Jia et al. (2017b). This policy however, did not find much uptake in the industry (Broersma, 2021). The reason for this is that there are sharp financial incentives not to delay arrival of a vessel as well as a problematic relationship with fear of losing port services in a "first come, first serve" system (Poulsen and Sampson, 2020).
In recent literature on port call optimization, the main reason for inefficiencies is contributed to a lack of information-sharing and situational awareness (Lind et al., 2015), (Broersma, 2021), (Wijma, 2018), (Molkenboer, 2020). Poulsen and Sampson (2020) describe increased information-sharing (real-time) as one of the solutions to increase efficiency in the port call process. Such a solution helps reducing traffic congestion for trucks and trains, by timing departure and arrival as choosing optimal routes. However, Poulsen et al. (2018) found that due to the complexity of the port call involving many actors the implementation of such measures has still failed in major ports.

2.2 Information-sharing in the port call

2.2.1 Data vs. information

As stated in the previous section of this review, information-sharing could benefit the efficiency of the port call process. Where data or data-sharing is related to the collection of uninterpreted facts, information is derived from interpretation and processing of this data. It presents a useful and meaningful basis to create knowledge and situational awareness (Bergmann et al., 2021). This relation is presented in the *pyramid of competence* in figure 2.3.

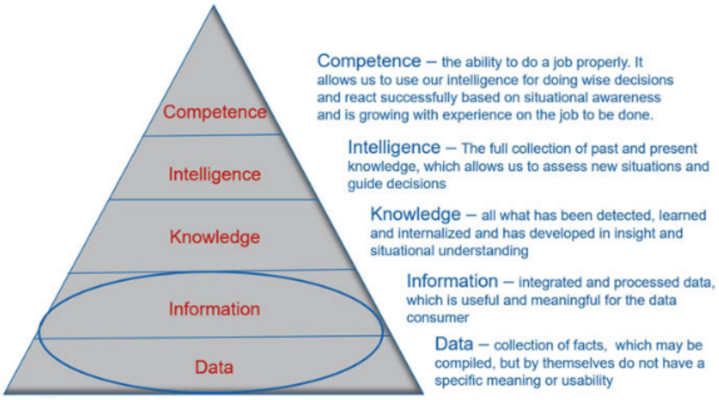


Figure 2.3: Pyramid of Competence (Bergmann et al., 2021)

A similar definition was described by Simatupang and Sridharan (2001): data is the record of real-world phenomena through letters, numbers or pictures. Data is transferred into knowledge upon interpretation by people who also attach meaning. Based on this information, knowledge can be built which can be used for problem solving and decision-making.

Shared information

The question rises what information is shared among the actors of the port call process. Lind et al. (2015) concludes that there is no predefined protocol what information should be shared and with whom and that there is a lack of definition on measures to be used. Other remarks in literature could not be found, as noted by Molkenboer (2020). She, however, tried to capture information-sharing in her research of the nautical chain in Port of Rotterdam. The conclusion is that indeed information is shared between partners, but that terminal operators lack a view of the situation because of access rights to data. Furthermore, there is a scattered use of communication tools. Updates about operations and planning are transferred by phone between different organisations and on VHF-radio or phone for internal matters, this results in many bi-lateral communications which reduces the situational awareness of everyone involved. This information is then used by internal operators to make decisions based on their knowledge, but taking action upon this information by other parties is limited, because the information does not reach them (in a timely manner).

2.2.2 Influence on performance

Information-sharing as a concept is widely discussed in literature on supply chain management (SCM). Where Molkenboer (2020) assumes that there are similarities between supply chains and the processes in the nautical chain due to their serial composition, Alavi et al. (2018) argues that the relations described in supply chain management regarding supplier-manufacturer relations do no right to the complexity and demand uncertainty that is experienced in port operations. This raises the question if lessons learned and impact found on supply chains through information-sharing are readily adaptable to the port call process. However, the general notes about information-sharing on performance improvement will be noted here, because the give a general insight in the workings of the concept.

Information-sharing in a supply chain setting is aimed at distributing meaningful information for systems, people and organisations (Lotfi et al., 2013). This is in line with the distinction made above. The main influence of information-sharing on performance as seen in SCM is that it is able to reduce costs, inventory, bull-whip effect and uncertainty (Lotfi et al., 2013), (Yu et al., 2001).

In research on the port call process, the influence of information-sharing on the efficiency was found to be large on the emission of GHG's. Arjona Aroca et al. (2020) showed that there could be a decrease of 15-23% of GHG's if information-sharing would elevate the barriers for just-in-time shipping. Wijma (2018) also found a considerable impact on the port call efficiency through information sharing. A note should be made that these studies either estimated the impact of reduction in waiting times in port from increased information-sharing (Arjona Aroca et al., 2020) or assumed centralized control that could influence vessel speed under voyage (Wijma, 2018).

The reason why information-sharing can influence the performance of the supply chain is because it enables members to adopt quickly to uncertainties in the market place, it can help to optimise resource allocation and distribution of burdens and benefits and more importantly, it is a facilitator for coordination. (Simatupang and Sridharan, 2001).

Coordination is defined as an operational plan to coordinate the operations of individual members of the supply chain and improve the profit of the system (Li and Wang, 2007). In literature on port call efficiency, there is a call for more coordination among stakeholders to improve the port call process. Lind et al. (2018c) calls for more coordination as a prerequisite to synchronization of the port call process. Coordination is then the *master plan* under which the plans, actions and communication flows are outlined to support synchronization of actions relating to the sequential operations that should be performed on a ship.

In light of ports as parts of global (container) supply chains, Van Baalen et al. (2008) also calls for coordination mechanisms within Port Community Systems. Coordination according to Van Baalen et al. (2008) is essential for optimizing supply chains and is therefore of utmost importance to port operations.

Ascencio et al. (2014) states that *port logistic chains* through its complexity (of stakeholders) and variability in operations is vulnerable should create better coordination among physical and document flows to overcome variability in sea and land side operations.

2.3 Coordination

Coordination was already described in the previous section as an operational plan to coordinate the operations of individual members of the supply chain and improve the profit of the systems (Li and Wang, 2007). In addition to this, Simatupang et al. (2002) describe coordination in supply chain as the act of properly combining (relating, harmonising, adjusting, aligning) a number of objects (actions, objectives, decisions, information, knowledge and funds) for the achievement of the chain goals. This chapter considers some coordination concepts for port call optimization.

2.3.1 Port Logistics Synchronization

The call for coordination in port operations can be regarded in two ways: from the logistics synchronization perspective as well as the information-sharing perspective (Simatupang et al., 2002). As described in section 2.2, there is currently little structured information-sharing in the ports.

As far as logistics synchronization goes, Ascencio et al. (2014) proposed an integration framework for port operations relating to three decision-levels for synchronization of land-side port operations. Relating to the port call process of sea-going vessels and synchronization of the operations involved, the literature is very thin. A search of literature only yielded the *just-in-time* concept proposed by the IMO (GloMEEP, 2018) for sea-going vessels as well as a new concept called *Port Collaborative Decision Making* (Port CDM) (Lind et al., 2015). The Port CDM concept designed by Lind et al. (2015) in the Sea Traffic Management project is an extension of the strategy by the IMO. Based on an elaborate port management system relating to standardized messages and milestones in the port operations the concept tries to enable actors to synchronize their operations for a smooth port call.

The IMO JIT concept is based on the notion that today's "hurry up and wait" strategy used by captains is non-beneficial to the overall performance of the maritime industry. The suggestion is to reduce speeds along the voyage to ensure that upon arrival a ship can be handled by nautical services, terminal and vessel services. If a delay occurs at the port of call, the ETA at the port is revised to a later moment. The captain can reduce its speed during the voyage, leading to decreased emissions while not lengthening the voyage duration. Thus, the port call is synchronized through the arrival time of the incoming vessel. The concept is shown in figure 2.4

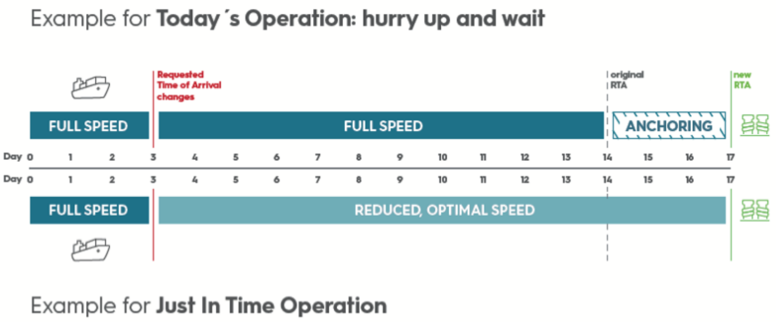


Figure 2.4: Just-in-Time shipping strategy (GloMEEP, 2018)

2.3.2 Virtual Arrival

The concept of *Just-in-Time shipping* is aided by the work of researchers through a concept called Virtual Arrival. The aim of this concept is to change vessel speed during port approach based on information regarding delays in the port. Watson et al. (2015) already showed the impact of such a strategy by assessing data from port of Gothenburg and calculating the difference in emissions for optimal speeds and current approach speeds. In many papers, the influence on container liner scheduling was shown using influences from port delays during operations and the impact of large disruptions on the container liner schedule (Broersma, 2021).

The biggest gain of Virtual Arrival can be obtained when vessels are aware of their optimal speeds at all the time. The new speed for the vessel based on a delay can then be determined as described by Jia et al. (2017a):

$$v_{ij}^{'} = \frac{D_j}{t_{0,ij} + \Delta t_{ij}} \tag{2.1}$$

Where the new speed $v_{ij}^{'}$ is calculated based on the distance D_j divided by the original time to the destination port $t_{0,ij}$ plus predicted waiting time in port which can be taken into the time spent on the sea leg Δt_{ij}. When such a strategy is implemented, it is of vital importance that communication and information-sharing between port operations is high, because only then the full gain from virtual arrival can be obtained.

As discussed before, Poulsen et al. (2018) found that Virtual Arrival might not be applicable to the bunker vessel fleet. The reason for this is that commercial incentives outweigh the gains in fuel consumption reduction and emissions. However, the release of the European Green Deal has brought to attention that emissions of sea-going vessel maybe taken into the European Trading System (European Comission, 2021). This would significantly increase the benefit, because every reduced ton of emissions has a monetary value. Lastly, Virtual Arrival might diminish resting times for vessel crews which could lead to increased fatigue among crews (Poulsen et al., 2018).

Due to engine characteristics, it is unfavorable for vessel engines to constantly change speed. Deceleration and subsequent acceleration lead to higher fuel consumption. It is therefore advised that speed updates are reduced to a minimum to overcome the problem and more importantly to keep differences between speeds on updating vessel arrival times. Based on this notion, Broersma (2021) created a Virtual Arrival scheme where vessels are updated with delays at dedicated waypoints among the sea leg. If a vessel is notified of extended waiting times because of those delays a new *Dynamic Arrival Time* is calculated. This strategy, tested under several risk scenario's showed large reductions in carbon dioxide emissions for delayed vessels.

2.3.3 Collaborative Decision Making

Collaborative Decision Making is a concept first coined in the aviation industry, researchers have now brought this concept to the port operations domain in the Sea Traffic Management project. Both will be discussed here shortly.

Aviation industry

In the 1990's, the Federal Aviation Authority (FAA) in the US designed a system to cope with capacity shortages during periods of heavy weather at airports (Wambsganss, 1996). This system was able, based on information-sharing, to give authority to airlines to decide for themselves which aircraft should be prioritized in this time of shortage.
Currently, the CDM concept is rolled out in Europe focusing more on ground operations than traffic management. The concept is used for systems where shared resources exist that cannot be used if they are occupied by an entity within the system. The goal is to provide actors with information to allow for close monitoring of interlinked events to help stakeholders make informed decisions on the deployment of resources and capacity (Verkerk, 2018). The system is based on a *milestone approach*, this means that 16 important milestones during the turnaround process have been defined, which are used as beacons for operators to plan their operations on. Whenever a delay occurs in an upstream milestone, the downstream milestones are updated continuously and operators can re-plan their operations accordingly. The milestone approach is shown in figure 2.5.

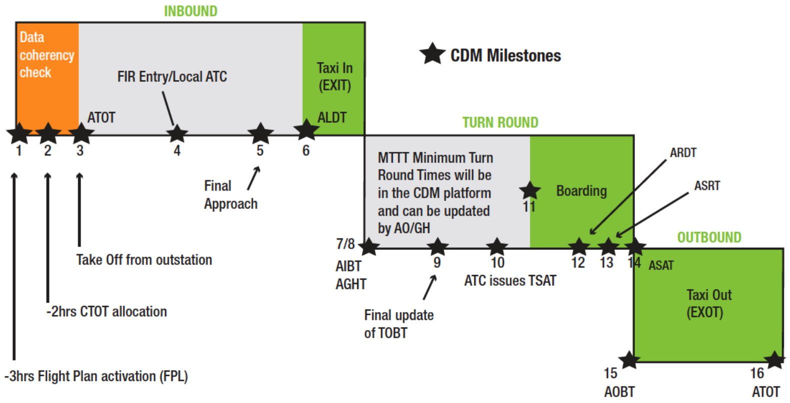


Figure 2.5: Milestone approach Eurocontrol (EUROCONTROL, 2017)

As can be seen in the figure, the milestones start before an aeroplane takes off from its departure airport and end when the plane has taken off. The impact of this system has been measured to reduce air traffic delays by 10% in airports using ACDM as well as a reduction of 7% in taxi time.
Research efforts in the field of ACDM have focused on mainly on air traffic control. Research has been done mostly on sequence planning in the pre-departure of airplanes relating to ground movements, minimization of taxi times and delay prediction. Focus on the turnaround has yielded information on prediction on delays in the turnaround, researched the information position of pilots as well as the extension of ACDM with all airport data through *Total Airport Management* (Verkerk, 2018).

Port environment

This concept was later introduced in the Sea Traffic Management program. This research program aimed at improving efficiency of the maritime industry through digitalization of the vessel voyage. PortCDM is the facilitator for port call coordination and port call synchronization (Lind et al., 2018b). The concept is aimed at supporting the port call process optimization through the extension of planning horizons, sharing and timing of future events for coordination and the combination of multiple sources of data for enhanced predictability (Lind et al., 2018b).

Port call coordination is aimed at the internal alignment of actions in the port call in relation to other actors as described in the previous part of this review. Port call synchronization is aimed at the continuous coordination of the vessel operations based on arrival times, operators plans and progress in the port call (Lind et al., 2018b). As with ACDM, the researchers of the STM project have devised a milestone approach to the port call. The overview of this approach is given in figure 2.6. An important distinction made in the PortCDM concept is that unlike the aviation industry, the maritime industry is a diversified place with many actors who work on own authority, with captains as the most prominent example. This means that for CDM a more distributed approach should be taken instead of the more centralized approach with one governing body in the aviation industry. To accomplish a smooth transfer of information, a standardized message format was devised for the port CDM concept. It uses several states which can be depicted by the following message format. The message format has been introduced in a new standard by the IMO and IALA (International Association Lighthouse Authorities), called S-211. The idea is that this creates a general overview of operations that can be made available for all actors involving a port call. Based on the generation of these states, posterior data-analysis can be performed in to root causes of delays and disruptions(Lind et al., 2015).

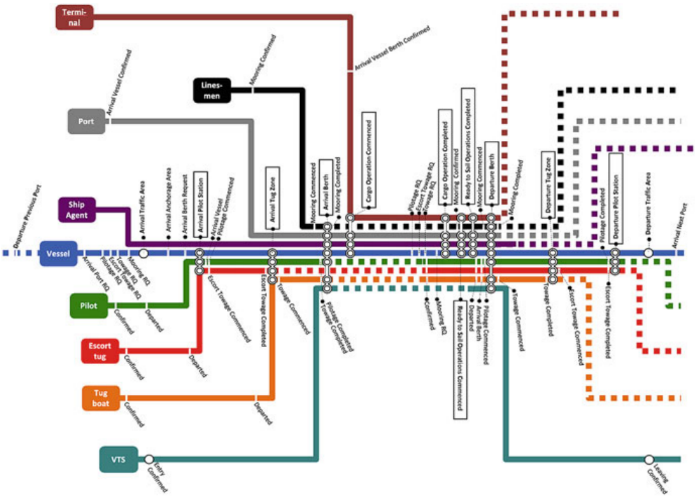


Figure 2.6: Port Call Milestones and interactions (see appendix F) Lind et al. (2015)

The concept of PortCDM was validated through living labs in the Mediterranean and the Baltic. In a large EU funded project, the portCDM concept using the timestamps and milestones described above were introduced in several ports (STM, 2019). Based on a qualitative analysis of the project. There was a measured reluctance among actors about information-sharing that could harm their business position. Quantitative analysis of the concept was deemed not possible, so no data is available on the actual improvement of the port call process due to the implementation of Port CDM (STM, 2019).

2.3.4 Scheduling the port call process

A focus in literature is on optimization of vessel arrival scheduling to overcome congestion at ports due to resource unavailability. This part describes the focus of these researches and their findings.

Focus in literature

An extensive overview of literature on vessel arrival and departure scheduling is given in Abou Kasm et al. (2021). In contrast to other port operations, such as land and sea side operations, the vessel arrival problem has received limited attention in literature and is in practice done by hand. Main considerations in vessel scheduling literature are focused on ports where geographic limitations apply, i.e port entry is constrained by channel size limitations which leads to congestion. In this case, vessel arrival and departure scheduling is focused on the optimal throughput of the bottleneck and in some cases the optimal change of direction in the entry channel. Lin et al. (2014) proposed an MIP model based on a weighted function that schedules vessel entry of a channel according to their importance to the port assuming a berth has been allocated. Zhang et al. (2017) researched channel restrictions and berth allocation. Based on a scheduling optimization using genetic algorithms, they found that waiting times could significantly be reduced. In their next paper, Zhang et al. (2018) extended their research by creating a multi-objective optimization problem for the same situation as before minimizing vessel wait times as well as the time needed to move from berth to anchorage or vice versa. They advise the adoption of a berth allocation model into the optimization problem. Another study by Lalla-Ruiz et al. (2018) proposes a *Waterway Ship Scheduling Problem*. The goal of this study was to provide an optimal schedule of incoming and outgoing ships through different one-directional waterways. It was concluded that such a schedule could deliver important benefits in terms of waiting times and pollution to vessel owners and port operators. The authors considered that unfortunately optimization of the problem is time-consuming and could lead to delay in decision-making in port arrival scheduling. Corry and Bierwirth (2019) researched an optimization problem regarding berth allocation as well as channel restrictions by combining a new MIP model of channel restrictions (prohibition of passing and channel conditions) and heuristic to solve this problem together with a berth allocation problem. Zhang et al. (2019) discribes previous models as unfit for use in practice. They aim to create an optimization model for waterways with difficult geography that solves vessel traffic conflicts according to daily arrival and departure information. Jia et al. (2019) provides an optimization model concerning optimal channel navigation and anchorage utilization. Zhang et al. (2020) focuses their study on the tidal-aspect of the channel scheduling problem, by optimizing channel throughput based on vessel dimensions and tidal information. Zhang et al. (2020) extended the work before by adding a dynamic function relating to the tide at the position of the vessel during movement.

Only a small part of vessel literature focuses on the use of resources such as pilots and tugs in the scheduling problem. If resources are taken into account, this is only done for either tugs or pilots. For instance, Xu et al. (2012) created an optimization model for the use of tugs in the port call process taking into account types of movement and different vessel locations. Wang et al. (2014) defined a tugboat assignment problem with the goal to minimize the turnaround times of vessels in port. Kang et al. (2020) defined an model of port operations with the aim to schedule tugboat allocation under the uncertainty of arrival, departure and operation times. Jia et al. (2020) extended their previous models cited before by taking availability of pilots into account for optimal vessel scheduling through a constrained channel. Only Abou Kasm et al. (2021) took into account all resources involved in the port call. The aim of their study was to optimize vessel arrival and departure times according to available resources in the port. The model was optimized to minimize the maximum delay incurred from unavailability of resources.

Lastly, all studied researches have used static scheduling problems for a finite time-horizon. In a highly volatile systems as the port call where delays and changes can occur at any moment, this yields the question of how these scheduling problems can be used for that specific situation. Scheduling of vessel arrival is not a static exercise at the beginning of the day, but should be updated based on real-time information about the system.

2.4 Intelligent infrastructures

2.4.1 Potential for optimization

Congested infrastructure such as busy ports can suffer from sub-optimal resource and capacity use which can lead to said congestion and unnecessary pollution. These transportation networks can be seen as a set of nodes, sources and sinks which are interconnected in space and handle 'commodities'. They typically span large areas, have many actuators and sensors and consist out of many different subsystems (Negenborn and Hellendoorn, 2010).

In case of ports these specifics can also be found: vessels (the 'commodity') arrive from and depart to sea (source and sink) and in the port environment they are directed by fairways. These different legs of the inner port travel are constrained by factors such as maximum draft, length and width of vessels as well as separation in terms of distance. System overflow is directed to anchorages to wait until the system is capable to handle new vessels. Lastly, the port environment is comprised of many different interacting systems of resources that handle incoming and departing vessels.

Solutions to tackle the problem of congested infrastructures can lie in updating current infrastructure, but this is time-consuming and expensive. A less intensive way of infrastructure optimization can be obtained by creating *intelligent infrastructure* where parts of the system are made intelligent so that they can cooperate and coordinate actions to improve use of current infrastructures. These intelligent infrastructures are aimed at coordination in transportation networks. Since port lay-out is hard to alter, think about the investment in the Maasvlakte II extension at Port of Rotterdam, and additional resources such as tugs or pilots are not readily available for deployment this approach could serve as a proper way of port call optimization without extensive investments.

2.4.2 Coordination in intelligent infrastructures

The coordination of machines in this light is described as *continuously processing relevant information and take action to achieve desired behaviour* (Reppa et al., 2019) and lies at the basis of intelligent infrastructures. Formal description of infrastructures can be given with a classic systems and control approach as shown below in figure 2.7 (Negenborn and Hellendoorn, 2010). Within this structure the system is the (physical) system which should be controlled, while the control structure measures system output and defines input to steer the system to desired behaviour. In this case, the port network is the system and this system is controlled by parties involved, such as the harbour master, terminal operators and nautical services.

Some examples of intelligent infrastructures are described in Negenborn and Hellendoorn (2010), the focus lies on transportation networks regarding electricity networks, road transport and waterways. In electricity networks the control approach can help overcome the problems that arise due to a more diversified power distribution that is the consequence of the implementation of renewable energy sources. It can help to guarantee service levels and stability in the power network. In road transport, intelligent infrastructures can help to streamline traffic flow in highly congested areas by imposing speed limits or input flows but is also vital to help the introduction of autonomous vehicles that have to communicate in order to navigate safely. Lastly, intelligent water infrastructure can help tackle the problems that rise with climate change. Use of optimization techniques can help to

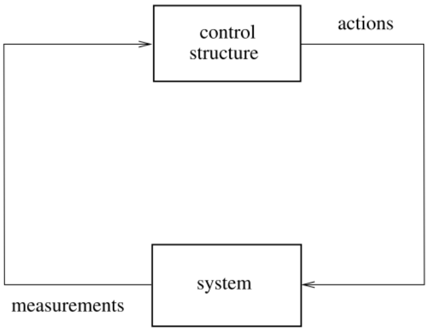


Figure 2.7: The relation between a general system and the control structure that controls the system. (Negenborn and Hellendoorn, 2010)

create better performing local control by taking into account actions performed by other controllers in the water network.
In the port environment, the use of computational intelligence is still in its infancy. However, the development of concepts such as PortCDM and Virtual Arrival give opportunity to regard waterway transport in ports from this intelligent perspective. PortCDM can help retrieve measurements about the system and the system can be actuated by changing starting times for vessel arrival (and departure). In literature on control in relation to vessel operations, the main focus lies in the control of waterborne agv's and collision avoidance. Intelligently controlled port operations are discussed in literature on terminal operations in Vullings (2008) and Cahyono (2012). Furthermore Li et al. (2015) proposes an MPC approach for barge rotational problems. In this research, the problem of barges that have to visit several terminals in the port is solved using a tactical level vessel rotation planning is solved to control the movement of a waterborne automatic guided vehicles. However, the conclusion of the author is that intelligent control as an approach for vessel movement operations in the port call has not been researched so far.

2.5 Preliminary model

The previous sections have discussed in following order: the port call and its inefficiencies, importance of information-sharing and coordination, concepts for logistics synchronization, collaborative decision making, intelligent control of infrastructures and vessel operations scheduling. This section proposes a preliminary model to harness these concepts for reduction of emissions in the port call.

2.5.1 Port call optimization

As discussed by Molkenboer (2020), Lind et al. (2015), Broersma (2021) and others, a conclusion can be drawn that the port call process regarding to the in and outgoing operations of sea going vessels suffers from inefficiencies. These inefficiencies lead to increased turnaround times for vessels as well as waiting times. Both lead to unnecessary emissions of greenhouse gasses by the port call process. The reasons for these inefficiencies are widely recognised as a lack of (accurate) information-sharing by actors during the port call as well as uncertainty in arrival times (Broersma, 2021), (Lind and Haraldsson, 2015), (Molkenboer, 2020). Coordination of the port call process is deemed a solution, based on increased information-sharing, that can resolve the issues at hand (Lind et al., 2018b). The concept of coordination can be found in literature on supply chain management and is described as the *operational plan* to coordinate operations of individual members of the supply chain. This can refer to coordination of information-sharing and logistics synchronization. To create coordination of information-sharing, the PortCDM concept has been designed to ensure a standardised data-sharing among port call actors upon which everybody can act. This leads to a common sense of the goals and context in which the system operates. coordination of logistics synchronization in the case of port call optimization can be found in the Just-in-Time concept from the IMO, together with the virtual arrival concepts as proposed by Jia et al. (2017a) and Broersma (2021). This concept contributes to value creation by diminishing waste in the process as described by Broersma (2021). The concepts have proven to increase on the one hand situational awareness and on the other hand have shown the ability to decrease emissions and turnaround times.

2.5.2 Coordination of port call

Based on the notion of coordination in large infrastructures from Reppa et al. (2019), it can be shown that this is not the complete picture for port call optimization. Said definition states that coordination is *continuously processing relevant information and take action to achieve desired behaviour*. This definition makes more clear what is lacking from the concepts for information-sharing and logistics synchronization discussed in the previous to create an optimal port call: the way information-sharing and logistics synchronization are steered by an *operational plan* to find the desired behaviour.

Therefore the researcher argues that coordination as a means for port call optimization can be obtained not only through information-sharing (e.g. PortCDM) or logistics synchronization (e.g. IMO JIT shipping), but that it also needs a mechanism that helps steer the system towards desired behaviour. As discussed in section 2.3.4, several attempts have been made to create such an operational plan. Optimal scheduling approaches have been designed to create an optimal schedule for vessel arrival according to constraints in the system. In figure 2.8 this extension of the notion of coordination based on the previous is shown.

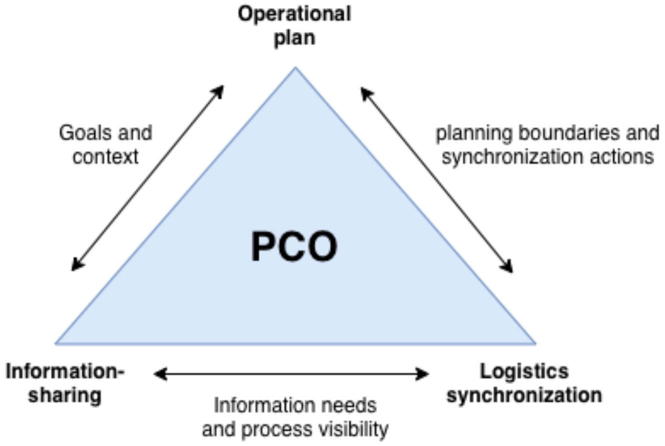


Figure 2.8: Value drivers for coordination in Port Call Optimization (PCO)

The relation between these value drivers can be found in the following: first and foremost, Simatupang et al. (2002) conclude that success for coordination can only be achieved when logistics synchronization is used in response to shared information. Logistics synchronization determines the amount and contents of shared information and in return shared information reduces the lack of visibility in logistic processes. With respect to the operational plan, information-sharing gives the goals and context in which an operational plan is created, the logistics synchronization gives the boundaries and possibilities wherein the operational plan can respond to situations that occur in the system.

2.5.3 Literature in relation to value drivers

If we take the proposed value drivers in figure 2.8 and relate it to literature, it becomes clear that while logistics synchronization and information-sharing have been studied together, the creation of an operational plan together with information-sharing and logistics synchronization has not been researched in light of the port call. This is shown in table 2.2. A more holistic view in which these value drivers are combined, can be found in the intelligent infrastructure section of this review. This type of coordination through intelligent control of large infrastructures has been studied extensively for traffic, waterway and electricity networks. It has shown that with measurements about the system, a good choice of actuation and real-time control of these networks can improve their efficiency (Negenborn and Hellendoorn, 2010). One can assume that this is a valuable approach for port call optimization. The question of how to actuate inflow in the port call system has been answered in literature about just in time shipping and virtual arrival, information-sharing in the port call has been described in literature on PortCDM and gives a way of system measurement, lastly the optimization through arrival and departure scheduling has been researched and shown to be able to assist in creating more optimal (less delay) operational schedules for port call operations.

2.6 Conclusion

This chapter set out to answer the first research question underlying this thesis:

How can information-sharing be used for optimization of the port call process?

Information-sharing systems have been devised and deemed as an integrator for coordination in the port call process (Lind et al., 2015), but it is unclear how this should be harnessed. The wanted effects are related to increased situational awareness to make better decisions on real-time information, for reduction of delays. Optimization in vessel arrival has been apparent in literature but is mainly focused on geographic constraints of fairways and creating schedules that optimize fairway use or optimal allocation of tugs and pilots. Vessel arrival scheduling based on resource availability has not been researched much in literature and the influence of real-time updates of those scheduling solutions on vessel emissions has also not been found. The Virtual Arrival concept proposed in literature gives a way to reduce approach speeds of incoming vessels based on delay information from the port (Broersma, 2021). Literature on other infrastructure optimization shows that creating coordination through real-time control can lead to better performance of the controlled system (Negenborn and Hellendoorn, 2010), but this concept has not been applied to the arrival of vessels. Based on the concepts of coordination found in literature a preliminary model for port call optimization can be defined as done in this chapter. It can be concluded that information-sharing can be used in several ways for optimization of the port call, however no combination of these concepts have been researched to see how vessel scheduling, real-time control and virtual arrival together can create less emissions in the port call.

Study	Summary	Value driver
Van Baalen et al. (2008)	Discussion of IT concepts and needed to address future challenges in the port environment relating to optimization of operations.	IS
Watson et al. (2015)	Discussing the concept of green steaming together with a method to calculate the impact of such a system.	IS, LS
Lind et al. (2015)	Introduction of PortCDM as a means to integrate information-sharing in the port call process.	IS
Jia et al. (2017b)	Empirical assessment of the impact of Virtual Arrival policy on vessel emissions in relation to Just-in-Time Shipping.	LS
Wijma (2018)	Quantification of the impact of data-sharing as well as the impact of green steaming on vessel emissions	IS, LS
Arjona Aroca et al. (2020)	Analysis of the impact of information-sharing systems on emissions in the port call	IS
Molkenboer (2020)	Research of causes for inefficiency in port call process and handles for port call optimization.	IS, LS
Poulsen and Sampson (2020)	Research of aspects of waiting time reduction in the port call and its impact on the system.	LS
Abou Kasm et al. (2021)	Definition of optimal vessel operations schedule based on resource constraints and MIP optimization.	OP
Broersma (2021)	Introduction of Virtual Arrival to container shipping line network to reduce emissions.	IS, LS

Table 2.2: Overview matrix of literature on port call optimization with value drivers. (OP = operational plan, IS = information-sharing, LS = logistics synchronization)

Chapter 3

Requirements for intelligent port call

The control structure shown in figure 2.7 is very general and can be designed in many ways relating to the system under control and the current control in place (Negenborn and Hellendoorn, 2010). To create such a structure, the system that is to be under control should be reviewed together with capacities for measurement and actuation. This chapter will propose to the reader an intelligent control approach for port call optimization based on Port CDM as well as Virtual Arrival to answer the second sub-research question of this thesis. The contents will be as follows: first, a description of the system together with the objectives of the system are presented to the reader. Second, measurements about the port call with PortCDM are discussed and control of the system through Virtual Arrival will be proposed. Lastly a control structure and approach will be proposed to the reader.

3.1 System & performance

As discussed in section 2.1, the port call process is an intricate process with many actor who rely on each other for the harmonization of operations. This section describes the port call process together with objectives for optimization.

3.1.1 Port Call overview

The port call process is constructed around the loading and unloading operations of seagoing vessels. They can be carrying containers, bulk goods, or for instance cars and trucks for Roll-On Roll-Off carriers as well as people for ferries and cruise ships. The port call for a vessel from an operations perspective is devided in different *movements*, a movement can either be *In* when a vessel arrives, *Out* when a vessel departs or a *Shift* movement when a vessel is moved from one terminal in the port to another for further loading or unloading operations.

During these operations the vessel is supported by different resources in the port. For safe navigation vessels are aided by a pilot that has local knowledge. In case of a captain or first officer with local knowledge, common in ferry operations, the vessel can have a *pilot exemption* and enter the port area without a pilot. The pilot remains with the vessel during the whole movement and is picked up or dropped off at a designated pilot boarding area at the most outer point of the port approach in sea. For safe maneuvering, vessels are assisted by tug services. Tugs are placed strategically throughout the port. Based on the length, draft and maneuvering capability of the vessel as well as weather and tidal conditions the amount of tugs and their tugging capacity is determined by the harbour masters office. For *In* movements tugs are met at a designated *tug meeting point*. In general, this meeting point is closer to the port area than the pilot meeting point. When arriving at berth, linesmen crews are met to handle the final berth operations until the "all fast" command

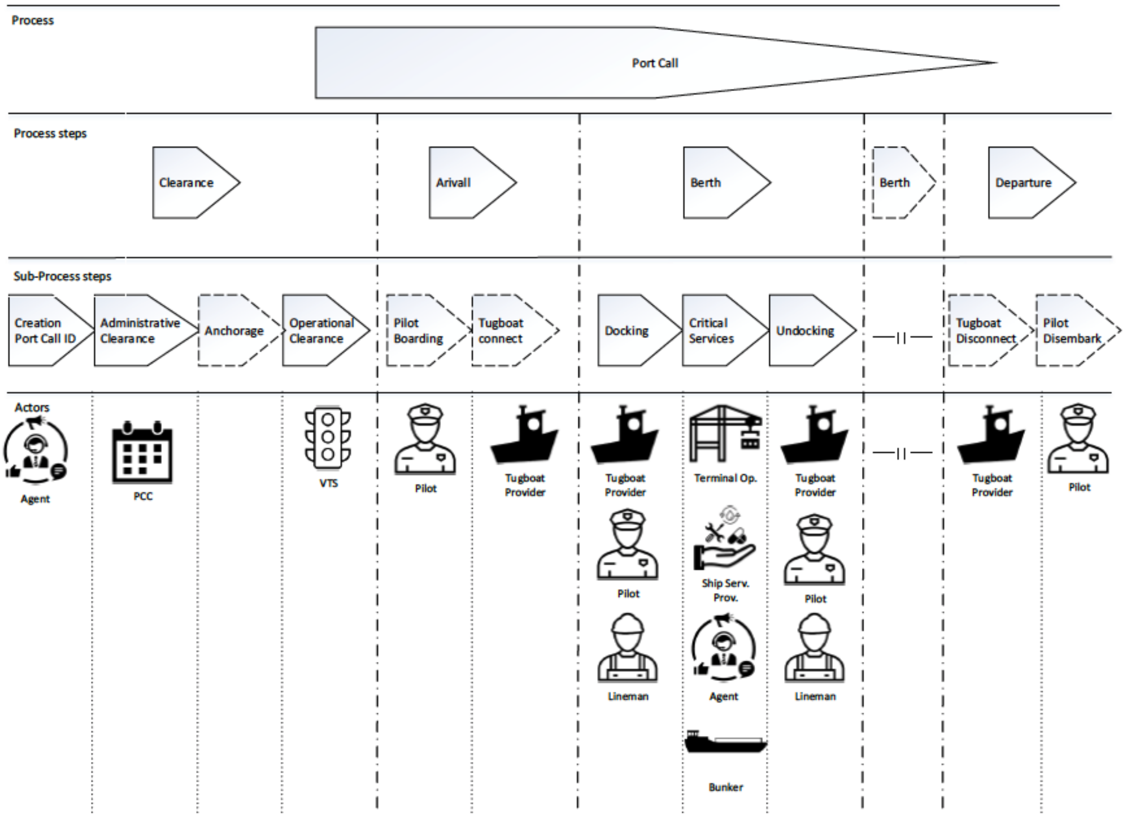


Figure 3.1: Overview of actors involved in the port call (Mašović, 2019)

is given and the vessel can start terminal operations. For *Out* movements the vessels meet these supporting resources at their current berth and depart in the opposite order of operations.

The order of vessels that enter the port is determined by the harbour masters office and related to tidal and safety restrictions as well as resource capacity. In most ports the harbour masters office is not responsible for tugging and pilot operations. These are handled by contracted companies and organisations. In some ports however, the harbour masters office is responsible for everything relating to safe berthing of a vessel. As can be seen in section 2.1 the process of synchronizing operations to move vessels in and out of ports is done using different timed events. The harbour master tries to create a schedule with as main focus the Planned Time of Arrival at the Pilot Boarding Point (PTA PBP). From this point forward, which is based on the ETA provided by the vessel agent and the Planned Time of Arrival at terminal berth, the rest of the nautical services are planned. If a vessel arrives before the planned time of arrival or because of a delay in port operations, the vessel is directed to an anchorage area where it waits until it can be served by nautical services. In case of a delay in terminal and auxiliary operations or unavailability of resources, departing vessels remain at berth until resources are available to maneuver the vessel out of the port area.

3.1.2 Objectives

Since many actors are working together in the port call the objectives for smooth port call operations differ a lot. For instance, tug and pilot organisations focus on optimal resource use. Their objective in creating a streamlined port call is considers mainly the use of their assets. Research in this direction has focused on optimal tug stationing or optimization of

vessel arrival focused on the optimal utilisation of pilots and tugs available. Vessel arrival and departure schedules are devised around their limitations and constraints.
Terminal operators are focused on vessel operations scheduling that optimizes their berth use, with vessels not laying unnecessarily long at berth waiting for nautical services to take them to sea or terminals waiting idle until a vessel arrives.
Captains want their vessel to be handled in a timely manner while keeping to schedule. If possible a container vessel or cruise ship will want to be handled immediately upon arrival. A bulk carrier captain might not see waiting times as problematic, because demurrage contracts can be beneficial to the vessel owner (Poulsen et al., 2018). The harbour master will want to create a port call system that is aimed at retaining safety while throughput is not jeopardized. A short overview is shown in table 3.1.

Actor	**Optimization objective**
Captain	Vessel arrival and departure without waiting times (depending on type)
Nautical services	Optimal asset use and allocation
Harbour master	Operations optimized regarding safety and throughput
Terminal operator	Berth utilization

Table 3.1: Optimization objectives for a smooth port call

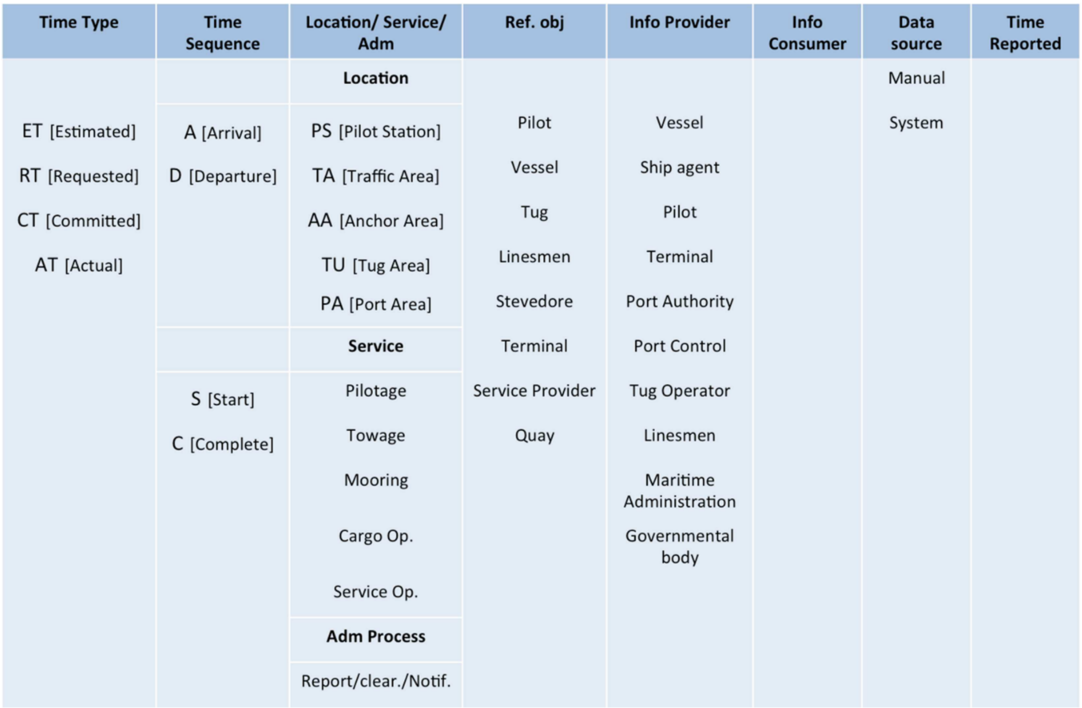
In light of this study, the focal point of the port call is to streamline operations in order to create a reduction of emissions during the port call based on increased information-sharing. As was discussed, the IMO proposes a 50% reduction of emissions in 2050 (International Maritime Organisation, 2018). This can be obtained by reduction of waiting times in the port call process (Arjona Aroca et al., 2020) and by advising arriving vessels to reduce their speed to arrive at the scheduled time for handling the vessel (Jia et al., 2019), (Broersma, 2021). If this is considered, next to the objectives stated above, the aim for optimization of the port call should be in creating a vessel arrival and departure schedule that on the one hand takes into account the available resources and safety regulations to ensure optimal movement planning in the port which can be used to update vessels on their optimal approach speed or departure time and on the other hand is capable of adapting to the frequently changing profile of operations in the port call due to delays that occur and cause inefficiencies in the port call.

3.2 Measurement and control of port call operations

To create a control structure that is able to steer the system to desired behaviour, the system should be measured. In the port call process, there is a lack of situational awareness, because actors do not share data on operations with each other (Lind et al., 2015). Therefore, when a certain operation is delayed, subsequent operations might also be delayed leading to an unfeasible schedule for port call operations. In this part, the use of the PortCDM concept as well as Automatic Identification Systems (AIS) are proposed as measurement systems for the control structure of the port call process. Secondly, control actions that can be implemented on the system are discussed.

3.2.1 Port Collaborative Decision Making

As discussed in section 2.3.3, PortCDM is a concept proposed in the Sea Traffic Management system. The aim of the project is to increase information-sharing among actors in the port call. This could lead to better situational awareness and therefore a more streamlined port call process (Lind et al., 2018b). Below is an overview given of the data points used in the currently designed S-211 standard for IALA.



Time Type	Time Sequence	Location/ Service/ Adm	Ref. obj	Info Provider	Info Consumer	Data source	Time Reported
		Location				Manual	
ET [Estimated]	A [Arrival]	PS [Pilot Station]	Pilot	Vessel		System	
RT [Requested]	D [Departure]	TA [Traffic Area]	Vessel	Ship agent			
CT [Committed]		AA [Anchor Area]	Tug	Pilot			
AT [Actual]		TU [Tug Area]	Linesmen	Terminal			
		PA [Port Area]	Stevedore	Port Authority			
		Service	Terminal	Port Control			
	S [Start]	Pilotage	Service Provider	Tug Operator			
	C [Complete]	Towage	Quay	Linesmen			
		Mooring		Maritime Administration			
		Cargo Op.		Governmental body			
		Service Op.					
		Adm Process					
		Report/clear./Notif.					

Figure 3.2: Sample of states used in S-211 standard (Lind et al., 2015)

The messages comprise of timestamps (see figure 3.2) relating to important information categories about locations, services and administrative tasks coupled with a reference object. The idea is that this creates a general overview of operations that can be made available for all actors involving a port call. Based on the generation of these states, posterior data-analysis can be performed in to root causes of delays and disruptions(Lind et al., 2015). But more importantly, the system can also create real-time updates of operations in the port call process. This means that the system can be used to detect delays when they occur as well as serve as input for a control structure to define control actions.

3.2.2 Automatic Identification System

The Automatic Identification System (AIS) is a transponder system on-board sea-going vessels. All vessels over 300 Gross Tonnage are outfitted with this system as per the Chapter V, Regulation 19.2.4 of the Safety of Life at Sea Convention. The AIS sends 3 types of data over the Very High Frequency (VHF) band used for maritime communication (Lessing et al., 2006). These data types are *static*, *dynamic* and *voyage related*. The first is information about vessel characteristics such as name and dimensions. Dynamic information comprises of heading, course, speed and position of the vessel. Voyage related information is for instance vessel destination and hazardous nature of the cargo on board. Dynamic information about the vessel is relayed to surrounding transponders every 2 to 10 seconds while underway. The other information is relayed in 6 minutes intervals (Lessing et al., 2006). The AIS system is adopted for safety reasons and can be used for collision avoidance, a means for States to obtain information about approaching vessels, but more importantly: as a Vessel Traffic Services tool, i.e. traffic management.

The information of the AIS system on-board vessels can be used in the context of this research as the latter describes. For traffic management, the dynamic information can help to predict if an approaching vessel is in time to get to the Pilot Boarding Point according to the Planned Time of Arrival. If this is not the case a good assumption can be made about what a revised ETA will be. Secondly, the static information about vessel dimensions can help to make a prediction about the resources a vessel needs during port call operations.

A minor set back with AIS is that currently the directly transmitted VHF signal, due to its wave form, travels transversely. This means that the range of AIS is around 40 Nautical Miles between sender and receiver. However, the installation of satellites that can pick up AIS signals from further away is currently underway reducing the problem.

3.2.3 Control actions in the port call

To optimize the port call of sea-going vessels in relation to the objectives stated in section 3.1.2 as well as the literature on vessel arrival and departure scheduling, it becomes clear that constantly considering the order of vessel movements in relation to the available resources and safety guidelines is a way of optimizing the port call process. This can be done by revising approved times of arrival and departure for the vessels. For vessels at berth a revision of departure times is, operationally, not a big impact. It can create friction, because a vessel might have to wait longer at berth which leads to idle times at both the vessel as well as the terminal, but there are no physical restrictions that impose constraints on changing the vessel movement order.

The concept of Virtual Arrival was designed to create speed and emissions reduction by updating approaching vessels of delays in port (Poulsen et al., 2018). This delay could be smeared out along the vessels' approach by reducing its speed in accordance to the renewed PTA. In the case of intelligent control we can use the concept to control the inflow of vessels to the port area. Based on real-time updates of the port area, new arrival and departure schedules can be devised and approach speeds are updated.

A problem with this is the operational profile of vessel engines. Vessel engines operate at a certain operational point at which the fuel efficiency is best. Constant reduction and increase of speeds during the voyage leads to higher fuel consumption than at constant speeds (Broersma, 2021). Secondly, vessel speeds are constrained by several limits, as discussed in Notteboom and Cariou (2009) the different speeds for container ship range from an optimal design speed between 20-25 kts, the lowest possible speeds are assumed to be 12-15 kts. At those speeds, container ships use minimal fuel but the level of service would be to low over long distances. Therefore, the approaching vessels can only be controlled in a discretized way, relating to to virtual arrival concept proposed by Jia et al. (2017a) and the way point approach proposed by Broersma (2021). The mathematical formulation of this concept is as follows:

Given a set of way points $WP = [1 \dots I]$, where the first way point is a distance D_{owp} from the arrival port and waypoint I is located at the port entrance. There exists a constant distance d between the way points. On approach to the port a vessel will hit this number of way points to update its speed to the revised schedule as proposed in this control structure. The distance to the port at waypoint i is than given as:

$$D_{port} = D_{owp} - WP_i * d \tag{3.1}$$

Based on the updated PTA and the current time t, a new Time to Arrival (TTA) can be calculated as follows:

$$TTA_{new} = PTA_{new} - t \tag{3.2}$$

From equations 3.1 and 3.2, the new approach speed V_{va} can be calculated as follows:

$$V_{va} = \frac{D_{port}}{TTA_{new}} \tag{3.3}$$

Where the distance D_{port} is calculated in Nautical Miles (NM) and TTA_{new} is calculated in hours. Which yields a result for V_{va} in knots (NM/hr). This new speed is constrained by the vessel speed limitations as follows:

$$V_{min} \leq V_{va} \leq V_{max} \tag{3.4}$$

In the case that equation 3.4 does not hold, the new speed V_{va} should be updated to the closest feasible value (either 12 or 25 knots). A new PTA should be communicated to the port through the following relation:

$$PTA_{new} = TTA_{new} + t = \frac{D_{port}}{V_{va}} + t \tag{3.5}$$

With this construction the control structure is able to steer the system of vessel operations in the port call to optimal speeds reducing emissions and enabling just-in-time arrival.

3.3 Control structure

This section proposes a control structure that is compatible with control as assumed in port call operations at this moment. To do so, first some general considerations are described. Secondly, a control structure for the port call process is proposed.

3.3.1 Considerations for control structures

A first distinction between control structures is the number of control agents that constitute the structure. In case of one control agent, the structure is deemed *single-agent* control. The control structure can in principle determine actions that give optimal performance of the system. In case multiple controllers are used, this is called a *multi-agent* structure. If agents communicate with each other this is *distributed* control and if there is no communication this is called *decentralized* control. If in a multi-agent environment there is an authority relation between controlling agents, the control structure is defined as *multi-layer*. This control structure is found in systems where one agent defines set-points for other agents in the system (Negenborn and Hellendoorn, 2010). For examples of the control systems, the reader is referred to Negenborn and Hellendoorn (2010).

Definition of control structures is not theorized for systems and is therefore based on preferences for one type or the other. For large scale systems, single-agent control is complicated by the fact that there exist problematic issues regarding control access and information unavailability. Furthermore, computational requirements can be very high for large scale controllers prohibiting their use in real-time environments. lastly, due to the large system a single-agent has to control it can suffer from reliability, scalability and robustness issues. These problems can be tackled by defining multi-agent control structures, but the performance of such a system is generally lower and implementation is far from trivial. In practice, choosing the best control structure is not the question. The question is how current control structures can be changed so that performance of the system is improved (Negenborn and Hellendoorn, 2010).

3.3.2 Control structure for the port call process

If we relate the last remark by Negenborn and Hellendoorn (2010) to vessel operations in the port call, it can be concluded that the control structure is very decentralized. Captains are responsible for their vessel and chosen speed during their voyage to port. The harbour master will devise a Planned Time of Arrival based on berth scheduling provided by terminal operators and the use of assets is determined by nautical service providers, of which in many ports exist more than one for the same service (e.g. multiple tugboat operators). This means that controlling the system is a complicated task. Based on these remarks, it would seem preferable to create a *multi-agent multi-layer distributed* control structure. In that case, the harbour master can devise set points for vessel arrival and departure in conjunction with for instance system optimization for nautical services allocation, berth allocation and dynamic speed adaption by vessels. These agents can communicate about preferences to optimize the system as a whole. Unfortunately, implementation is far from trivial. due to time and resource limitations this study cannot provide such an elaborate control structure for port call optimization.
However, if we take into account that the main anchor point for operations planning for all services is the movements schedule as created by the harbour master with PTA's and PTD's. Based on this planning, nautical services can create their own asset use and terminals know better in advance how to plan terminal operations. Furthermore, the virtual arrival concept is also conceived around these data-points. A *single-agent* control structure could be designed for this problem. This control agent resembles the harbour masters task of creating an arrival and departure schedule that is in line with resource availability and safety measures. In relation to problems with information acces, the PortCDM concept is able to provide in real-time a good overview of current port operations with inputs from all actors involved. It was furthermore proven in vessel scheduling optimization literature that such a controller can optimize throughput in ports and is tractable for problem sizes that occur in real-world situations (Abou Kasm et al., 2021).

3.3.3 Relation with preliminary model

The relation between the preliminary model proposed in the previous chapter can be readily obtained from the statements above. As far as the operational plan goes, this responsibility lies with the harbour master which acts as an overall system controller by defining start times of operations through scheduling optimization. The logistics synchronization is obtained through the use of virtual arrival in the port approach. The PortCDM concept can be used for increased information-sharing in the port call. The information needs are

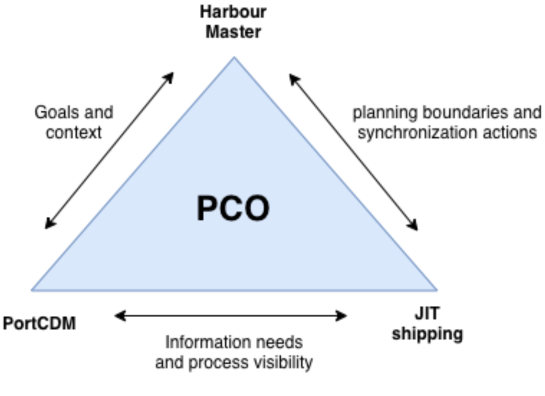


Figure 3.3: Implementation of preliminary model

provided by the just-in-time shipping concept through virtual arrival. These needs relate to the information about vessel specific information such as speed and location as well as other process markers ("milestones") as proposed in the PortCDM concept. This in turn leads to visibility of the process since everyone involved is updated of the status of different actions in the port call. The Harbour Master in turn, based on the information obtained through the CDM concept, can align the goals in port call operations with the operational context provided. The relation between the harbour master and just-in-time shipping as a form of logistics synchronization is obtained from the operational perspective in which the harbour master sets the boundaries for the operations and the synchronization of actions leads to obtaining the goals set out by the Harbour Master.

3.4 Conclusion

This section aimed at giving an answer to the second research question of this thesis:

How can a control structure for vessel operations in the port call be designed?

From the previous section it follows that vessel operations in the port call are largely controlled by the movements schedule created by the harbour masters office. All nautical services depend on this schedule for creating their own planning. The objectives for an optimized port call are distributed among actors and relate to asset use for nautical service providers, safe and timely movements for the harbour master and optimal terminal use for terminal operators. In relation to the IMO goal of emissions reduction and just-in-time arrival, it was shown that a vessel schedule that is constantly updated based on real-time information sharing could be an integrator for port call optimization.
This thesis proposes therefore a single-agent control structure for vessel movement scheduling and vessel inflow regulation. The single-agent control structure was deemed feasible to handle the vessel arrival problems in reasonable time and with profitable results for delay reduction. Measurement inputs for the vessel operations scheduling comes from the proposed PortCDM concepts as described in sections 2.3.3 and 3.2 and AIS data of approaching vessels. The system can be controlled by postponing or advancing vessel movements in time to ensure optimal resource use and turnaround times. Secondly, approaching vessels can be advised to decrease their speed as per the virtual arrival concept developed in literature. Due to vessel engine characteristics this should happen at virtual way points along the approach and within certain boundaries. An overview of the control structure including actuation of the system and measurements is given in figure 3.4

The question remains how such a vessel movement controller can be designed taking into account the constraints and limitations that are imposed on the system through physical properties of the system, resource availability and optimization goals. The next chapter of this thesis will try to answer this question.

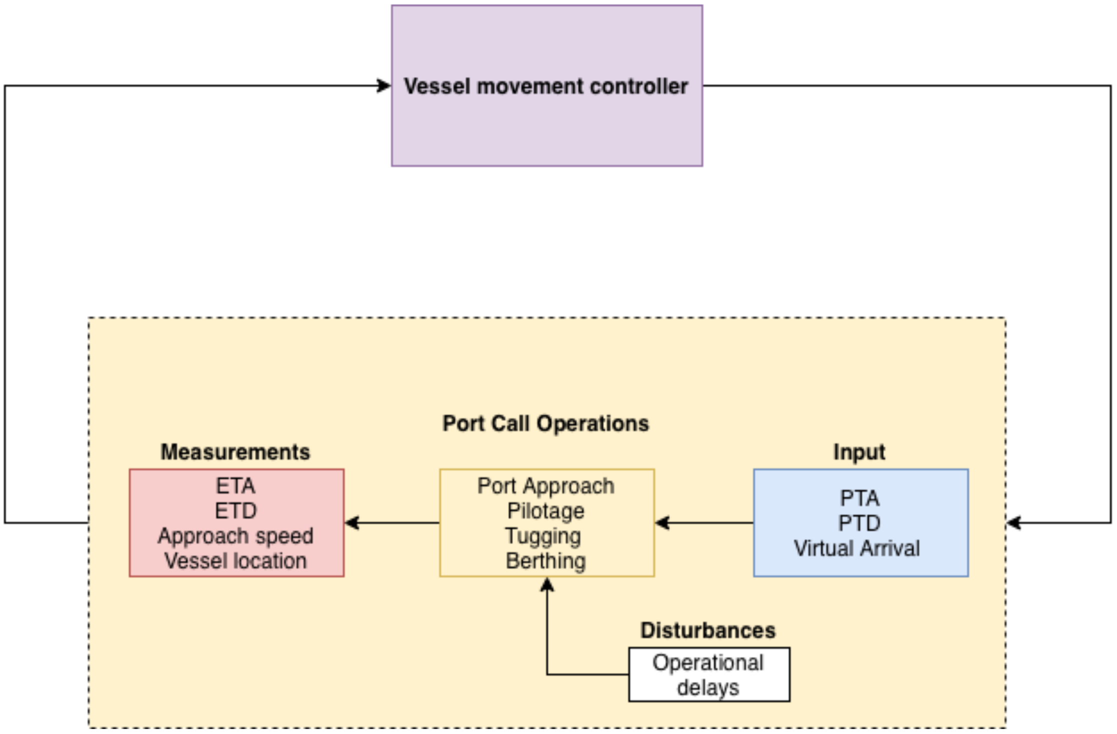


Figure 3.4: Control structure for vessel movements in the port call process

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Chapter 4

Controller design

This chapter will answer the third subresearch question posed in the section on research approach. To do so, first a suitable control approach is discussed. Secondly, a description of the system under control and it's objectives are described. A mathematical prediction model based on the work of Abou Kasm et al. (2021) is presented to the reader together with considerations about a rolling horizon scheduling approach and solution methods.

4.1 Control approach

If the control structure has been chosen, it is important to make sure the controller finds the right actions that meet control objectives and system constraints. Relevant information about the system should be used to calculate the consequences of different actions (Negenborn and Hellendoorn, 2010). A control form that can do this and is proposed in literature is *Model Predictive Control* (MPC). This control strategy is able to take all kinds of information and tries to calculate the impact of inputs on the system over a given time-horizon. In between control cycles, inputs are considered constant. For this reason, this technique is also called rolling-horizon approach (Atabay, 2018). The concept for a single-agent controller is shown in figure 4.1.

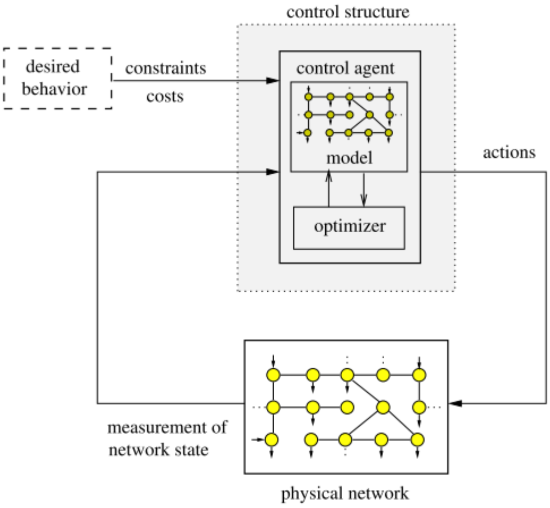


Figure 4.1: View of single-agent MPC (Negenborn and Hellendoorn, 2010)

This approach calculates the impact of actions on the system by assessing dynamics of the system in discrete time-steps using a prediction model. This assessment is done based on an objective function that specifies the goals of the system mathematically. The time-horizon is an important and has a effect on the outcomes of the system, because the model is able to see the impact of its actions better. However, computationally this increases the burden on computing power and might render the prediction model intractable. Too short of a time-horizon, however, can lead to system states it cannot escape and lead to failure of the system.

The algorithm behind MPC is given in Negenborn and Hellendoorn (2010) and is defined as:

1. Measure the current state of the system
2. Determine which actions optimize the performance over the prediction horizon by solving the following optimization problem:

   minimize the objective function in terms of actions over the prediction horizon
   subject to the dynamics of the whole network over the prediction horizon, the constraints on, e.g., ranges of actuation inputs and link capacities, the measurement of the initial state of the network at the beginning of the current control cycle.

3. Implement the actions until the next control cycle, and return to step 1.

Some important considerations have to be made when using MPC to be succesful. First of all, it is important to specify the control goals of the system. Secondly, a prediction model of the system has to be constructed and measurements of the system have to be available. Lastly, a suitable optimization method should be found that can solve the optimization problem in reasonable time (Negenborn and Hellendoorn, 2010). Atabay (2018) proposes for MPC some of these solution methods for handling MPC problems. The model that describes the system is of importance because not only does it defines the accuracy of the prediction, but also the solution approaches that can be used. For instance, linear or quadratic models are less accurate than nonlinear models of the system, but they can be solved by reliable and widely available solvers whereas nonlinear systems are much more computationally heavy and cannot guarantee global optima(Atabay, 2018).

4.1.1 Rolling horizon approach for (arrival) scheduling

Rolling horizon approaches for decision-making have extensively been studied in literature (Sethi and Sorger, 1991). Rolling horizon approaches were developed for lot-sizing in production scheduling, operation room scheduling in hospitals and stochastic supply chain management planning of goods transportation (Glomb et al., 2022). In case of arrival scheduling, a comparison can be drawn between aircraft arrival and departure scheduling and vessel operations in the port call. Aircraft, like sea-going vessels, arrive at outer perimeters of the airport airspace and make their arrival known to air traffic control (ATC). ATC operators then guide the aircraft to the airport using automated paths until they reach the point of final approach (Furini et al., 2015). Based on the Estimated Time of Arrival at this point and the estimated final approach time an Estimated Landing Time can be calculated. Based on Estimated Landing Times, a scheduling optimization can be used to calculate the optimal sequence in which aircraft should arrive constrained by safety distances between consecutive aircraft and runway capacity. This Estimated Landing Time can be related to the Estimated Arrival Times used in the operations scheduling of ports. Secondly, the constraints such as safety distances between consecutive vessels as well as capacity constraint regarding resources can also be found in vessel arrival scheduling. Furini et al. (2012) proposed a rolling horizon approach to schedule aircraft arrivals and departures from a single runway. To do so, 2 separate sets of arrival movements were considered. One set in the total planning horizon that could be altered according to certain safety measures as well as a set of arrivals in their final approach that could not be altered. Girish (2016) proposed a heuristic solution to the aircraft scheduling problem based on an objective function that minimizes the deviation from the planned schedule at the beginning of the time horizon for approaching aircraft. Both approaches showed that the rolling horizon approach for aircraft scheduling is performing better than a first come, first serve strategy.

In most cases, the rolling horizon approach for scheduling is performed by solving a static scheduling model for a certain period of time, i.e. the scheduling horizon, and fixed for a certain amount of time after which the static scheduling model is recalculated with new input (Ouelhadj and Petrovic, 2009). These time periods are described as the time horizon and control cycle or roll period.

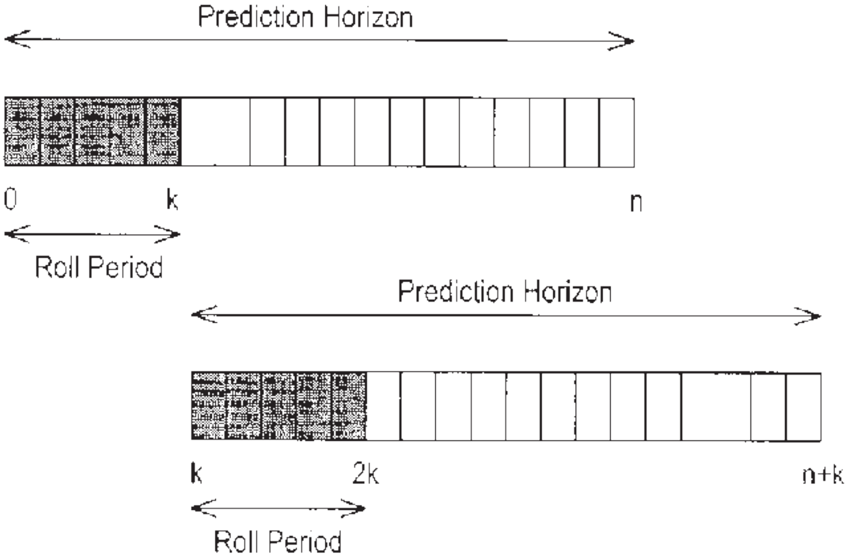


Figure 4.2: Schematic view of rolling horizon approach (Gartner and Stamatiadis, 1998)

As discussed before, the length of the time-horizon determines the outlook of the optimization model and therefore the assessment of impact of actions in the current roll period on the system. Secondly, the roll period marks the time period in which nothing changes. In case of vessel movement scheduling with virtual arrival, this means that within this period all vessels that are ready for movement, are expected to start at the optimal starting time defined at the beginning of that roll period and for vessels approaching the port that come upon a virtual arrival way point change their speed to the predicted optimal arrival time as defined at the beginning of this roll period.

The determination of a control cycle is a hard exercise and not necessarily a deterministic one (Ouelhadj and Petrovic, 2009). For different manufacturing problems, it was shown that increasing the control period yields worse results in terms of scheduling optimization, but that it shows better performance than other dispatch rules (Ouelhadj and Petrovic, 2009). This means that the control period under review in this thesis should be subject to experimentation, to find its influence on the system.

A pitfall of periodic rescheduling is that sometimes intermediate operations or production, i.e. within the roll period, are not carried out according to the most optimal solution that can be found based on available information. A solution to this problem is to update the schedule based on major events to be ensured of optimal scheduling information. However, rolling horizon schedules have proven to be less nervous and better equiped to create scheduling stability. Secondly, the event-based approach brings up the question of when a disruption is large enough to justify a schedule change in relation to the impact of the schedule change on the system. This question is hard to answer and without definitive conclusions about assumptions to be made in general Ouelhadj and Petrovic (2009). With a rolling horizon approach, this question is avoided.

4.2 Prediction model

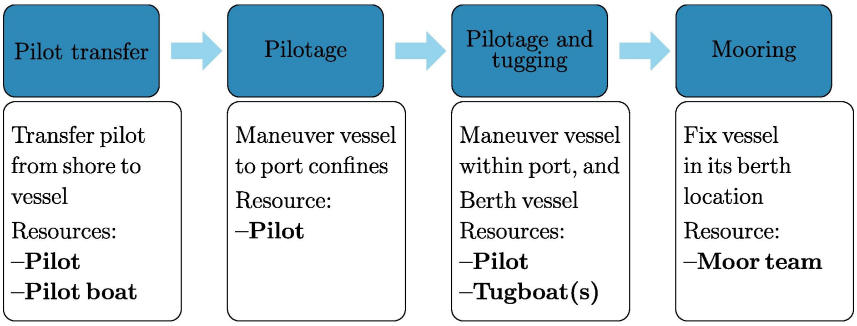
This section will describe the the proposed prediction model used to optimize port call operations based on arrival scheduling. As discussed in the first chapter of this thesis, arrival scheduling of vessels has been researched in light of channel restrictions as well as resource constraints. This study focuses on resource constraints in the nautical sector in relation to port call optimization and therefore, the model proposed by Abou Kasm et al. (2021) is used and adapted to predict system behaviour and make decisions about movement starting times to optimize the port call. First, the static scheduling model is presented and afterwards adaptations to the model relating to rolling horizon optimization are discussed.

4.2.1 System description

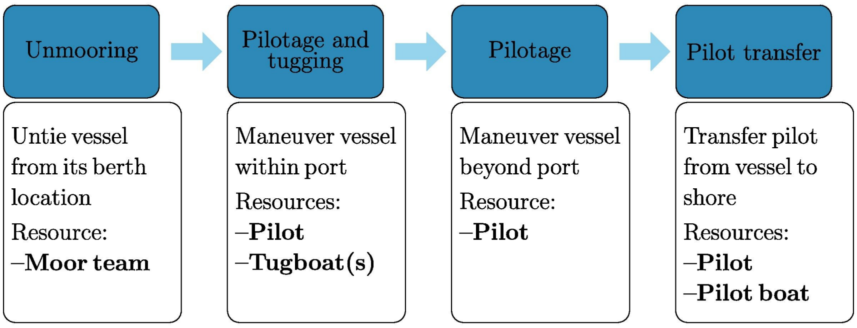
Section 2.1 describes the port call process regarding the in and out movements of vessels in the port call and their needed resources. In a prediction model, the separate parts of the *in*, *out* and *shift* movements are taken. For every incoming vessel a number of pilots is needed. These pilots need to be transported to the vessel by pilot boats to the pilot boarding ground at the outer perimeter of the port. After boarding a vessel, the vessel moves towards the tug meeting point, which is closer to berth. At this meeting point, tugs are available and attached to the vessel. After this the vessel moves through the approach channel towards the berth. At the berth, mooring teams will attach the ship to the quay after which terminal operations can commence. After the ship has moored, the tug boat leaves the terminal area and the pilot is, in most cases, transported back to its station by car. For *out* and *shift* movements tug boats, pilots and mooring teams arrive at the designated berth. After terminal operations are completed, the vessel is released from the dock by mooring teams and escorted by pilot and tugs to its next destination. In case of an out movement, tugs detach from the vessel at the tug meeting point and the pilot at the outer boarding ground. In case of a shift movement, both detach from or leave the vessel at its next destination within the port. An overview of berthing operations is shown in figure 4.3.

Resource needs are determined based mostly on the dimensions of the vessel. For most ports, vessels are obligated to enter the port area with a pilot on board. In some cases, such as ferries, officers on board can have large local knowledge and apply for a *pilot exemption certificate* (Abou Kasm et al., 2021). In that case, pilot assistance is not needed for port manoeuvres. The assistance of tugs is determined by the harbour master. The amount of tugs and their towing capacity is determined based on local knowledge and safety regulations and are based on length of the vessel, tide, the availability of bow thrusters and the side surface of the vessel (Darwin Port, 2021).

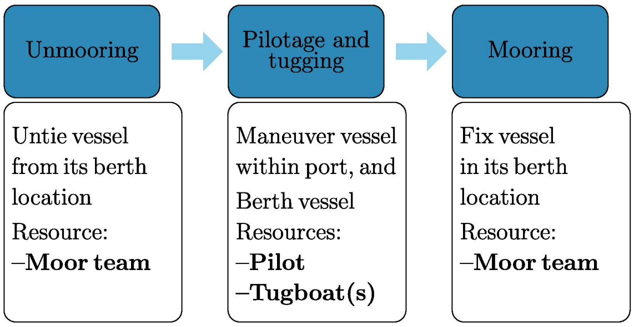
In relation to the virtual arrival concept discussed previously, not only berthing operations are regarded but also the approach voyage of incoming vessels. As discussed, under the virtual arrival policy vessels can be advised to change speeds to acquire an optimal arrival time. However, There are some constraints to be made on the maximum and minimum vessel speeds as discussed in the previous chapter. This should be taken into account when creating a prediction model.



(a) In movement



(b) Out movement



(c) Shift movement

Figure 4.3: Overview of operations and resource use per movement type (Abou Kasm et al., 2021)

4.2.2 System objectives

The aim of this study is to reduce emissions by sea-going vessels in the port call. One could argue that therefore the objective of the system should lie in creating a schedule that reduces the amount of emissions the most as possible, i.e. retarding the arrival of more heavily polluting vessels in the arrival schedule to make them reduce their speed and therefore create a bigger gain in emission reduction. This approach, however, would mean that that the burden of disturbances in the systems would unfairly be distributed between arriving vessels.

As discussed previously, vessel agents agree with terminal operators on a certain arrival window in which the vessel can be handled with the terminal operator. Based on this planned terminal arrival time, the harbour master proposes an arrival time for the vessel at the port perimeter to meet pilot and later on tugs. For arrival optimization it is therefore important that the optimized arrival time does not deviate too much from the ETA provided by the vessel agent, which is in line with the planned terminal arrival time. The same goes for departing vessels. If a vessel is ready to leave it should be handled as closely possible to the agreed departure time to reduce the amount of idle time for either terminal as well as the vessel itself in relation to emissions this means that a vessel that does not wait to long at berth before it can be escorted out of the port area produces less emissions in those shorter times.

Another important aspect with respect to virtual arrival and optimal scheduling is the fact that large and frequent speed changes for vessels are unfavourable to the emissions of the vessel (Broersma, 2021), (Wijma, 2018). In practice, vessels have an optimal design speed at which the engine performance is best. One should aim to adhere to this optimal design speed if possible.

If we relate this notion and the the previous about generating arrival and departure schedules that reduce the deviations between planned and optimal operations start times for all vessels it can be concluded that the system objective should be to create an arrival schedule that minimizes the maximum deviation between the vessel ready time for an operation and its actual start time given the available resources in the port. One the one hand, for departing vessels, this reduces idle times and therefore emissions in the port area. Secondly, reducing the deviation of arrival times determined by vessel agents and terminals also reduces the amount of speed change for vessels in the virtual arrival approach. This can be mathematically shown through the following relation:

$$v = \frac{D_{port}}{TTA} \tag{4.1}$$

The vessel speed v is calculated with respect to the vessel distance to port D_{port} divided by the Time to Arrival TTA. If the new optimized arrival time deviates from the current TTA by δ than the new speed for virtual arrival can be written as:

$$v_{new} = \frac{D_{port}}{TTA + \delta} \quad \delta \in \Re \tag{4.2}$$

The relative change in vessel speed due to the deviation from the original TTA can be calculated as:

$$\frac{v_{new}}{v} = \frac{TTA}{TTA + \delta} \tag{4.3}$$

And therefore minimizing the absolute value of δ through mathematical optimization will lead to the following:

$$\lim_{\delta \to 0} \frac{TTA}{TTA + \delta} = 1 \tag{4.4}$$

From equation 4.4, it becomes clear that the minimization of the maximum deviation in scheduling vessel arrivals not only benefits idle times and schedule adherence in relation to agreements between vessel agents and terminal, but it also reduces the changes in vessel speeds occurring during the virtual arrival approach.

4.3 Mathematical formulation of prediction model

This section will describe the mathematical formulation of the static prediction model. First, the input parameters based on the system description are presented to the reader. After this, the objective function as well as constraints are presented and discussed.

4.3.1 Model input parameters

Sets:

I:	set of all vessel movements	$i, j \in I = \{1{:}\lvert I\rvert\}$
K:	set of vessel movements	$k \in K$ where $k = 1$ is IN, $k = 2$ is OUT, $k = 3$ is SHIF
T:	set of all time periods in scheduling horizon	$t \in T$

Decision variables:

s_{it}: binary decision variable to start vessel movement i at time period t $\forall$i $\in I$, $t \in T$

Γ : Maximum deviation from expected time of arrival or departure

Parameters:

Q_t	Number of available tug boats
Q_i	Number of tug boats needed for vessel movement i, $\forall i \in I$
P_i	Number of periods needed for tugging and pilotage of vessel movement i , $\forall i \in I$
A^{in}	Minimum time between the start of two *in* operations
A^{out}	Minimum time between the start of two *out/shift* operations
N	Number of pilots available at the port
A^n_i	Number of periods vessel movement i requires piloting without tug assistance, $\forall i \in I$
A^{ti}	Number of periods a tugboat needs to reach a vessel for an *in* operation
A^{to}	Number of periods a tugboat needs to reach a vessel for an *out/shift* operation
R_i	Binary variable, if vessel movement i requires a pilot $\forall i \in I$
V	Number of pilot boats available in the port
A^v	Number of time periods a pilot boat needs to carry out a one-way journey
W	Number of available mooring teams in the port
A^W_i	Number of time periods needed for mooring vessel movement i, $\forall i \in I$

O_{ik}	Binary variable, if vessel movement i is of type k, $\forall i \in I$, $k \in K$
E_{it}	Binary variable, if vessel movement i is ready to start at time period t, $\forall i \in I$, $t \in T$
G_{ij}	Binary variable, if vessel movement i and j relate to the same vessel. $\forall i, j \in I$
C_i^r	Number of time periods for vessel movement i to reach the channel. $\forall i \in I$
C_i^n	Number of time periods for vessel movement i to move through the channel. $\forall i \in I$
B	Number of berthing locations in the port
B_v	Number of vessels berthed at the start of the planning horizon
D_{owp}	Distance from outer Virtual Arrival way point to port entrance
d_{wp}	Distance between Virtual Arrival way points
WP	Total number of way points in Virtual Arrival area
v_i^{max}	Maximum speed for vessel movement i in virtual arrival, $\forall i \in I$, $k = 1$
v_i^{min}	Minimum speed for vessel movement i in virtual arrival,$\forall i \in I$, $k = 1$
WP_i	Next way point to be hit by vessel in related to *in* movement i, $\forall i \in I$, $k = 1$
t_i^{WP}	time period at which vessel related to *in* movement i reaches next Virtual Arrival waypoint.
M	Big-M value for calculation purposes
tp	length of time period in hrs

4.3.2 Mathematical formulation of objective function

As discussed in 4.2.2, the system objective is to minimize the maximum deviation between the time a vessel is ready to start a movement and the time the movement is planned to start. The maximum deviation between start and ready times for all vessels is described as:

$$\Gamma = \max_{i \in I} \sum_{t}^{|T|} |t(s_{it} - E_{it})| \tag{4.5}$$

However, if we would only minimize the maximum deviation this would not lead to the most optimal schedule. If a movement i had incurred a deviation of 11 hours, subsequent vessel movements can be delayed by the model with 11 hours without costs. This can not be the case, since the objective is that all vessels start operations as close to ready time as possible. To overcome this problem, (Abou Kasm et al., 2021) append a weight function to the maximum delay as well as a function to calculate the total time needed in the time horizon to schedule all vessel movements. This gives a new objective function that minimizes the maximum delay, penalizes extra delay for subsequent vessels and tries to schedule operations in the shortest time window possible:

$$Z = MIN \quad \Gamma \sum_{i \in I} (|T| - \sum_{t \in T} E_{it}) + \sum_{t \in T} \sum_{i \in I} t s_{it} \tag{4.6}$$

4.3.3 Mathematical constraints

$$\Gamma - \sum_{t=1}^{|T|} t(s_{it} - E_{it}) \geq 0 \quad \forall i \in I \tag{4.7}$$

$$-\Gamma + \sum_{t=1}^{|T|} t(s_{it} - E_{it}) \leq 0 \quad \forall i \in I \tag{4.8}$$

$$\sum_{t=1}^{|T|} s_{it} = 1 \quad \forall i \in I \tag{4.9}$$

$$\sum_{i\in I} \sum_{t'=g(t-P_i+1)}^{g(t-A_i^n+A^{ti})} O_{i1} Q_i s_{it'} + \sum_{i\in I} \sum_{t'=g(t-P_i+A_i^n-A_i^W+1)}^{g(t-A_i^W+A^{to})} \sum_{k=2}^{3} O_{ik} Q_i s_{it'} \leq Q_t \quad \forall t \in T \tag{4.10}$$

$$\begin{aligned} \sum_{i\in I} \sum_{t'=g(t-P_i+1)}^{g(t+A^v} O_{i1} R_i s_{it'} + \sum_{i\in I} \sum_{t'=g(t-P_i-A_i^W-A^v+1)}^{g(t-A_i^W)} O_{i2} R_i s_{it'} \\ + \sum_{i\in I} \sum_{t'=g(t-P_i-A_i^W+1)}^{g(t-A_i^W)} O_{i3} R_i s_{it'} \leq N \quad \forall t \in T \end{aligned} \tag{4.11}$$

$$\sum_{i\in I} \sum_{t'=t}^{g(t+A^{in}-1)} O_{i1} s_{it'} \leq 1 \quad \forall t \in T \tag{4.12}$$

$$\sum_{i\in I} \sum_{t'=g(t-A_i^W)}^{g(t-A_i^W+A^{out}-1)} \sum_{k=2}^{3} O_{ik} s_{it'} \leq 1 \quad \forall t \in T \tag{4.13}$$

$$\sum_{i\in I} \sum_{t'=g(t-A^V+1)}^{g(t+A^V)} O_{i1} R_i s_{it'} + \sum_{i\in I} \sum_{t'=g(t-P_i-A_i^W-A^v+1))}^{g(t-P_i-A_i^W+A^V)} O_{i2} R_i s_{it'} \leq V \quad \forall t \in T \tag{4.14}$$

$$\begin{aligned} \sum_{i\in I} \sum_{t'=g(t-P_i-A_i^W+1)}^{g(t-P_i)} O_{i1} s_{it'} + \sum_{i\in I} \sum_{t'=g(t-P_i-A_i^W+1)}^{t} \sum_{k=2}^{3} O_{ik} s_{it'} \\ + \sum_{i\in I} \sum_{t'=g(t-P_i-2A_i^W+1)}^{g(t-P_i-A_i^W)} O_{i3} s_{it'} \leq W \quad \forall t \in T \end{aligned} \tag{4.15}$$

$$s_{it} - \sum_{t'=1}^{t} E_{it'} \leq 0 \quad \forall i \in I : O_{i2}, O_{i3} = 1, \forall t \in T \tag{4.16}$$

$$\sum_{t\in T} ts_{it} - \sum_{j=1}^{i-1} G_{ij} \sum_{t\in T} ts_{it} - \sum_{t\in T} tE_{it} + \sum_{j=1}^{i-1} G_{ij} \sum_{t\in T} tE_{jt} \geq 0 \quad \forall i \in I \tag{4.17}$$

$$\begin{aligned} &\sum_{t''=g(t+C_i^r)}^{g(t+C_i^r+C_i^n+1)} \sum_{j\neq i} \sum_{t'=g(t''-C_j^r-C_j^n-A_j^W+1)}^{g(t''-C_j^r-A_j^W)} O_{j2}s_{jt'} \\ &\qquad + (s_{it}-1)\sum_{j\in I} O_{j2} \leq 0 \quad \forall i \in I : O_{i1} = 1, \forall t \in T \end{aligned} \tag{4.18}$$

$$B^v + \sum_{i\in I} \sum_{t'=1}^{g(t-P_i)} O_{i1}s_{it'} - \sum_{i\in I} \sum_{t'=1}^{g(t-A_i^W} \sum_{k=2}^{3} O_{ik}s_{it'} + \sum_{i} \sum_{t'=1}^{g(t-P_i-A_i^W))} O_{i3}s_{it'} \leq B \quad \forall t \in T \tag{4.19}$$

$$\begin{aligned} &(D_{owp} - (WP_i * d_{wp})) - (v_i^{max} * ((s_{it} * t) - t_i^{wp})) \\ &\qquad \leq 0 + M * (1 - s_{it}) \quad \forall i \in I : O_{i1} = 1, \forall t \in T \end{aligned} \tag{4.20}$$

$$s_{it} - \sum_{t\in T} E_{it} = 0 \quad \forall i \in I : O_{i1} = 1, WP_i = WP - 1 \tag{4.21}$$

$$s_{it} \in 0,1 \quad \forall i \in I, \forall t \in T \tag{4.22}$$

$$\Gamma \geq 0 \tag{4.23}$$

4.3.4 Time bounding function

To make sure that the time constraints are enforced within the time horizon from $T = \{t_0 : T\}$, the function $g(x)$ is introduced for the model. This has to do with the fact that whenever an operation starts near the beginning or end of the planning horizon, the calculations on resource use can fall out of range T, because resources are seized before or after the planning horizon starts or ends.

$$g(x) = max\{min\{x, |T| + 1\}, 0\} \tag{4.24}$$

This function prohibits this from happening and sets the calculated values for the time resources are seized equal to 0 or $T+1$ when the time period falls out of the feasible range. To ensure this feasibility, starting times of operations at 0 or $T+1$ are not allowed and the following constraint is adhered to the model:

$$s_{it} = 0 \quad \forall i \in I, T = \{0, T+1\} \tag{4.25}$$

4.3.5 Description of constraints

Since the objective function in equation 4.6 is non-linear and related to the absolute value of the schedule deviation, constraints 4.7 and 4.8 linearize the objective function. Constraint 4.9 ensures that a vessel operation i is only performed once during the time horizon. Resource use in time period t is constrained by constraints 4.10, 4.11, 4.14, 4.15. 4.12 and 4.13 ensure that the time between consecutive movements are taken in to account. Constraint 4.12 prohibits planning of out and shift movements before ready time. For in movements, this is ignored, because they can be moved to an earlier time or later time of arrival in accordance with Virtual Arrival. 4.17 is used to propagate delays if consecutive vessel movements are known at the moment of planning and an arrival movement is retarded. 4.18 is used to ensure safe distances in the fairway between vessel movements and constraint, 4.19 ensures berth availability at for all vessels in the planning horizon. 4.20 is appended to the model of Abou Kasm et al. (2021) and relate to the virtual arrival of in movements. The speed of the vessel is constrained by a maximum speed. This constraint is only enforced on the planned starting time s_{it} through the use of the big M. 4.21 ensures that when vessels are in the last virtual arrival leg of their approach, the scheduled start time of the in-operation is not changed.

Abou Kasm et al. (2021) propose the time limits on resource constraints, because of the overlap in operations that occurs within port operations. The logic behind this is that the starting time variable s_{it} is the reference point for all resources to adhere to. This means looking in reverse as well as forward for different movements, because resources have to travel to and from the departing or arriving vessel. This means that resources are seized before and after the starting time of movement i, introducing the need for constraints that assess variable times. For an example, the reader is referred to Abou Kasm et al. (2021).

4.4 Rolling horizon approach

For the rolling horizon approach, important considerations are the time-horizon over which the controller determines the impact of its decisions to actuate the system. This section will discuss that aspect with regards to the static vessel scheduling problem.

4.4.1 Scheduling horizon

With regards to the prediction period, or scheduling horizon in this case, single-agent controllers perform better when the prediction horizon is increased. However, increasing the time horizon heavily burdens computing power and speed of the optimization (Atabay, 2018). Therefore, a suitable planning horizon should be chosen to ensure that the system is able to perform better in terms of delay optimization, without taking up considerable calculation time. The set of time periods is than updated every control cycle to create the following:

T: set of all time periods in scheduling horizon $t \in T = \{t_0 : t_0 + |T|\}$

In this case, t_0 denotes the time period at which the scheduling period is commenced, i.e. the current time in the system and $|T|$ is the length of the scheduling horizon in time periods.

A second observation should be made with regards to the feasibility of the static MILP model. To ensure feasibility over the time horizon, Abou Kasm et al. (2021) provide an equations to determine the scheduling horizon $|T|$ based on the possible latest finishing time of the last movement $|I|$ in the movement set I. This algorithm is as follows:

$$|T| = \begin{cases} max\{F_{|I|-1}, E_{|I|}\} + max\{A^{v} + A^{n}_{|I|}, A^{ti}\} + P_{|I|} - A^{n}_{|I|} + A^{W}_{|I|}, if \quad O_{|I|,1} = 1 \\ max\{F_{|I|-1}, E_{|I|}\} + max\{A^{to}, A^{W}_{|I|}\} + P_{|I|} + A^{v}, \qquad if \quad O_{|I|,2} = 1 \\ max\{F_{|I|-1}, E_{|I|}\} + max\{A^{to}, A^{W}_{|I|}\} + P_{|I|} + A^{W}_{|I|}, \qquad if \quad O_{|I|,3} = 1 \end{cases} \tag{4.26}$$

$$F_i = \begin{cases} max\{F_{i-1}, E_i\} + max\{A^{v} + A^{n}_{i}, A^{ti}\} + P_i - A^{n}_{i} + A^{W}_{i}, if \quad O_{i1} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A^{W}_{i}\} + P_i + A^{v}, \qquad if \quad O_{i2} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A^{W}_{i}\} + P_i + A^{W}_{i}, \qquad if \quad O_{i3} = 1 \end{cases} \tag{4.27}$$

$$E_i = E_i + max\{F_{j-1}, E_j\} - E_j \quad \forall i, j \in I : G_{ji} = 1, \quad j < i \tag{4.28}$$

However, for the sake of speed of calculation and since the scheduling horizon should be fixed, a subset S of I is presented which represents all vessel movements that can be finished within the scheduling horizon |T|. By sorting all movements in I based on their ready time E_i a list of feasible movements within the time horizon can be made. Algorithm 1 shows this logic. As can be seen, this algorithm determines the subset of all vessels that

Algorithm 1 Determining $S \subset I$

```
$i = 1, S = \{\}, t_0, |T|, G_{ij}$
Sort $I$
while $i <= |I|$ do:
    for $j$ in $I$ do:
        if $G_{ji} = 1$ & $j < i$ then:
            Calculate $E_i$
        end if
    end for
    calculate $F_i$
    calulate $T_i$
    if $T_i < t_0 + |T|$ then:
        append $i$ to $S$
        $i \leftarrow i + 1$
    else
        $i \leftarrow i + 1$
```

can be feasibly scheduled in the time horizon. The static scheduling problem defined in the previous section, is than changed with regards to the sets to incorporate S rather than the overall movement set I.

Another problem with the static scheduling model is the occurrence of vessel movements that have started in a previous control period and, based on their ready-time E_i, do not fall in the scheduling horizon. However, these movements still burden the system in terms of resource use in the current scheduling period, when the movement has not finished. To overcome this problem, a variable is introduced that checks if the movement is *underway* at this time period.

$$r_i \quad \text{binary variable to determine if movement } i \text{ is underway} \quad \forall i \in I \tag{4.29}$$

Algorithm 2 Determine new t_0 for all movements i that have started before beginning of planning horizon t_0

```
$S, E_i, t_0$
Sort $E_i$   $\forall i \in S$
if $min(E_i) < t_0$ then:
    $t_0 \leftarrow min(E_i)$
else
    $t_0 \leftarrow t_0$
```

To accommodate these movements in the current scheduling horizon, the time horizon is extended backwards in time to be started at the earliest starting time of all movements that are underway at the moment of scheduling t_0. Algorithm 2 shows this.

Since some movements already have started, they will need their movement starting times to be fixed in the scheduling model. This leads to the following constraint:

$$s_{it} - \sum_{t'=t_0}^{t} E_{it} = 0 \quad \forall t \in T \forall i \in S : r_i = 1 \tag{4.30}$$

4.5 Solution approaches

This section will discuss solution approaches that can be used for solving the optimization problem based on the objective function and prediction model of the system described in the previous sections of this chapter.

4.5.1 Solution Approaches

In the literature on vessel scheduling, all authors have chosen to model their scheduling systems as Mixed Integer Programs. Mixed Integer (Linear) Programs (MILP) use (binary) decision variables to determine the sequence of operations. To find an optimal solution of the problem, these decision variables are mathematically related to an objective function through constraints and model parameters. It is the aim of the researcher to model the system at hand in the best way by expressing the system in this set of parameters and constraints. MILP models can be more easily solvable than other MPC models which mostly constitute of non-linear problems. They are, however, less detailed and able to harness the dynamics of systems (Atabay, 2018).

In the current literature extensive comparisons have been made between performance of commercially available solvers, in most cases GAMS-CPLEX, and other (meta)heuristics. In almost all cases the problems showed problematic behaviour, because most scheduling problems are NP-hard and can therefore not be solved to optimality in polynomial time (Jonker, 2017). For small problem instances traditional solvers have shown reasonable behaviour (Abou Kasm et al., 2021). For real-time use it is important to search for a solution approach that can on the one hand find an optimal solution to the given prediction model as well as do this in reasonable time. In the scheduling literature of vessel arrival most researchers choose for a Genetic Algorithm to solve the optimization problem (Lin et al., 2014), (Zhang et al., 2016) (Zhang et al., 2017) (Zhang et al., 2018) (Zhang et al., 2019) (Zhang et al., 2020). Lin et al. (2014) argue that Genetic Algorithms are capable of solving complex problems and are therefore suitable for the vessel scheduling program. Atabay (2018), however, argues that the Genetic Algorithms performance reduces drastically if the search space (i.e. large problems) increase. Zhang et al. (2016) does not provide any reasoning for the choice of a genetic algorithm, although they try to optimize for multiple objectives. Genetic Algorithms have proven to be very suitable for that purpose.

Other researchers used Simulated Annealing for optimization of the vessel arrival problem. Xu et al. (2012) propose simulated annealing together with ant colony optimization. They argue that ant colony optimization is a proven optimization technique for MIP models as the travelling salesman problem, but accompany this technique with Simulated Annealing to ensure a global optimum is found in reasonable time. Lalla-Ruiz et al. (2018) use Simulated Annealing, because of its properties to escape local optima in the problem. Other used metaheuristics are Lagrangian Relaxation (Jia et al., 2019) or Branch-and-Cut (Wei et al., 2020), Branch-and-Price (Wu et al., 2020) or constraint separation (Abou Kasm et al., 2021).

Abou Kasm et al. (2021) et al. have shown that commercial solvers are also capable of solving the problem all be it slower than the meta-heuristics named above. The purpose of this study is to assess the impact of a rolling horizon optimization on vessel emissions during the port call and not on creating a system that can be readily used in real-time the slower performance of these commercial solvers is accepted. GUROBI, a commercial solver that uses the common branch-and-bound heuristics together with pre-solving methods, claims to obtain optimization results in good time and will be used to solve the prediction model for vessel arrival scheduling in this study.

4.6 Conclusion

This chapter answers the third research question posed in the research approach of this thesis:

How can a controller for vessel operations in the port call be designed?

First, it was determined that the rolling horizon approach is a suitable method to create an optimal vessel arrival schedule. This approach has been used in many other areas of research, including aircraft sequencing in airport approaches and yielded better results than first come, first serve policies. The success of such a strategy in reducing vessel emissions should be determined by experimenting with the control period and time horizon over which the controller determines its course of action.

This approach can be designed around a static MILP model with the objective to minimize the maximum deviation from the vessel ready times for movements in the port was described to create an optimal schedule according to resource use and the virtual arrival concept. This static model is than extended to accommodate the rolling horizon approach above, by regarding only subsets of vessels in the scheduling optimization and fixing arrival times for vessels in close proximity to the port.

As far as solution approaches go, most of the scheduling models relating to vessel movements are solved using meta-heuristics. The reason for this is that commercial solvers usually are slow in calculating optimal solutions to the scheduling problem. For this study, however, it is deemed feasible to solve the scheduling model with a commercial solver. The aim of this study is not to create a near real-time controller, but to merely assess the impact of such as control scheme on the emissions of incoming vessels. Therefore it is reasonable to use a simpler and more readily available commercial solver.

The suitability of the rolling horizon approach and its parameters time horizon and control period for vessel scheduling should be subject to experimentation. Although it is known that longer periods yield worse results for optimization or computing time, there is no deterministic approach to these parameters and their influence and suitability can be determined by experimentation with different values.

Chapter 5

Port call simulation - case study

This chapter will answer the 4th research question posed in section 1.4.2. This question relates to the testing of the intelligent port call concept proposed in chapters 3 and 4 of this thesis. First, an approach to assessing the impact of intelligent control is proposed. Secondly, the design of the simulation model is discussed and lastly, a verification of the design for both the simulation model and the controller based on the rolling horizon approach is provided.

5.1 Approach

To determine the impact of the intelligent control concept proposed in the previous chapters of this work, several methods can be applied. First and foremost, the rolling horizon model can be tested on real-life cases as was done in for instance Furini et al. (2012) and Girish (2016). Another option is to simulate the port call process in the computer using a simulation engine. This chapter proposes a Discrete Event Simulation (DES) together with the rolling horizon vessel scheduling model implemented in python.

5.1.1 Discrete Event Simulation

To assess the impact of the rolling horizon controller together with Virtual Arrival and information-sharing through PortCDM, the controller should be tested on cases of port operations. As discussed, checking the validity of the concept can be done based on historical data. In this case, that is not a feasible option. Since the aim is to estimate the impact of virtual arrival as well as the impact of disruptions in the system on the model, the dynamic properties should be explored. To do so, this research proposes a Discrete Event Simulation model that models the port environment and vessel arrival and departure. Discrete Event Simulation has been widely used in production environments as a decision-making tool (Babulak and Wang, 2010). Possible uses are the design and evaluation of manufacturing processes, experimentation with designs for performance improvement and as an algorithm to support planning and scheduling (Babulak and Wang, 2010). The inner workings of DES models constitute of the modelling of processes in the system under review.
The main difference with continuous simulation models is that the underlying assumption is that the model changes only in discrete time, rather than continuously. Discrete even models consist out of *inputs*, *outputs*, *states* that are induced by *entities* in the system. These entities can be subject to delays (processing), queues and logic during the process. Secondly, resources are part of DES models. They are time-shared by entities and entities should wait in queues if a resource is busy. Entities are typically delayed when they use a resource. The conceptual flow of vessels through the port call can easily be related to

these concepts.
The DES-model will simulate the real world situation by taking into account the inbound voyage of a vessel as well as port operations (loading/unloading process, outbound navigation etc.) In the DES model, vessels will spawn at a source and travel towards the port of destination. Along the way, the vessel will encounter way points used to calculate a dynamic arrival time as stated in Broersma (2021) and receive an optimal approach speed for the reduction of greenhouse gasses. Upon arrival of the port, the inbound navigation as well as terminal operations and outbound and shift operations will be simulated according to process information obtained from the data set belonging to SAAB technologies. The simulation engine used for this study is *Anylogic*. This program is a combination program in which Discrete Event, Continuous and Agent-Based simulation can be combined.

5.1.2 Rolling horizon model in simulation

The scheduling model will be used alongside the DES model. The outputs of the DES model regarding ETAs and ETD's for inbound vessels and updated ready-times according to the simulated processes will be used as input for the scheduling model. Within the scheduling model this information will be used to calculate the optimal movement schedule. The rolling horizon scheduling model is implemented in *Python* to be solved by the already discussed solver GUROBI. The simulation outputs are transferred to an excel file from which the optimization model reads the inputs. Outputs regarding optimal starting times of operations are transferred to the Anylogic model using the same excel file.

5.2 Simulation model

This section will describe the modelled port and its operations regarding the movement of vessels.

5.2.1 Port environment

SAAB Technologies B.V. has provided this research with a data set on arrivals and departures in the port of Darwin. The port of Darwin is located in the Northern part of Australia. It consists out of 5 different terminals, with facilities for cruise operations, loading and unloading of general cargo, livestock, containers and bulk goods, 2 LNG terminals and a terminal for offshore operations supplies. From the data set, which is presented in Appendix B it was found that the most visited terminal is the East Arm Wharf terminal. This terminal has therefore been chosen as the location of berths in the model.

5.2.2 Process logic

The process logic is as follows, vessels arrive in the model around 650 NM from the port. After arriving, the vessels travel in a straight path to the outer boarding ground of Darwin Port with an initial speed determined from the vessel type. After arrival at the outer boarding ground, the vessel *seizes* all resources necessary for their in movement, the resource need is determined based on vessel specifics such as length. This means that vessels can only enter the port area when pilots, tugs and terminal are ready to process the incoming vessel. After the pilot has boarded at the pilot boarding ground (outer point of port perimeter), the vessel proceeds to the tug meeting point. Here, the tugs are attached to the vessel. After this, the vessel proceeds towards the terminal. Upon arrival at the terminal, the vessel is delayed in the modelling process with a delay that resembles the planned terminal operation time for that specific vessel type obtained from the data set. During these operations a deviation from this planned terminal operations time is fired

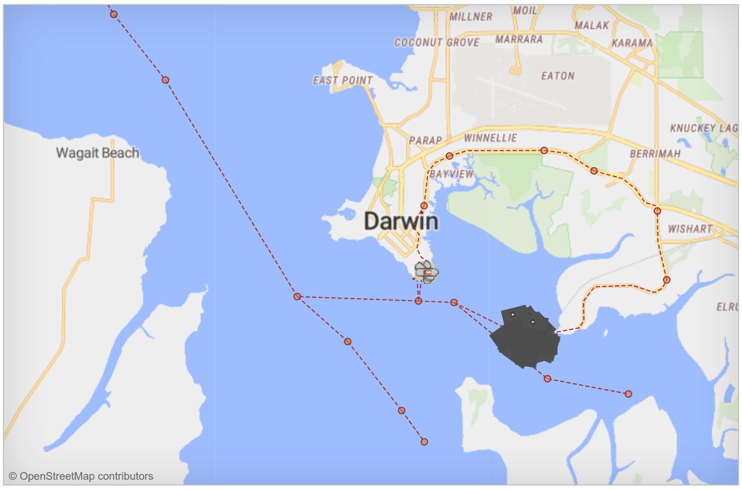


Figure 5.1: Overview of modeled Darwin Port

at the process. This deviation is also determined from the data set. After finishing the terminal operations, the vessel seizes all needed resources. After the pilot and tug(s) have arrived, the vessel moves along the same path out of the harbour to the sink. To determine if a movement can start, the current model time is compared to the calculated optimal start time in the rolling horizon model. If the model time is equal or later than the optimal starting time, the vessel can proceed immediately with operations. If the the optimal start time has not been reached, the vessel waits at the outer perimeter of the port. Environmental restrictions such as tides or weather restrictions have been left outside the scope of this research. Vessels are able to move in or out of the port at any point in time. The scheduling model is accessed every control period through an event sequence in the model. If the past time since the last scheduling update is equal to the control period, the model starts the scheduling application in *python*.

5.2.3 PortCDM

The use of Port Collaborative Decision Making as a means to update the system is modelled through regular updates of information about port call processes. As discussed, the information-sharing will be done based on the milestone approach created in the PortCDM concept Lind et al. (2015). Since the system at hand is related to the in and out movements of vessels in relation to the resource uses, we use the presented milestones for those movements. For an *in* movement this means that the actual operation start time is logged when the pilot has boarded the vessel. Upon tug attachment, the model recalculates the time it will take to reach the terminal. Secondly, when the vessel arrives at the terminal the Estimated Time of Departure is updated according to the arrival time at the terminal and the planned terminal operations time. When a delay in terminal operations is incurred, the new Estimated Departure Time for that vessel is logged. For an *out* movement, this process is similar but in reverse order.

5.2.4 Virtual Arrival

The virtual arrival concept with way points as discussed in Broersma (2021) is implemented through event based logic. Based on the distance between way points, the model calculates if a way point has been hit by the vessel at that time in the model. If this is the case, the vessel speed is recalculated as in equations 3.1 - 3.4, based on optimal arrival times provided by the scheduling model.

5.3 Key perfomance indicators

This section will discuss the key performance indicators related to the study at hand. Since the goal is to reduce emissions during the port approach and port call by optimizing arrival times, this KPI will be discussed first. Secondly, the time in system as a KPI will be discussed.

5.3.1 Emission calculation

To calculate the emissions from the port call of different vessels, the emissions are related to the fuel use of each vessel. The main emissions coming from combustion engines in ports are carbon dioxide (CO_2), sulphur dioxide (SO_2), water (H_2O) and nitrogen oxide (NO), which is converted to nitrogen dioxide after combustion (Stapersma, 2010). Since carbon dioxide is a greenhouse gas it effects the environment on the long term. Sulphur dioxide and nitrogen oxide should be considered polluting emissions (Stapersma, 2010). The emissions from combustion can be related to the fuel quantity used in the following way:

Table 5.1: Emissions related to combustion of fuel (Stapersma, 2010)

emission	amount (g/kg)	Fuel contents
CO_2	3150	86% C
SO_2	20	% S
NO_2	3.3	0.1 %N

The contents of the fuel are determined by the type of fuel used. Most sea-going vessels use Heavy Fuel Oil (HFO) to run the engine (Thuy et al., 2016). For HFO, the sulphur content is maximum 3.5%, but new regulations only allow for fuel with a sulphur content of 0.5% and 0.1% within certain Emission Control Areas. Darwin port, however, is not an ECA and therefore a sulphur content of 0.5% will be assumed. The nitrogen content of HFO is assumed to be 0.68% (Thuy et al., 2016). The calculation of fuel use is provided in Jia et al. (2017b) for calculations on virtual arrival. The fuel consumption of a vessel over time is related to the vessel speed and displacement through the following proposed function:

$$F_{i,j} = \sum_{t=1}^{T} \left(\frac{v_{i,j,t}}{v_{d,i}} \right)^{n} * \left(\frac{\nabla_{i,j}}{\nabla_{d,i}} \right)^{(2/3)} * F_{d,i} \tag{5.1}$$

Where $F_{i,j}$ is the fuel consumption over the voyage j by vessel i, $v_{i,j,t}$ is the sailing speed of vessel i during the voyage j at time t, where the time is measured in hours. $v_{d,i}$ and $\nabla_{d,i}$ are the design speed and displacement (tonnes). $\nabla_{i,j}$ is the vessel displacement during voyage j. $F_{d,i}$ is the fuel use at the designated design speed (g/kWh). A value of n of 3 is proposed for large displacement vessels in Psaraftis and Kontovas (2013). However, such data was not available to the researchers. A simpler method for fuel consumption estimation based on the vessel displacement is described in Barrass (2004), here the fuel use per day is calculated as:

$$C(\nabla) = \lambda * v_i^3 * \nabla_i^{(2/3)} \tag{5.2}$$

In which λ is the consumption coefficient, which is approximately 1/110000 for diesel engines. This calculates the fuel consumption per day. The fuel consumption per time period can be calculated with the following formula:

$$C(\nabla, t) = \sum_{t=1}^{T} \frac{1}{t_d} * \lambda * v_{i,t}^3 * \nabla_i^{(2/3)} \tag{5.3}$$

where t_d is the unit of time over which the fuel consumption is determined. Since, the data set provided by SAAB technologies provides information about vessel dimensions, the displacement of the vessel can be readily determined from the data set. Based on equation 5.3 the fuel consumption underway can be determined from the model. For port operations, Arjona Aroca et al. (2020) estimate that emissions by vessels constitute of around 15% of the total emissions. Therefore, when the vessel is idle, the fuel consumption is determined to be 15% of the fuel consumption when at design speed.

To compare different scenarios and the impact of the rolling horizon scheme, determination of the *average* fuel use per vessel will be used. Since the scheduling program will influence the amount of vessels that will have finished operations within the simulation time the total fuel use output cannot be regarded as a reliable measure. The average fuel use, although not a good predictor for specific vessel fuel use, can assess the impact of the scheduling optimization better. The average fuel use is than combined with the emission calculations presented above the assess the impact of a rolling horizon optimization.

5.3.2 Time in system

Another important factor is the *time in system*. The aim of the rolling horizon scheduling model is to plan vessels in order to reduce waiting times at the port. Instead, this time is spread out over the approach to the port. Therefore, the question is if due to planning and speed reduction the time in system is reduced or increased with implementations of the scheduling model. The time in system for vessels in the port call is measured from the moment they enter the system until they leave the system through the sink. The reason to compare this time in system is that it can give an accurate measure of the impact the scheduling has on the complete port call for vessels.

5.4 Model inputs

This section will discuss the model inputs that run the stochastic model. The following model inputs are of importance to modelling the port call and will be discussed separately. The process times for the subsequent process in the model and the vessel characteristics are derived from the data-analysis presented in Appendix B of this thesis.

5.4.1 Vessel Characteristics

Vessel characteristics are important for the calculation of fuel consumption, resource needs and process times in the simulation model. Tug boat need, for instance, is largely determined based on the length of the vessel. Secondly, the previous section showed that fuel consumption is related to the displacement of the vessel.

From the available data, it was found that the main categories of visits during a 5 year period were from [redacted]. Secondly, it was found that the [redacted] [redacted]. Therefore, the vessel characteristics from these individual vessels, together with their prevalence, have been taken as an input for the simulation model. These include, vessel length, type and displacement. The vessel displacement

(∇_i)is not available in data, but can be calculated from the vessel dimensions in the following way:

$$\nabla_i = C_b * LBP * B * D \tag{5.4}$$

Where LBP is the Length between perpendiculars, B is the vessel beam and D is the vessel draught. The block coefficient C_b is used to determine the ratio of the underwater volume to the block volume. Typical values were obtained from (Barrass, 2004), (Shah and Patel, 2016).

Table 5.2: Typical values of C_b-coefficient for fully loaded vessels (Barrass, 2004), (Shah and Patel, 2016)

vessel type	C_b
Container ships	0.575 - 0.7
General Cargo ships	0.7
VLCC	0.825
Oil tankers	0.8
Passenger liners	0.625
Ro-Ro	0.65

However, the data set only provided Lenth Over All (LOA), which is larger than the LBP. We use this value to calculate the displacement of the vessel, thus accepting an overestimation of the vessel displacement. For the livestock carrier the chosen C_b coefficient is set to that of a Ro-Ro vessel. For Rig Tender, which are fast moving vessels, the C_b coefficient was chosen to be lower than that of container vessels.

For vessel speeds, some general speeds found by were used as inputs for the model. The vessels enter the model with the following respective speeds:

Table 5.3: Average speeds per vessel type (Trozzi, 2006)

Vesseltype	sailing speed (kts)
Container vessels	19.09
Livestock Carrier	16.49
General Cargo	16.49
Rig Tender	18

5.4.2 Vessel arrival

The arrival of vessels is determined based on the data set. It was chosen to take the interarrival times of all vessels in the dataset that arrive from sea. Not only the vesseltypes described above. This was done to create some strain on the available resources in the model, to better assess the impact of the constrained scheduling model. The distribution of interarrival times can be determined from the interarrival time histogram, shown in figure 5.2

[redacted]

Figure 5.2: Interarrival times of vessels coming from sea

The stochastic distribution for arrivals can be described with the following Gamma-distribution which will be used as an input for the model.

Table 5.4: Parameters of fitted inter-arrival distribution

[redacted]

5.4.3 Resources

The available resources in Darwin port are based on information found in the documents on safe navigation in port as well as the data set. The berths have been generalized to 12 discretized berths. The placement of vessels alongside the berth has been ignored.

Table 5.5: Resources available in Darwin Port simulation model

Resources	Capacity
Berths	12
Pilots	2
Tugs	4
Pilot boats	2

It is assumed that all resources work 24/7. Furthermore, it was found from the data set that all vessels requiring a pilot (>35m) requested one. Therefore it is assumed that there are no pilot exemptions. Furthermore, tug requests are based on vessel length. A matrix provided by Darwin Port shows that these request on length, tide, side surface area and bow thruster availability. For the sake of simplicity, the tug needs for vessels are determined solely on length in the following fashion:

Table 5.6: Tug need per vessel related to LOA

Vessel LOA	Tug need
<90	0
90 - 120	2
120 - 160	3
>160	4

5.4.4 Process times

As discussed, the operations time per vessel can differ due to size cargo or conditions. The data analysis provided in Appendix B has yielded the following results to model these stochastic process for different vessel types.

Table 5.7: Stochastic distribution of process time per process in the model

[redacted]

5.5 Verification

Verification of the model is done in two separate ways. Verification is the act of checking if the computerized model is a correct implementation of the conceptual models as described in the previous sections of this thesis Sargent (2009). First, the static scheduling model is verified by assessing the impact of changes in parameters. Secondly, the simulation model was verified.

5.5.1 Scheduling model

The scheduling model is verified, by experimenting with several parameters in the model. The experiments and their projected outcome are determined in the following table:

Table 5.8: Outcomes of verification experiments

Experiment	Expected outcome	Total delay (hr)	Maximum deviation (hr)
Base case 24 hr	-	8.75	3.5
Base case 2 control periods	-	18.25	8
Increased # tugs to 8	Smaller deviations due to increased resource availability	0.5	0.25
192 hr horizon	Better performance due to longer outlook in comparison to 2 control periods	16.25	4.5
Increased port movement times	More deviation due to longer resource use period	7.25	6.25
Change of objective function to total delay	Increase in total delay	9	3.5

The base case inputs were taken from Abou Kasm et al. (2021) where a case study based on Abu Dhabi port was presented. The inputs and outcomes of the verification experiments are presented in appendix C. Since the restricted horizon presented in chapter 4 did not allow for planning all the vessels in the verification input data, the rolling horizon optimization was assessed for 2 control periods as well.

The first verification experiment regarded the increase of tugs in the port. This means that more tugs are available to handle in and outgoing vessels. It is therefore expected that the total delay and maximum deviation will decline. Secondly, a comparison was made to assess the impact of a longer time horizon. It is expected that due to the less restricted outlook, the model is able to perform better in terms of maximum deviation and total delay, because it can see if delays have to be propagated according to constraint 4.17. With increased port movement times, the scheduling model is assumed to perform worse. Since the time horizon is still fixed, the model is unable to plan as many vessels as in the base case. The total delay, therefore, is lower than in the base case but the maximum deviation has increased by almost 80% and due to the smaller group of planned vessels the total delay will be performing worse than in the base case if another control cycle is performed. Lastly, the objective function was changed to only incorporate total delays and not restrict the maximum deviation. The maximum deviation did not change, but the total delay increased and it was shown that delays were more spread out between the consecutive vessels in the input set. The outcomes of the verification experiments have shown that the behaviour of the computerized scheduling model is as expected from the conceptual model.

5.5.2 Simulation model

The simulation model was verified firstly by animation verification. Secondly, the calculation of output statistics was verified.

The model was checked if the process described in this chapter were followed by animation verification. The model showed that vessels started at the source, followed the path to the port and waited for resources to become available. After arriving at terminal, the vessels showed delayed behaviour for terminal operations. After operations, the vessels seized the needed resources and travelled outwards of the port. The propagation of updated ETA's was also shown in the animation as well as the right update of virtual arrival speeds.

The calculation of the output statistic average fuel use was verified by tracing one vessel during 24 hrs of port call and checked against the formula proposed by Barrass (2004) for fuel calculation per day. This implementation was shown to be right as can be concluded from table 5.9 and figure 5.3. The time in system calculation is a built in feature of AnyLogic and therefore assumed to be correct.

Table 5.9: Calculation of fuel use over 24 hrs for a specific vessel

Vessel	Type	λ	∇_i	v_i	$C(\nabla_i)$
A47	Livestock carrier	1/110000	11.677.994	16.5	21.02

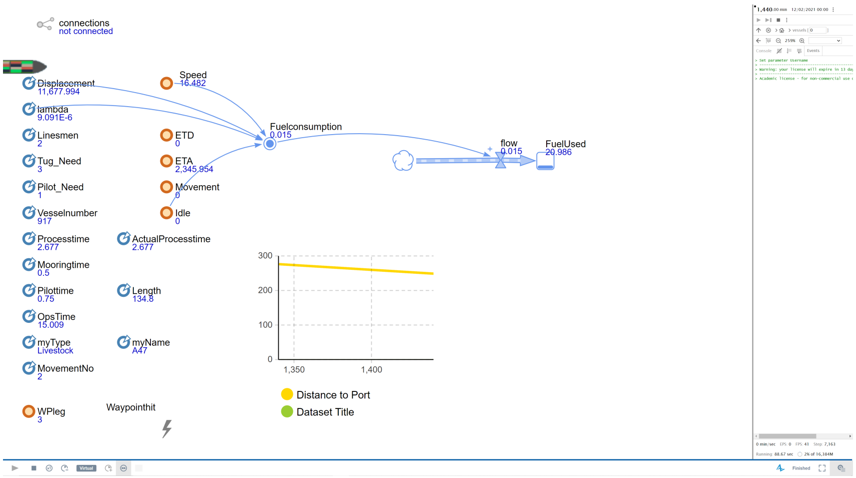


Figure 5.3: Vessel state after 24 hrs simulation

5.6 Conclusion

This chapter set out to answer the fourth research question posed in the beginning of this thesis:

4. *How can the impact of a controller for vessel scheduling be tested?*

Several approaches can be regarded to test a rolling horizon approach. For this study, a Discrete Event Simulation of the port call process and port approach is proposed to measure the impact of the controller. The DES approach models the system at hand as a set of subsequent processes. In the proposed model, this relates to the port approach of vessels, the port movements and terminal operations. This DES model can be combined with a computerized implementation of the rolling horizon scheduling model that calculates optimal movement starting times. A strong feature of DES is that the model can fire and respond to uncertain events. This way delays in the port call can be modelled and reaction of vessels and resources tracked. To realize realistic model outcomes, a data set of vessel movement in Darwin Port is assessed to calculate process times and to find relevant information on vessel types and arrivals. To measure the impact, the output of the DES model shows the average fuel used by vessels during their port call as well as their time in system. This way, the influence on emissions can be found between experiments.

Chapter 6

Experiments & results

To answer the fifth research question underlying this research, this chapter will discuss some experiments performed with the simulation and rolling horizon scheduling models. First, 3 different scenario's are discussed as well as the experiment set up. After that the 3 different scenario's are defined and outcomes are presented. Lastly, a comparison between the three scenario's is presented.

6.1 Scenario's

Three different scenario's are proposed to measure the impact of the rolling horizon scheduling optimization. First of all a base case is tested in which the common first in, first out policy is assessed. Vessels will travel through the model and can start port operations whenever the needed resources are available. Virtual arrival, information sharing and rolling horizon scheduling are ignored in this base case. As discussed before, the control period (or rescheduling period) as well as the time horizon over which the scheduling model schedules the vessel movements can influence the outcomes of the scheduling model. Ouelhadj and Petrovic (2009) note that larger control periods can lead to sub optimal behaviour of the system, because relevant information about processes is missed and ignored between control periods. The effect of the time horizon has to do with the calculation time. For larger time horizons, the impact of the scheduling model is assumed to be bigger, because the model can assess its actions better (Negenborn and Hellendoorn, 2010). Therefore, this research proposes three simulation experiments to assess the impact of those factors on the performance of the model. First, an experiment is conducted with a short control period and a limited scheduling horizon. In the second experiment a larger time-horizon is chosen together with the same short control period. Lastly, a scenario with a longer scheduling horizon and control period are combined. These three scenario's give a first impression of the behaviour of the system under control. In all scenario's, the virtual arrival scheme is implemented with the way point approach as proposed by Broersma (2021). The following parameters are used as input for both the scheduling optimization and the virtual arrival concept.

6.2 Experiment Set-up

Since the simulation model is based on stochastic inputs, some considerations have to be made for the warm-up time, run length and number of replications. The warm-up time of the simulation allows the model to fill itself with entities before relevant statistics on the model are measured. If no warm-up time is used, the experiment outcomes found will not resemble the actual outcomes of the system. A warm-up time of approximately 3 times the longest time in system is taken to be a valid warm-up time (Verbraeck, 2021). For the

Table 6.1: Experiment parameters

Parameter	
$\|T\|$	Length of the scheduling horizon (hr)
t_c	Length of the control period (hr)
D_{owp}	Distance from outer Virtual Arrival way point to the port (NM)
d_{wp}	Distance between Virtual Arrival way points (NM)

port call this is approximately 3 weeks. After three weeks, the model is assumed to be in steady-state. The run length should be in the same range for non-terminating systems (Verbraeck, 2021). So this will also be chosen to model 3 weeks of port arrival. Secondly, the number of replications is determined by the relative confidence interval for which the KPI's can be determined from the simulation. The relative confidence interval, which determines the certainty and implications of the found outcomes, should be less than 10% Verbraeck (2021). However, to compare the outcomes of the different experiments at least 20 replications will be provide for the sake of statistical analysis. Furthermore, some fixed input parameters obtained from data-sheets provided by Darwin port have been used as an input to the scheduling model alongside the simulation model. For the simulation, the channel restriction constraint 4.18 is relaxed, since no channel restrictions could be found regarding in and out movements in port of Darwin. Secondly, the separation constraint between vessels has been relaxed due to problematic behaviour with rounding time stamps from simulation to scheduling model.

Table 6.2: Experiment set-up

Experiment set-up	
Warm-up time	3 wks
Run length	3 wks
Iterations	$N \geq 20$

6.3 First Come, First Serve

6.3.1 Inputs

This experiment only assumes first come, first serve policy with regards to the vessel movements. No virtual arrival policy and optimal scheduling are used in this experiment. It serves as a baseline for comparison to the other implementations. The input parameters as discussed above are shown in table 6.7.

6.3.2 Results

The results regarding the KPI's presented in the previous section are shown here.
From the experiment results in table 6.4, it can be concluded that the average fuel use during the port call per vessel is approximately 45.69 tonnes over the modeled time. This may seam low, but the data set for Darwin Port finds that the majority of vessel movements regards Rig tender which are have a much smaller displacement than other vessel types. The experiment runs have shown that the confidence interval is reasonable with regards to

Table 6.3: Experiment parameters

Parameter	
$\lvert T \rvert$	Not applicable
t_c	Not applicable
D_{owp}	Not applicable
d_{wp}	Not applicable

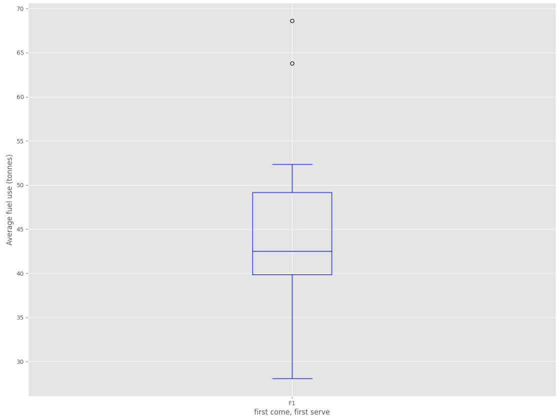


Figure 6.1: Boxplot of FCFS experiment outputs wrt. fuel use

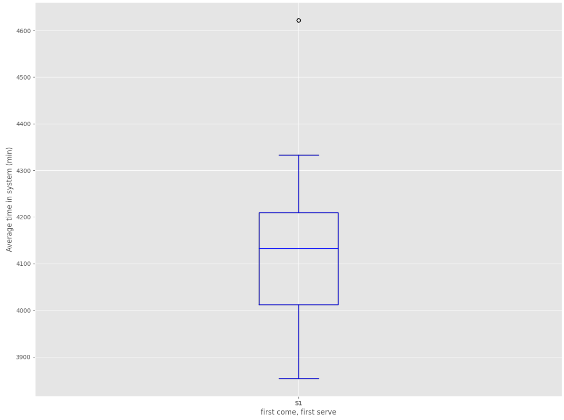


Figure 6.2: Boxplot of FCFS experiment outputs wrt. system time

the calculated mean. The average time in system for the First Come, First Serve scenario, shows that vessels stay in the system on average 4132 minutes, which is approximately 3 days.

Table 6.4: Statistics of experiment outcomes for FCFS

FCFS	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	45.69	4131.93
σ	8.46	165.17
σ^2	71.54	27282.13
CI	3.96	77.30
CI_{rel} (%)	8.66	1.87

6.4 Short control period and time horizon

6.4.1 inputs

The second experiment tries to assess the influence of a shorter control period. As discussed before, the shorter control horizon could lead to better performance of the scheduling optimization. The system is able to adapt better to information that has been provided on terminal operations or vessel movements. Approaching vessels can respond to newer information and can thus make better decisions about arrival and departure movements. Secondly, when vessels hit a way point they do so based on information that is not older than 1 hr prior to the speed change. This approach is combined with a shorter outlook of 24 hrs. This outlook means that vessels are put in the movement subset to be planned on a later moment in their approach. This could lead to a subperforming model and the reduction could be lower than for a longer outlook. However, it is normal that vessel ETA's are only provided at the latest 24 hr before arrival, meaning that vessels will only enter the system at this point in time.

Table 6.5: Experiment parameters

Parameter	
$\lvert T \rvert$	24 hr
t_c	1 hr
D_{owp}	500 NM
d_{wp}	100 NM

6.4.2 Results

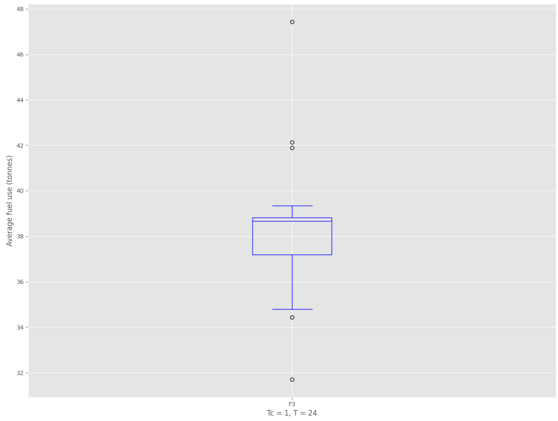


Figure 6.3: Boxplot of $T_c = 1$, $|T| = 24$ experiment outputs wrt. fuel use

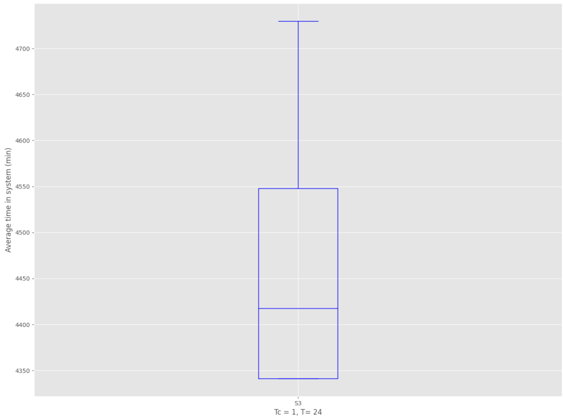


Figure 6.4: Boxplot of $T_c = 1$, $|T| = 24$ experiment outputs wrt. system time

Table 6.6: Statistics of experiment outcomes $T_c = 1$, $|T| = 24$

$T_c = 1$, $\|T\| = 24$	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	38.38	4452.33
σ	3.17	120.96
σ^2	10.06	146333.16
CI	1.48	62.20
CI_{rel} (%)	3.87	1.40

6.5 Long control period and scheduling horizon

6.5.1 Inputs

This experiment assumes a longer control period than the previous one. The assumption is that the longer control period will deteriorate performance of the model in terms of handling up-to-date information (Ouelhadj and Petrovic, 2009) and thus making unfavourable decision because information is missed. The longer outlook however, could make up for this deterioration because the model is able to see the outcomes of its actions better towards the future.

Table 6.7: Experiment parameters

Parameter	
$\|T\|$	42 hr
t_c	5 hr
D_{owp}	500 NM
d_{wp}	100 NM

6.5.2 Results

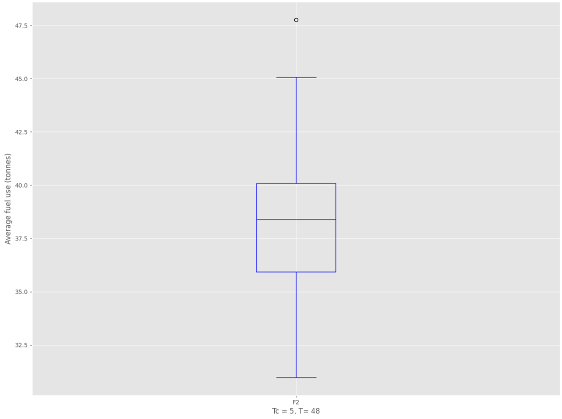


Figure 6.5: Boxplot of $T_c = 1$, $|T| = 24$ experiment outputs wrt. fuel use

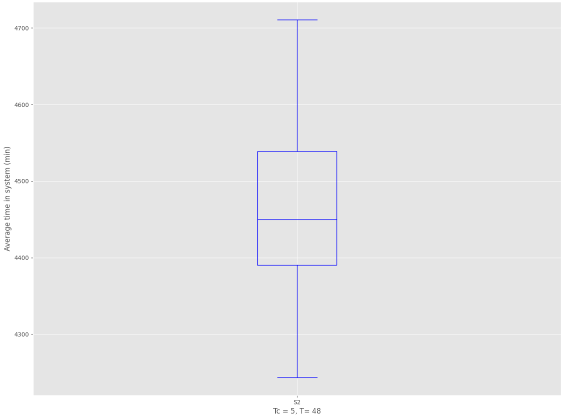


Figure 6.6: Boxplot of $T_c = 1$, $|T| = 24$ experiment outputs wrt. system time

Table 6.8: Statistics of experiment outcomes $T_c = 5$, $|T| = 48$

$T_c = 5$, $\vert T\vert = 48$	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	38.74	4470.44
σ	3.90	125.97
σ^2	15.18	156999.54
CI	1.82	58.64
CI_{rel} (%)	4.70	1.31

6.6 Emission reduction and experiment comparison

The reduction of emissions is calculated based on the relations between fuel contents and emission factors provided in table 5.1. This yields the following results for the three experiments: From the statistcal analysis in table 6.10 and 6.11 it becomes clear that the optimal scheduling model indeed reduces the vessel average fuel use and emissions by 16.5% in comparison to the first come, first serve case. However, no difference in emission reduction could be found between the two rolling horizon scheduling experiments. For both scheduling scenario's the average time in system is significantly larger than the first come first serve base. This increase amounts to around 8% in comparison to the base case. Between the scheduling experiments no difference in mean time in system per vessel could be observed.

Table 6.9: Comparison of average emissions per vessel between experiments

Emissions (Tonnes)	FCFS	$T_c = 1$, $\|T\| = 24$	$T_c = 5$, $\|T\| = 48$
Avg. fuel use	45.96	38.38	38.74
CO_2	144.77	120.90	124.68
SO_2	0.45	0.38	0.39
NO_2	1.03	0.86	0.88

Table 6.10: Comparison of means between experiments wrt. average fuel use

				P value (post hoc analysis)	
		N	$\bar{x}$	$T_c = 1$, $\|T\| = 24$	$T_c = 5$, $\|T\| = 48$
Average fuel use per vessel	FCFS	20	45.96	0.0138	0.0221
	$T_c = 1$, $\|T\| = 24$	20	38.38	-	1.00
	$T_c = 5$, $\|T\| = 48$	20	38.74	-	-
$\chi^2 = 10.87, df = 2, p = 0.004$					

Table 6.11: Comparison of means between experiments wrt. average time in system

				P value (post hoc analysis)	
		N	$\bar{x}$	$T_c = 1$, $\|T\| = 24$	$T_c = 5$, $\|T\| = 48$
Average time in system per vessel	FCFS	20	4121.37	p<0.001	p<0.001
	$T_c = 1$, $\|T\| = 24$	20	4470.44	-	1.00
	$T_c = 5$, $\|T\| = 48$	20	4452.33	-	-
$F = 53.76, p < 0.001$					

6.7 Conclusion

This chapter answered the last research question posed in section 1.4.2:

What is the effect of intelligent control of vessel operations on the emissions of vessels in the port call?

The experiments performed in this chapter were designed to assess the impact of the parameters belonging to rolling horizon scheduling, control period and scheduling horizon. It was shown that for both scheduling scenario's a better performance was obtained with regards to vessel emissions. A reduction of 16.5% fuel use was obtained by the implementation of the intelligent control strategy with information-sharing and virtual arrival. However, no significant difference could be found between the different set of parameters in the experiments. With regards to the time in system, it was shown that the current experiment set-up leads to an increase of around 8% for the average time in system for vessels.

Chapter 7

Discussion

This chapter will discuss the chosen methodology and modelling assumptions made to obtain the results found in the previous chapter as well as the societal and scientific relevance.

7.1 Discussion

The aim of this research is to incorporate information-sharing, virtual arrival of vessels and optimal vessel movement scheduling in one concept to reduce emissions in sea ports.

7.1.1 Preliminary model

The preliminary model presented in chapter 2 of this thesis was the onset of the development of the rolling-horizon scheduling approach presented in this thesis. The idea was formed based on concepts developed on coordination in large technical systems and supply chains. Doing so assumes that the same mechanisms apply in the port environment. The question remains if these concepts can be translated to the port environment in real-life. As far as logistics synchronization goes, the just-in-time concept through virtual arrival is a hard nut to crack. On the one hand, there are fixed schedules for cruise ships and ferries as well as tight deadlines for container vessels. On the other hand, bulk shipping liners are not eager to delay their operations because of their demurrage contracts (Poulsen and Sampson, 2020). This means that it could be hard to change arrival times for vessels and have actors willing to participate.
Secondly, in the PortCDM trials it was found that participants saw the benefits of information-sharing , but that there were still concerns about competitive information (Lind et al., 2018a). This could lead to decreased process visibility if not enough or the wrong information is shared. In creating an operational plan, the main goals have to be determined. Already stated was that this is a hard task in the port environment due to the diversity of the system. All in all, these are hurdles to be taken in order to let the concept function at its prime. However, by showing the benefits of such a system and looking at the port call a more aligned operational profile might be created in the port call.

7.1.2 Methodology

The chosen methodology to combine the different optimization methods has proven to be feasible in terms of emission reduction. A first remark should be made about the choice for a single-agent control structure. The assumption that the Harbour Master plans and determines all vessel movements unilaterally was made to justify this approach. In real life however, the port call is an intricate network of actors whose decisions influence each other and events in the port which have an impact on the system and optimal outcomes. An argument can be made that to control the movements in the port call, a more diversified control approach should be chosen. Such a control structure might replicate the communication between nautical services, terminals, vessels and Harbour Master. Distributed or multi-layer control structures as proposed in Negenborn and Hellendoorn (2010) might help to do so. Secondly, the intelligent control strategy assumes some kind of logical behaviour through mathematical or physical relations. In environments where humans still rule the machines, such as the port, this assumption might lead to an overestimation of the adherence to optimal solutions provided by intelligent control. Such deviations by human actions might lead to sub optimal performance of the proposed concept.

7.1.3 Simulation model

Some assumptions in the simulation model may influence the results obtained in the previous section. The used formula on fuel consumption is very generic. This choice was made due to a lack of data on the specific fuel consumption by the vessels in the dataset. Fuel consumption is specific per vessel and this generalization might lead to an over- or underestimation of the fuel use during the port call. An improvement to the model could be the introduction of the real fuel use of vessels based on their specifications.
Vessel delays in port have been taken into account in the simulation model, but the delays incurred by vessels during their voyage have not, since no data was available. This could lead to a much more volatile optimized schedule under which the virtual arrival approach could yield less beneficial results. This could be implemented in the model by assessing AIS data of approaching vessels for a case study.
Lastly, vessel dynamics have not been taken into account in this simulation model. Vessels are large and changes in course and speed are hard to obtain. The model assumes that a vessel's speed is immediately reduced after a new ETA has been provided at the way point. However, in real life the vessel reduces it's speed over time. These dynamics could be taken into account in the Anylogic model, especially since this program is able to combine the Discrete Event System with continuous simulation.

7.1.4 Experiment results

With regards to the experiment results the findings on emissions reduction by vessels are in line with the findings presented by Arjona Aroca et al. (2020), Wijma (2018) and Jia et al. (2017b) on the impact of information-sharing as well as virtual arrival policies. The found increase in system time however, is unexpected. The goal of the vessel movement scheduling model is to create an optimal schedule that incorporates the availability of resources in the best possible way Abou Kasm et al. (2021). A possible explanation for this increase may be found in the chosen parameter settings as described by Ouelhadj and Petrovic (2009). In the short horizon experiment, the model is not able to look ahead for a long period of time. This can make that the propagation of delays is not correctly forwarded to the ships in the model, therefore yielding higher average time in system. A similar explanation can be found for the longer control period. Since vessel are not updated on new arrival times often, they may keep waiting until their optimal ETA at the port entrance while resources are available.
The trade-off between extra time for a voyage in comparison with reduced fuel use is an interesting ground for research.

7.2 Societal relevance

As discussed in the introduction of this thesis, the global shipping business is responsible for 2.9% of the human CO_2-emissions. This study proposes a way to reduce these emissions in line with the goals set by the IMO for the year 2050. Efficiency of operations is important in global shipping, because new technology that enables the use of green fuels will arrive too late to contribute to this challenge. This thesis underlines again the importance in speed reduction for sea-going vessels for the reduction of their emissions and the possible gain that is to be made from optimally using the resources available. Furthermore, when the European Union implements the Emission Trading System for shipping, the importance of reduction of emissions becomes larger. The approach discussed in this thesis gives ports and Harbour Masters the opportunity to assist shipping companies with this reduction. Furthermore, as discussed in the introduction of this thesis, this is the low-hanging fruit in shipping emissions optimization and therefore can be of large benefit to the system.

7.3 Scientific relevance

This thesis set out to assess the impact of a combination of concepts already described in literature that can be used for either optimization of the port call and large infrastructures. The current body of knowledge existed out of research into the following:

- Information sharing for increased awareness about disruptions in the port call
- Virtual Arrival approach to reduce emissions during the port approach
- Optimal scheduling of vessel movements based on resource constraints

The identified gap in literature showed that there had been no research into the combination of these three topics. The main contribution to literature of this study is the combined use of these proposed optimization techniques through the use of the intelligent control concept coined in literature. Secondly, the literature on optimization of vessel scheduling only considered static scheduling models. This research has provided a dynamic scheduling model for vessel movements. Lastly, research on intelligent control had not focused on port operations relating to the movements of sea-going vessels, which has been researched in this thesis.

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Chapter 8

Conclusion

This thesis set out to asses the impact of information-sharing in the port call. Over the last few years, several concepts for information-sharing have been developed (Lind et al., 2015). This trend originates from the fact that inefficiencies in the port call can mainly be attributed to a lack of situational awareness among port actors. Information is shared too little, too late and is thus not harnessed to take action upon (Molkenboer, 2020). Since most ports use a first come, first serve policy and captains therefore apply a "hurry up and wait"-strategy with regards to voyage speeds, this leads to unnecessary emissions during the port approach and port call (Broersma, 2021). In line with the emissions reduction goals set by the IMO and the notion that port call optimization is the low-hanging fruit with regards to emissions optimization the question remains:

”How can increased information-sharing reduce emissions of sea-going vessels in the port call process?”

This thesis aimed at answering this question by first assessing how information-sharing can be used for optimization of the port call. Secondly, a control structure was proposed that can be used in real-time optimization of the port call. The control structure is guided by a controller that is designed afterwards. Lastly, a simulation model of the port call in relation to a case study of Darwin Port was proposed and results on emissions reduction where obtained.

Information-sharing systems have been devised and deemed as an integrator for coordination in the port call process (Lind et al., 2015), but it is unclear how this should be harnessed. The wanted effects are related to increased situational awareness to make better decisions on real-time information, reducing delays. Optimization in vessel arrival has been apparent in literature but is mainly focused on geographic constraints on fairways and creating schedules that optimize fairway use or optimal allocation of tugs and pilots. Vessel arrival scheduling based on resource availability has not been researched much in literature and the influence of real-time information updates of those scheduling solutions on vessel emissions has not been found. The Virtual Arrival concept proposed in literature gives a way to reduce approach speeds of incoming vessels based on delay information from the port (Broersma, 2021). In relation to the IMO goal of emissions reduction and just-in-time vessel arrival, it can be concluded that a vessel schedule that is constantly updated based on real-time information sharing could be an integrator for port call optimization by harnessing the power of information-sharing and the use of the virtual arrival concept. Literature on other infrastructure optimization shows that creating coordination through real-time control can lead to better performance of the controlled system (Negenborn and Hellendoorn, 2010), but this concept has not been applied to the arrival of vessels. It is therefore of interest to assess such an intelligent control structure together with the information-sharing and virtual arrival concepts already apparent in literature.

Vessel operations in the port call are largely controlled by the movements schedule created by the harbour masters office. All nautical services depend on this schedule for creating their own planning. The objectives for an optimized port call are distributed among actors and relate to asset use for nautical service providers, safe and timely movements for the harbour master and optimal terminal use for terminal operators. An intelligent control structure for port call optimization can be proposed based on a single-agent control structure for vessel movement scheduling and vessel inflow regulation is proposed resembling movement scheduling by the Harbour Master. Single-agent control structure is deemed feasible to handle the vessel arrival problems in reasonable time and with profitable results for delay reduction. Measurement inputs for the vessel operations scheduling comes from the proposed PortCDM concepts as described in sections 2.3.3 and 3.2 and AIS data of approaching vessels. The system can be controlled by postponing or advancing vessel movements in time to ensure optimal resource use and turnaround times. Secondly, approaching vessels can be advised to decrease their speed as per the virtual arrival concept developed in literature. Due to vessel engine characteristics this should happen at discretized virtual way points along the approach and within certain boundaries.

The rolling horizon approach is a suitable method to create an optimal vessel arrival schedule. This approach has been used in many other areas of research, including aircraft sequencing in airport approaches and yielded better results than first come, first serve policies for arrival scheduling. This approach can be designed around a static MILP model with the objective to minimize the maximum deviation from the vessel ready times for movements in the port. It was designed to create an optimal schedule according to resource use and the virtual arrival concept. This static model is then extended to accommodate the rolling horizon approach above, by regarding only subsets of vessels in the scheduling optimization and fixing arrival times for vessels in close proximity to the port. The suitability of the rolling horizon approach and its parameters time horizon and control period for vessel scheduling should be subject to experimentation. Although it is known that longer periods yield worse results for optimization or computing time, there is no deterministic approach to these parameters and their influence and suitability can be determined by experimentation with different values.

The impact of the scheduling optimization has been calculated by the construction of a Discrete Even Model. Such model types allow for accurate modelling of process flows and the occurrence of delayed events as well as individual process times. Since the aim is to see how information-sharing regarding disruptions can help to reduce vessel emissions this is an important attribute of the system modelling. Three experiments were performed to asses the impact of intelligent control of vessel movements. To calculate the impact of optimal scheduling, a base case was proposed where a standard first come, first serve policy was implemented. A second experiment assess the the scheduling model together with a small control period and outlook. A third scenario was designed to see the impact of a larger control period together with a longer horizon.
The results show that the provided concept is indeed able to reduce emissions during the port call for sea-going vessels. A reduction of 16.5% of average emissions could be observed for both implementations of the scheduling horizon. However, also the observed time in system increased by 8% in comparison to the base case. This trade-off between extra time per voyage in relation to the reduction of fuel use has not been part of this research, but remains an interesting ground for further research in port call optimization.

To answer the main research question of this thesis, it should be concluded that the power of information-sharing lies in *using* the provided information about port call operations for the coordination of actions in the port. This can be achieved by combining information-sharing, vessel movement scheduling optimization and virtual arrival. Through intelligent control based on rolling-horizon scheduling, this combined concept can help to reduce emissions by vessel during their port call significantly and thus supporting the goals set by the IMO.

8.1 Recommendations for further research

8.1.1 Solution approach

The solution approach for the scheduling model chosen in this study was a Branch-and-Bound heuristic applied in GUROBI. As already concluded in other literature on vessel movement scheduling, meta-heuristics approaches perform better in terms of computation time. This could help to increase the time horizon and decrease the control period yielding even better results regarding emission reduction and reduced time in system for vessels during their port call. This in turn can validate the use of the concept in real life. It is therefore recommended to research suitable meta-heuristic solution approaches and their influence on the performance of the proposed control structure and system.

8.1.2 Control structure

As discussed in chapter 3 of this thesis, the choice of control structure is not deterministic but based on preferences. The single-agent controller is in most able to calculate optimal outcomes better than other suggested approaches. Since the port environment is a complex and dynamic multi-actor system it is worth to research the implementation of other control structures that might be better at describing the real decision-making chain. For instance optimal tug and pilot allocation and berthing optimization problems might be combined with the vessel scheduling problem to create elaborate control of the port environment.

8.1.3 Impact of environment on movement scheduling

Vessels travel through water and therefore inherently have to deal with tides and currents. On the one hand this means that ports have time restrictions for fairway entry of vessels with a certain draft. Secondly, it means that captains will try to harness favourable currents to reduce their fuel use. An interesting approach to optimal vessel scheduling would be the implementation of tidal restrictions on vessel movements as well as harnessing currents to obtain virtual arrivals.

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Appendix A

Scientific paper

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Appendix B

Data-analysis

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Appendix C

Verification

In this appendix, the outcomes of the verification experiments regarding the rolling horizon scheduling model are presented. First, the inputs for the verification experiments are provided and the vessels to be scheduled. Secondly, the outcomes of the experimentation runs in calculated with GUROBI are shown.

C.1 Inputs

Table C.1: Movements to be scheduled and parameters

i	**vessel**	E_i	Q_i	R_i	**Linesmen**	**movement**	P_i	A_i^n	A_i^W	WP_i	t_{wp}	B^v	r_i
1	1	240	2	1	1	inbound	2	0	0,25	5	240	3	0
2	2	360	2	1	1	outbound	1,5	0	0,25	0	0		0
3	3	420	2	1	1	inbound	2	0,5	0,5	4	67		0
4	4	540	2	1	1	inbound	1,5	0,5	0,25	4	187		0
5	5	540	0	1	1	inbound	2	0	0,5	4	187		0
6	6	660	2	1	1	outbound	1,5	0	0,5	0	0		0
7	7	660	2	1	1	outbound	1,5	0	0,5	0	0		0
8	5	900	0	1	1	outbound	1	0	0,25	0	0		0
9	9	960	2	1	1	inbound	1,5	0,5	0,25	2	254		0
10	4	1080	2	1	1	outbound	1	0	0,25	0	0		0
11	1	1200	2	1	1	outbound	1,5	0	0,25	0	0		0

C.2 Output of verification experiments

Table C.2: Base case schedule with 24 hrs horizon

i	s_{it}	E_i	**deviation (hr)**	**max deviation (hr)**	**total delay (hr)**
1	240	240	0	3.5	8.75
2	375	360	0.25		
3	510	420	1.5		
4	660	540	2		
5	540	540	0		
6	750	660	1.5		
7	870	660	3.5		

Table C.3: Base case schedule with 24 hrs horizon - 2 control periods

i	s_{it}	E_i	**deviation (hr)**	**max deviation (hr)**	**total delay (hr)**
1	240	240	0	8	18.25
2	375	360	0.25		
3	510	420	1.5		
4	660	540	2		
5	540	540	0		
6	750	660	1.5		
7	870	660	3.5		
8	900	900	0		
9	1440	960	8		
10	1080	1080	0		
11	1290	1200	1.5		

Table C.4: Base case schedule with 192 hr scheduling horizon

i	s_{it}	E_i	**deviation (hr)**	**max deviation (hr)**	**total delay (hr)**
1	240	240	0	3.5	16.25
2	375	360	0.25		
3	510	420	1.5		
4	750	540	3.5		
5	540	540	0		
6	900	660	3		
7	660	660	0		
8	900	900	0		
9	1050	960	1.5		
10	1290	1080	3.5		
11	1200	1200	1.5		

Table C.5: Verfication experiment with 8 tugs

i	s_{it}	E_i	**deviation (hr)**	**Maximum deviation (hr)**	**Total delay (hr)**
1	240	240	0	0.25	0.5
2	360	360	0		
3	420	420	0		
4	540	540	0		
5	555	540	0.25		
6	660	660	0		
7	675	660	0.25		

Table C.6: Verfication experiment with total delay reduction objective

i	s_{it}	E_i	**deviation (hr)**	**Maximum deviation (hr)**	**Total delay (hr)**
1	255	240	0	3.5	9
2	375	360	0.25		
3	510	420	1.5		
4	660	540	2		
5	555	540	0.25		
6	750	660	1.5		
7	870	660	3.5		

Table C.7: Verfication experiment with increased process times

i	s_{it}	E_i	**deviation (hr)**	**Maximum deviation (hr)**	**Total delay (hr)**
1	255	240	0	6.25	7.25
2	735	360	6.25		
3	420	420	0		
4	600	540	1		
5	540	540	0		

Appendix D

Experiment outcomes

Table D.1: Outcomes of experiment runs

	FCFS		$T_c = 1.\ \lvert T \rvert = 24$		$T_c = 5.\ \lvert T \rvert = 48$	
run	avg. Fuel use	avg. time in system	avg. Fuel use	avg. time in system	avg. Fuel use	avg. time in system
1	42.00	4143.95	38.42	4344.19	38.68	4345.19
2	42.41	4050.84	30.97	4425.10	37.08	4364.38
3	38.33	4252.01	39.66	4473.09	42.13	4625.38
4	50.47	4274.14	47.76	4243.35	47.43	4434.53
5	46.35	3907.37	36.10	4453.04	36.25	4400.39
6	41.75	4239.08	35.43	4472.70	41.90	4438.97
7	44.21	4013.39	38.37	4688.78	37.23	4584.29
8	28.09	3853.84	41.86	4416.00	38.68	4341.30
9	52.37	4151.09	38.42	4344.19	39.34	4729.61
10	37.49	4058.98	44.38	4446.18	34.79	4361.43
11	45.42	3977.24	36.97	4624.03	38.35	4528.17
12	38.08	3963.60	35.45	4419.78	31.70	4479.70
13	40.65	4147.20	45.07	4377.85	38.15	4559.67
14	63.79	4273.35	38.56	4710.80	38.68	4341.30
15	39.78	4133.15	35.42	4492.56	38.68	4341.30
16	68.62	4011.11	38.11	4527.33	39.20	4602.95
17	42.51	4185.40	35.11	4394.58	34.45	4544.20
18	35.71	3948.01	38.35	4336.14	38.68	4341.30
19	48.21	4092.85	41.41	4645.14	38.68	4341.30
20	47.41	4332.70	38.98	4573.93	38.68	4341.30

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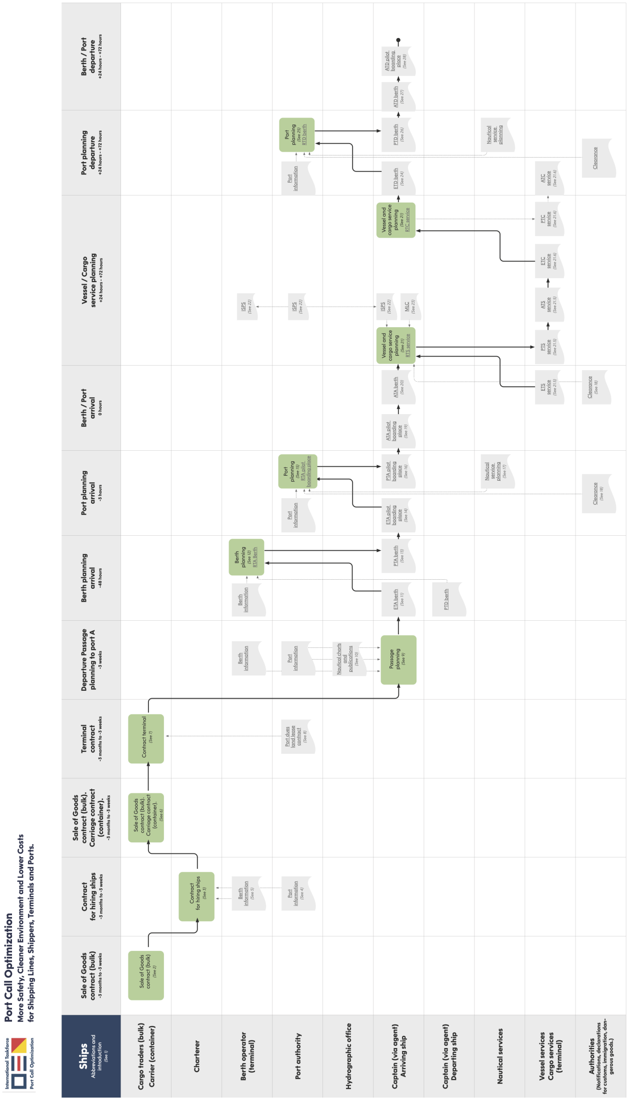
Appendix E

Port call process



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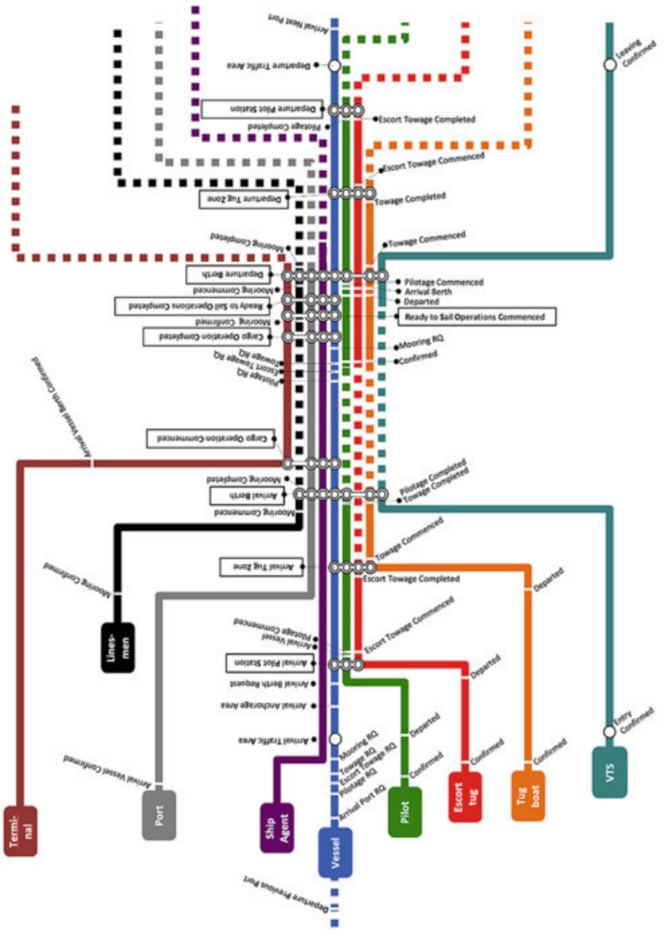
Appendix F

Port Collaborative Decision Making



Rolling horizon scheduling optimization of sea-going vessel movements in sea ports for the reduction of vessel emissions

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***Abstract*—This paper discusses the use of intelligent control of vessel movements in sea ports. Through the use of information-sharing, the virtual arrival concept and a rolling-horizon scheduling model of vessel movements emissions of vessel are reduced. Results show that such a concept can reduce average vessel emissions in the port call by 16.5%.**

***Index Terms*—Port Call Optimization, Port Collaborative Decision Making, Virtual Arrival, Emission reduction, Vessel movement scheduling, rolling-horizon optimization**

I. INTRODUCTION

The International Maritime Organisation (IMO) has adopted a resolution to reduce emissions of sea-going vessels by 50% in 2050 in comparison to the emissions of the year 2008 as well as a decline in emissions from 2030 onwards. [International Maritime Organisation, 2018]. The sea going trade produces around 2.9% of global CO2-emissions and so this reduction has a large impact on global climate goals. Not only during their voyages do ships impact the environment, but also when anchored or at berth. It was estimated that around 15% of the total emissions of vessels are produced during port visits [Arjona Aroca et al., 2020]. These emissions have a large effect on the local environment, because emissions not only contain carbon dioxide (CO_2), but also nitrogen oxides (NO_x) and sulfur dioxides (SO_2) as well as particulate matter (PM) which can lead to health problems and impact on nature [Stapersma, 2010].

To reduce the impact and reach the goals set by the IMO, steps have to be taken to reduce the emissions of sea-going in ports as well as during their voyage. Some of the solution areas are presented in [Broersma, 2021]. Efficiency optimization can, on the one hand, focus on creating more fuel efficient ships to reduce emissions. However, these new techniques will not arrive in time to obtain the goal set by the IMO. In ports, other concepts are developed such as shore power for sea-going ships to reduce local emissions [European Comission, 2021]. The low-hanging fruit is, however, in optimization of port and voyage operations [WSPS, 2020].

The optimization of port operations has been studied extensively for terminal operations and berth allocation problems [Wijma, 2018] [Abou Kasm et al., 2021]. For voyage optimization, research has focused on reducing speeds during the voyage with Virtual Arrival, see [Jia et al., 2017a] and [Poulsen et al., 2018]. A large limitation of the Virtual Arrival scheme, which aims at reducing voyage speeds based on optimal arrival times, is that there exist technical issues to update ships of these optimal arrival times [GloMEEP, 2018]. Another aspect of port operations has recently caught interest of research. Due to unreliable estimated times of arrival (ETA), movements of ships within port perimeters with the help of tugs, pilots and linesmen are subject to delays [Broersma, 2021]. In [Molkenboer, 2020] this process is extensively studied in the Port of Rotterdam. It was shown that a lack of information-sharing during operations leads to unnecessary delays in port operations regarding the movements of ships.

To overcome this problem, in analogy to the air transportation world, a new concept was introduced regarding information-sharing. This concept, called *Port Collaborative Decision Making*, is deemed the integrator of port operations information-sharing [Lind et al., 2015]. By dividing the port call in subsequent blocks with milestones, the process is continuously updated in regards to the latest finishing times of the subsequent milestones. The aim of the system is to increase more situational awareness, upon which actors can change their operations in compliance with delays in the process. Such a scheme has already been tested in ports in the Baltic region, where participants thought the system indeed increased situational awareness among actors in the port [Lind et al., 2015]. The influence of increased information-sharing among port actors on reduction of emissions in the port call process was estimated to be around 35% in [Wijma, 2018] and 25% in

[Arjona Aroca et al., 2020] as well as a reduction of waiting times by 10%.

A. *Problem statement*

As can be seen, several concepts have been developed to reduce emissions during the voyage of sea-going ships and port operations. The main goal of these concepts is to create *coordination* within the port call process [Lind et al., 2015]. Coordination is a term that has been coined in for instance literature on supply chain management. There, coordination in supply chain is the act of properly combining (relating, harmonising, adjusting, aligning) a number of objects (actions, objectives, decisions, information, knowledge and funds) for the achievement of the chain goals [Simatupang et al., 2002]. As discussed in [Molkenboer, 2020], [Lind et al., 2015] and [Broersma, 2021] a conclusion can be drawn that the port call process regarding the in- and outgoing operations of sea going vessels suffers from inefficiencies. These inefficiencies lead to increased turnaround times for vessels as well as waiting times. Both lead to unnecessary emissions of greenhouse gasses by the port call process.

The reasons for these inefficiencies are widely recognised as a lack of information-sharing by actors during the port call as well as uncertainty in arrival times [Broersma, 2021], [Lind et al., 2015], [Molkenboer, 2020]. Coordination of the port call process is deemed a solution, based on increased information-sharing, that can resolve the issues at hand [Lind et al., 2018a]. To create coordination of information-sharing, the PortCDM concept has been designed to ensure standardised data-sharing among port call actors upon which everyone can act. This leads to a common sense of the goals and context in which the system operates. Coordination of logistics synchronization in the case of port call optimization can be found in the Just-in-Time concept from the IMO, together with the virtual arrival concepts as proposed by [Jia et al., 2017a] and [Broersma, 2021]. This concept contributes to value creation by diminishing waste in the process as described by [Broersma, 2021]. The concepts have proven to increase on the one hand situational awareness and on the other hand have shown the ability to decrease emissions and turnaround times.

Based on another notion of coordination in large infrastructures from [Reppa et al., 2019] it can be shown that this is not the complete picture for port call optimization. Said definition states that coordination is *”continuously processing relevant information and take action to achieve desired behaviour”*. This definition makes more clear what is lacking from the concepts for information-sharing and logistics synchronization discussed previously to create an optimal port call: the way information-sharing and logistics synchronization are steered by an *operational plan* to find the desired behaviour.

Therefore the researcher argues that coordination as a means for port call optimization can be obtained not only through information-sharing (e.g. PortCDM) or logistics synchronization (e.g. IMO JIT shipping), but that it also needs a mechanism that helps steer the system towards desired behaviour. Several attempts have been made to create such an operational plan. Optimal scheduling approaches have been designed to create an optimal schedule for vessel arrival according to constraints in the system. In figure 1 this extension of the notion of coordination based on the previous is shown. The relation between these value drivers can be found in the following: first and foremost, [Simatupang et al., 2002] conclude that success for coordination can only be achieved when logistics synchronization is used in response to shared information. Logistics synchronization determines the amount and contents of shared information and in return shared information reduces the lack of visibility in logistic processes. With respect to the operational plan, information-sharing gives the goals and context in which an operational plan is created, the logistics synchronization gives the boundaries and possibilities wherein the operational plan can respond to situations that occur in the system. In the literature on port call optimization this combination of value drivers has not been described. In [Van Baalen et al., 2008], [Lind et al., 2015] and [Arjona Aroca et al., 2020] the need for information-sharing, ways of information-sharing and impact on the port call process are discussed. A combination of logistics synchronization and information-sharing is made in [Broersma, 2021] and [Jia et al., 2017a].

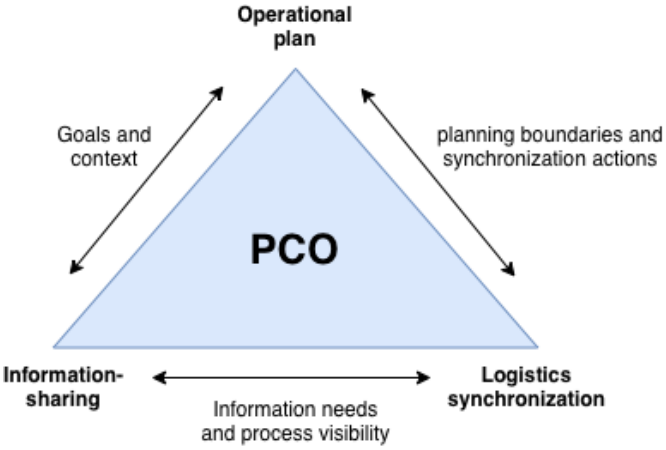

Fig. 1. Value drivers for coordination in Port Call Optimization (PCO)

The main contribution of this study is therefore to propose a suitable concept that increases coordination in the port call based on the concepts of virtual arrival and information-sharing together with a sound operational plan.

II. METHODOLOGY

Congested infrastructure such as busy ports can suffer from sub-optimal resource and capacity use which can lead to said congestion and unnecessary pollution. These transportation networks can be seen as a set of nodes, sources and sinks which are interconnected in space and handle ’commodities’. They typically span large areas, have many actuators and sensors and consist out of many different subsystems [Negenborn and Hellendoorn, 2010].

In case of ports these specifics can also be found: vessels (the 'commodity') arrive from and depart to sea (source and sink) and in the port environment they are directed by fairways. These different legs of the inner port travel are constrained by factors such as maximum draft, length and width of vessels as well as separation in terms of distance. System overflow is directed to anchorages to wait until the system is capable to handle new vessels. Lastly, the port environment is comprised of many different interacting systems of resources that handle incoming and departing vessels.

Solutions to tackle the problem of congested infrastructures can lie in updating current infrastructure, but this is time-consuming and expensive. A less intensive way of infrastructure optimization can be obtained by creating *intelligent infrastructure* where parts of the system are made intelligent so that they can cooperate and coordinate actions to improve use of current infrastructures [Negenborn and Hellendoorn, 2010].

Some examples of intelligent infrastructures are described in [Negenborn and Hellendoorn, 2010], the focus lies on transportation networks regarding electricity networks, road transport and waterways. In electricity networks the control approach can help overcome the problems that arise due to a more diversified power distribution that is the consequence of the implementation of renewable energy sources. It can help to guarantee service levels and stability in the power network. In road transport, intelligent infrastructures can help to streamline traffic flow in highly congested areas by imposing speed limits or input flows but is also vital to help the introduction of autonomous vehicles that have to communicate in order to navigate safely. Lastly, intelligent water infrastructure can help tackle the problems that rise with climate change. Use of optimization techniques can help to create better performing local control by taking into account actions performed by other controllers in the water network.

In the port environment, the use of computational intelligence is still in its infancy. However, the development of concepts such as PortCDM and Virtual Arrival give opportunity to regard waterway transport in ports from this intelligent perspective. PortCDM can help retrieve measurements about the system and the system can be actuated by changing starting times for vessel arrival (and departure) and subsequently updating them of optimal arrival speeds.

This study thus proposes such an intelligent coordination scheme for port call optimization. To do so, first the conceptual design of intelligent control is discussed in relation to the port call. Secondly, an rolling-horizon scheduling approach for the port call is presented to the reader. To test the influence of this scheduling approach with regards to emissions from sea-going vessels a simulation model based on a case study of Darwin Port, Australia is designed. The results of this simulation approach are discussed in in the last section of this paper.

III. INTELLIGENT CONTROL OF PORT CALL OPERATIONS

Formal description of infrastructures can be given with a classic systems and control approach as shown below in figure 2. Within this structure the system is the (physical) system which should be controlled, while the control structure measures system output and defines input to steer the system to desired behaviour. In this case, the port network is the system and this system is controlled by parties involved, such as the harbour master, terminal operators and nautical services.

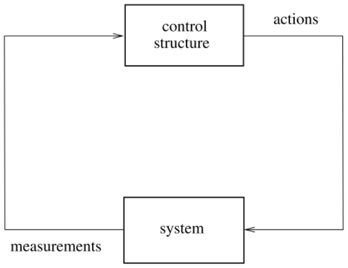

Fig. 2. The relation between a general system and the control structure that controls the system. [Negenborn and Hellendoorn, 2010]

To create such a structure, the system that is to be under control should be reviewed together with capacities for measurement and actuation. This section will first briefly discuss the port call system as well as its objective. Secondly, the measurements that can be taken from the system as well as actuation are discussed. Lastly, this section will propose a control structure based on the system objectives, measurement and actuation possibilities.

A. System & objectives

The port call process is constructed around the loading and unloading operations of sea-going vessels. They can be carrying containers, bulk goods, or for instance cars and trucks for Roll-On Roll-Off carriers as well as people for ferries and cruise ships. The port call for a vessel from an operations perspective is divided in different *movements*, a movement can either be *In* when a vessel arrives, *Out* when a vessel departs or a *Shift* movement when a vessel is moved from one terminal in the port to another for further loading or unloading operations.

During these operations the vessel is supported by different resources in the port. For safe navigation vessels are aided by a pilot that has local knowledge. In case of a captain or first officer with local knowledge, common in ferry operations, the vessel can have a *pilot exemption* and enter the port area without a pilot. The pilot remains with the vessel during the whole movement and is picked up or dropped off at a designated pilot boarding area at the most outer point of the port approach in sea. For safe maneuvering, vessels are assisted by tug services. Tugs are placed strategically throughout the port.

Based on the length, draft and maneuvering capability of the vessel as well as weather and tidal conditions the amount of tugs and their tugging capacity is determined by the harbour masters office. For *In* movements tugs are met at a designated *tug meeting point*. In general, this meeting point is closer to the port area than the pilot meeting point. When arriving at berth, linesmen crews are met to handle the final berth operations until the "all fast" command is given and the vessel can start terminal operations. For *Out* movements the vessels meet these supporting resources at their current berth and depart in the opposite order of operations. The order of vessels that enter the port is determined by the harbour masters office and related to tidal and safety restrictions as well as resource capacity.

In light of this study, the focal point of the port call is to streamline operations in order to create a reduction of emissions during the port call based on increased information-sharing. As was discussed, the IMO proposes a 50% reduction of emissions in 2050 [International Maritime Organisation, 2018]. This can be obtained by reduction of waiting times in the port call process and by advising arriving vessels to reduce their speed to arrive at the scheduled time for handling the vessel [Jia et al., 2017a] [Broersma, 2021] [Arjona Aroca et al., 2020]. If this is considered, next to the objectives stated above, the aim for optimization of the port call should be in creating a vessel arrival and departure schedule that on the one hand takes into account the available resources and safety regulations to ensure optimal movement planning in the port which can be used to update vessels on their optimal approach speed or departure time and on the other hand is capable of adapting to the frequently changing profile of operations in the port call due to delays that occur and cause inefficiencies in the port call.

B. System measurements & actuation

To determine the order of movements, the harbour master currently uses manually updated information provided by vessel agents. As discussed before, the PortCDM concept has been developed to create a real-time overview of port operations and the status of vessels. The IALA S-211 message standard was proposed together with PortCDM to create a standardized message format. These messages comprise of timestamps and certain actions in the port in relation to the proposed milestone-approach [Lind et al., 2018b]. Based on this approach, the system is updated with ready times whenever an operation, such as loading/unloading or bunkering is finished, started or delayed. This information can be used to update a controller in real-time of the progress in port operations.

The Automatic Identification System (AIS) is a transponder system on-board sea-going vessels. All vessels over 300 Gross Tonnage are outfitted with this system as per the Chapter V, Regulation 19.2.4 of the Safety of Life at Sea Convention. The AIS sends 3 types of data over the Very High Frequency (VHF) band used for maritime communication [Lessing et al., 2006]. These data types are *static*, *dynamic* and *voyage related*. The first is information about vessel characteristics such as name and dimensions. Dynamic information comprises heading, course, speed and position of the vessel. Voyage related information is for instance vessel destination and hazardous nature of the cargo on board. Dynamic information about is relayed to surrounding transponders every 2 to 10 seconds while underway. The other information is relayed in 6 minutes intervals [Lessing et al., 2006]. The information of the AIS system on-board vessels can be used in the context of this research for traffic management. The dynamic information can help to predict if an approaching vessel is in time to get to the Pilot Boarding Point according to the Planned Time of Arrival. If this is not the case a good assumption can be made about what a revised ETA will be. Secondly, the static information about vessel dimensions can help to make a prediction about the resources a vessel needs during port call operations.

To optimize the port call of sea-going vessels in relation to the objectives stated above as well as the literature on vessel arrival and departure scheduling, it becomes clear that constantly considering the order of vessel movements in relation to the available resources and safety guidelines is a way of optimizing the port call process. This can be done by revising approved times of arrival and departure for the vessels. For vessels at berth a revision of departure times is, operationally, not a big impact. It can create friction, because a vessel might have to wait longer at berth which leads to idle times at both the vessel as well as the terminal, but there are no physical restrictions that impose constraints on changing the vessel movement order.

The concept of Virtual Arrival was designed to create speed and emissions reduction by updating approaching vessels of delays in port [Poulsen et al., 2018] [Jia et al., 2017a]. This delay could be smeared out along the vessels' approach by reducing its speed in accordance to the renewed Planned Time of Arrival (PTA). In the case of control we can use the concept to control the inflow of vessels to the port area. Based on real-time updates from the port area, new arrival and departure schedules can be devised and approach speeds are updated.The approaching vessels can be controlled in a discretized way, relating to to virtual arrival concept proposed in [Jia et al., 2017a] and the way point approach proposed in [Broersma, 2021]. The mathematical formulation of this concept is as follows:

Given a set of way points $WP = [1 \dots I]$, where the first way point is a distance D_{owp} from the arrival port and waypoint I is located at the port entrance. There exists a constant distance d between the way points. On approach to the port a vessel will hit this number of way points to update its speed to the revised schedule as proposed in this control structure. The distance to the port at waypoint i is than given as:

$$D_{port} = D_{owp} - WP_i * d \tag{1}$$

Based on the updated PTA and the current time t, a new Time to Arrival (TTA) can be calculated as follows:

$$TTA_{new} = PTA_{new} - t \tag{2}$$

From equations 1 and 2, the new approach speed v_{va} can be calculated as follows:

$$v_{va} = \frac{D_{port}}{TTA_{new}} \tag{3}$$

Where the distance D_{port} is calculated in Nautical Miles (NM) and TTA_{new} is calculated in hours. Which yields a result for v_{va} in knots. This new speed is constrained by the vessel speed limitations as follows:

$$v_{min} \leq v_{va} \leq v_{max} \tag{4}$$

In the case that equation 4 does not hold, the new speed v_{va} should be updated to the closest feasible value (either 12 or 20-25 knots [Notteboom and Cariou, 2009]). A new PTA should be communicated to the port through the following relation:

$$PTA_{new} = TTA_{new} + t = \frac{D_{port}}{v_{va}} + t \tag{5}$$

With this construction the control structure is able to steer the system of vessel operations in the port call to optimal speeds reducing emissions and enabling just-in-time arrival. The relation between the preliminary model proposed in the previously can be readily obtained from the statements above. As far as the operational plan goes, this responsibility lies with the harbour master which acts as an overall system controller by defining start times of operations through scheduling optimization. The logistics synchronization is obtained through the use of virtual arrival in the port approach. The PortCDM concept can be used for increased information-sharing in the port call. The information needs are provided by the just-in-time shipping concept through virtual arrival. These needs relate to the information about vessel specific information such as speed and location as well as other process markers ("milestones") as proposed in the PortCDM concept. This in turn leads to visibility of the process since everyone involved is updated of the status of different actions in the port call. The Harbour Master in turn, based on the information obtained through the CDM concept, can align the goals in port call operations with the operational context provided. The relation between the harbour master and just-in-time shipping as a form of logistics synchronization is obtained from the operational perspective in which the harbour master sets the boundaries for the operations and the synchronization of actions leads to obtaining the goals set out by the Harbour Master.

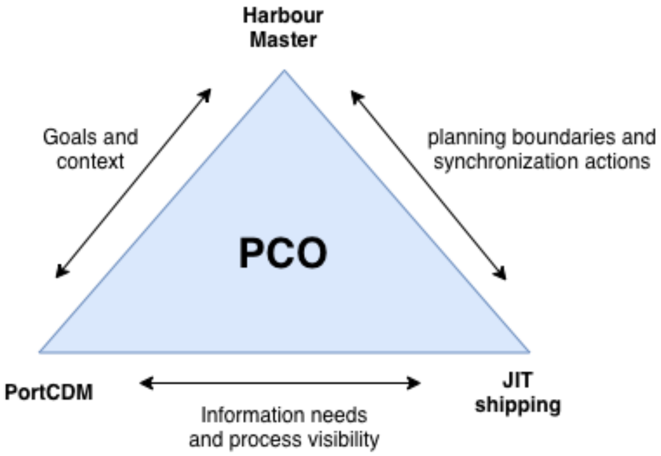

Fig. 3. Implementation of preliminary model

C. Control structure

A first distinction between control structures is the number of control agents that constitute the structure. In case of one control agent, the structure is deemed *single-agent* control. The control structure can in principle determine actions that gives optimal performance of the system. In case multiple controllers are used, this is called a *multi-agent* structure. If agents communicate with each other this is *distributed* control and if there is no communication this is called *decentralized* control. If in a multi-agent environment there is an authority relation between controlling agents, the control structure is defined as *multi-layer*. This control structure is found in systems where one agent defines set-points for other agents in the system [Negenborn and Hellendoorn, 2010]. For examples of the control systems, the reader is referred to [Negenborn and Hellendoorn, 2010].

Definition of control structures is not theorized for systems and is therefore based on preferences for one type or the other. For large scale systems, single-agent control is complicated by the fact that there exist problematic issues regarding control access and information unavailability. Furthermore, computational requirements can be very high for large scale controllers prohibiting their use in real-time environments. lastly, due to the large system a single-agent has to control it can suffer from reliability, scalability and robustness issues. These problems can be tackled by defining multi-agent control structures, but the performance of such a system is generally lower and implementation is far from trivial. In practice, choosing the best control structure is not the question. The question is how current control structures can be changed so that performance of the system is improved [Negenborn and Hellendoorn, 2010].

A single-agent control structure for vessel movement scheduling and vessel inflow regulation is proposed here. The single-agent control structure is seen as suitable to handle the vessel arrival problems in reasonable time and with profitable results for emission reduction. Measurement inputs for the vessel operations scheduling comes from the PortCDM concept as described and AIS data of approaching vessels. The system can be controlled by postponing or advancing vessel movements in time to ensure optimal resource use and turnaround times. Secondly, approaching vessels can be advised to decrease their speed as per the virtual arrival concept developed in literature. Due to vessel engine characteristics this should happen at virtual way points along the approach and within certain boundaries. An overview of the control structure including actuation of the system and measurements is given in figure 4

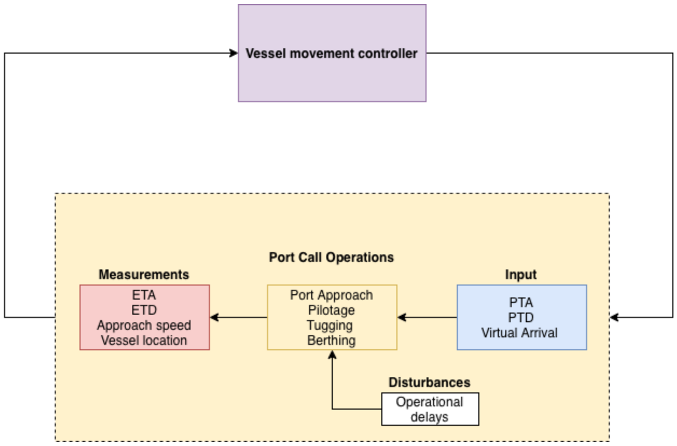

Fig. 4. Control structure for vessel movements in the port call process

IV. Rolling horizon approach for port call operations scheduling

A. *Rolling horizon approach*

Rolling horizon approaches for decision-making have extensively been studied in literature [Sethi and Sorger, 1991]. Rolling horizon approaches were developed for lot-sizing in production scheduling, operation room scheduling in hospitals and stochastic supply chain management planning of goods transportation [Glomb et al., 2022]. In most cases, the rolling horizon approach for scheduling is performed by solving a static scheduling model for a certain period of time, i.e. the scheduling horizon, and fixed for a certain amount of time after which the static scheduling model is recalculated with new input [Ouelhadj and Petrovic, 2009]. These time periods are described as the time horizon and control cycle or roll period [Ouelhadj and Petrovic, 2009].

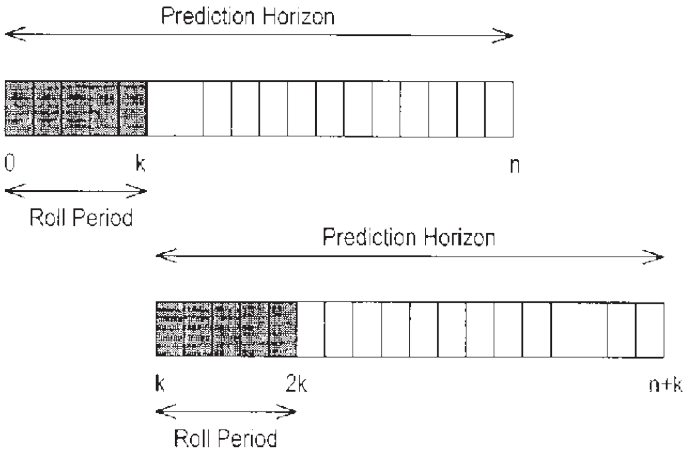

Fig. 5. Schematic view of rolling horizon approach [Gartner and Stamatiadis, 1998]

The length of the time-horizon determines the outlook of the optimization model and therefore the assessment of impact of actions in the current roll period on the system. Secondly, the roll period marks the time period in which nothing changes. In case of vessel movement scheduling with virtual arrival, this means that within this period all vessels that are ready for movement, are expected to start at the optimal starting time defined at the beginning of that roll period and for vessels approaching the port that come upon a virtual arrival way point change their speed to the predicted optimal arrival time as defined at the beginning of this roll period.

The determination of a control cycle is a hard exercise and not necessarily a deterministic one [Ouelhadj and Petrovic, 2009]. For different manufacturing problems, it was shown that increasing the control period yields worse results in terms of scheduling optimization, but that it shows better performance than other dispatch rules [Ouelhadj and Petrovic, 2009]. This means that the control period under review in this thesis should be subject to experimentation, to find its influence on the system.

B. *Static scheduling model*

Several scheduling models for port operations have been reviewed. As concluded by [Abou Kasm et al., 2021], most vessel scheduling optimization problems are focused on geographical restrictions such as optimal scheduling for one-way channels. To create an optimal controller for rolling horizon vessel scheduling with virtual arrival and information-sharing the model proposed in [Abou Kasm et al., 2021] is adapted to be used here. The model parameters are shown in table I - III.

TABLE I
Sets in model

I:	set of all vessel movements	$i, j \in I$ = $\{1{:}\|\|I\|\|\}$
K:	set of vessel movements	$k \in K$, where $k = 1$ is IN, $k = 2$ is OUT, $k = 3$ is SHIFT
T:	set of all time periods in planning horizon	$t \in T = \{t_0 : t_0 + \|T\|\}$

TABLE II
Decision variables

s_{it}:	binary decision variable to start vessel movement i at time period t $\forall$i $\in I$, $t \in T$
Γ :	Maximum deviation from expected time of arrival or departure

C. *Mathematical formulation of objective function*

As discussed in the previous section, the system objective is to minimize the maximum deviation between the time a vessel is ready to start a movement and the time the movement is planned to start. This in turn also reduces the variability in speeds along the virtual arrival approach. The maximum deviation between start and ready times for all vessels is described as:

$$\Gamma = \max_{i \in I} \sum_{t=t_0}^{|T|} |t(s_{it} - E_{it})| \tag{6}$$

TABLE III
PARAMETERS RELATING TO THE STATIC SCHEDULING MODEL

Parameters:

Q_t	Number of available tug boats
Q_i	Number of tug boats needed for vessel movement i, $\forall i \in I$
P_i	Number of periods needed for tugging and pilotage of vessel movement i , $\forall i \in I$
A^{in}	Minimum time between the start of two *in* operations
A^{out}	Minimum time between the start of two *out/shift* operations
N	Number of pilots available at the port
A_i^n	Number of periods vessel movement i requires piloting without tug assistance, $\forall i \in I$
A^{ti}	Number of periods a tugboat needs to reach a vessel for an *in* operation
A^{to}	Number of periods a tugboat needs to reach a vessel for an *out/shift* operation
R_i	Binary variable, if vessel movement i requires a pilot $\forall i \in I$
V	Number of pilot boats available in the port
A^v	Number of time periods a pilot boat needs to carry out a one-way journey
W	Number of available mooring teams in the port
A_i^W	Number of time periods needed for mooring vessel movement i, $\forall i \in I$
O_{ik}	Binary variable, if vessel movement i is of type k, $\forall i \in I$, $k \in K$
E_{it}	Binary variable, if vessel movement i is ready to start at time period t, $\forall i \in I$, $t \in T$
G_{ij}	Binary variable, if vessel movement i and j relate to the same vessel. $\forall i, j \in I$
C_i^r	Number of time periods for vessel movement i to reach the channel. $\forall i \in I$
C_i^n	Number of time periods for vessel movement i to move through the channel. $\forall i \in I$
B	Number of berthing locations in the port
B_v	Number of vessels berthed at the start of the planning horizon
D_{owp}	Distance from outer Virtual Arrival way point to port entrance
d_{wp}	Distance between Virtual Arrival way points
WP	Total number of way points in Virtual Arrival area
v_i^{max}	Maximum speed for vessel movement i in virtual arrival, $\forall i \in I$, $k = 1$
WP_i	Next way point to be hit by vessel in related to *in* movement i, $\forall i \in I$, $k = 1$
t_i^{WP}	time period at which vessel related to *in* movement i reaches next Virtual Arrival waypoint.
M	Big-M value for calculation purposes
tp	length of time period in hrs
t_0	time period at beginning of the scheduling horizon

However, if we would only minimize the maximum deviation this would not lead to the most optimal schedule given the known state of the system. If a movement i had incurred a deviation of 11 hours, subsequent vessel movements can be deviated by the model with 11 hours without costs. This can not be the case, since the objective is that all vessels start operations as close to ready time as possible. To overcome this problem, Abou Kasm et al. [Abou Kasm et al., 2021] append a weight function to the maximum deviation as well as a function to calculate the total time needed in the time horizon to schedule all vessel movements. This gives a new objective function that minimizes the maximum deviations, penalizes extra deviations for subsequent vessels and tries to schedule operations in the shortest time window possible:

$$Z = MIN \quad \Gamma \sum_{i \in I} (|T| - \sum_{t \in T} E_{it}) + \sum_{t \in T} \sum_{i \in I} t s_{it} \tag{7}$$

D. Mathematical constraints

$$\Gamma - \sum_{t=t_0}^{|T|} t(s_{it} - E_{it}) \geq 0 \quad \forall i \in I \tag{8}$$

$$-\Gamma + \sum_{t=t_0}^{|T|} t(s_{it} - E_{it}) \leq 0 \quad \forall i \in I \tag{9}$$

$$\sum_{t=t_0}^{|T|} s_{it} = 1 \quad \forall i \in I \tag{10}$$

$$\sum_{i \in I} \sum_{t'=g(t-P_i+1)}^{g(t-A_i^n+A^{ti})} O_{i1} Q_i s_{it'} + \sum_{i \in I} \sum_{t'=g(t-P_i+A_i^n-A_i^W+1)}^{g(t-A_i^W+A^{to})} \sum_{k=2}^{3} O_{ik} Q_i s_{it'} \leq Q_t \quad \forall t \in T \tag{11}$$

$$\sum_{i \in I} \sum_{t'=g(t-P_i+1)}^{g(t+A^v)} O_{i1} R_i s_{it'} + \sum_{i \in I} \sum_{t'=g(t-P_i-A_i^W-A^v+1)}^{g(t-A_i^W)} O_{i2} R_i s_{it'} + \sum_{i \in I} \sum_{t'=g(t-P_i-A_i^W+1)}^{g(t-A_i^W)} O_{i3} R_i s_{it'} \leq N \quad \forall t \in T \tag{12}$$

$$\sum_{i \in I} \sum_{t'=t}^{g(t+A^{in}-1)} O_{i1} s_{it'} \leq 1 \quad \forall t \in T \tag{13}$$

$$\sum_{i \in I} \sum_{t'=g(t-A_i^W)}^{g(t-A_i^W+A^{out}-1)} \sum_{k=2}^{3} O_{ik} s_{it'} \leq 1 \quad \forall t \in T \tag{14}$$

$$\sum_{i \in I} \sum_{t'=g(t-A^V+1)}^{g(t+A^V)} O_{i1} R_i s_{it'} + \sum_{i \in I} \sum_{t'=g(t-P_i-A_i^W-A^v+1))}^{g(t-P_i-A_i^W+A^V)} O_{i2} R_i s_{it'} \leq V \quad \forall t \in T \tag{15}$$

$$\sum_{i\in I}\sum_{t'=g(t-P_i-A_i^W+1)}^{g(t-P_i)} O_{i1}s_{it'} + \sum_{i\in I}\sum_{t'=g(t-P_i-A_i^W+1)}^{t}\sum_{k=2}^{3} O_{ik}s_{it'} + \sum_{i\in I}\sum_{t'=g(t-P_i-2A_i^W+1)}^{g(t-P_i-A_i^W)} O_{i3}s_{it'} \leq W \quad \forall t \in T \tag{16}$$

$$s_{it} - \sum_{t'=t_0}^{t} E_{it'} \leq 0 \quad \forall i \in I : O_{i2}, O_{i3} = 1, \forall t \in T \tag{17}$$

$$\sum_{t\in T} ts_{it} - \sum_{j=1}^{i-1} G_{ij}\sum_{t\in T} ts_{it} - \sum_{t\in T} tE_{it} + \sum_{j=1}^{i-1} G_{ij}\sum_{t\in T} tE_{jt} \geq 0 \quad \forall i \in I \tag{18}$$

$$\sum_{t''=g(t+C_i^r)}^{g(t+C_i^r+C_i^n+1)} \sum_{j\neq i} \sum_{t'=g(t''-C_j^r-C_j^n-A_j^W+1)}^{g(t''-C_j^r-A_j^W)} O_{j2}s_{jt'} + (s_{it}-1)\sum_{j\in I} O_{j2} \leq 0 \quad \forall i \in I : O_{i1} = 1, \forall t \in T \tag{19}$$

$$B^v + \sum_{i}\sum_{t'=1}^{g(t-P_i} O_{i1}s_{it'} - \sum_{i}\sum_{t'=1}^{g(t-A_i^W}\sum_{k=2}^{3} O_{ik}s_{it'} + \sum_{i}\sum_{t'=1}^{g(t-P_i-A_i^W} O_{i3}s_{it'} \leq B \quad \forall t \in T \tag{20}$$

$$(D_{owp} - (WP_i * d_{wp})) - (v_i^{max} * ((s_{it} * t) - t_i^{wp})) \leq 0 + M * (1 - s_{it}) \quad \forall i \in I : O_{i1} = 1, \forall t \in T \tag{21}$$

$$s_{it} - \sum_{t'=t_0}^{t} E_{it'} = 0 \quad \forall i \in I : O_{i1} = 1, WP_i = WP - 1 \tag{22}$$

$$s_{it} \in 0, 1 \quad \forall i \in I, \forall t \in T \tag{23}$$

$$\Gamma \geq 0 \tag{24}$$

Since the objective function in equation 7 is non-linear and related to the absolute value of the schedule deviation, constraints 8 and 9 linearize the objective function. Constraint 10 ensures that a vessel operation i is only performed once during the time horizon. Resource use in time period t is constrained by constraints 11, 12, 15, 16. 13 and 14 ensure that the time between consecutive movements are taken in to account. Constraint 13 prohibits planning of out and shift movements before ready time. For in movements, this is ignored, because they can be moved to an earlier time or later time of arrival in accordance with Virtual Arrival. 18 is used to propagate delays if consecutive vessel movements are known at the moment of planning and an arrival movement is retarded. 19 is used to ensure safe distances in the fairway between vessel movements and constraint, 20 ensures berth availability at for all vessels in the planning horizon. 21 is appended to the model of [Abou Kasm et al., 2021] and relate to the virtual arrival of in movements. The speed of the vessel is constrained by a maximum speed. This constraint is only enforced on the planned starting time s_{it} through the use of the big M. Constraint 22 ensures that when vessels are in the last virtual arrival leg of their approach, the scheduled start time of the in-operation is not changed to an earlier moment. [Abou Kasm et al., 2021] propose the time limits on resource constraints, because of the overlap in operations that occurs within port operations. The logic behind this is that the starting time variable s_{it} is the reference point for all resources to adhere to. This means looking in reverse as well as forward for different movements, because resources have to travel to and from the departing or arriving vessel. This means that resources are seized before and after the starting time of movement i, introducing the need for constraints that assess variable times. For an example, the reader is referred to [Abou Kasm et al., 2021].

With regards to the prediction period, or scheduling horizon in this case, single-agent controllers perform better when the prediction horizon is increased. However, increasing the time horizon heavily burdens computing power and speed of the optimization [Atabay, 2018]. Therefore, a suitable planning horizon should be chosen to ensure that the system is able to perform better in terms of delay optimization. To ensure feasibility over the scheduling horizon, the set of vessel movements that can feasibly planned can be found with the following relations in equations 25-27. a subset S of I is presented which represents all vessel movements that can be finished within the scheduling horizon $|T|$. By sorting all movements in I based on their ready time E_i a list of feasible movements within the time horizon can be made. Algorithm 1 shows this logic. The static scheduling problem defined in the previous section, is then changed with regards to the sets

Algorithm 1 Determining $S \subset I$

```
$i = 1, S = \{\}, t_0, |T|, G_{ij}$
Sort $I$
while $i <= |I|$ do:
    for $j$ in $I$ do:
        if $G_{ji} = 1$ & $j < i$ then:
            Calculate $E_i$
        end if
    end for
    calculate $F_i$
    calulate $T_i$
    if $T_i < t_0 + |T|$ then:
        append $i$ to $S$
        $i \leftarrow i + 1$
    else
        $i \leftarrow i + 1$
```

$$T_i = \begin{cases} max\{F_{I-1}, E_I\} + max\{A^v + A_I^n, A^{ti}\} + P_I - A_I^n + A_I^W, if \quad O_{I,1} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A_i^W\} + P_i + A^v, illif \quad O_{i,2} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A_i^W\} + P_i + A_i^W, \qquad if \quad O_{i,3} = 1 \end{cases} \tag{25}$$

$$F_i = \begin{cases} max\{F_{i-1}, E_i\} + max\{A^v + A_i^n, A^{ti}\} + P_i - A_i^n + A_i^W, if \quad O_{i1} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A_i^W\} + P_i + A^v, \qquad if \quad O_{i2} = 1 \\ max\{F_{i-1}, E_i\} + max\{A^{to}, A_i^W\} + P_i + A_i^W, \qquad if \quad O_{i3} = 1 \end{cases} \tag{26}$$

$$E_i = E_i + max\{F_{j-1}, E_j\} - E_j \quad \forall i, j \in I : G_{ji} = 1, \quad j < i \tag{27}$$

to incorporate S rather than the overall movement set I.

Another problem with the static scheduling model is the occurrence of vessel movements that have started in a previous control period and, based on their ready-time E_i, do not fall in the scheduling horizon. However, these movements still burden the system in terms of resource use in the current scheduling period, when the movement has not finished. To overcome this problem, a variable is introduced that checks if the movement is *underway* at this time period.

r_i binary variable to determine if movement i is underway $\forall i \in I$ (25)

To accommodate these movements in the current scheduling horizon, the time horizon is extended backwards in time to be started at the earliest starting time of all movements that are underway at the moment of scheduling t_0. Algorithm 2 shows this.

Algorithm 2 Determine new t_0 for all movements i that have started before beginning of planning horizon t_0

```
$S, E_i, t_0$
Sort $E_i \quad \forall i \in S$
if $min(E_i) < t_0$ then:
    $t_0 \leftarrow min(E_i)$
else
    $t_0 \leftarrow t_0$
```

Since some movements already have started, they will need their movement starting times to be fixed in the scheduling model. This leads to the following constraint:

$$s_{it} - \sum_{t'=t_0}^{t} E_{it} = 0 \quad \forall t \in T \quad \forall i \in S : r_i = 1 \tag{26}$$

The algorithm is implemented in *python* and solved with GUROBI optimization software.

V. RESULTS

The impact of the rolling horizon scheduling optimization on vessel emissions is assessed using a *Discrete Event Simulation* model (DES). DES is a way of modelling processes and flows and used in manufacturing and service optimization [Babulak and Wang, 2010] . The main advantage of using such a simulation is that it is able to cope with disturbances and individual process times. The DES model is implemented using AnyLogic, an alround software package for DES. Inputs for the simulation model are provided by SAAB Maritime Traffic Management and regard 5 years of data on movement within Darwin Port, Australia.

A. Process logic

The process logic follows vessels from a certain point around 650 NM from the port. Vessels travel along a path with a speed defined by the vessel type. After arriving at the port, the vessel seizes the needed resources, tugs, pilots and terminal before the vessel enters the port area. The vessel is brought to its berth were the terminal operations commence. A deviation from the scheduled terminal operation times due to delays or fast operations is incurred by a vessel during the terminal operations. After operations have finished, the vessel seizes the needed resources and travels out of the port.

The implementation of information-sharing is done through the real time updating on the status of terminal operations and the use of milestones as proposed in [Lind et al., 2015]. Vessels share Estimated Time of Arrival (ETA) upon arriving at the outer perimeter of the virtual arrival approach. Secondly, updates on ETA/D's and process times are provided to the scheduling model when an operation starts, when a pilot boards the vessel for and in movement and when the tug meeting point has been reached.

The virtual arrival policy is implemented using way points as discussed in [Broersma, 2021]. Vessels will relay ETA's and revise their speed in conjunction with the outcomes of the scheduling model at discrete points in time.

Furthermore, the scheduling optimization can be accessed from the simulation model and is calculated at predetermined intervals from the DES model.

B. Key Performance Indicators

Two key performance indicators have been selected to be used as outputs of the simulation model. First of all, vessel emissions can directly be related to the amount of fuel a vessel has used for propulsion [Stapersma, 2010]. The following formula is used to calculate the vessel fuel use during one time step in the model [Barrass, 2004]:

$$C(\nabla, t) = \sum_{t=1}^{T} \frac{1}{t_d} * \lambda * v_{i,t}^3 * \nabla_i^{(2/3)} \tag{27}$$

where $v_{i,t}$ is the vessel speed in knots at the current time step. ∇_i is the vessel displacement and λ is the fuel coefficient. For diesel engines, this coefficient is approximately $\lambda = 1/110000$.

The emissions per tonne fuel can be calculated with the following relations shown in table IV

TABLE IV
EMISSIONS RELATED TO COMBUSTION OF FUEL [STAPERSMA, 2010]

emission	amount (g/kg)	Fuel contents
CO_2	3150	86% C
SO_2	20	% S
NO_2	3.3	0.1 %N

For Heavy Fuel Oil, the most used fuel in sea going vessels, the amount of sulphur has been regulated by the IMO to be maximum 0.5% [Thuy et al., 2016]. For nitrogen, the mass by mass value is 0.68%. [Thuy et al., 2016]. To compare the results of different simulation runs and the experiments, the average fuel use per vessel is calculated.

Secondly, average *time in system* was measured for all vessels in the port call to assess if the virtual arrival policy retards vessels in their port approach and operations.

C. Inputs

The inputs for the model are determined from a data set provided for vessel movement in Darwin Port, Australia. The port consists out of several berths for cruise ships, bulk, general, livestock and container cargo. Furthermore two lng terminals are present as well as a terminal for offshore supply. The modeled terminal is the East Arm Wharf terminal. Four most visiting vessel types where determined, these are *general cargo*, *livestock carrier*, *rig tender* and *container vessels*. The vessel characteristics such as length and displacement are taken from the entries provided in the data set. The resources available in the port are shown in table V. Tug need is determined based on vessel length and is shown in in table VI.

TABLE V
RESOURCES AVAILABLE IN DARWIN PORT SIMULATION MODEL

Resources	Capacity
Berths	12
Pilots	2
Tugs	4
Pilot boats	2

Process times for subsequent movements and terminal operations are determined based on statistical analysis of the data set.

TABLE VI
TUG NEED PER VESSEL RELATED TO LOA

Vessel LOA	Tug need
<90	0
90 - 120	2
120 - 160	3
>160	4

D. Results

Three experiments have been performed to research the impact of the scheduling optimization together with virtual arrival. First a base case with a *first come, first serve policy* is run without virtual arrival and scheduling. Second an experiment is performed where the control period is short as well as the scheduling horizon. Lastly, an experiment is performed with a long scheduling horizon and control period. The parameters are shown in table VII. Each experiment is replicated 20 times to account for stochastic variables. The warm-up time of the experiment is 3 weeks and the measurements are taken from movements within another 3 week time period. The outcomes of the experiment runs with regards to fuel consumption are shown in tables VIII - X

TABLE VII
EXPERIMENT PARAMETERS

Parameter	Experiment 1	Experiment 2	Experiment 3
$\|T\|$	na	24 hr	48 hr
t_c	na	1 hr	5 hr
D_{owp}	na	500 NM	500 NM
d_{wp}	na	100 NM	100 NM

TABLE VIII
STATISTICS OF EXPERIMENT OUTCOMES FOR FCFS

FCFS	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	45.69	4131.93
σ	8.46	165.17
σ^2	71.54	27282.13
CI	3.96	77.30
CI_{rel} (%)	8.66	1.87

TABLE IX
STATISTICS OF EXPERIMENT OUTCOMES FOR $t_c = 5$, $|T| = 48$

FCFS	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	45.69	4131.93
σ	8.46	165.17
σ^2	71.54	27282.13
CI	3.96	77.30
CI_{rel} (%)	8.66	1.87

The outcomes of the experiments with regards to average emissions are shown in in table XI. From the statistcal analysis in table XII and XIII it becomes clear that the scheduling model indeed reduces the vessel average fuel use

TABLE X

STATISTICS OF EXPERIMENT OUTCOMES FOR $t_c = 1, |T| = 24$

FCFS	Average fuel use (tonnes)	Average time in system (min)
N	20.00	
$\bar{x}$	38.38	4452.33
σ	3.17	120.96
σ^2	10.06	14633.16
CI	1.48	62.20
CI_{rel} (%)	3.86	1.40

TABLE XI

COMPARISON OF AVERAGE EMISSIONS PER VESSEL BETWEEN EXPERIMENTS

Emissions (Tonnes)	FCFS	T_c = 1, $\|T\|$ = 24	T_c = 5, $\|T\|$ = 48
Avg. fuel use	45.96	38.38	38.74
CO_2	144.77	120.90	124.68
SO_2	0.45	0.38	0.39
NO_2	1.03	0.86	0.88

TABLE XII

COMPARISON OF MEANS BETWEEN EXPERIMENTS WRT. AVERAGE FUEL USE

				P value (post hoc analysis)	
		N	$\bar{x}$	T_c = 1, $\|T\|$ = 24	T_c = 5, $\|T\|$ = 48
Average fuel use per vessel	FCFS	20	45.96	0.0138	0.0221
	T_c = 1, $\|T\|$ = 24	20	38.38	-	1.00
	T_c = 5, $\|T\|$ = 48	20	38.74	-	-
$\chi^2 = 10.87, df = 2, p = 0.004$					

TABLE XIII

COMPARISON OF MEANS BETWEEN EXPERIMENTS WRT. AVERAGE TIME IN SYSTEM

				P value (post hoc analysis)	
		N	$\bar{x}$	T_c = 1, $\|T\|$ = 24	T_c = 5, $\|T\|$ = 48
Average time in system per vessel	FCFS	20	4121.37	p¡0.001	p¡0.001
	T_c = 1, $\|T\|$ = 24	20	4470.44	-	1.00
	T_c = 5, $\|T\|$ = 48	20	4452.33	-	-
$F = 53.76, p < 0.001$					

and emissions by 16.5% in comparison to the first come, first serve case. However, no difference in emission reduction could be found between the two rolling horizon scheduling experiments. For both scheduling scenario's the average time in system is significantly larger than the first come first serve base. This increase amounts to around 8% in comparison to the base case. Between the scheduling experiments no difference in mean time in system per vessel could be observed.

VI. DISCUSSION

A. Preliminary model

The preliminary model presented in chapter 2 of this thesis was the onset of the development of the rolling-horizon scheduling approach presented in this thesis. The idea was formed based on concepts developed about coordination in large technical systems and supply chains. Doing so assumes that the same mechanisms apply in the port environment. The question remains if these concepts can be translated to the port environment in real-life. As far as logistics synchronization goes, the just-in-time concept through virtual arrival is a hard nut to crack. On the one hand, there are fixed schedules for cruise ships and ferries as well as tight deadlines for container vessels. On the other hand, bulk shipping liners are not eager to delay their operations because of their demurrage contracts Poulsen2020. This means that it could be hard to change arrival times for vessels and have actors willing to participate. Secondly, in the PortCDM trials it was found that participants saw the benefits of information-sharing , but that there were still concerns about competitive information Lind2018c. This could lead to decreased process visibility if not enough or the wrong information is shared. In creating an operational plan, the main goals have to be determined. Already stated was that this is a hard task in the port environment due to the diversity of the system. All in all, these are hurdles to be taken in order to let the concept function at its prime. However, by showing the benefits of such a system and looking at the port call a more aligned operational profile might be created in the port call.

B. Methodology

The chosen methodology to combine the different optimization methods has proven to be feasible in terms of emission reduction. A first remark should be made about the choice for a single-agent control structure. The assumption that the Harbour Master plans and determines all vessel movements unilaterally was made to justify this approach. In real life however, the port call is an intricate network of actors whose decisions influence each other and events in the port which have an impact on the system and optimized outcomes. An argument can be made that to control the movements in the port call, a more diversified control approach should be chosen. Such a control structure might replicate the communication between nautical services, terminals, vessels and Harbour Master. Distributed or multi-layer control structures as proposed in [Negenborn and Hellendoorn, 2010] might help to do so. Secondly, the control strategy assumes some kind of logical behaviour through mathematical or physical relations. In environments where humans still rule the machines, such as the port, this assumption might lead to an overestimation of the adherence to optimized solutions provided by intelligent control. Such deviations by human actions might lead to suboptimal performance of the proposed concept.

C. Simulation model

Some assumptions in the simulation model may influence the results obtained in the previous section. The used formula on fuel consumption is very generic. Fuel consumption is specific per vessel and this generalization might lead to an over- or underestimation of the fuel use during the port call. An improvement to the model could be the introduction of the real fuel use of vessels based on their specifications.

Vessel delays in port have been taken into account in the simulation model, but the delays incurred by vessels during their voyage have not, since no data was available. This could lead to a much more volatile optimized schedule under which the virtual arrival approach could yield less beneficial results. This could be implemented in the model by assessing AIS data of approaching vessels for a case study.

Lastly, vessel dynamics have not been taken into account in this simulation model. Vessels are large and changes in course and speed are hard to obtain. The model assumes that a vessel's speed is immediately reduced after a new ETA has been provided at the way point. However, in real life the vessel reduces it's speed over time. These dynamics could be taken into account in the Anylogic model, especially since this program is able to combine the Discrete Event System with continuous simulation.

D. Results

With regards to the experiment results the findings on emissions reduction by vessels are in line with the findings presented by [Arjona Aroca et al., 2020], [Wijma, 2018] and [Jia et al., 2017b] on the impact of information-sharing as well as virtual arrival policies. The found increase in system time however, is unexpected. The goal of the vessel movement scheduling model is to create an optimized schedule that incorporates the availability of resources in the best possible way [Abou Kasm et al., 2021]. A possible explanation for this increase may be found in the chosen parameter settings as described by [Ouelhadj and Petrovic, 2009]. In the short horizon experiment, the model is not able to look ahead for a long period of time. This can make that the propagation of delays is not correctly forwarded to the ships in the model, therefore yielding higher average time in system. A similar explanation can be found for the longer control period. Since vessel are not updated on new arrival times often, they may keep waiting until their optimized ETA at the port entrance while resources are available. Extra research on the standpoint of shipping companies should focus on the increased time vessels spend in the system. The trade-off between extra time for voyages in comparison to reduced emissions is an interesting ground for research.

VII. CONCLUSION

This research set out to asses the impact of information-sharing in the port call for the reduction of emissions. Over the last few years, several concepts for information-sharing have been developed [Lind et al., 2015]. This trend originates from the fact that inefficiencies in the port call can mainly be attributed to a lack of situational awareness among port actors. Information is shared too little, too late and is thus not harnessed to take action upon [Molkenboer, 2020]. Since most ports use a first come, first serve policy and captains therefore apply a ”hurry up and wait”-strategy with regards to voyage speeds, this leads to unnecessary emissions during the port approach and port call [Broersma, 2021]. In line with the emissions reduction goals set by the IMO and the notion that port call optimization is the low-hanging fruit with regards to emissions optimization the question remains how increased information-sharing can be harnessed to improve emissions reduction during the port call.

Information-sharing systems have been devised and deemed as an integrator for coordination in the port call process [Lind et al., 2015], but it is unclear how this should be harnessed. The wanted effects are related to increased situational awareness to make better decisions on real-time information, reducing delays. Optimization in vessel arrival has been apparent in literature but is mainly focused on geographic constraints on fairways and creating schedules that optimize fairway use or optimal allocation of tugs and pilots. Vessel arrival scheduling based on resource availability has not been researched much in literature and the influence of real-time information updates of those scheduling solutions on vessel emissions has also not been found. The Virtual Arrival concept proposed in literature gives a way to reduce approach speeds of incoming vessels based on delay information from the port [Broersma, 2021]. In relation to the IMO goal of emissions reduction and just-in-time vessel arrival, it can be concluded that a vessel schedule that is constantly updated based on real-time information sharing could be an integrator for port call optimization by harnessing the power of information-sharing and the use of the virtual arrival concept. Literature on other infrastructure optimization shows that creating coordination through real-time control can lead to better performance of the controlled system [Negenborn and Hellendoorn, 2010], but this concept has not been applied to the arrival of vessels. It is therefore of interest to assess such an intelligent control structure together with the information-sharing and virtual arrival concepts already apparent in literature.

Vessel operations in the port call are largely controlled by the movements schedule created by the harbour masters office. All nautical services depend on this schedule for creating their own planning. The objectives for an optimized port call are distributed among actors and relate to asset use for nautical service providers, safe and timely movements for the harbour master and optimal terminal use for terminal operators. An intelligent control structure for port call optimization can be proposed based on a single-agent control structure for vessel movement scheduling and vessel inflow regulation is proposed resembling movement scheduling by the Harbour Master. Single-agent control structure is deemed feasible to handle the vessel arrival problems in reasonable time and with profitable results for delay reduction. Measurement inputs for the vessel operations scheduling comes from the proposed PortCDM concept and AIS data of approaching vessels. The system can be controlled by postponing or advancing vessel movements in time to ensure optimal resource use and turnaround times. Secondly, approaching vessels can be advised to decrease their speed as per the virtual arrival concept developed in literature. Due to vessel engine characteristics this should happen at discretized virtual way points along the approach and within certain boundaries.

The rolling horizon approach is a suitable method to create an optimized vessel arrival schedule. This approach has been used in many other areas of research, including aircraft sequencing in airport approaches and yielded better results than first come, first serve policies for arrival scheduling. This approach can be designed around a static MILP model with the objective to minimize the maximum deviation from the vessel ready times for movements in the port was described to create an optimized schedule according to resource use and the virtual arrival concept. This static model is than extended to accommodate the rolling horizon approach above, by regarding only subsets of vessels in the scheduling optimization and fixing arrival times for vessels in close proximity to the port. The suitability of the rolling horizon approach and its parameters time horizon and control period for vessel scheduling should be subject to experimentation. Although it is known that longer periods yield worse results for optimization or computing time, there is no deterministic approach to these parameters and their influence and suitability can be determined by experimentation with different values.

The impact of the scheduling optimization has been calculated by the construction of a Discrete Even Model. Such model types allow for accurate modelling of process flows and the occurrence of delayed events as well as individual process times. Since the aim is to see how information-sharing about disruptions can help to reduce vessel emissions this is an important attribute of the system modelling. Three experiments were performed to asses the impact of intelligent control of vessel movements. To calculate the impact of optimized scheduling, a base case was proposed where a standard first come, first serve policy was implemented. A second experiment assess the the scheduling model together with a small control period and outlook. A third scenario was designed to see the impact of a larger control period together with a longer horizon. It was shown that for a scheduling optimization with virtual arrival, the average emissions can be reduced by 16.5%. However, this comes at the cost of an increase of 8% for the average time for the total port call and approach. This trade-off between extra time per voyage in relation to the reduction of fuel use has not been part of this research, but remains an interesting ground for further research in port call optimization

The power of information-sharing lies in the suitable *use* of information to create coordination in the port call. This can be achieved by combining information-sharing, vessel movement scheduling optimization and virtual arrival. Through intelligent control based on rolling-horizon scheduling, this combined concept can help to reduce emissions by vessels during their port call significantly and thus supporting the goals set by the IMO.

VIII. RECOMMENDATIONS FOR FURTHER RESEARCH

A. Solution approach

The solution approach for the scheduling model chosen in this study was a Branch-and-Bound heuristic applied in GUROBI. As already concluded in other literature on vessel movement scheduling, meta-heuristics approaches perform better in terms of computation time. This could help to increase the time horizon and decrease the control period yielding even better results regarding emission reduction and reduced time in system for vessels during their port call. This in turn can validate the use of the concept in real life. It is therefore recommended to research suitable meta-heuristic solution approaches and their influence on the performance of the proposed control structure and system.

B. Control structure

As discussed in chapter 3 of this thesis, the choice of control structure is not deterministic but based on preferences. The single-agent controller is able to calculate optimal outcomes better than other suggested approaches. But since the port environment is diversified and full of actors it is worth to research the implementation of other control structures that might be better at describing the real decision-making chain surrounding movement planning and where for instance optimal tug and pilot allocation and berthing optimization problems are combined with the vessel scheduling problem to create elaborate control of the port environment.

C. Impact of environment on movement scheduling

Vessels travel through water and therefore inherently have to deal with tides and currents. On the one hand this means that ports have time restrictions for fairway entry of vessels with a certain draft. Secondly, it means that captains will try to harness favourable currents to reduce their fuel use. An interesting approach to optimized vessel scheduling would be the implementation of tidal restrictions on vessel movements as well as harnessing currents to obtain virtual arrivals.

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