Bridging the gap between strategy and operations in autonomous maritime logistics

Developing and implementing a simulation-based model

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by

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TU Delft

Abstract

The complexity of the maritime industry is evident. Ships have to adhere to various rules, regulations and guidelines—especially now in the world's race against climate change—and day-to-day operations are dependent on volatile market conditions and increasingly busy ports and waterways. And while new ships can be designed with alternative fuel types and advanced technology in mind, a significant portion of existing ships will have to rely on operational adaptation to keep up with the rapidly changing industry.

However, it is becoming increasingly difficult for ship operators to effectively assess and respond to the dynamic and complex maritime environment. To deal with complex and dynamic situational information, ship operators are already being supported by autonomous technology and the use of simulation in complex manoeuvres and when dealing with environmental conditions. However, there still is potential for autonomous technology and simulation to support ship operators in dealing with logistics information. Recent studies on autonomous shipping and intelligent vessels in inland shipping underpin the need for research on the application of computational logistics for green and energy-efficient control of ships. This need can be described as a gap between strategic planning and operational decision-making in (autonomous) maritime logistics. Consequences of this misalignment include the increasing number of ships at anchor in ports and emissions through unnecessary speeding. The described problem is formulated into the main research question as such: 'How can simulation be used to bridge the gap between strategic planning and operational decision-making in autonomous maritime logistics?'.

This study aims to support ship operators in processing and evaluating situational awareness information to improve the alignment of operational decision-making and strategic objectives. To achieve this, a practical method was developed that integrates autonomous technology and a simulation-based model and its ability to assess and respond to logistics information was tested. The first challenge was to integrate the simulation software OpenTNSim and an autonomous control system operated via Robotic Operating Service (ROS). To realize this integration, a real-time variant of OpenTNSim and a communication component that could link the OpenTNSim simulation and the ROS system were developed. To demonstrate the integration, three experiments were conducted that tested the operational capabilities of the newly developed components. Given the scope and available resources, the experiments were conducted at a lab scale. This was done to emphasize the practical potential without requiring full-scale ships.

Experiment Green Routing was designed to test the ability of the autonomous vessel to follow a path provided by the simulation. This experiment showed that the integration functioned correctly and the provided path was followed.

Experiment Green Steaming was designed to test the vessel's ability to adapt its speed according to information generated by the simulation. The experiment showed that the vessel was successful in registering and maintaining the imposed reference velocity.

Experiment Port Call was designed to show a potential use case of the integrated system. A logistic scenario was scaled down to fit the lab-scale environment, and a component was created that uses simulation to evaluate and implement different response options—or tactics— based on a predetermined strategy and available logistic information. Logistic information was added in the form of berth availability and three different strategies—reduce emissions, reduce time and reduce costs—were determined. The berth availability was varied and the automated response of the vessel, generated by the simulation software, was observed. The experiment showed that the vessel was able to adapt its sailing speed and route choice according to the logistic information and chosen strategy.

The conducted experiments were done on a lab scale and considered simplified and disproportionally scaled logistic scenarios. This limits the use of quantitative data and conclusions. However, this study shows that the gap between strategic planning and operational decision-making in (autonomous) maritime logistics can be bridged partly by creating a simulation environment in which strategies and tactics form a quantitative framework. And partly, by creating a system that improves the information flow and integration of systems. Furthermore, it can be concluded that this study shows that autonomous technology and simulation can be used to process, evaluate and respond to logistics information. This means that the developed method is suited to support ship operators in the complexity of current maritime logistics by providing the computational capabilities for green and energy-efficient control of ships, that the human mind lacks. Further development and testing of the simulation-based model are required and recommended to quantify the practical implications and potential of improving maritime operations. It should be investigated how more advanced software like Artificial Intelligence can improve the simulation-based model. Furthermore, more advanced and properly scaled experiments or simulations should be conducted to validate the practical value of the developed method.

Preface

Before you lies the thesis "Bridging the gap between strategy and operations in autonomous maritime logistics: Developing and implementing a simulation-based model". It has been written to fulfil the graduation requirements of the Master's program in Hydraulic Engineering at the Delft University of Technology. This work was performed at Deltares, an independent knowledge institute for water and the subsurface, over 9 months from September 2022 to June 2023.

I would like to thank my thesis committee for helping me realize this thesis. Thank you, Fedor Baart—my daily supervisor at Deltares—for guiding me along the way. Your ever-critical mind and willingness to help were really appreciated. Furthermore, with your combination of compassion and expertise, you overshadowed all the hype around AI models overtaking the world. Secondly, I would like to thank the chair of my committee, Mark van Koningsveld. As mentioned in almost all of the theses you guide, your enthusiasm really made a difference for me too. Additionally, I enjoyed the discussions we had on the position of this thesis in the research field of Ports and Waterways. Thirdly, I would like to thank José Álvarez Antolínez for providing crucial feedback and advice on this thesis. José's ability to look at the research from a different perspective and ensure the academic standard was met, was very valuable. Furthermore, I would like to thank Bart Boogmans from the Researchlab Autonomous Shipping. Without you, the research could not have succeeded and I look back at our collaboration with joy, regardless of the struggles we encountered.

Finally, I would like to thank the members of the DigiPACT project for providing advice and support where possible. I enjoyed being a part of this team and felt supported at all times.

M.W. van Gijn
Delft, June 2023

Contents

Acronyms

AI Artificial Intelligence. viii, 2, 3, 66, 72

AIS Automatic Identification System. viii, 17, 21, 22

CEMT Conférence Européene Ministres de Transport. viii, 37, 81

DES Discrete Event Simulation. viii, 13, 61

FoR Frame of Reference. viii, 10, 77

HIL Hardware-in-the-Loop. viii, 47, 68

IMO International Maritime Organization. viii, 10, 11, 17, 81

MASS Maritime Autonomous Surface Ship. viii, 3, 10, 11, 64, 65

MCDM Multi-Criteria Decision-Making. viii, 41

PID Proportional-Integral-Derivative. viii, 12, 18, 30, 50, 51, 77

RAS Researchlab Autonomous Shipping. viii, 12, 21, 22, 61

RBA Rule-Based Algorithm. viii, 41

ROS Robotic Operating System. viii, 25, 46, 61, 62, 68

SA Situation Awareness. viii, 14, 16

SOT Strategy-Operations-Tactics. viii, 18

1
Introduction

1.1. Complexity of the maritime industry

With ships carrying 90% of world trade, maritime transport is a crucial industry for the global economy (International Chamber of Shipping, 2020). Besides influencing the global economy, maritime transport also affects the global environment and climate, as it produces about 2-3% of global anthropogenic CO_2 emissions (International Maritime Organization, 2020). In the Netherlands, maritime transport has an even greater impact. For the last decade, inland shipping was responsible for at least 40% of the total freight transport including road, railway and inland shipping (Kriedel et al., 2022). And whilst transporting goods over water may seem like a simple process, inland shipping is a complex industry. Ships are subject to rules, regulations, and guidelines both before sailing, during sailing and after sailing. These restrictions range from technical standards on a ship's design and build, to operational regulations involving fuel types and energy efficiency. Furthermore, day-to-day operations of ships depend on market conditions, such as freight rates, oil prices and canal fees (Poulsen et al., 2022), and resource and service availability in ports and on waterways. For example, if fuel costs are low, voyage planners will prefer routes with higher fuel consumption to avoid routes with higher canal fees. And in the current market, with highly volatile oil prices (Nagle & Temaj, 2022), these conditions could change significantly during a voyage, creating the need to change operations. And even though ship operators have access to an abundance of situational awareness information, managing and evaluating all relevant information is complex and a root cause for maritime accidents (van der Weide & Schreibers, 2020). Taking then also into account the frequent delays in shipping (Martin Placek, 2022), it is becoming increasingly difficult for ship operators to assess and respond to the dynamic and complex maritime environment. In other words, it is becoming increasingly difficult for ship operators to dynamically change operations, while also taking into account complex limitations and goals, such as regulations, restrictions and strategic objectives of companies. This discrepancy between high-level goals and low-level operations can be described as a gap between strategic objectives and operational decisions.

1.2. Strategic objectives and operational decisions

In the global shipping industry, strategic objectives are the long-term goals and plans that shipping companies set to achieve their desired outcome. The strategic objectives are generally focused on improving the overall efficiency, safety, and profitability of the shipping operations while considering current and future regulations imposed by regulatory bodies (Brooks, 2000) (L, 2022). To achieve these objectives, shipping companies must effectively and accurately translate these strategies into operational decisions. Operational decisions are day-to-day choices and actions that are made to manage daily operations. For example, optimizing vessel routing and speed is an operational decision that can be made if the ambition, or strategic objective, of the company, is to be an efficient and sustainable company. Two examples of this are 'Green Steaming' and 'Green

Routing'. Green Steaming and Green Routing are methods used by the shipping industry to sail more efficiently, reduce fuel consumption and lower greenhouse gas emissions (Andersson & Ivehammar, 2017; van Nieuwenhuizen-Wijbenga et al., 2019). Green Steaming is a technique in which a ship's speed is adjusted to match the optimal speed for the given weather, sea conditions and traffic while taking into account fuel consumption and emissions. Green Routing, on the other hand, involves selecting the most optimal route for a vessel based on factors such as ocean currents, wind, waves and other weather patterns, as well as water depth and other geographic features, to minimise fuel consumption and emissions. Green Routing and Green Steaming are tactics that can be used to achieve strategic objectives by translating them into operational objectives. Reducing emissions as a company (strategy) is translated into the optimization of vessel speed or route (operations). Decisions on speed and routing are made by humans, autopilots and in the near future possibly also by autonomous ship systems (van Dijk et al., 2018). For this research, regarding decisions on Green Steaming and Green Routing, the focus will be on autonomous ship systems. It was chosen to focus on autonomous technology because of its potential to support ship operators with operational decision-making. All across the world, examples can be found where decision-making is taken over by autonomous systems to improve accuracy, reproducibility, efficiency, reliability, and safety. And considering the fact that human errors are the dominant cause of failures in inland shipping (van der Weide & Schreibers, 2020), applying autonomous technology can replace human decision-making where necessary and possible. Furthermore, it becoming more difficult for ship operators to optimize ship operations because 'optimal' operations do not only depend on fuel consumption anymore. Currently, data on vessel performance, environmental conditions, waterway traffic and port availability are all available to ship operators. However, optimizing operations while considering all these changing factors is a process that exceeds human computational capabilities. Therefore, it is also assumed one can improve reliability, safety and efficiency in inland shipping by supporting operations through autonomous technology.

1.3. Autonomous shipping

Autonomous shipping is an emerging technology that has the potential to transform the maritime industry. It involves the use of advanced sensors, communication technologies, and Artificial Intelligence (AI) to enable ships to operate without human intervention. The expected benefits of autonomous shipping include increased safety, reduced operating costs, and improved efficiency. However, there are also significant challenges to be overcome to realize the full potential of this technology. Currently, extensive research is being done on increasing the safety and efficiency of autonomous ships through high-level control (Haseltalab et al., 2020; Huang et al., 2020; van Dijk et al., 2018). High-level control of autonomous ships involves making decisions about the overall operation of the vessel, including route planning, collision avoidance, and other strategic decisions. This type of control is typically managed by a shore-based control centre that communicates with the ship over a wireless network. The development of high-level control systems for autonomous ships is a complex and challenging task. One of the key challenges is developing algorithms that can effectively and efficiently process large amounts of data and make informed decisions in real-time. Several companies are actively working on the development of high-level control systems for autonomous ships. For example, Rolls-Royce has developed an intelligent awareness system that uses sensors and machine learning algorithms to help ships detect and avoid obstacles, even in challenging weather conditions. Wärtsilä has developed a voyage optimization system that uses data analytics to help ships navigate more efficiently, reducing fuel consumption and emissions (Rolls Royce, 2016; "Wärtsilä Advanced Assistance Systems", 2023). Despite this progress, there are still many challenges to be overcome. This becomes even more clear when addressing the research gap of this study.

1.4. Research gap

The previous sections provide context for the problem that will be addressed in this research. Before the problem is addressed, the existing research gap has to be determined. Multiple existing commercial products already show that autonomous technology and computers are being used in complex situations to support decision-making in the maritime environment. For example, Wärtsilä, a world-leading maritime technology company is working on "Advanced Assistance Systems" that use improved situational awareness and real-time simulation to provide support or take over control during complex manoeuvres such as docking or harbour entry ("Wärtsilä Advanced Assistance Systems", 2023). Secondly, Sofar Ocean is a technology company that has created the 'WayFinder' system. This system can dynamically optimize a ship's route and speed according to real-time vessel performance and environmental conditions (Emily Heaslip, 2023). Finally, 'Awake.ai' is a platform that aims to optimize port operations using AI. It aims to maximize port capacity, enable just-in-time arrival and improve turnaround times.

The first two examples show that real-time situational awareness information can be used effectively to support ship operators in operational decision-making. However, these systems focus mainly on improving the safety and efficiency of a ship by adapting to its immediate surroundings. These two systems do not consider efficiency in the context of logistics processes. Awake.ai does consider logistic processes and optimizes these using advanced computer models. However, this system lacks the integrated decision support that is provided by the two other systems. Awake.ai can be used by port operators but not by ship operators. This means that there is a potential for the use of autonomous technology and computers to support ship operators in operational decision-making while considering logistics processes. The existence of this gap is supported by recent studies in this research field.

A study on the application of Maritime Autonomous Surface Ship (MASS) in ports done by Devaraju et al. (2018) explains that for the future of MASS in ports, many challenges have to be overcome. This was done by identifying technologies and port infrastructure for autonomous surface vessels and determining their technological readiness. This analysis shows that for autonomous technologies, computational logistic technologies and control strategies are the most important challenges that need to be addressed. It is described that current situation awareness methods should be combined with optimization models and algorithms for global planning and efficient scheduling. The technological readiness of these technologies is classified as 2, on a scale of 1-9. This means that there is a need for research that addresses computational logistics technologies and control strategies.

Liu et al. (2023) conducted a study on green and intelligent inland vessels and they summarize the development status of five key technologies. Intelligent navigation is one of the considered technologies and a common architecture of autonomous control is proposed in this study to address this. Furthermore, regarding energy efficiency, this study considers intelligent decision-making based on energy efficiency optimization. These optimization models can provide crew members with better suggestions on operations to achieve emissions reduction. And while this study provides several examples of the application of autonomous technologies to real vessels in experimental form, it recommends future work in the application of autonomous navigation of green and intelligent ships and green energy-efficient control of intelligent ship equipment.

Finally, Gu et al. (2021) describe the research of autonomous shipping to be at a transition between fundamental and application. This is shown by the difference in the amount of research in the transport and logistics field when comparing autonomous shipping and autonomous vehicles. The development of autonomous vehicles is ahead of autonomous shipping and this is shown by the lack of application research for autonomous shipping. This study shows the need for research that applies autonomous technology in real-world scenarios.

The studies and existing products show that there is a need for research on the application of computational logistics combined with green energy-efficient control of autonomous ships to provide decision support to ship operators. This has led to the following problem statement.

1.5. Problem statement

The maritime industry is a significant contributor to global anthropogenic greenhouse gas emissions. Rules, guidelines, regulations, and technological advancements are being made to reduce the impact that the industry has on climate change. Adhering to all existing and future rules and regulations and keeping up with technology is a complex and strategic process. Translating this into day-to-day operations that already depend on volatile market conditions (Poulsen et al., 2022) and congested logistic systems (Martin Placek, 2022) is a complex process.

Therefore, it is becoming increasingly difficult for ship operators to effectively assess and respond to the dynamic and complex maritime environment while also considering strategic processes. I.e., it is becoming increasingly difficult for ship operators to process and evaluate all available information and make the correct operational decisions. Autonomous technology and simulation are already being used to support ship operators in decision-making in complex manoeuvres and dealing with environmental conditions. However, there still is potential for autonomous technology and simulation to support ship operators in dealing with logistics information. This potential can be described as a gap between strategic planning and operational decision-making in maritime logistics. A consequence of this misalignment is the increasing number of ships at anchor in ports that arrive too early without considering the availability of the logistic resources and cause unnecessary emissions (Heaver, 2021; van den Elshout et al., 2022).

A method to support ship operators in processing and evaluating logistics information could be by using real-time maritime logistics simulation software and integrating this into the control system of a ship. Such a system would have the computational capabilities to determine optimal operational responses while also considering a number of strategic processes related to emissions reduction and energy efficiency. This is translated into the following main research objective.

1.6. Research objective and questions

The main objective of the research is to support ship operators in processing and evaluating situational awareness information and improve the alignment of operational decision-making and strategic objectives. To achieve and test this, a practical method will be developed that integrates autonomous technology and logistics simulation software to respond to situational awareness information. This method will consist of the development of different software modules and the integration of these into existing hard- and software used for lab-scale autonomous shipping experiments. By conducting a series of experiments and simulations, this study aims to assess the performance of a lab-scale autonomous vessel and the developed method in a logistics scenario. The findings of this research will contribute to the application of simulation and autonomous technology in transport and logistics research. This objective is translated into the main research question as follows:

How can simulation be used to bridge the gap between strategic planning and operational decision-making in autonomous maritime logistics?

1. What is the gap between strategic planning and operational decision-making in (autonomous) maritime logistics?
2. What are the challenges for integrating autonomous technology into maritime logistics simulation?
3. How can the integration of autonomous technology and maritime logistics simulation be tested and validated in a lab-scale environment, to reach the research objective?
4. How can the integration of autonomous technology and maritime logistics simulation improve the efficiency and sustainability of maritime operations?

1.7. Research outline

The following figure shows the outline of the research and can be used to find the answers to the different research questions.

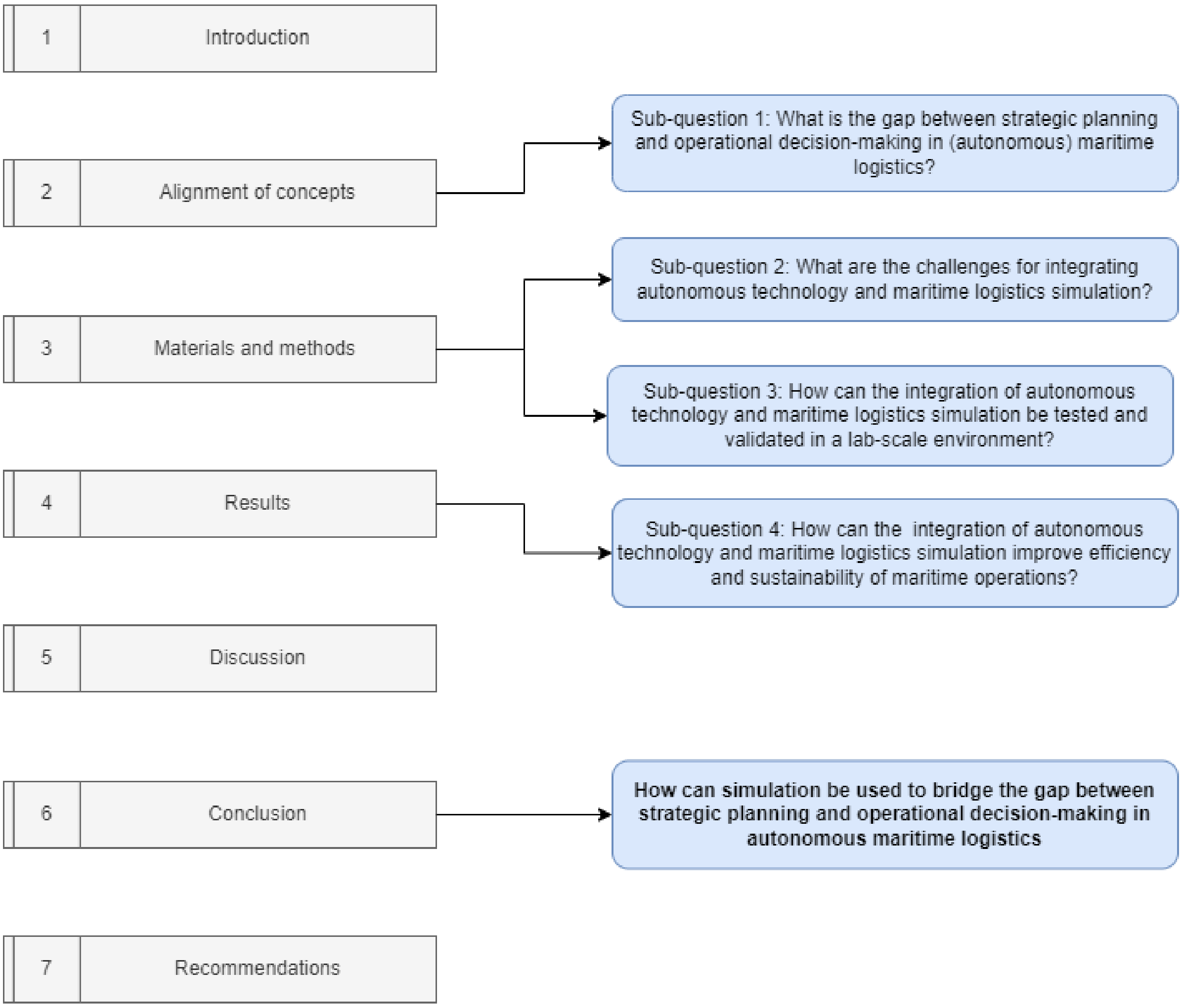


Figure 1.1: Schematic of report structure and chapters in this report. In the blue, the research questions are shown, and it is indicated in which chapter they are answered.

2
Alignment of concepts

In the domain of maritime logistics, autonomous shipping and strategy, it is crucial to establish a shared understanding of the terminologies and principles that underpin our study. By clarifying the concepts of strategy, tactics, and operations, as well as exploring the domains of autonomous shipping, maritime logistics, and situational awareness, a framework is created for our subsequent analyses and discussions. Additionally, the alignment of concepts in this chapter will be used to answer the first research sub-question.

2.1. Strategy, tactics, and operation in the maritime industry

To bridge the gap between strategy, tactics and operation, a comprehensive understanding of these concepts is required. In this section, these concepts will be defined and explained within the context of the maritime industry, providing some real examples to help illustrate their practical application and determine which will be relevant for this research. Furthermore, a framework, based on the FoR approach, will be presented which will form the rationale for the remainder of the report.

2.1.1. Defining the concepts

Strategy, tactics, and operations are terms originating from the military industry but are frequently used in business nowadays. In general, strategy, tactics, and operation are interrelated concepts that are used to guide decision-making and achieve organizational goals.

Strategy can generally be defined by an underlying reason that something is done. This is represented by asking: Why? When applied to the maritime industry, strategy can refer to the overarching plan or approach that a shipping company takes to achieve its long-term goals and objectives. This might include decisions about the types of vessels to invest in, the routes to operate on, and the target markets to serve (Fagerholt & Lindstad, 2007). Furthermore, strategy is also applicable in port or waterway development, which could include decisions about the types of equipment and services to invest in (van Koningsveld et al., 2021). And lastly, in the current energy transition, strategic maritime planning is also greatly influenced by emission regulations (Balland et al., 2013).

Tactics can generally be defined by the actions or methods used to implement a strategy. This is represented by asking: How? Tactics are often focused on the short-to-medium term and are designed to achieve specific objectives within the context of the overall strategy. For example, a shipping company might adjust its sailing routes and speeds to respond to changes in market conditions or to compete with rival companies (Fagerholt & Lindstad, 2007).

Operations refer to day-to-day activities and can generally be defined by asking: What? In the maritime industry, this might include tasks such as loading and unloading cargo, maintaining vessels, managing crews, and navigating ships on their intended routes depending on weather and hydrodynamic conditions. In short, strategy, tactics, and operation are interconnected and used to achieve goals. Important distinctions between the concepts are the questions by which they are defined: 'Why', 'How', and 'What', as well as the temporal scales to which they apply, ranging from long-term to short-term.

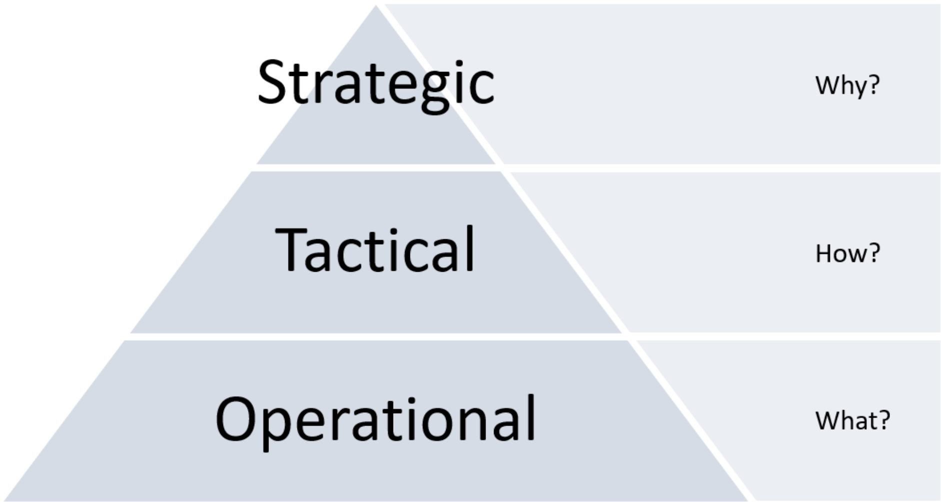


Figure 2.1: Schematic of the relation between the defined concepts. Each layer of the pyramid represents a different level of planning, temporal scale and underlying question. The width of each layer represents relative quantity.

2.1.2. Real world application of the concepts

In describing general definitions related to maritime transport networks and supply chains, (van Koningsveld et al., 2021) divide maritime logistics into three general components:

- the transport network;
- infrastructure;
- operations.

The transport network is described as a network consisting of nodes and edges, represented by ports and shipping routes, with the main purpose of enabling waterborne transportation. When looking at transport networks strategically, it is important to understand their role in the existing supply chains and economy. And while most transport networks can be improved, optimized and adapted to increase their economic value, a waterborne transport network is mainly dependent on its geographical location (Button & Hensher, 2005). And while there are different types of networks (Christiansen et al., 2007), considering the great effort it would take to relocate entire waterway systems, waterborne transport networks are strategically, relatively limited and are thus not considered in this research.

Infrastructure in maritime logistics mainly consists of ports, waterways, bridges, and locks. The biggest component, port infrastructure, is an essential element of the maritime transport network, and its development is crucial for the growth and competitiveness of ports. Strategic planning of port infrastructure involves identifying the needs and priorities of the port, developing a master plan, and coordinating with stakeholders to secure funding and resources. Effective port infrastructure strategies also take into account environmental and social impacts and aim to ensure the sustainability and resilience of the port and its operations (Mezak & Jugovi, 2006; van Koningsveld et al., 2021). While strategic, tactical and operational planning is commonplace in maritime infrastructure, and more specifically ports, this will not be considered in this research.

Operations, the component of maritime logistics that will be considered in this research, can be seen as the activities performed on the transport network, making use of the infrastructure. To avoid confusion, we will call these 'maritime activities' in the remainder of the report. Specifying these activities, this research will focus on the transportation of goods of a ship or shipping fleet, over inland waterways, making use of port facilities. Section subsection 2.1.2 will provide examples of strategic, tactical and operational planning for these activities and introduce topics that will be used in the research.

Strategic, tactical and operational planning in maritime activities

Strategic planning in the maritime industry entails substantial investments over a long period, particularly in fleet acquisition, composition, and renewal (Christiansen et al., 2007). Fleet size and composition significantly affect the fixed and variable costs of a shipping company (Ksciuk et al., 2022) and depend on the required activities. With the emergence of new ship and fuel types, as well as digitization (van Dijk et al., 2018), determining the optimal fleet size and composition has become increasingly complex and critical. In addition, the control of air emissions has become a crucial component of strategic planning due to regulatory restrictions aimed at reducing global GHG emissions (International Maritime Organization, 2020). As the implementation of these measures occurs over a considerable timescale, it is considered strategic planning. While fleet size and composition will not be addressed in this research, strategic decisions regarding air emission control will be studied.

At the tactical, medium-term level, decisions involve fleet deployment, (multi-)ship routing and scheduling, bunker management and speed management (Balland et al., 2013; Christiansen et al., 2007). In this research, only ship routing and speed management are considered. More specifically, two types are defined: Green Steaming and Green Routing. Green steaming is an approach to speed management, where ships lower their speed according to resource and service availability to arrive just in time, with the potential to reduce emissions (Andersson & Ivehammar, 2017; Watson et al., 2015). Green Routing is an adaptation of Green Steaming and is defined as an approach to adapt one's route according to resource and service availability to increase systems efficiency while minimizing the increase of emissions. These tactics will be explained in more detail in chapter 3.

In maritime transportation, executing the plans developed at the strategic and tactical level is achieved through operational planning. This level of planning involves day-to-day decision-making, with important aspects including environmental routing, speed selection, and single voyage routing and scheduling (Christiansen et al., 2007; Ksciuk et al., 2022). Environmental routing involves navigating ships under varying environmental conditions such as winds, waves, tides, currents, and weather. Short-term decisions must be made within the proposed plan to ensure the safety and efficiency of the ship in the present conditions. Speed selection is another important operational component, and, similar to adaptive environmental routing, speed must be selected appropriately based on the given circumstances. While these concepts seem similar to those described in tactical planning, the temporal scale differs. Operational planning can be described as the concrete steps necessary to achieve strategic and tactical objectives while adapting to situational changes in the environment.

2.1.3. The Framework

A systematic way to describe and approach the process of achieving certain objectives is the Frame of Reference (FoR) approach, developed by van Koningsveld (Van Koningsveld, 2003). It describes a rational approach that matches specialist knowledge with the needs of decision-makers. In this study, specialist knowledge in the form of ship controllers should be matched with decision-makers such as policymakers or company executives. In shipping, strategies determined by decision-makers often take the form of rules, regulations, guidelines, restrictions, or performance indicators. The quantitative nature of these forms of strategy in shipping makes it a good match with the rational FoR approach. Figure 2.2 shows the FoR framework within the dotted lines. For this research, the concepts 'strategy', 'tactics' and 'operations' were added. Unlike the conventional framework, it shows that strategic objectives consist of multiple operational objectives, which are reached by applying different tactics. Furthermore, a single strategy can then also consist of multiple strategic objectives. This 'extended' framework will be implicitly used throughout this study in the context of strategy, tactics and operations.

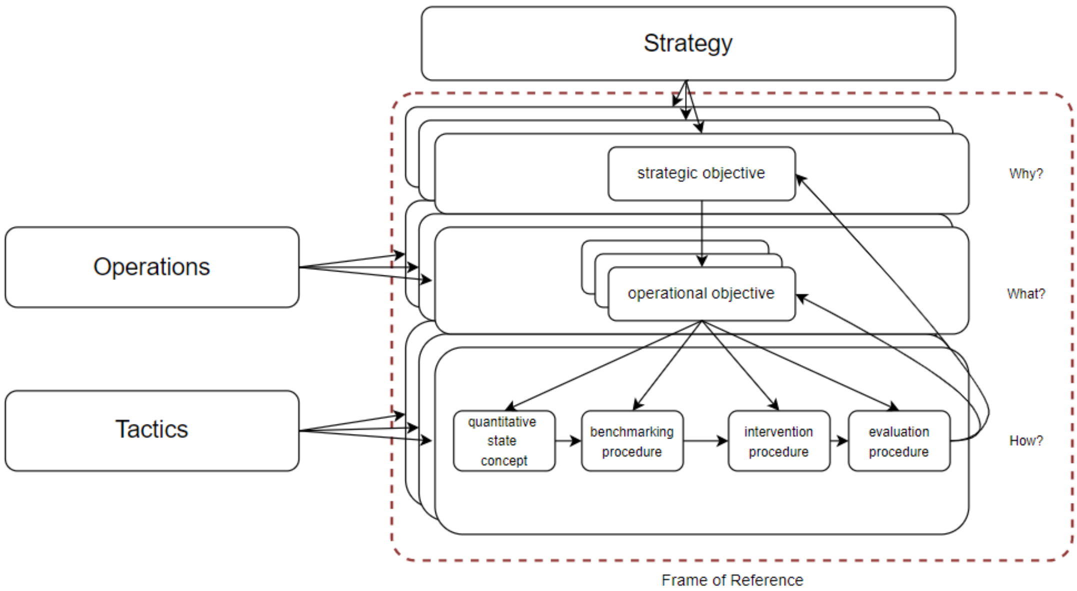


Figure 2.2: Extended FoR-framework. The existing framework was altered by adding quantities and overarching concepts to put the framework in the context of this research.

2.2. Autonomous maritime logistics

In this section, the basic concepts of autonomous maritime logistics will be defined and explained. Furthermore, the elements from this field that are relevant to this research will be introduced and described.

2.2.1. Defining and explaining the concepts

Autonomous maritime logistics refers to the use of autonomous technologies, such as unmanned vessels and drones, to carry out logistics operations at sea. These technologies are increasingly being developed and implemented in the maritime industry to improve the efficiency, safety and sustainability of maritime logistics operations. The International Maritime Organization (IMO) describes ships that can operate independently of human interaction as MASS. The IMO describes 4 degrees of autonomy used to classify MASS (International Maritime Organization, 2021):

Degree	Description
Degree One	Ship with automated processes and decision support
Degree Two	Remotely controlled ship with seafarers on board
Degree Three	Remotely controlled ship without seafarers on board
Degree Four	Fully autonomous ship

Table 2.1: Degrees of autonomy as organized by the IMO (International Maritime Organization, 2021)

However, the levels of autonomy described by the IMO are limited and do not cover the required nuances in current autonomous technology. For this research, we make use of Lloyd's Register (Sivori & Brunton, 2023) that defines seven levels of autonomy:

Level	Description
AL0	Manual
AL1	On-ship decision support
AL2	On and off-ship decision support
AL3	Active human in the loop
AL4	Human in the loop - operator/supervisory
AL5	Autonomous - rarely supervised
AL6	Full autonomous - unsupervised

Table 2.2: Levels of autonomy as organized by Lloyd's Register. This comprehensive description of different levels of autonomy in autonomous shipping serves as a guideline for this study. In this research, testing will be done at levels AL5, as the vessel is given a task which it performs without intervention. The vessel is only supervised to avoid situations that are dangerous to the surroundings or itself. For the application of this study, the focus will be on the AL4 and AL5 levels as autonomous technology is still in development and full-scale fully autonomous ships are still rare.

In this research, testing will be done at level AL4, as the vessel is given a task which it performs without intervention. The vessel is however supervised to avoid situations that are dangerous to the surroundings or itself because of the experimental environment. The objective of this study focuses on support for ship operators which technically is level AL1. However, combined with more advanced autonomous technology, the outcome of this study could be relevant for levels AL3, AL4 and possibly higher. This is further discussed in chapter 5 and the following sections further elaborate on the basic concepts of MASS.

Compared to a conventional ship, a MASS has to solve problems without human interference. In the following paragraphs, it is explained how this is solved for motion control and awareness, as these are aspects where humans normally play a big role. Additionally, specific autonomous capabilities used for this research are introduced: 'path following' and 'velocity control'.

Awareness

In autonomous ships, awareness refers to the ability of the ship to sense and perceive its environment, including the surrounding vessels, obstacles, weather conditions, and any other relevant information. This involves the use of various sensors such as cameras, radars, LIDARs, and other technologies to gather information about the ship's surroundings. The information gathered is then processed and analysed by the ship's onboard computer systems, which can make decisions based on this data. Awareness is a critical component of autonomous ships, as it allows them to safely navigate through the water and avoid collisions with other vessels or obstacles. section 2.4 further explains the concept of awareness.

Motion control

In conventional ships, motion control is the responsibility of a ship's captain. Decisions are made regarding a ship's course and speed, depending on higher-level goals, and this is translated into control operations by the captain. And while autonomous shipping is an emerging technology, autonomous motion control in ships is not. Currently, so-called autopilots are capable of basic course-keeping to more complex manoeuvres such as turning and docking (Fossen, 2011). The main functioning of an autopilot is based on the calculation of desired states of a ship, such as speed and heading, and the process of reaching those desired states. A basic example is a course-keeping autopilot that continuously calculates the desired heading, compares it with the actual heading and determines the required output of the rudders and engines to reach the desired heading. For this research, path following and velocity control will be required. These are two control systems that autonomously control the path and speed to be sailed.

Path following (heading control) and velocity control

Autonomous control capabilities that will be used in this research are path following and velocity control. In this research, path-following capabilities by means of heading control will be used. And while numerous complex path following methods exist (Haseltalab et al., 2020; Wang et al., 2022; Zaccone, 2021; Zhao et al., 2019), the heading control method is relatively simple. This is also how current autopilots operate. In this research specifically, the heading is controlled by using a Proportional-Integral-Derivative (PID) controller. A PID controller is a feedback control mechanism that uses a feedback loop to adjust the process input based on the difference between a desired value and an actual value. The three terms represent three different methods of determining the control output. In this research, only the proportional term is considered, and this term provides a control output proportional to the error between the desired and actual value. In the case of the heading controller, this means that at certain frequencies, the heading of the vessel is measured and compared to the desired heading. Proportional to the error, an output value of the rudders is determined. Figure 2.3 shows a schematic visualizing the control loop system.

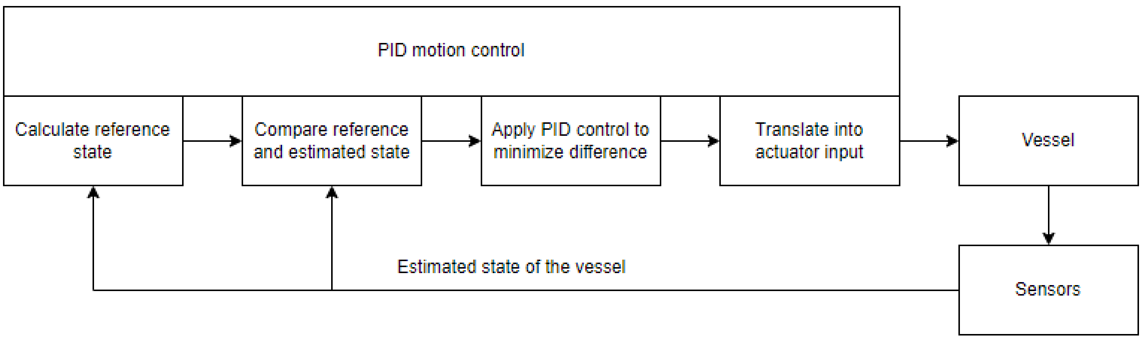


Figure 2.3: Simplified and research specific schematic of the PID control loop responsible for the heading control. This schematic is roughly based on schematics of the RAS.

Regarding the velocity control, a controller developed at the Researchlab Autonomous Shipping (RAS) was used (Boogmans, 2023c). This controller estimates the velocity of the vessel by measuring the location, compares it to a desired velocity and used a PID controller to determine an output for the vessel's thrusters. The specifics of this system are not relevant for this research and more details can be found through the provided reference.

2.3. Maritime logistics simulation (OpenTNSim)

For the simulation of maritime processes, an abundance of software is available. There is software that focuses on ship design and the simulation of a ship's response to environmental conditions. Companies like MARIN and NAPA are specialized in this area. Furthermore, a number of commercial tools exist that can simulate port traffic, optimize port processes and simulate vessel control. Wärtsilä is a leading company that focuses on this in-house software. However, for the simulation of logistic processes, Discrete Event Simulation (DES) is widely used and lends itself well to problems on both strategic, tactical and operational levels (Tako & Robinson, 2012). There are numerous, well-known commercial DES software products, including AnyLogic and FlexSim (Attajer et al., 2021). While these products would probably be suited for this research, it was chosen to focus on open-source software considering the scope and resource availability of this research. From the list of open-source DES software, it was chosen to use OpenTNSim, a software focused on the simulation of transport systems. An underlying reason to make this choice was the available expertise on the software as this research was done under the supervision of the developers of OpenTNSim.

OpenTNSim is an open-source Python package that was developed as an adaptation of the OpenCLSim package which was developed by the Ports and Waterways department of TU Delft, Van Oord, and Deltares. OpenTNSim provides a framework for modelling and analysing various types of transportation systems, such as maritime, inland shipping, and intermodal transportation. OpenCLSim and OpenTNSim utilize the SimPy package to enable event simulation. This allows for the incorporation of real-world events such as congestion and delay, as well as creates interdependencies between different processes to create a schematization of a chain of events. OpenCLSim also adds maritime-specific activities and components such as ports, terminals, storage, quays, cranes, and vessels, and uses mixin classes to represent a set of parameters that apply to a type of activity or component, making it easier to configure complex supply chains (van Koningsveld et al., 2022; van Koningsveld et al., 2021). More specifically, OpenTNSim is a simulation tool that models vessels navigating waterway networks, providing useful features such as visualizations of route selection, traffic intensities, and transport capacity. It also enables the analysis of vessel behaviour and interaction, integration of real-world data such as water levels and currents, and estimation of energy consumption, fuel use, and emissions. OpenTNSim is particularly valuable given the growing demand for sea-going and inland shipping, along with societal changes related to digitalization, sustainability, and climate change. As such, it can aid researchers and practitioners in investigating the complexity of water transport networks and support decision-making in uncertain conditions.

2.3.1. Capabilities of OpenTNSim

To give the reader an idea of the capabilities of OpenTNSim, this section describes how a basic simulation of OpenTNSim is created and executed and shows a more complex practical use case where OpenTNSim was utilized. In a basic simulation of OpenTNSim, there are three general steps:

1. Create a vessel
2. Create a graph
3. Run a simulation

To create a vessel, you have to create an instance of the vessel and give it properties. Properties can be limited to the basics, such as speed and name, or be as detailed as the type of ship, width, length, installed power, and engine age.

The second step is to create a graph. This is done using the 'networkx' Python package. A basic graph could look like Figure 2.4. It is also possible to add hydrodynamic data to the network, to recreate existing, real-world networks.

Figure 2.4: A basic graph created in networkx. The blue dots represent nodes and the red lines represent edges.

It is then possible to simulate the vessel moving over the network. Running this simulation can provide the data shown in Figure 2.5. It is also possible to use certain plugins to generate more insightful data, such as emissions data.

	Message	Timestamp	Value	Geometry
0	Sailing from node 0 to node 1 start	2022-09-21 07:17:51.000000	0	POINT (0 0)
1	Sailing from node 0 to node 1 stop	2022-09-21 10:23:22.949079	0	POINT (0.1 0)
2	Sailing from node 1 to node 2 start	2022-09-21 10:23:22.949079	0	POINT (0.1 0)
3	Sailing from node 1 to node 2 stop	2022-09-21 13:28:54.898159	0	POINT (0.2 0)
4	Sailing from node 2 to node 3 start	2022-09-21 13:28:54.898159	0	POINT (0.2 0)
5	Sailing from node 2 to node 3 stop	2022-09-21 16:34:26.847238	0	POINT (0.3 0)

Figure 2.5: Data output of a basic OpenTNSim simulation. The message states what happens in the corresponding step and data on the time and location is given in the following columns.

While the previous examples are basic, the use of OpenTNSim can be significantly more complex and practical. An example of this is the 'Digital Twin waterways' (SmartPort, 2021). This is a web-based app that uses OpenTNSim to simulate real vessels that move over the Dutch, and partly European, waterway network. Different scenarios can be created by changing cargo types, fleet compositions and climate conditions. The results include trip duration, number of trips, energy consumption and other operational parameters that can be used to optimize strategies and tactics.

2.4. Situational Awareness

Situational or Situation Awareness (SA) refers to a person's perception of the environment around them and their understanding of the situation they are in. It involves being aware of what is happening in your surroundings, and understanding how this information is relevant to your goals and objectives. Situational awareness is important because it allows a person to anticipate and respond to changes in the environment, and to make informed decisions in real-time. Several key cognitive skills make up situational awareness, with the first one being the ability to perceive and interpret the environment and the events occurring in it. Secondly, situational awareness involves making the distinction between relevant information and distractions. Thirdly, this relevant information should be saved and can be recalled when necessary. Finally, the information perceived and gathered should be understood. This involves the ability to interpret and make sense of the information gathered. Situational awareness is a continuous process. Information about the environment should be gathered and processed frequently to update your understanding of the environment and the evolving situation (Endsley & Garland, 2000).

2.4.1. Endsley's model on situation awareness

One of the most widely cited models is the Situation Awareness Global Assessment Technique (SAGAT), which was developed by Dr Mica Endsley, a cognitive psychologist and expert on human performance in complex systems. Figure 2.6 shows his model of SA in dynamic decision-making. According to SAGAT, situational awareness is composed of three levels (Endsley & Garland, 2000):

'Level 1 SA: Perception' involves the ability to accurately perceive and interpret the various elements (e.g., people, objects, events) in the environment. Perception is the basis of situational awareness and without it, it becomes really difficult to paint a correct picture of the situation. A study on the causes of SA errors in aviation (Endsley & Jones, 1996) found that about 76% of SA errors can be accounted for failures in perception. Either failures of humans or problems with the used systems are at the base of this.

'Level 2 SA: Comprehension' involves understanding the relationships between the various elements in the environment and how they are changing over time. Level 2 SA involves the ability to give meaning to Level 1 SA information. Furthermore, it entails the combination, interpretation and storing of information. The same study as above described shows that SA errors that can be accounted to Level 2 SA problems make up about 20% of the total.

'Level 3 SA: Projection', the highest level of SA, involves anticipating how the situation is likely to evolve in the future and how it may affect one's goals and objectives. Level 3 SA builds on the accurate functioning of levels 1 & 2 and adds to it by being able to make predictions of the future. Errors in Level 3 SA are significantly less common and mostly involve over-projection, the study on aviation shows.

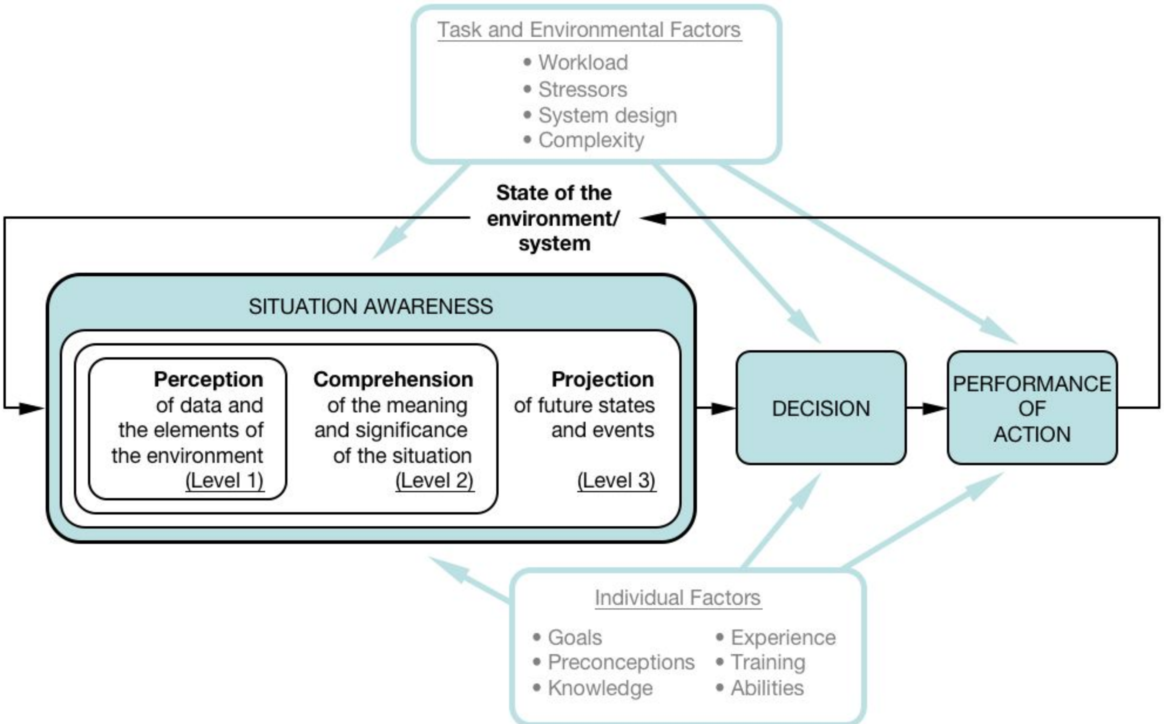


Figure 2.6: Endsley's model of SA in dynamic decision-making (Endsley & Garland, 2000). The centred section describes the decision-making process for different levels of SA. The two transparent sections each describe factors that influence the decision-making process. This research considers Level 2 SA Comprehension.

This research considers the second level, Level 2 SA Comprehension, of SA. The first level of SA is characterized by the recognition and monitoring of information (Endsley & Garland, 2000). In this research, the recognition and monitoring of operational information of ships are crucial and achieved by the sharing of data between the different lab-scale vessels and the developed systems that will be used for testing. Level 2 SA involves the integration of different information to reach an understanding of the situation (Endsley & Garland, 2000). This is achieved in this research by the integration of multiple dynamic and static forms of information that are combined in a simulation environment to create an understanding of the logistic situation. In this research, multiple different information sources are combined and acted upon. This requires Level 2 SA. However, no predictions are yet made of the future state of the situation so Level 3 SA is not reached.

2.4.2. Situational Awareness in maritime transport

Situational awareness in shipping refers to the ability of a ship's crew to understand and accurately assess the current situation they are in, including the vessel's surroundings, potential hazards and risks, and the ship's capabilities and limitations. This involves monitoring and interpreting a wide range of information, such as weather conditions, navigation information, and the actions and intentions of other vessels in the area.

Maintaining situational awareness is critical for the safe operation of a ship, as it allows the crew to anticipate and avoid potential dangers, respond effectively to emergencies, and make informed decisions about the vessel's course and speed. It is especially important in dynamic and high-risk environments, such as in crowded shipping lanes or in rough sea conditions.

Effective situational awareness requires constant vigilance and communication among the crew, as well as access to accurate and up-to-date information about the ship's surroundings. It is also essential for maintaining compliance with international maritime regulations and standards, which require ships to operate safely and avoid collisions and other accidents (International Maritime Organization (IMO), 2023; National Transportation Safety Board (NTSB), 2000).

2.4.3. Safety and accidents in maritime transport

The safety of ships is critical for the protection of human life, the environment, and property, and it is essential for the smooth and sustainable operation of the maritime industry. Ships and their cargo can be worth millions of dollars, and the loss or damage to a vessel or its cargo can have significant financial consequences. Ensuring the safety of ships helps to reduce the risk of accidents or incidents that could result in property damage. Furthermore, shipping is a major contributor to global trade and economic development, but it can also have negative impacts on the environment. Ensuring the safety of ships helps to minimize the risk of accidents or spills that could harm marine life or damage sensitive ecosystems. And most importantly, the safety of the crew and passengers on board a ship is of the utmost importance. Ships often operate in challenging and hazardous environments, and accidents or emergencies can have serious consequences.

As described by the European Maritime Safety Agency (EMSA), maritime accidents can be categorized into different a number of 'contributing factors'. Figure 2.7 is taken from the annual overview of marine casualties and incidents of 2022 (European Maritime Safety Agency (EMSA), 2022) and shows the percentage of contributing factors ordered in these different categories. It shows that human action during shipboard operations is the biggest cause of accidents for 2014-2021 by a great margin. A study from 2020 on the human factors in accidents in inland shipping in the Netherlands, even shows that for 70-80% of the incidents, human errors are the root cause (van der Weide & Schreibers, 2020).

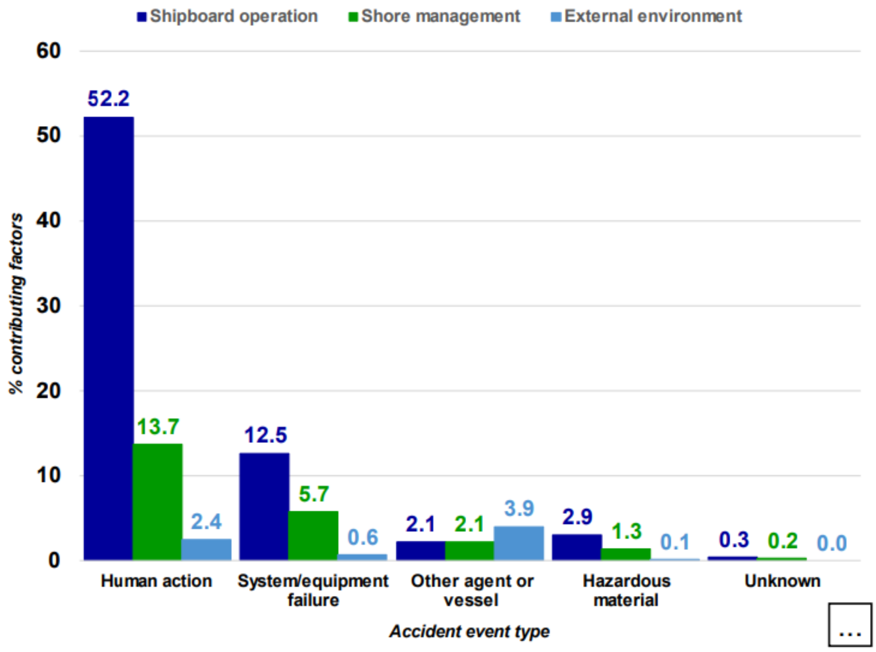


Figure 2.7: Percentage of contributing factors to maritime accidents for the period 2014-2021, organized by contributing factor types and accident event types. It can be seen that human action is the main contributing factor to maritime accidents.

The human-machine-interface

Before conclusions can be drawn, it is important to define 'the human element'. The IMO refers to the complete range of human operations carried out by ship crews when talking about the human element (International Maritime Organization (IMO), 2023). Besides defining the human part of the equation, it is also essential to find the underlying causes of human failure. Because the statistics from the previous section not only show a high human failure rate but also a high human dependency on maritime transport. This means that the cause of the error can also be at the interface of human-machine instead of just at the human.

A study done on inland shipping in the Netherlands found that the main underlying causes of human failure in maritime accidents lie with communication, time of the day, support systems (Automatic Identification System (AIS), CCTV, radar, etc.), age and fatigue (van der Weide & Schreibers, 2020). Communication failures, miscommunication, lack of communication, misuse of communication equipment and language skills are seen as the underlying causes of accidents. The time of the day is significant as this influences fatigue and distraction. Fatigue itself has been identified as one of the main contributing factors. Another important underlying cause is the interaction of a ship's crew with the available support systems. Support systems are seen to be added to the control system in a bridge without proper integration. A lack of integration of these systems makes, causes distraction and results in a lack of situational awareness. The opposite of what these systems are supposed to do.

2.5. Summary

This section provides a summary of this chapter and aims to answer the related research sub-question: 'What is the gap between strategic planning and operational decision-making in (autonomous) maritime logistics?'.

In chapter 2, the foundation was laid for this research by defining and aligning the key concepts that will be used throughout the thesis. The goal of the research is to bridge the gap between strategic planning and operational decision-making in autonomous maritime logistics. The foundation for this is to define the concepts of strategy, tactics and operations, and relate them to maritime logistics.

The Strategy-Operations-Tactics (SOT) framework is most commonly known and used in the military. Here, the strategy encompasses high-level policies and plans and overlaps with operations. At the operational level, the realization of strategies is key, which consists of campaigning and major operations. Then, the tactical level follows. This involves the plans in battle and considers small, unitized areas of the military. In this research, this framework was slightly altered. Strategy, tactics and operations in maritime logistics are considered in that order and as levels of planning that differ in temporal scale and reasoning (Figure 2.1). I.e., at the strategic level, high-level decisions are made regarding fleet size and composition, and the control of air emissions of a fleet. At the tactical level, medium-term level decisions are made regarding fleet deployment, (multi-)ship routing, and speed and bunker management. Finally, at the operational level, day-to-day decision-making involves environmental routing, speed selection, and single-voyage routing. The efficient functioning of the maritime industry requires decision-making to trickle down (and up) these different levels of planning.

At the interfaces of these levels of planning, communication is crucial. And with the upcoming developments regarding autonomous shipping, autonomous systems may also be at these interfaces. The current state of autonomous shipping is at a transitional stage between fundamental research on motion control, awareness and safety, and the application to transport logistics and economics. In this research, lab-scale autonomous vessels controlled by basic PID motion control systems will be used. This research aims to take a step in the direction of application and transport and logistics while keeping the autonomous technology as simple as possible.

An important aspect of autonomous technology, and its integration with maritime logistics, is situational awareness. Situational awareness refers to an individual's perception of their environment and their understanding of the situation they are in. In the context of maritime transport, this translates to the ship's crew's ability to accurately assess the current situation, encompassing the vessel's surroundings, potential hazards, and the ship's capabilities and limitations. Situational awareness also plays a crucial role in safety and accident in maritime transport. And especially the human role is significant as for 70-80% of the accidents, human errors are at the root. In this research, different to most research on situational awareness in autonomous shipping, a more high-level form of situational awareness is considered. The majority of research considers situational awareness of ships in the context of the interaction of one (or multiple) ships with other objects on a waterway. This research considers situational awareness in the context of a logistic network, where the interaction between ships and the logistic objective is more important.

The answer to the first research sub-question can be found at the interface of the defined concepts. The gap between strategic planning and operational decision-making in autonomous maritime logistics, and maritime logistics as such, can be explained by four key factors: timeframe, information flow, adaptability, and the integration of technology. As described in this chapter, a natural gap exists due to the different temporal levels of strategy and operations. While this gap exists, proper alignment of planning at each level can fill this gap. To ensure this, excellent information flow between the different levels of planning is required. As the research on safety and accidents in maritime transport shows, human errors can increase the gap, disregarding the quality of information flow. So while information flow is crucial, it is the only solution. Another factor contributing to the gap is adaptability. Strategies should be able to adapt to changing markets and unforeseen events, while the adaptability of operational decision-making is focused on executing day-to-day activities. Finally, the integration of technology, or the lack of it, is a key factor contributing to the gap and is also described as one of the contributors to accidents in maritime transport. Adding autonomous technology to this can be a part of the solution or add to the complexity of the system. In short, the described gap between strategic planning and operational decision-making is a gap that can occur due to misalignment of timeframes, information flows, adaptability and technologies.

3 Materials and Methods

The materials and methods chapter plays a significant role in this report by outlining and describing the software developments, experiment designs and experimental procedures. The research approach is experimental, involving model development and the execution of three experiments. The key aspects investigated include the integration of autonomous technology and maritime logistics simulation software, the response to situational logistics information and the potential impact of this integration on the efficiency of maritime operations. It is expected that the developed method can enable an automated and strategy-specific behavioural response of a lab-scale autonomous vessel to logistics information. The methods used in this study involved the development of different Python modules, simulation experiments, lab-scale experiments and data analysis. The details of the methods used in this study are described in the following sections.

The first section provides an overview of the chosen research facilities and the corresponding systems. This is followed by three sections describing the development of the model components and the design of the experiments, grouped by the different experiments. Finally, this chapter also aims to answer the second and third research sub-questions.

3.1. Research facilities

In deciding the approach for conducting experiments in this study, multiple options were considered: simulation, lab-scale and full-scale experiments. While each method has its pros and cons, it was chosen to conduct lab-scale experiments at the RAS for several reasons.

Firstly, the DigiPACT project made it possible to easily work with the RAS. And given the scope of this research, conducting the experiments at this lab was the most logical choice. However, this was not the only reason to conduct the experiments at a lab scale.

Secondly, as opposed to simulation experiments, conducting the experiment at a lab scale provides a more practical result as real-world dynamics are being considered. This research could have been done using simulation experiments only. However, this research aims to provide results that advance the application of computational logistics to support ship operators. So, by conducting real-life experiments, this study aims to take the first steps in bridging the gap between technological development and the real-world application of computational logistics as decision support for ship operators.

Lastly, lab-scale experiments are more cost-effective than full-scale experiments. Full-scale experiments would have required full-scale (autonomous) ships and the time and money to have this operating, which was not possible given the scope of the research. In some cases, full-scale logistic research can be mimicked by using historic AIS data to create case studies with real data. However, the developed method is based on the changing behaviour of ships or ship operators following the input of information. When using historic data, no adaptation in behaviour can be observed. However, using AIS data for case studies is something worth further investigating and is described in chapter 7.

To conclude, the decision to conduct lab-scale experiments was driven by practicalities and the research objective. The facilities of RAS provide the required lab-scale environment and these will be described in the following section.

3.1.1. Researchlab Autonomous Shipping

For this research, RAS Delft provided the facilities. RAS is located at the faculty of 3ME at the Delft University of Technology. The lab promotes the growth of Smart Shipping in the Netherlands. It does this by establishing a collaborative research agenda and testing environment involving government, academia, and industry so that new technologies can be quickly adopted and integrated. RAS facilitates cross-industry knowledge sharing and accelerate the development of profitable use cases by combining research on autonomous driving and shipping. The RAS focuses on specific areas such as autonomous navigation around bridges and locks, autonomous docking and undocking, navigating mixed autonomous and non-autonomous shipping traffic, platooning, and reducing CO_2 emissions (RAS, 2023).

3.1.2. Vessel and location choice

RAS conducts research on small-scale autonomous ships and multi-vessel systems, as well as interactions between large-scale vessels and waterway infrastructure. The RAS has a fleet of over 15 autonomous ships used for research and education. These ships are fitted with various sensor and hardware configurations, making them suitable for conducting all sorts of experiments, including dynamic positioning, environmental disturbances, and complex multi-vessel and obstacle avoidance manoeuvres. The RAS has both indoor and outdoor testing facilities. In partnership with other organizations, RAS also works on autonomy for larger-scale, real-life-size vessels.

Given the scope of the research, the goal of the experiments and facility availability, it was chosen to conduct the experiments at the ’3ME Pond’ and with the autonomous vessel ’TitoNeri’. The 3ME pond was chosen for its availability and the less controlled environment. The 3ME Pond is exposed to weather, waves and waterborne obstacles. This gives a more realistic environment and potentially a better-suited method for real-world implementation. Figure 3.2 shows a picture of the 3ME pond.

The Tito Neri ship was also chosen for its availability. The Tito Neri ship is a scale model of a tug boat with the same name. The model is 1.45 meters, weighs 16 KG and has a mono hull. The ship is fitted with accelerometers, encoders, distance measurement sensors, gyro, and GPS. The controller on the ship is an ARM Cortex 32-bit CPU processor, and it uses a wireless network connection for communication. The ship is physically controlled by a bow thruster and two azimuth propellers. Figure 3.1 shows the Tito Neri before being used for the experiment.

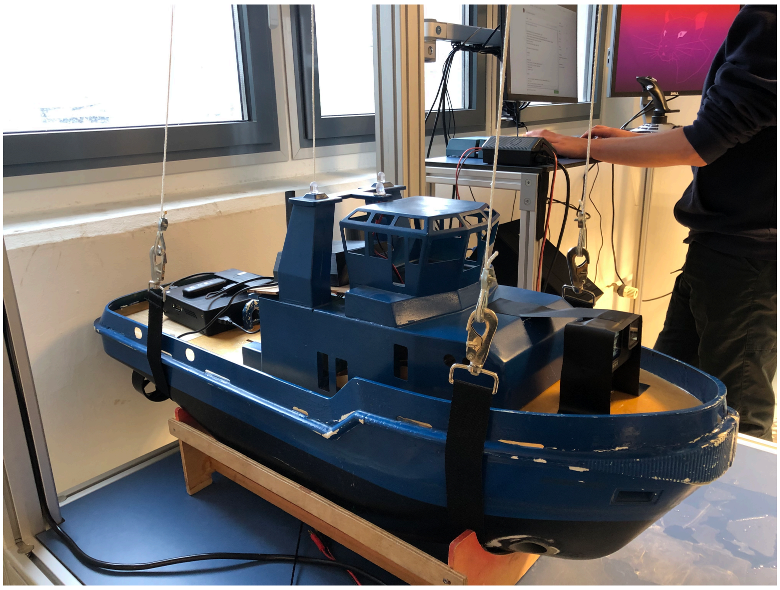


Figure 3.1: Photo of Tito Neri scale model ship (RAS Delft). Length: 1.45 meters, weight: 16 kilograms, hull type: mono hull.

Figure 3.2: Photo of the experiment location, '3ME Pond'

3.2. Experiment Green Routing

This section describes the methods used and developed for the Green Routing experiment. The goal of this experiment was to realize the connection between autonomous technology and maritime logistics simulation software and test the Green Routing capability. This is the capability of adaptively changing one's route based on situational information to reduce emissions (subsection 2.1.2). To conduct this experiment, two software components had to be created. First, the developments required for the integration of the systems are described. And secondly, it is shown how the Green Routing capability was tested by conducting an experiment.

Experiment Green Routing Overview

Goal(s): Test the ROS - OpenTNSim connection and Green Routing capability for different RPM, find functional RPM limits
Related research question(s): Sub-question 2
Location: 3ME Pond
Vessel(s): Tito Neri Dark Blue (RAS_TN_DB)
Objective(s): Sail correct route (at least one lap)
Independent variable(s): RPM
Dependent variable(s): Velocity, heading, sailed path

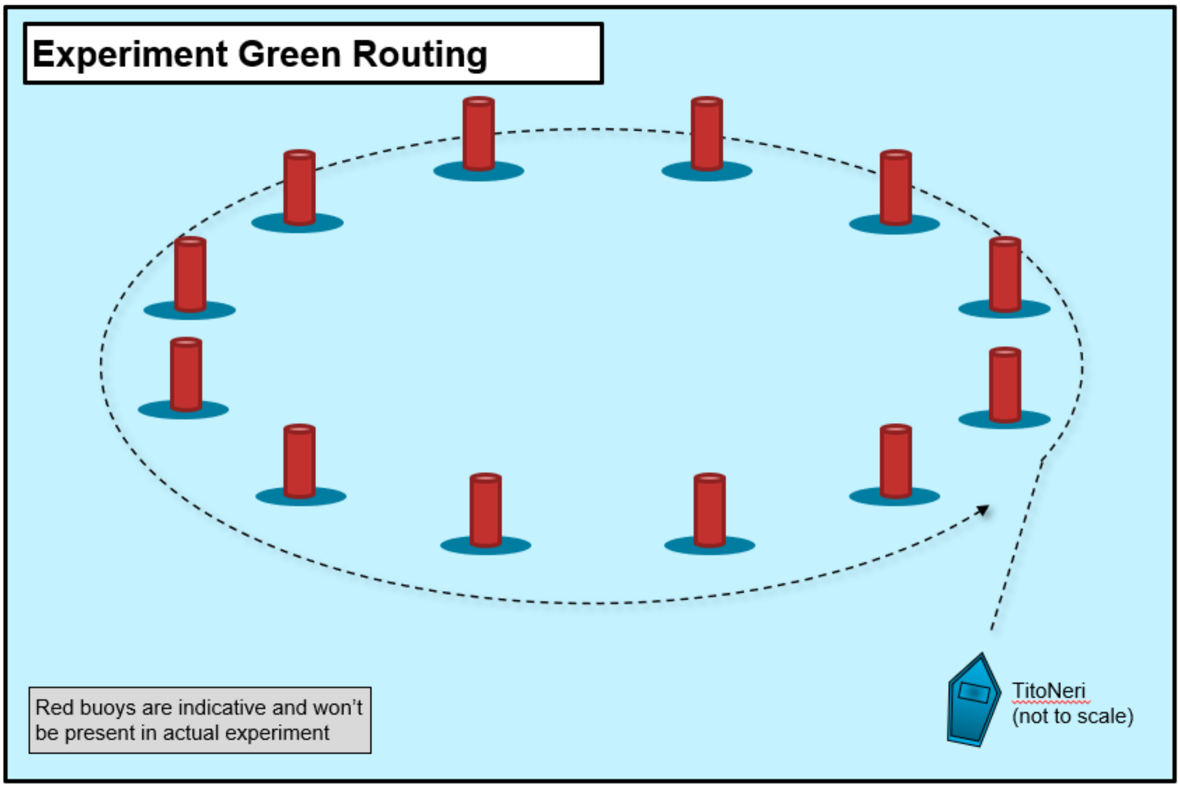


Figure 3.3: Visualization of experiment Green Routing

3.2.1. Integrating autonomous technology and maritime logistics simulation

Before the experiment could be conducted, software developments had to be made. This section gives an overview of the steps that were taken to integrate autonomous technology and maritime logistics simulation. In the subsections, relevant steps are described in more detail.

The goal is to show that an autonomous ship can be informed by strategic decisions. So, we have to set up two-way communication between the strategic simulations and the positional awareness of the ship. To do this, we had to develop the ROS - OpenTNSim connection module. Before this was developed, a comprehensive analysis of the logistics simulation software, OpenTNSim was conducted to understand the existing capabilities and limitations of the software. This analysis included a review of the documentation, core code and tutorial notebooks. In addition, frequent discussions and work sessions with experts on the software were held to determine the possibilities. Next, the facilities and procedures at RAS were analysed to determine the required interfaces and protocols that would be needed to integrate the autonomous vessel with OpenTNSim. This required review of basic control engineering principles and a study of the control systems used by the RAS, including the Robotic Operating System (ROS). Additionally, the guidance and support of the technical coordinators from the RAS made it possible to quickly gain the required knowledge and skills to conduct this research and develop this method. Following the analysis of OpenTNSim and the autonomous technology at RAS, a conceptual design of the software architecture was made. Then, the integration was implemented, and testing was carried out to ensure that the two systems were communicating effectively and that the integration was functioning as expected. The testing involved both functional testing, to ensure that the integration was working correctly, and performance testing, to ensure that the integration was not impacting the performance of the logistics simulation software (subsection 3.2.2).

Connecting ROS and OpenTNSim

ROS is an open-source framework used for building robotic systems, and it is the framework used by the RAS to communicate with autonomous vessels. ROS provides a wide range of tools, libraries, and conventions for creating complex robot applications. ROS is designed to be modular and flexible and is widely used in autonomous vehicle control due to these properties (Ricardo Tellez, 2017). It provides a common message-passing interface that allows different parts of the system to communicate with each other, regardless of the programming language or hardware platform being used. For more detailed information on ROS, I refer to the documentation (ROS, 2020). The main takeaway is that ROS uses a topic-based, publish-subscribe messaging structure (Figure 3.4). To communicate, one can send messages by publishing or receiving messages by subscribing to a topic.

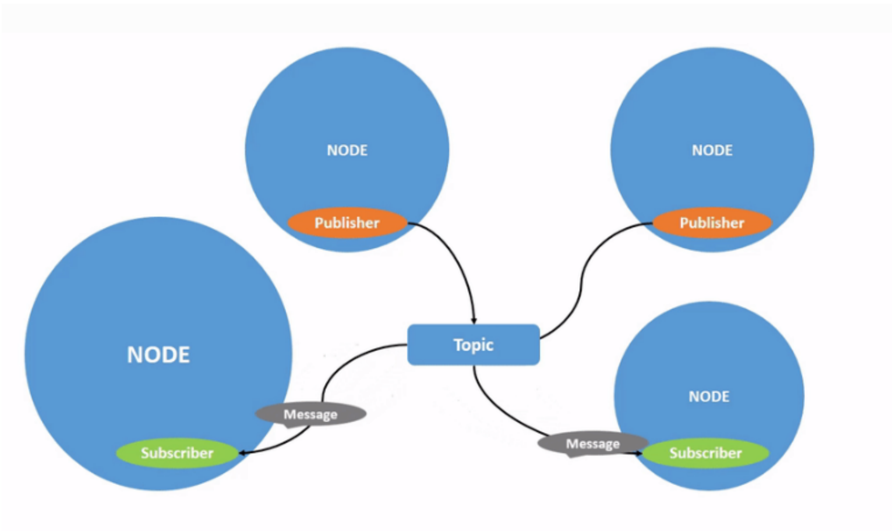


Figure 3.4: Messaging structure ROS (ROS, 2020). Communication is done through 'topics' on which you can publish to send a message and on which you can subscribe to receive a message.

OpenTNSim is a Python-based simulation framework for maritime logistics. It allows for the creation of discrete-event simulations to model the operations of a container terminal, port facility, dredging project, or inland waterway transport, taking into account factors such as ship arrivals and departures, container loading and unloading, and other operational processes. OpenTNSim is designed to be modular, allowing users to easily extend and customize the simulation to fit their specific needs. It is an open-source project, meaning that the code is available for anyone to use and contribute to. For more detailed information on OpenTNSim, I refer to the documentation and article (de Boer et al., 2022; van Koningsveld et al., 2021).

ROS can be used in multiple programming languages, however, OpenTNSim is written in Python. Because of this, it was decided to create a Python module to integrate autonomous technology and simulation software. ROS has a Python package called 'rospy' which is a client library that enables Python programmers to quickly interface with ROS Topics, Services and Parameters ("ROS Wiki", 2023). The goal of connecting ROS and OpenTNSim was to be able to receive relevant data from the autonomous vessel and send back relevant operational instructions for the vessel to follow. The following steps were undertaken to realize this:

1. Create a ROS node to receive data from a ROS topic. This node was created to receive sensor data of the ship.
2. Modify OpenTNSim to receive this input data from the ROS node. This was achieved by modifying the existing code to include a ROS subscriber, which listens to the ROS topic and receives the data from the ROS node. This data is then available to be used as input for the simulation in OpenTNSim.
3. Modify OpenTNSim to send operational instructions to the ship. To send this output data, a ROS publisher was created which publishes the output data to a node, making it available to the ship.
4. Rewrite an existing control script of the RAS to include the output data from OpenTNSim. An existing Matlab control script, created by Bart Boogmans, was translated to Python and rewritten to be able to handle data types inherent to OpenTNSim.

Steps 1-4 were combined into a single Python module that replaced an existing Matlab script of the RAS. The created module takes in sensor data of the ship (location and heading) and a graph network created in OpenTNSim and is able to send control instructions to the ship in the form of a desired heading. To create the route in OpenTNSim, a network had to be designed. This network was then translated into the World Geodetic Coordinate System (WGS 84) to fit the 3ME Pond. To communicate this route to the Tito Neri vessel, the developed ROS - OpenTNSim module was required. Figure 3.6 and Figure 3.5 show schematic overviews of the module. This created module was tested on basic functionality using simulations experiments, described in the following section. This was done to avoid basic practical errors before conducting the real experiment.

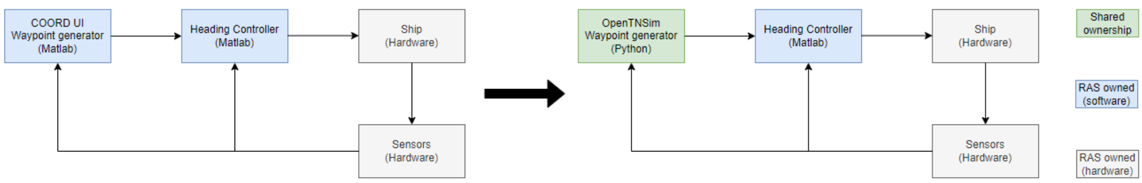


Figure 3.5: Simplified schematic of the control system before and after the connection between OpenTNSim and ROS. The legend shows the difference in ownership of the developed modules.

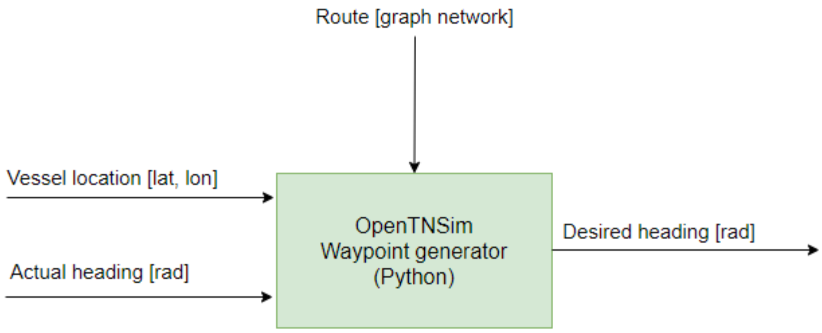


Figure 3.6: Schematic of the input and output of the Python module that connects ROS and OpenTNSim

Simulation experiments

A series of simulation experiments were conducted to improve familiarity with the different systems and reduce the risk of having issues with practicalities during the real experiment. The first step was to verify that the two systems were properly connected and communicating with each other. This was first done by replaying recordings of previously done experiments at the RAS, so-called 'rosbags'. These datasets are recordings of all messages sent to and from the different active topics ("ROS Wiki", 2023). Replaying such a dataset allows one to emulate a live data stream and thus test if the correct data is received and if this is handled correctly. Using a relevant rosbag-file, it was validated that the established connection was functioning properly, and the model correctly handled the incoming data.

The method of replaying rosbags is however limited because it is not possible to test the response of the ship to input. And because the newly created Python module also controls the lab-scale vessel, it was important to test if the control input generated by the new module, resulted in desired behaviour of the ship. Because physical testing was limited due to the limited availability of facilities, an emulator was used to simulate the lab-scale vessel. This emulator called the NausBot (developed at the RAS by Bart Boogmans), is a discrete physics-based calculations model of the real-world lab-scale vessels used at the lab. The NausBot was used to test if the Python module was capable of returning the desired control parameters, given the sensor data of the ship. Due to the discrete nature of the NausBot and its approximation of reality, the control system had to be tuned iteratively before realistic results were found. After 9 iterations, the correct settings were found for the control system of the ship, and the emulated ship was able to follow a predetermined route with reasonable accuracy. This route was defined as a graph network, as done in OpenTNSim. The resulting trajectory is shown in Figure 3.7.

3.2.2. Experiment Green Routing setup and procedure

This section describes the setup and procedure of the Green Routing experiment. This experiment was designed with the objective to test the connection between ROS and OpenTNSim and the Green Routing capability. The setup consisted of the Tito Neri Dark Blue and was at the 3ME Pond. To realize the experiment, a number of software components were required (see Figure 3.8):

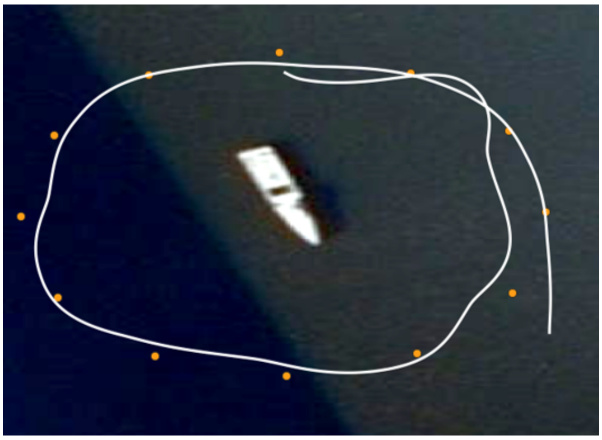


Figure 3.7: The trajectory of the NausBot is shown in white and waypoints are shown in orange. The NausBot is a virtual emulator of the lab-scale vessel from the RAS. It approximates the behaviour of the real-world vessel through discrete, physics-based calculations. This trajectory is from a virtual version of the Green Routing experiment.

- the 3ME Pond circle;
- the OpenTNSim route;
- the ROS - OpenTNSim module;
- the heading controller;
- the vessel system.

For the procedure of the experiment, it was decided to let the Tito Neri sail a predetermined, constant route at multiple different RPMs. Where RPM represents the revolutions per minute of the ship's thrusters and is a measure of power output. The experiment was done for 2000, 1600, 1200 and 800 RPM. This range was defined with the help of the RAS coordinators and represents upper and lower use limits (from experience). Varying the RPMs was done to analyse the Green Routing capability at different power outputs and to define upper and lower power output limits for the following experiments. A Python module called 'Sail2Point' was created to combine the created route and the ROS - OpenTNSim connection. The module can be seen in section A.1. This Sail2Point script will be responsible for generating and providing the correct waypoints for the Tito Neri to follow. In the Sail2Point script, an acceptance radius was added to the waypoints. This is a circle with a radius of 3 meters, within which the vessel is assumed to have reached the waypoint. This was done to allow for smooth cornering and was advised by the lab coordinators. The goal of this experiment was to enable route following and not highly accurate positioning. Research on dynamic coordination of multiple tugboats (Du et al., 2022) is one of many examples that shows that this is available knowledge to the RAS. Figure 3.8 shows the relation between the Sail2Point script and the existing systems during an experiment. At the beginning of the experiment, the vessel system and the heading controller are started, and the vessel is placed in the 3ME Pond. To start the experiment, the Sail2Point script is run. Appendix C shows a log of the experiments.

Data analysis

To analyse the functioning of the systems, recordings of all communication on ROS were made and a video recording of the experiment was made. The relevant data collected through these methods are:

- the vessel position;

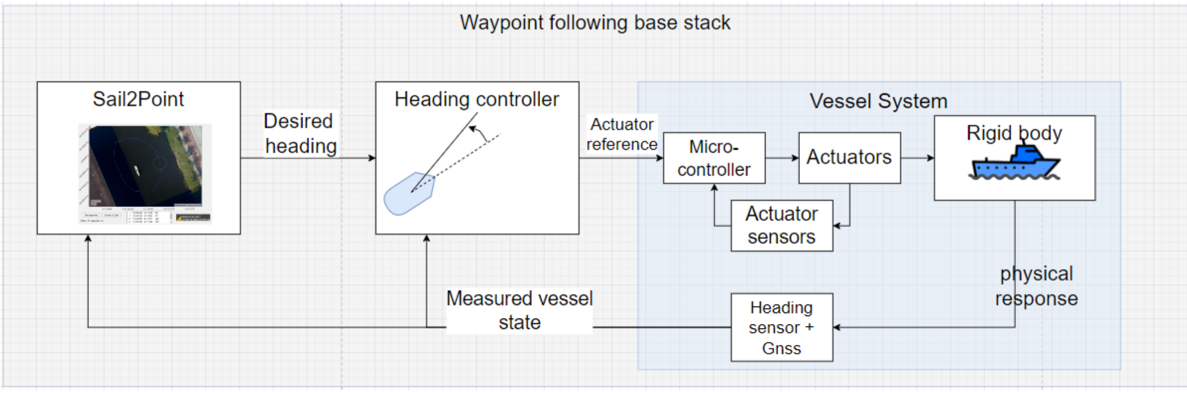


Figure 3.8: The collection of components required for the Green Routing experiment (by Bart Boogmans)

- the vessel heading
- the reference heading
- the input of actuators
- the output of actuators

The analysis of the experiment was done both qualitatively, by observation, and quantitatively, by data analysis. The goal was to observe the vessel sail the correct route and to see in the data that the correct messages were sent to the vessel. For this experiment, discrete measurements of position in time were differentiated to find the body-fixed velocities of the vessel per RPM. Due to the discrete nature of the measurements and occurring inaccuracies, outliers (>10 m/s) were present in the differentiated data (caused by time steps approaching 0). The outliers were removed. Furthermore, filtering was applied to smoothen the data and determine the average velocity. Similar methods were applied in the developed velocity controller. Details on the differentiation can be found on the corresponding GitHub page (Boogmans, 2023b).

3.3. Experiment Green Steaming

This section describes the methods used and developed for the Green Steaming experiment. The goal of this experiment was to test the Green Steaming capability. This is the capability of adaptively changing one's velocity based on situational information to reduce emissions (subsection 2.1.2). To conduct this experiment, the velocity control component had to be developed, which is described in the following section. Subsequently, it is shown how the Green Steaming capability was tested by conducting an experiment. Figure 3.9 shows an overview of the experiment.

Experiment Green Steaming Overview

Goal(s): Test the Green Steaming capability
Related research question(s):
Location: 3ME Pond
Vessel(s): Tito Neri Dark Blue (RAS_TN_DB)
Objective(s): Sail at the correct (alternating) reference velocities
Independent variable(s): Reference velocity
Dependent variable(s): Actual velocity

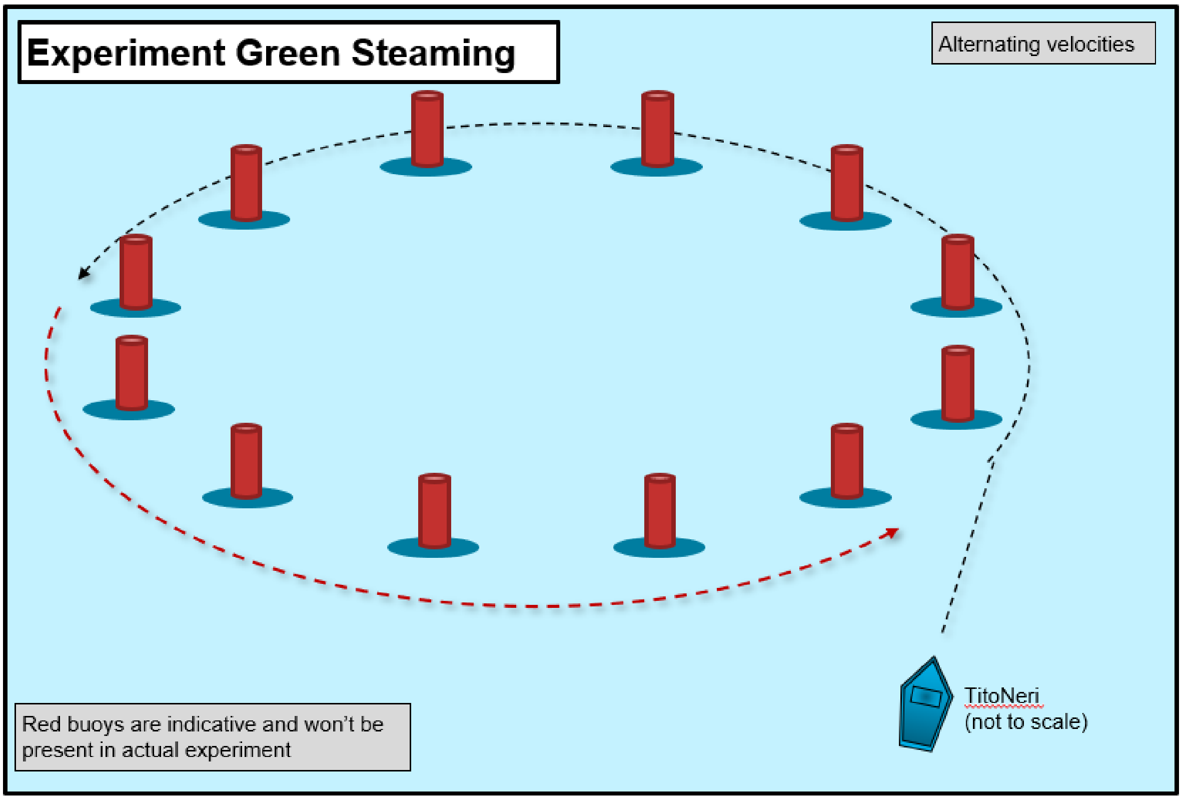


Figure 3.9: Visualization and overview of experiment Green Steaming

3.3.1. Velocity control

Before this research, the velocity of the Tito Neri vessel was controlled statically by changing the input RPM for the thrusters. For the Green Steaming capability, dynamic velocity control was required. Developing a velocity controller was also an objective of the RAS. So, for this and future research, Bart Boogmans developed a basic PID controller capable of velocity control. Figure 3.10 shows a diagram of the velocity controller. For details, I refer to the GitHub page regarding this (Boogmans, 2023c).

3.3.2. Experiment Green Steaming setup and procedure

This section describes the setup and procedure of the Green Steaming experiment. This experiment was designed with the objective to test the Green Steaming capability. The setup consisted of the Tito Neri Dark Blue and was at the 3ME Pond. To realize the experiment, the same software components were required as for the Green Routing experiment, with one addition: the velocity controller. Figure 3.11 shows the components required for the experiment. For the procedure of the experiment, it was decided to let the Tito Neri sail a predetermined constant route with varying input reference velocities. These reference velocities were generated by a square wave generator (Figure 3.11). For periods of 20 seconds, alternating velocities of 0.4 m/s, 0.6 m/s and 0.3 m/s were imposed on the Tito Neri. Appendix C shows a log of the experiments.

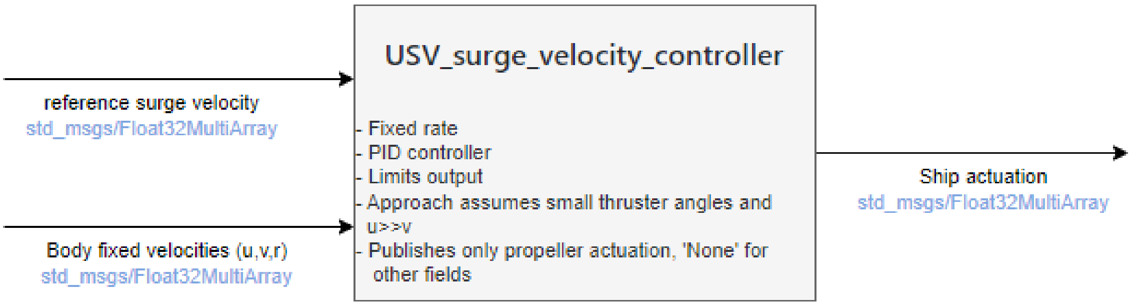


Figure 3.10: Diagram of the velocity controller developed by Bart Boogmans (Boogmans, 2023c). The diagram shows the input of the controller on the left and the output on the right. In the block itself, some specifics are noted.

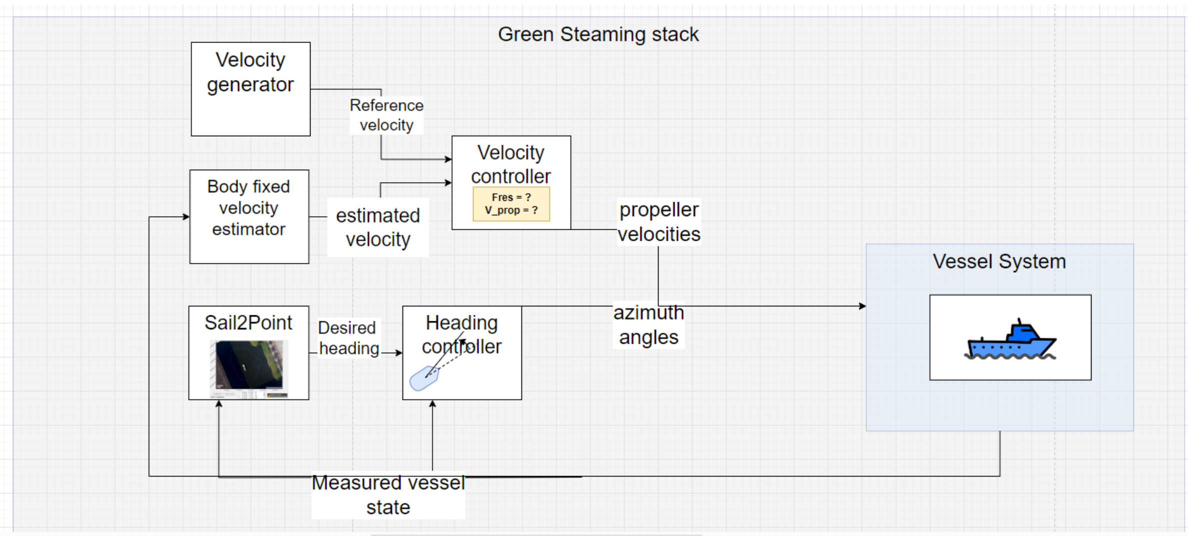


Figure 3.11: The collection of components required for the Green Steaming experiment (by Bart Boogmans)

Data analysis

To analyse the functioning of the velocity control, recordings of all communication on ROS were made and a video recording of the experiment was made. The relevant data collected through these methods are:

- the vessel position;
- the reference vessel velocity
- the actual vessel velocity

The actual velocity was determined by differentiation of the positional data as described in the data analysis of the Green Routing experiment. The analysis of the experiment was done both qualitatively, by observation, and quantitatively, by data analysis. The goal was to observe the vessel respond correctly to the different reference velocities and approximate the reference velocity with reasonable accuracy. Details on this are discussed in the results (section 4.2).

3.4. Experiment Port Call

This section describes the methods used and developed for the Port Call experiment. The goal of the experiment was to test the automated response to logistics situational awareness information by the Tito Neri. To achieve this goal, several methods were developed:

- Scaling down a real-life logistic scenario to fit the lab-scale environment
- Bridging the gap between strategy and operations by scenario simulation
- Creating a module to collect and process situational awareness information
- Creating automated decision support by adding a virtual operator

The methods are explained in more detail in the following sections. And lastly, it is shown how the experiment was set up to test the automated decision-making capability. Figure 3.12 shows an overview of the Port Call experiment.

Experiment Port Call Overview

Goal(s): Test automated response to logistic situational awareness information
Related research question(s): Sub-question 3, 4
Location: 3ME Pond
Vessel(s): Tito Neri Dark Blue (RAS_TN_DB) & Tito Neri Dark Green (RAS_TN_DG) (Virtual)
Objective(s): Choose the correct route and velocity based on the available situational awareness information and the chosen strategy
Independent variable(s): Strategy, berth availability
Dependent variable(s): Velocity, route

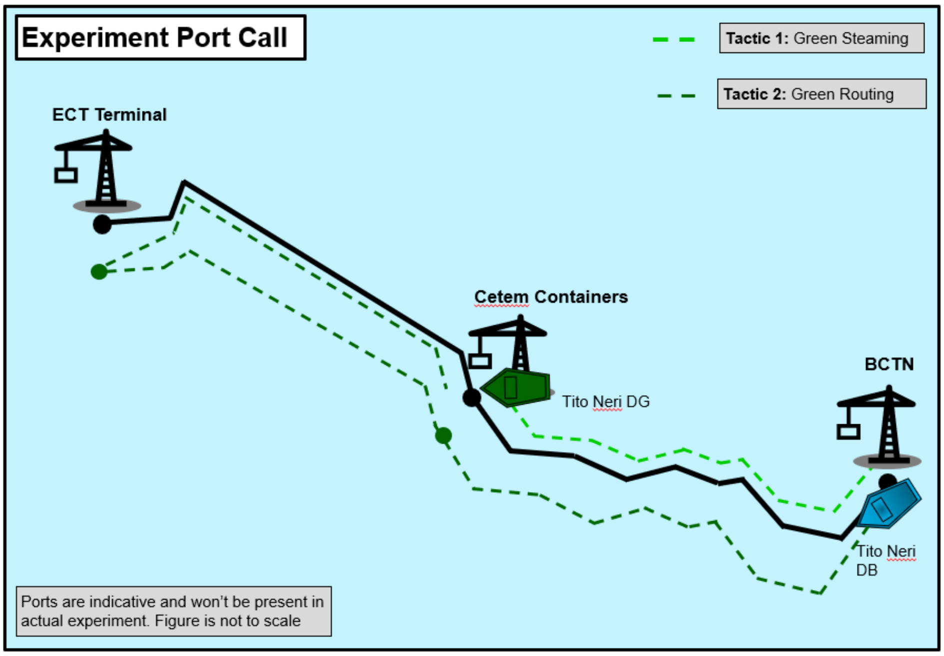


Figure 3.12: Visualization and overview of experiment Port Call

3.4.1. Scaling down from real-life to lab-scale: Port Call Case

To test the automated response to logistic situational awareness information of an autonomous vessel, a real-life logistic scenario was scaled down to a lab-scale experiment. The logistic scenario considered, involved the transportation of goods between the BCTN terminal in Alblasserdam, the Cetem Containers terminal, near Spijkenisse and the ECT Terminal, at the Maasvlakte. Figure 3.14 shows thus this scenario. This scenario was chosen because this research was done in the context of inland shipping in and around Rotterdam. These terminals were not specifically chosen for any reason other than the fact that they offer a clear route from the sea to an inland terminal. When scaling down this scenario for the lab-scale experiment, the main goal was to preserve the essence of the logistic process. This essence is in this case the transportation of goods between three terminals, where the middle terminal is approximately halfway between the other two. Based on this analysis, we decided to scale down the following parameters:

1. Distance: The distance between the source and destination ports was scaled down from 55 kilometres to 50 meters to fit the size of the 3ME Pond.

2. Vessel size: The Tito Neri is a lab-scale model and thus also scaled down from the vessels that would normally sail the chosen route. The size of the Tito Neri is 1.45 meters and the average inland ship's size range is 90-135 meters.

3. Speed: The speed of the vessel was reduced to fit the scale of the experiment. This is related to the scaling down of the vessel itself. The average inland ship sails at a range of approximately 1-7 m/s. For the Tito Neri, this range is approximately 0.1-0.6 m/s.

4. Navigation aids: To ensure better operation of the vessel in the lab-scale environment, an RTK GNSS receiver was placed beside the 3ME Pond. This receiver improves the GPS signal of the Tito Neri.

As can be seen in the enumeration, the distance, speed, and size of the vessel have not been scaled proportionally because this was not possible with the available facilities. This did not compromise the logistic essence of the experiment and was thus not a problem. The scaled-down route can be seen in Figure 3.12. Due to GPS signal quality, it was decided to put the route away from the buildings on the left. These buildings can interfere with the signal and cause problems. However, this also limited the design to this simplified design.

3.4.2. Bridging the gap between strategy and operations: Scenario simulation and performance indicators

This section gives an overview of the steps that were taken to bridge the gap between strategic, tactical and operational planning by using and adding to the maritime logistics simulation software OpenTNSim.

As described in section 2.1, different levels of planning in maritime activities involve different levels of decision-making. At the strategic level, decision-making involves fleet size, fleet composition and air emissions control. At the tactical level, one focuses more on medium-term level decision-making such as fleet deployment, multi-vessel routing and bunker management. And finally, at the operational level, decision-making involves short-term aspects such as environmental routing, speed selection, and single vessel routing and scheduling. OpenTNSim can be used at every level of planning and thus lends itself well to bridge the gap between these planning levels. While OpenTNSim can be used to simulate multiple aspects at each level of planning, for this research the focus will be on air emissions control, multi-vessel routing and speed selection, combining all levels of planning.

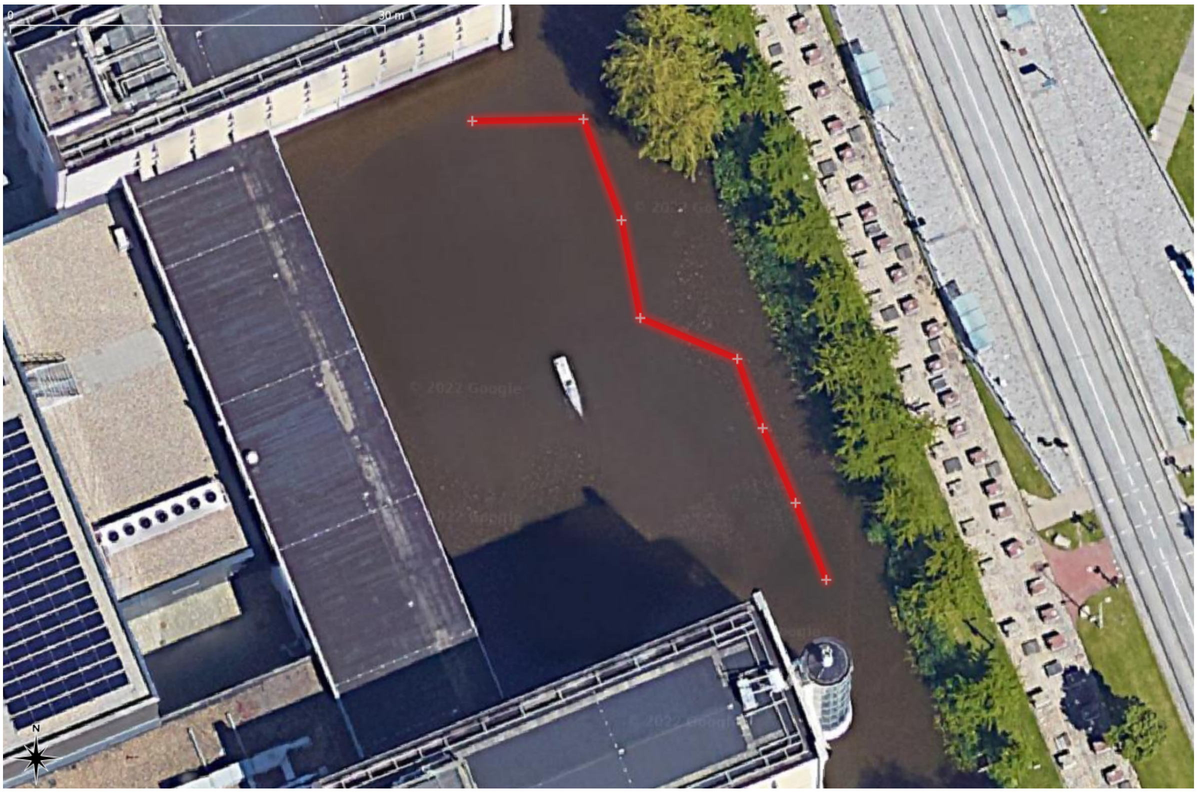


Figure 3.13: Route for Port Call experiment. This route is a scaled-down and simplified version of the route from the real logistic scenario shown in Figure 3.14. Source: Google Satellite

Figure 3.14: Shipping route on the Dutch inland waterways taken from the Digital Twin Waterways (SmartPort, 2021). This route is the inspiration for the lab-scale Port Call Case. Source: OpenStreetMap

Decision support methodology

The following section describes the conceptual methodology used for the decision support. While developing the method, research was found that describes a similar approach. (Fagerholt et al., 2010) describes a methodology for decision support for strategic planning in maritime transportation. While the two methods were developed independently of each other, after the discovery of the research previously done, one could not ignore this. To adhere to previous research, it was decided to use its methodology as a framework.

Simulations can be used to make predictions of the future. And while these simulations are only approximations of reality, the capability of simulating a high number of scenarios in a short amount of time makes it a useful tool for decision support. It was decided to use OpenTNSim as a tool to test the effect of different sets of strategic, tactical and operational decisions given the current situation that the ship is in. This conceptual model is shown in Figure 3.15 and the methodology involves the following steps:

- Firstly, a current situation must be defined. This current situation can be described as the real-time position of the ship(s) in relation to the transport network, the infrastructure, and other ships while taking into account the ship type, fuel type, ship dimensions, fairway dimensions, water depth and other operational parameters. In other words, a virtual representation of the logistic system should be created in OpenTNSim and real-time data can be used to increase situational awareness and make this a representation of the current situation.

- Next, a set of decisions must be defined that are based on different strategic and tactical objectives. These decisions can include routing options, vessel speed, cargo selection, and other relevant parameters that can affect the outcome of the simulation.

- Once the decisions have been defined, the real-time situation and decisions are inputted into the OpenTNSim software, which can then simulate the different outcomes and generate results. The simulation results can include data such as the time required to complete the task, fuel consumption, emissions, and other relevant parameters.

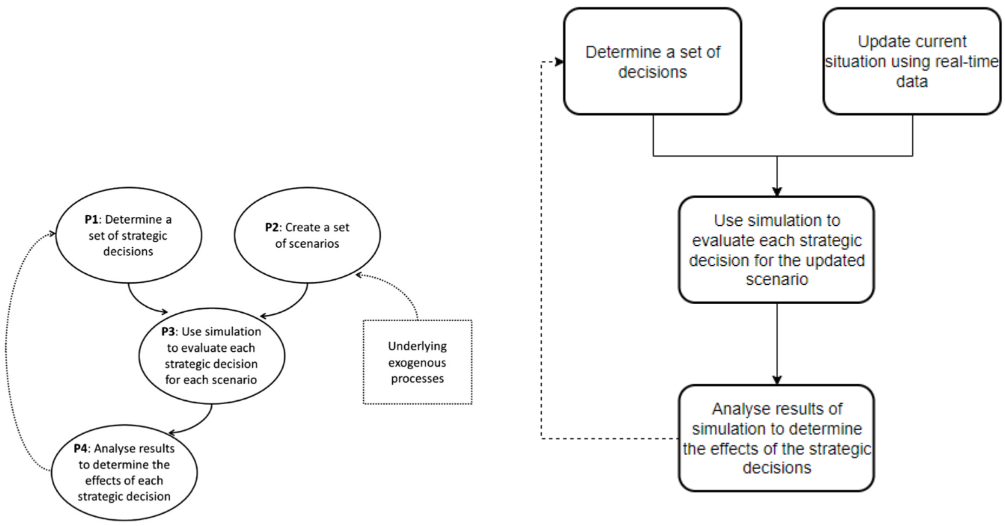
- The results of the simulation are then available for analysis and can be used as input for decision-making.

Following the above-described methodology, it is possible to create a transport network model in OpenTNSim, improve situational awareness by using real-time data and test different sets of planning decisions through simulation, and allow for decision support based on the results of the simulation. In the following sections, each of the different steps is explained in more detail.

Determining strategic, tactical, and operational decisions

Following the defined concepts and described framework from section 2.1, this section describes the method that was used to generate different simulation scenarios by determining sets of decisions, representing different strategies.

Following a strategy can be described as implementing tactics and operations in such a way that the strategic objectives are reached. This way, following a strategy can be described as a combination of tactical and operational decisions that best suit the strategic goal. To realize this in OpenTNSim it was decided to create different simulation scenarios by varying key operational parameters based on available tactics and desired strategies. These different simulation scenarios represent different combinations of tactical and operational decisions, and thus different ways to reach one's strategic goal.



(a) (Fagerholt et al., 2010) (b) This study

Figure 3.15: Conceptual models for decision support methodology. These models describe methodologies for decision support in strategic planning in maritime transportation. Figure 3.15a was adapted to form Figure 3.15b. The latter was used as a framework for the methodological steps in the decision support system of this research.

Working from top-to-bottom, it was chosen to consider three strategies:

1. As fast as possible (Time)
2. As clean as possible (Emissions)
3. As inexpensive as possible (Fuel)

In real life, shipping companies potentially have more complex strategies, however for now it is assumed that these three will provide significant results as almost all measures taken by shipping companies can be boiled down to minimizing either costs, sailing time or emissions. Because costs are largely determined by fuel costs (Poulsen et al., 2022), it was decided to look at fuel consumption for the costs' strategy. For the available tactics, it was decided to focus on Green Steaming and Green Routing besides conventional routing and steaming. Conventional routing and steaming are represented as base cases. For the routing, this means that the route is as simple and direct as possible, and for the steaming, this is represented by an engine order of one. Because of the simplified, scale model testing, there would be no significance in determining actual speeds. The described tactics then limit the operational parameters to vessel speed and vessel route. While nowadays, improving the efficiency of maritime operations can be done in a number of different ways, (Bouman et al., 2017) and (Poulsen et al., 2022) show that operational optimization of vessel speed and route are still among the most effective ways to improve maritime operations. Furthermore, with the changing ship technologies, vessel speed and route are relevant for all types of ships and fuels, so for this research, only these operational parameters will be considered. In short, this means that strategic decisions can be made to either minimize time, emissions or fuel. The available tactics to achieve these strategic objectives are conventional steaming and routing and Green Steaming and Green Routing. This means that operationally, it is possible to either do or not change your route or speed.

To implement this method in OpenTNSim a module was created that generates different route and speed alternatives and combines them into a dataset. This dataset can be used as input for simulations. Simulating these different alternatives creates different scenarios or predictions that can be evaluated. Table 3.1 shows an example of different generated alternatives. It should be noted from this table that different combinations of the tactics of Green Steaming and Green Routing are created based on different combinations of operational parameters. The following section (Table 3.4.2) how these different combinations are evaluated through simulation.

	Route	Waypoints	Nodes	Engine order	Green Routing	Green Steaming
1	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	0.5	False	True
2	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	0.5	True	True
3	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	0.6	False	True
4	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	0.6	True	True
5	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	0.7	False	True
6	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	0.7	True	True
7	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	0.8	False	True
8	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	0.8	True	True
9	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	0.9	False	False
10	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	0.9	True	False
11	direct	[A, D, H]	[A, B, C, D, E, F, G, H]	1.0	False	False
12	redirect	[A, H, D]	[A, B, C, D, E, F, G, H, G, F, E, D]	1.0	True	False

Table 3.1: Different simulation scenarios generated by varying vessel's engine order and route and creating combinations. When the engine order is less than 1.0, the vessel is considered to be Green Steaming. When the vessel takes an alternative route, the vessel is considered to be Green Routing.

Evaluation through simulation

This section describes how OpenTNSim was used to evaluate different sets of decisions based on different strategies. Simulation can be used to test the effect of certain decisions in a virtual environment. In a way, you can peak forward in time by simulating what will happen. In this research, the goal of this method is to test alternative routes and speeds to see if these better fit the chosen strategy.

The method developed for evaluating different route and speed options for vessels using OpenTNSim simulation allows for the comparison of different scenarios based on factors such as cost, fuel consumption, and emissions. The method involves setting up a simulation environment using OpenTNSim. The simulation environment includes the relevant vessels, the relevant nodes or destinations, and the routes connecting them. The vessel is defined by its characteristics, such as length, draft, and engine power, and its speed is varied according to the different scenarios being tested. For this research, all simulations were done with the characteristics of a 'Large Rhine vessel', as described by the Conférence Européene Ministres de Transport (CEMT). Table 3.2 shows these characteristics. For each scenario, the simulation is run to calculate the total duration, cost, and

Description	Vessel Type	CEMT-class	RWS-class	Length [m]	Beam [m]	Draught [m]	Engine age [year]
Large Rhine vessel	Motor vessel	Va	M8	110	11.4	3.5	1997

Table 3.2: Vessel characteristics used in the OpenTNSim simulations. The chosen vessel is a Large Rhine vessel as described by the CEMT. These characteristics influence the outcome of performance indicators calculated using the energy module.

emissions of the voyage. These results are then stored and made available for decision-making. This process is done once every five seconds and is dependent on the locations of the relevant vessels. In the sections below, the methods of calculation for the different performance indicators are described, and the assumptions made are discussed. These calculations are done in the code of OpenTNSim modules and for more details, I refer to the core code of this Python Package (Baart et al., 2022).

Calculation of voyage duration The calculation of the voyage duration is done in the OpenTNSim core code. This is an inherent functionality of running a simulation in OpenTNSim and thus the reason that this method was used.

This calculation is done by means of the 'move' functionality that simulates the moving of the virtual vessel over a set of nodes. The input parameters of this function are the vessel, including its characteristics, speed and location, and the route over the graph network. The function uses the speed of the vessel and the distance between the nodes of the route to perform a simple duration calculation:

$$\sum_{i=1} \mathrm{t}_{[i,i+1]} = \frac{\mathrm{S}_{[i,i+1]}}{\mathrm{v}_{[i,i+1]}} \tag{3.1}$$

where:

$\mathrm{t}_{[i,i+1]}$ = sailing duration from node i to node i+1
$\mathrm{S}_{[i,i+1]}$ = distance from node i to node i+1
$\mathrm{v}_{[i,i+1]}$ = sailing speed from node i to node i+1

The calculation of the duration is relatively simple due to the set-up of OpenTNSim, where the movement of a vessel is defined as one-dimensional movement over a graph network. For this research, it is assumed that this approach approximates reality enough to quantitatively compare different simulation scenarios.

An additional step had to be taken to account for waiting time in case of an unavailable berth. OpenTNSim does not allow for non-moving vessels. However, when a vessel should choose whether to change its route or speed according to an unavailable berth, potential waiting time is crucial information. Given the scope and time of this study and the expected duration of the experiment, it was chosen to manually add a delay of 20 seconds from the moment of berth unavailability. This delay of 20 seconds was chosen to fit the use case and did not rely on any research or statistics. Due to the disproportional scaling, it would have been too complex to relate this to actual delays in inland shipping. The delay was only added for the direct route scenarios (Table 3.1) as the redirect scenarios would avoid this berth. For the direct scenarios, the duration of sailing from the start to the unavailable berth was subtracted from the 20-second delay, leaving a waiting time that varies with engine order. This waiting time was added to the total duration of the simulation to simulate the vessel having to wait before the berth was available again.

$$t_{waiting} = 20 - t_{[A,D]} \tag{3.2}$$

where:

$\mathrm{t}_{waiting}$ = waiting time
$\mathrm{t}_{[A,D]}$ = duration from node A to D

Calculation of voyage costs For this research, the calculation of the voyage costs has been limited to determining fuel consumption. Ship costs generally consist of operating costs, freight costs and fuel costs, where fuel costs roughly take up 40-70% of the costs (Irawan, 2018). To limit the scope of the research, it was decided to limit the voyage costs to fuel costs. Furthermore, only one type of vessel was considered, limiting the fuel type to one as well. This means that for this method, given these limitations, it was possible to only consider fuel consumption. Calculating this to find the actual fuel costs would be the same for all scenarios, thus making it unnecessary.

This means that voyage costs are actually the fuel consumption per voyage. It was chosen to still use 'costs' for the naming as it originated from this and to show the potential of this method. How the fuel consumption is determined is described in the following section.

Calculation of voyage emissions Calculating the voyage emissions was done using the 'Energy'-module from OpenTNSim. This module is capable of calculating different types of emissions generated during the voyage of the vessel by determining the fuel consumption and calculating the resulting emissions through emissions factors. This method is clearly described in the research by Segers (Segers, 2020), where the goal was to map the emissions caused by inland ships between Antwerp and Rotterdam. This research formed the basis for the relationship between vessel speed, water depth and engine age, the main influencing factors for fuel consumption and emissions.

In short, the energy module computes an estimation of the required energy for a vessel to sail a certain distance, at a certain speed and at a given water depth. This required energy is then translated into emissions by means of emissions factors.

For this research, the comparison of simulation scenarios based on emissions was limited to using CO_2 and PM10. This was done to keep the results simple and clear. And given the research objective, this was assumed to suffice. PM10 was added as recent research on fine particulate emissions (van den Elshout et al., 2022) has shown that idling sea-going vessels are the number one source of pollution for inland waterway areas in Rotterdam and Zeeland. To account for this effect, PM10 emissions were taken into account in the analysis of emissions.

To realize this, an addition to the energy module had to be made as this only accounts for moving vessels, and not idling, waiting for vessels. This was done by determining the PM10 emissions per second for a partial engine load of 0.6 as this has a 1:1 relation to the PM10 emissions. This value was then multiplied by the relative PM10 emissions factor for a partial engine load of 0.05, which is the assumed partial engine load of a stationary, idling vessel. This gives the amount of PM10 emitted per second for a stationary, idling vessel, which can then be multiplied by the number of seconds waiting to find the total amount of PM10 emitted during waiting. This calculation can be found in section A.2.

3.4.3. Real-Time situational awareness information: Adding a (virtual) vessel

As described above, an updated version of the current situation is needed for the simulations to be relevant. An updated version of the current situation requires situational awareness. Real-time data plays a critical role in increasing situational awareness in autonomous maritime logistics. This information provides an accurate and up-to-date understanding of the vessel's location, speed, heading, and surrounding environmental conditions.

This research does not provide new or better ways to acquire this real-time data because modern ships have more than enough systems that provide this data (van der Weide & Schreibers, 2020). For this research, we will only use real-time data on location and heading. This method distinguishes itself from current methods by sharing this real-time data with other ships and using this information as input for discrete event simulations. The goal is to show that situational information, even if it is relatively basic, can be used to improve maritime operations if used in combination with a simulation-based model and autonomous technology.

In the Port Call experiment, a virtual version of a Tito Neri ship was added and the location of this virtual ship was monitored. This addition of real-time situational awareness information could then be used in the simulation of scenarios and the decision-making process. To integrate real-time data and situational awareness with OpenTNSim, a Python class was created. This 'Operator' class was created to serve as a way to collect situational information and process it accordingly. This is described in more detail in the following section.

3.4.4. Automated decision support: Adding a virtual Operator

To integrate real-time data and situational awareness information and provide automated decision support, the 'Operator' class was created. In this research, the function of the Operator is to track the position of the involved ships and determine the availability of port infrastructure. This information can then be used for decision support for the involved ships. This real-time information can be combined with existing situational data provided within the OpenTNSim environment, to create an approximation of reality in which simulations can be done to improve operations. These simulations require different scenarios that are based on a number of operational decisions that represent different strategies and tactics. This section describes how the different sets of decisions were determined and applied in OpenTNSim. The code of the Operator class can be found in Appendix A.

After determining different options by simulating different scenarios, the 'optimal' one should be chosen and implemented. In this case, optimal does not refer to an optimized solution considering all variables, it refers to a solution that is the best given a preferred performance indicator. The goal of this decision-making and implementation is to find and apply the scenario that is preferred based on a predetermined strategy. To do this, first, different strategies should be defined. Secondly, a decision algorithm should be created that can choose the preferred simulation scenario based on the defined strategies. Finally, the chosen simulation scenario should be translated into operational parameters and implemented automatically.

Strategy definition

In this study, three strategies were defined based on the criteria of time, costs, and emissions. These criteria were chosen as the driver behind most decisions in ship operations. Reducing time and costs for ship operations has always been an interest in the industry. Even in current research on energy efficiency in ship operations, costs are shown to be a driving factor in decision-making (Poulsen et al., 2022). Relatively new, but gaining more and more importance, are emissions. In the research on ship optimization, nowadays, the main focus is on reducing emissions. An overview of this is given by (Bouman et al., 2017). For now, the 'time', 'costs' and 'emissions' strategies are considered.

The time strategy focuses on minimizing the duration of the voyage. This strategy represents companies that prioritize speed and timely delivery of goods. On the other hand, the cost strategy aims to minimize the costs during the voyage. This strategy represents companies that want to maximize their profits by reducing operational costs. Lastly, the emissions strategy focuses on minimizing the environmental impact of the voyage. This strategy considers the amount of greenhouse gases emitted by the vessel during the voyage, such as CO_2 and PM10. It is important to note that in practice, a combination of these strategies is necessary to find the best solution. For this research, however, these strategies are assumed mutually exclusive for research purposes.

To define these strategies, the goal of the research, the functioning of the model and the experiment setup were taken into account. The relevant functioning of the model can be found in Table 3.4.2 and the experiment setup can be found in subsection 3.4.5. Taking into account these aspects, it was decided to define the strategies as the minimization of the corresponding operational performance indicator, calculated using OpenTNSim (Table 3.4.2). In other words, when choosing the time strategy, a simulation scenario is preferred where the voyage duration is minimal.

Overall, the three defined strategies provide a basic framework for evaluating the performance of the different simulation scenarios. These strategies will allow basic decision-making based on factors such as time, costs, and emissions by evaluating the corresponding performance indicators calculated using OpenTNSim. The following section describes how this process was realized.

Automated decision-making

In order to enable automated decision-making, a Rule-Based Algorithm (RBA) and Multi-Criteria Decision-Making (MCDM) were combined. An RBA uses rules to obtain knowledge from input data and is known for its simplicity and expressiveness (Dash et al., 2017). An MCDM is a method that supports decision-making by considering different qualitative and/ or quantitative criteria relating to the best solution (Taherdoost & Madanchian, 2023). Figure 3.16 shows a simplified schematic of the RBA and Table 3.3 shows the MCDM. These two methods were chosen as they were the simplest and most effective ways to reach the objective. The code corresponding to this can be found in section A.2.

The goal of the automated decision-making was to take the evaluation of the simulation scenarios and determine the preferred scenario based on a specific chosen strategy. The evaluations of the simulation scenarios are stored in easily accessible data types called 'DataFrames'. These DataFrames form a convenient framework for the MCDM. The relevant results and calculations described in Table 3.4.2 are stored in three different columns, representing the three different criteria. Depending on the chosen strategy, the criteria are combined differently, as shown in the equations below. The result of the MCDM is a preferred scenario and is a part of the RBA.

$$\text{Time} \rightarrow X_1 = T_1 + (0 \cdot C_1) + (0 \cdot E_1) \tag{3.3}$$

$$\text{Costs} \rightarrow X_1 = (0 \cdot T_1) + C_1 + (0 \cdot E_1) \tag{3.4}$$

$$\text{Emissions} \rightarrow X_1 = (0 \cdot T_1) + (0 \cdot C_1) + E_1 \tag{3.5}$$

The RBA is designed to be run during the sailing of a vessel to iteratively determine the best scenario and thus operational parameters. The strategy should be provided by the user and forms the input for the MCDM together with the results of the simulation scenarios. From the MCDM, a preferred scenario is found and this is used to extract the corresponding operational parameters from. These then form the input for the control system of the ship.

The above methods are relatively simple and more complex algorithms and decision-making systems would provide better-optimized solutions. This is not the objective of the research and the methods are assumed to be effective in providing automated decision-making, considering the objectives and limited time available for this research.

	Criteria			
Alternatives	**Time**	**Costs**	**Emissions**	**Total**
1	T_1	C_1	E_1	X_1
2	T_2	C_2	E_2	X_2
3	T_3	C_3	E_3	X_3
4	T_4	C_4	E_4	X_4
5	T_5	C_5	E_5	X_5
6	T_6	C_6	E_6	X_6
7	T_7	C_7	E_7	X_7
8	T_8	C_8	E_8	X_8
9	T_9	C_9	E_9	X_9
10	T_{10}	C_{10}	E_{10}	X_{10}
11	T_{11}	C_{11}	E_{11}	X_{11}
12	T_{12}	C_{12}	E_{12}	X_{12}

Table 3.3: MCDM matrix used to determine the preferred alternative. Each criterion is represented by a performance indicator, varying per alternative. 'X' is the weighted sum of all performance indicators, allowing for comparison and evaluation of all alternatives, relative to each other.

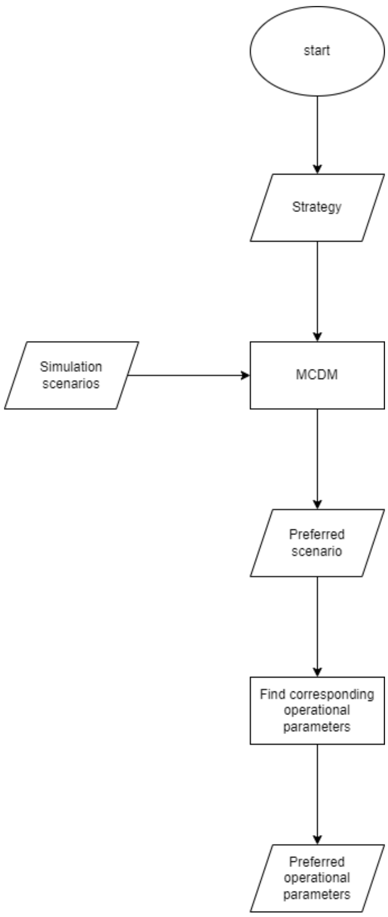


Figure 3.16: Schematic of the Rule-Based-Algorithm. The algorithm takes the chosen strategy and results of the simulations as input for the MCDM. From this, a preferred scenario is taken and translated into operational parameters for the vessel.

Automated operational implementation

After the decision-making, a method was created to implement the preferred operational parameters. It was decided to take the operational parameters from the preferred simulation scenario and use the ROS-OpenTNSim connection to impose them on the ship. In this research, the considered operational parameters are velocity and route. For the velocity, this was a straightforward process where the preferred velocity was published on the reference velocity topic, from which the vessel takes the velocity it is supposed to sail. In other words, we can just tell the vessel the velocity we want it to sail, and it uses its control systems to approach this velocity as accurately as possible.

For the route, this was more challenging, as the route you want to send to the vessel is dependent on the route it has already travelled. To solve this problem, the travelled route was stored and removed from the future routes. This can be seen in the 'update_route' functionality in section A.3.

Given the scope of the research and the time available, the developed solution was relatively simple. This method could be improved by developing a more dynamic routing system. This is discussed in more detail in chapter 5.

3.4.5. Experiment Port Call setup and procedure

This section describes the setup and procedure of the Port Cal experiment. This experiment was designed with the objective to test the automated response to situational awareness information in a logistics scenario. The setup consisted of the Tito Neri Dark Blue and a virtual version of the Tito Neri Dark Green and was at the 3ME Pond. Figure 3.17 show the required components for this experiment. The added component here is the 'Port Call module' component. This represents the developed Port Call module (section A.3). In summary, this module is responsible for the iterative determination of the optimal route and speed for the Tito Neri Dark Blue based on simulations and real-time locational data of the Tito Neri Dark Green. I.e., it is responsible for automated response to situational awareness information. The Port Call experiment required the development of three new components. A new network had to be created, based on the scaled-down logistics scenario, the OpenTNSim Operator module was developed, and the virtual version of the Tito Neri Dark Green (Ghost Ship) was developed.

For the procedure of the experiment, six variants were determined by dry runs of the decision-making model, of which four were executed. The goal was to test the automated behaviour of the Tito Neri based on the chosen strategy and logistics information, more specifically berth availability. As the model is based on simulations, these could already be done to test the outcomes before the actual experiment. These dry runs showed for each combination of strategy and berth availability which scenario would be the outcome. From this, six variants arose and these are shown in Table 3.1. These outcomes are based on the specific inputs and calculation method as described in the methods above. Of the 6 variants shown in Table 3.4, only four were executed in the experiment. The two variants from the 'costs' column were not executed. This was

		Strategy		
		Time	Costs	Emissions
Berth availability	TRUE	7	7	11
	FALSE	8	7	12

Table 3.4: The chosen alternatives (Table 3.1) per strategy and berth availability. These have been determined by doing simulations of the experiment and they form the six variants that will be executed.

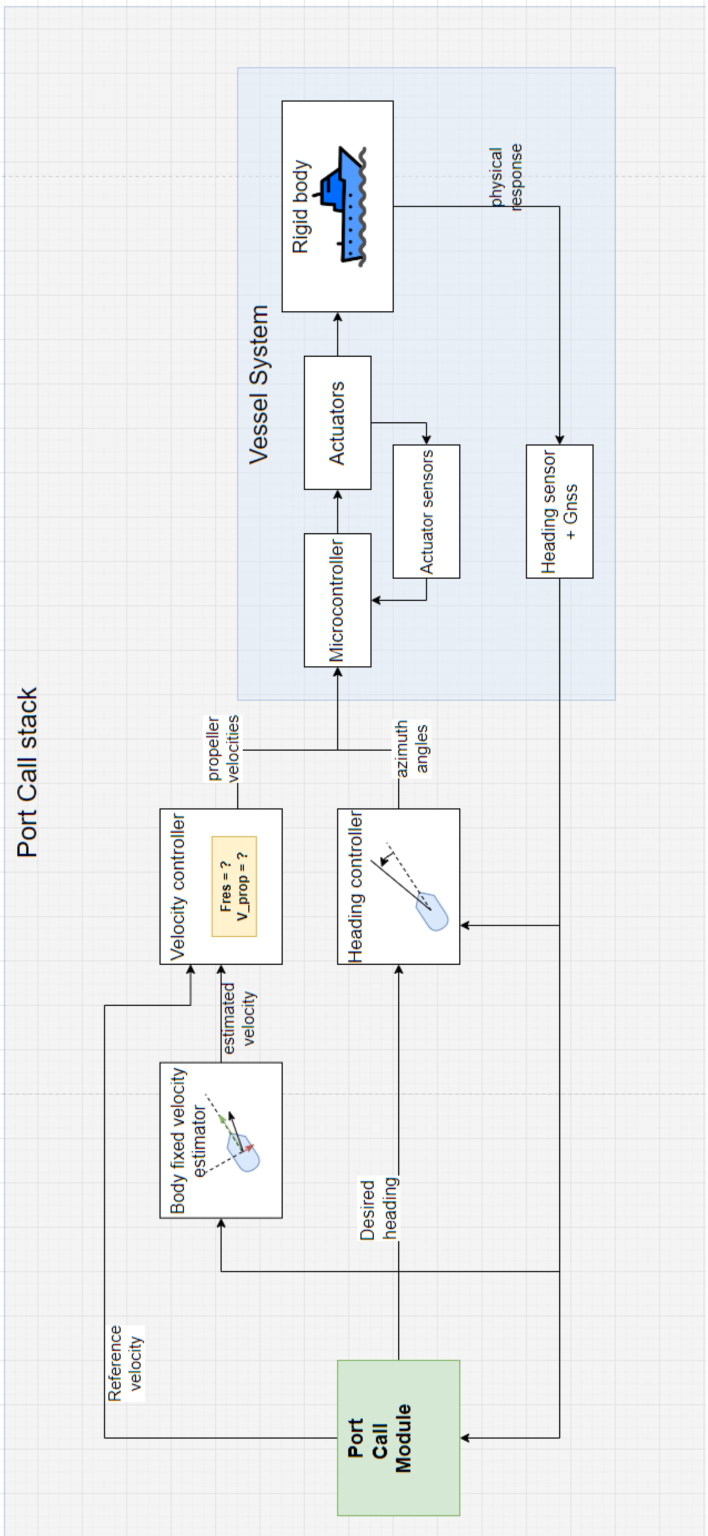


Figure 3.17: The collection of components required for the Port Call experiment (by Bart Boogmans)

decided because these would be practically the same as the execution of the variant for the 'Time' column and the 'TRUE' row. So proving the variants of the 'costs' column would be trivial if the other variants were all executed correctly. This saved valuable time and reduced the risk of practical delays. Before each experiment, the strategy choice was hard-coded into the Port Call module and the berth availability was realized by the placement of the virtual Tito Neri DG. A location in the pond was designated to serve as a berth. If the virtual vessel was at this location, the berth was unavailable and vice versa. At the start of each variant of the experiment, the vessel system, velocity controller, heading controller and virtual Tito Neri DG had to be started. To commence the experiment, the Port Call module was started. After the completion, these systems were all shut down and the Tito Neri Dark Blue was sailed back to the starting point via joystick. Appendix C shows a log of the experiments.

Additional simulation

After the Port Call experiment, an additional, virtual version of the experiment was conducted to collect additional data and test a slightly different procedure. This virtual experiment was conducted using virtual versions of the Tito Neri Dark Blue and the Tito Neri Dark Green and allowed for the testing of scenarios that were not tested in the physical experiment. In the physical experiment, the position of the Tito Neri Dark Green, and thus the berth availability, was kept constant. These experiments can prove that the vessel can display the correct behaviour based on the available logistics information. However, the goal of the experiment is to test a response to the logistics information.

To further test the capability of the automated response, it was decided to vary the berth availability during the virtual experiment. This will be done by having the berth be unavailable at first, and then changing this after the vessel has sailed a part of the route. The observed route and speed choices during this experiment can then be used to evaluate the vessel's ability to automatically change its route and speed as a response to new information. The results of this additional simulation are described in section 4.3

Data analysis

To analyze the automated response capability, recordings of all communication on ROS were made and a video recording of the experiment was made. The relevant data collected through these methods are:

- the vessel position (for both vessels)
- the reference vessel velocity
- the reference route
- the berth availability

3.5. Summary

This section provides a summary of this chapter and aims to answer the related research sub-questions:

- What are the challenges for integrating autonomous technology and maritime logistics simulation?
- How can the integration of autonomous technology and maritime logistics simulation be tested and validated in a lab-scale environment, to reach the research objective?

In chapter 3, the materials and methods that were used to reach the research objective are described. This consisted of developing different software modules and testing the accomplished integration by conducting three lab-scale experiments. This is summarized in the following paragraphs.

The Green Routing experiment showed the bridge between the control system of the autonomous vessel, operated via ROS, to the simulation environment of OpenTNSim. A real-time variant of OpenTNSim was developed together with a communication component that could expose the state of the OpenTNSim simulation with the ROS system. This experiment showed that the path provided by the simulation was followed by the autonomous vessel.

The Green Steaming experiment showed that the vessel could also adapt its speed based on information from the simulations. An additional communication component capable of providing the vessel with a reference velocity was developed. Together with the green routing capability, this forms the basis for more complex experiments.

The Port Call experiment showed a potential use case of green routing and green steaming capabilities. A logistic scenario was scaled down to fit the lab-scale environment. While the vessel was sailing, every five seconds, twelve simulations were computed depending on the vessel's real-time position. The scenarios varied in engine order and route choices, resulting in varying emissions, fuel, and cost. Logistic situational awareness information was added in the form of berth availability. An automated, tactical, response to situational awareness information was tested. This approach, using a real-time version of a vessel in the OpenTNSim simulation software, aims to enable predictive simulations to facilitate the chosen tactics based on a given strategy, resulting in correct operational decision-making.

The answer to the second research sub-question was found while developing and testing the software modules and during the conducted experiments. A combination of technical and practical challenges was found. It should be noted that the found challenges should be considered in the context of this research, where practicality and the lab scale played a significant role. The experienced challenges can be divided into four general areas: software integration, hardware-software integration, model validation, and experimental reproducibility.

Firstly, the integration of different software modules and programming languages posed challenges. The provided autonomous technology was designed using Matlab and ROS and the simulation software was written in Python. Furthermore, the autonomous technology functioned on a real-time messaging-based communication system, while the simulation software relied on offline, batch-processing of code. So, not only the different systems had to be aligned and able to communicate, but also the different temporal environments had to be aligned.

Secondly, some challenges were found when integrating the hardware and software components in the experiments. During an experiment, multiple computers, the vessel's hardware components and GPS receivers had to be running and communicating with the developed software modules. Besides initializing or starting up all these components, it was also crucial to do this in the correct order and on the same network. Aligning all these components was not complex, however, it did pose challenges during the research.

Thirdly, some challenges were found when developing accurate simulation models that would represent the essence of maritime logistics, as well as the lab-scale environment in which the experiments were conducted. The simulation software was designed for logistics scenarios at a real-life scale. Aligning this with the lab-scale environment was not always possible, given the scope and time of this research. This resulted in a difficult validation of the simulation model and inhibited the use of quantitative results for parts of the research.

Lastly, challenges were experienced with the reproducibility of experiments. The experiments were conducted outside in a non-controlled environment. And considering the high number of hardware components and software components that had to be aligned, a number of practical issues occurred. The saying 'lots of moving parts', means a situation with a lot of variables and components, applied. This influenced the reproducibility of the experiments negatively and made it difficult to generate significant and reliable quantitative data. The answer to sub-question #3 elaborates on the way this was handled in this research.

The answer to the third research sub-question lies in the applied methodology for the experiments. To reach the research objective, a combination of Hardware-in-the-Loop (HIL) and scenario-based testing was done. For scenario-based testing, it was crucial that the experiment scenarios contained the logistic essence that one aimed to test and would prove the method's potential. This was done by simplifying a common logistic process that would lay emphasis on the decision-making process following the input of logistic information. By designing a simple experiment in which an autonomous vessel was given three operational options as a response to a delay of an upstream vessel, a scenario was created where simulation could be used to support decision-making. The validation of this experiment was done by quantifying and qualifying the response options that were tested and collecting data that could prove the correct execution of these responses.

4
Results

The objective of this research is to develop a practical method that integrates autonomous technology and logistics simulation to respond to situational logistics information to improve maritime operations. A model was developed, and three experiments were conducted to reach this objective. This chapter describes the results of the Green Routing, Green Steaming and Port Call experiments. This chapter also answers the question of how the integration of autonomous technology and maritime logistics simulation software improves the efficiency and sustainability of maritime operations. It does this by assessing the capability of the developed method to realize automated operational decision-making based on strategic goals following situational awareness information.

All results data can be found on the following online repository on Zenodo (van Gijn et al., 2023)

4.1. Experiment Green Routing

This section shows the results of the Green Routing experiment. The goal of this experiment was to test the ROS - OpenTNSim connection, test the Green Routing capability at different RPM and find the functional RPM limits. Besides this, this experiment was also done to find the challenges associated with integrating autonomous technology and maritime logistics software and more specifically with integrating a ROS-based control system with OpenTNSim. For this experiment a module was created that connects ROS and OpenTNSim and an experiment was set up where the Tito Neri Dark Blue sailed a constant route at different RPM in the outdoor 3ME Pond.

4.1.1. Results overview

To show that it is possible to adapt routing based on situational awareness information and a simulation-based model we conducted the Green Routing experiment. The first challenge in this experiment was to integrate the developed software components with the existing software and hardware components. The second challenge was to have the vessel sail a path depending on its location and the imposed route. This experiment was conducted successfully on 30-1-2023. The following checks were done to confirm the successful execution:

- A stable connection between ROS and OpenTNSim was established.
- The Tito Neri Dark Blue managed to successfully navigate and complete the predetermined route for every RPM.
- Functional limits were found for the RPM. At the lowest RPM (800), the ship's heading control became unstable, mainly due to heavy wind.
- Data was collected on the vessel's performance, including the vessel's position and heading.

- Analysis of the data showed that the vessel correctly sailed the route but with varying levels of accuracy for the different RPM.

RPM	Completed route?	Average velocity [m/s]	Average absolute heading error [rad]
800	yes	0.21	0.380
1200	yes	0.36	0.294
1600	yes	0.45	0.322
2000	yes	0.59	0.296

Table 4.1: Overview of the relevant data from Experiment Green Routing

4.1.2. Results presentation and analysis

For the Green Routing experiment, a circle-shaped OpenTNSim route was translated into ROS messages on the reference heading. Figure 4.1 shows the sailed path at 800 RPM and 1200 RPM, and the circle-shaped route. The results show that the vessel was able to reach the corresponding waypoints by reaching the waypoint acceptance radius for both RPM. These are the grey circles in the figure and are described in subsection 3.2.2. These specific results show that for the lowest RPM, 800, some instability occurred in the sailed path. This was due to an average wind speed of 8-9 m/s and wind gusts of up to 14 m/s (WindFinder app). At this RPM, and given the settings of the PID heading controller, the vessel was not always able to counteract the forces from the wind, resulting in the missing of a waypoint or the physical turning of the vessel. This then resulted in the need for compensation, which is shown by the irregular paths. This shows that for these conditions and at 800 RPM, the vessel was able to follow the provided route but in an inefficient and irregular manner. At 1200 RPM, the sailed path is significantly smoother. Still, a slight leftward translation is observed. This can be accounted to the wind. From these results, it was decided that for the following experiments, in windy conditions, the lower functional RPM limit should be set to 1200 RPM. For conditions with minimal wind, 800 RPM can be used as the lower limit.

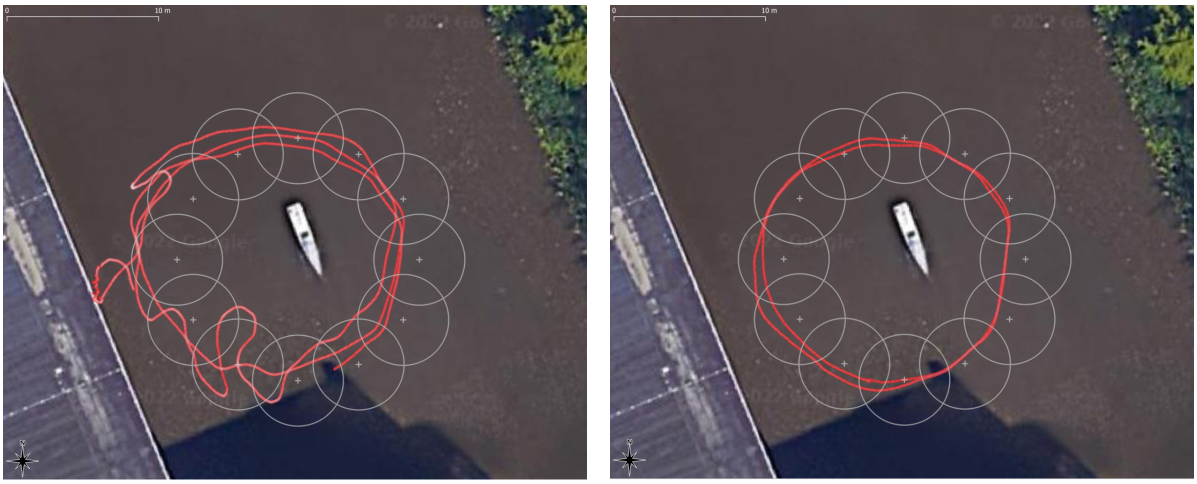


Figure 4.1: Sailed paths of the Tito Neri Dark Blue during Experiment Green Routing (left: 800 RPM, right: 1200 RPM). The grey circles represent the waypoint acceptance criteria. If the vessel moves within this radius, it is considered to have reached the waypoint and the next one is generated

Figure 4.2 shows the sailed paths for 1600 and 2000 RPM. For both of these RPM, the sailed path is also relatively smooth. Again, a slight leftward translation can be seen and there was some instability due to the wind. A noticeable and significant difference was found when comparing the average velocities of the vessel at different RPM. At 1600 RPM an average velocity of 0.45 m/s was found and at 2000 RPM an average velocity of 0.59 m/s was found.

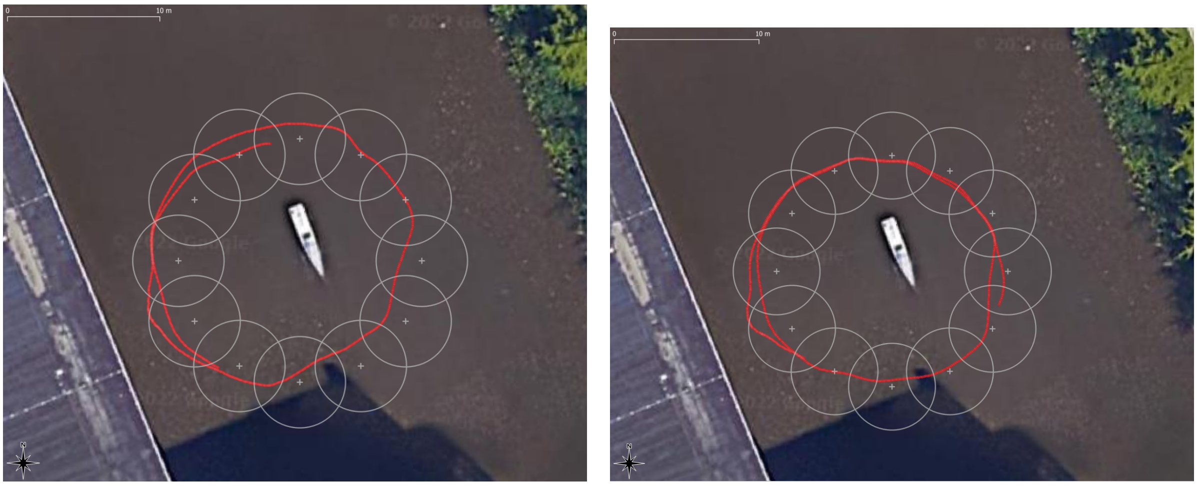


Figure 4.2: Sailed paths of the Tito Neri Dark Blue during Experiment Green Routing (left: 1600 RPM, right: 2000 RPM). The grey circles represent the waypoint acceptance criteria. If the vessel moves within this radius, it is considered to have reached the waypoint and the next one is generated

The positional data of the Green Routing experiment was also used for the analysis of the velocity profiles of the vessel for the different RPM. This data was used to test data processing and filtering methods that would later be used in the development of the velocity controller. The time derivative of the positional data was taken to determine the velocity. From this velocity data, outliers (>10 m/s) were removed and a Butterworth filter was applied. Figure 4.3 shows the results of these methods.

4.2. Experiment Green Steaming

This section shows the results of the Green Steaming experiment. The goal of this experiment was to test the Green Steaming capability. This was tested by letting the Tito Neri Dark Blue sail a predetermined constant route, during which alternating reference velocities were sent to the vessel as ROS messages. By measuring the actual velocity of the vessel and comparing it to the reference velocity, a conclusion could be made regarding the Green Steaming capability. For this experiment, a PID velocity controller was developed as described in subsection 3.3.1. It should be noted that this controller was in the development phase during this research. This means that the main goal was to reach an acceptable working state and not a perfectly accurate working state. An unexpected window in the scheduling presented itself, this allowed the experiment to be conducted without the main author of this thesis present. The data were analyzed with the main author present.

4.2.1. Results overview

To show that it is possible to adapt velocity based on situational awareness information and a simulation-based model we conducted the Green Steaming experiment. The challenge was to differentiate the live locational data and use it to accurately determine and control the vessel's velocity. Experiment Green Steaming was successfully conducted on 1-3-2023. The following checks were done to confirm the successful execution:

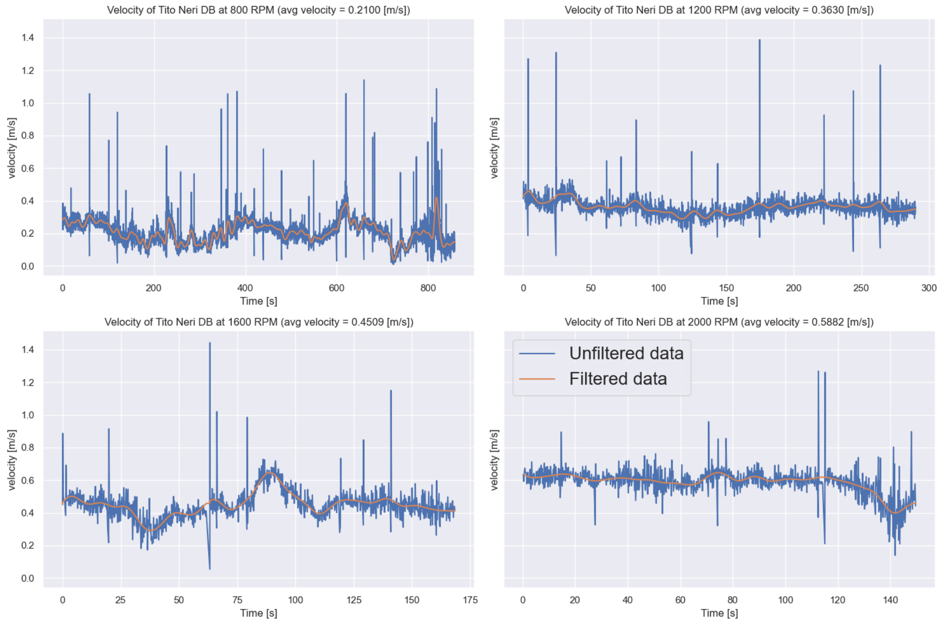


Figure 4.3: Velocity profiles of the Tito Neri DB for the Green Routing experiment. These profiles were found by differentiation of the positional data. Outliers (>10 m/s) were removed and a Butterworth filter was applied.

- Velocity control was reached (to a certain degree of accuracy): the Tito Neri Dark Blue managed to sail a predetermined route at alternating velocities corresponding to the alternating reference velocities.
- Data was collected on the vessel's performance, including the vessel's position, heading and velocity.
- Analysis showed that the correct messages were sent during the experiment.

4.2.2. Results presentation and analysis

For the Green Steaming Experiment, a square wave generator provided alternating reference velocities for the Tito Neri Dark Blue. Figure 4.4 shows the reference velocity and the actual velocity sailed by the vessel. The results show that the actual velocity roughly approximates the reference velocity. The velocity controller is not capable of exactly reproducing the reference velocity. However, these results do prove that it is possible to change the vessel's velocity with an external input. This level of velocity control was sufficient for the execution of the Port Call experiment.

The velocity data was relatively rough because no differential GPS (RTK GNSS) receiver was used during the Green Steaming experiment. Due to this, there were relatively big errors in the positional measurements. These measurements were differentiated to find the actual velocity. I.e, noisy input data was differentiated, which produced noisy output data. For the Port Call experiment, there was a differential GPS receiver. Figure 4.5 shows the reference and actual velocity for the Tito Neri Dark Blue for test 3 of the Port Call experiment. This shows that the accuracy of the velocity control greatly improves when a differential GPS receiver is used.

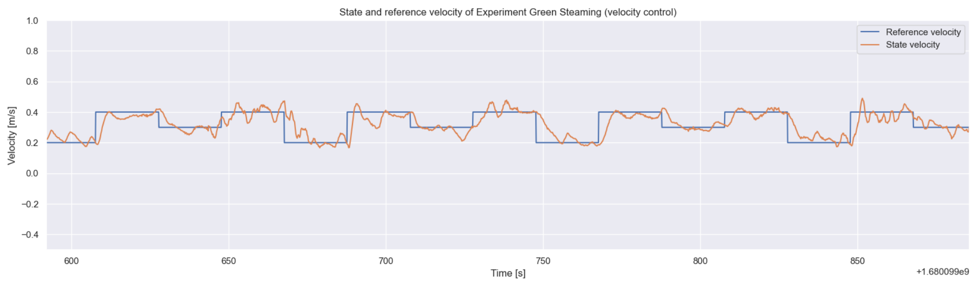


Figure 4.4: State and reference velocity of Tito Neri vessel measured during experiment Green Steaming (without RTK GNSS receiver).

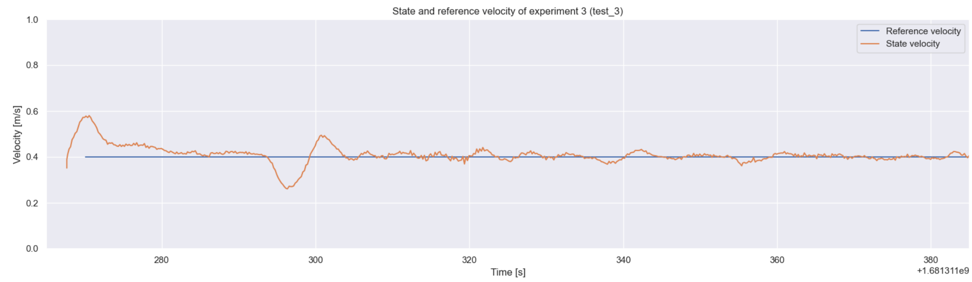


Figure 4.5: State and reference velocity of the Tito Neri vessel measured during test 3 of the Port Call experiment (with RTK GNSS).

4.3. Experiment Port Call

This section shows the results of the Port Call experiment. The goal of this experiment was to test the automated response to logistic situational awareness information. This was done by recreating a logistic process at a lab scale and observing the behaviour of the Tito Neri Dark Blue for different strategies and berth availabilities. The berth availability was determined according to the position of a virtual, additional ship, the Tito Neri Dark Green. The translation of vessel position into berth availability serves as the logistic situational awareness. This experiment also provides data to answer research sub-question 3 and to help answer sub-question 4. For this experiment, a real-life logistic scenario was scaled down to fit a lab environment, scenario simulation was applied to translate strategy into operation and a virtual operator was created to provide automated decision-making.

4.3.1. Results overview

To show that it is possible to adapt routing and speed based on situational awareness information and predefined strategies by using a simulation-based model we conducted the Port Call experiment. The main challenge was to run all involved software components and realize correct communication between every component. This experiment was successfully conducted on 12-4-2023. The following checks were done to confirm the successful execution:

- The Tito Neri Dark Blue managed to sail the correct route, at the correct reference velocity, for the given strategy and berth availability, for all variants.
- Data was collected on the vessel's performance, including the vessel's position and velocity and the decisions made by the Operator.
- Analysis showed that the correct messages were sent during the experiment.

- An additional simulation provided results that support the adaptability of the described response mechanism.

4.3.2. Results presentation and analysis

For the Port Call experiment, different combinations of strategy and berth availability were set up (Table 3.4), resulting in different chosen alternatives. It was decided to conduct the experiment for four cases. the results of these are described below.

Case 1: Strategy: Emissions, Berth available: No

For this case, the Emissions strategy was chosen and the Tito Neri Dark Green was at the berth location, so the berth was **not** available. The chosen alternative corresponding to this is alternative 8. This means that the redirect route should be chosen and an engine order of 0.8 (Table 3.1).

The results below show that the Tito Neri Dark Blue sailed the redirect route at a velocity of 0.4 m/s (= max velocity · engine order = 0.5 · 0.8). Observation of the messages that were sent, showed that the correct scenario was chosen given the situation. Furthermore, the results show that the chosen scenario was successfully implemented.

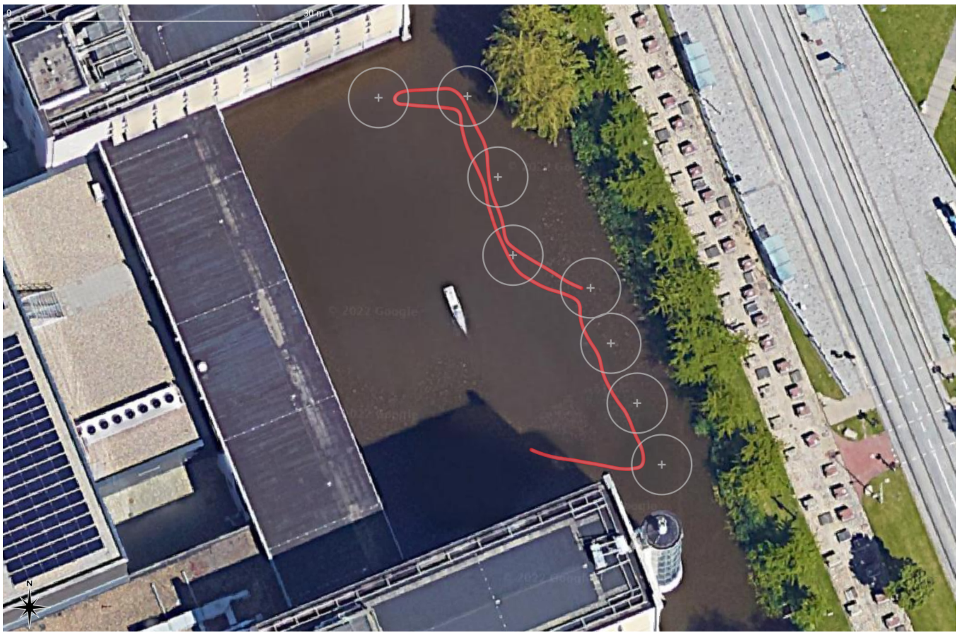


Figure 4.6: Sailed path of the Tito Neri Dark Blue during Port Call experiment (Strategy: Emissions, Berth available: No, Alternative: 8)

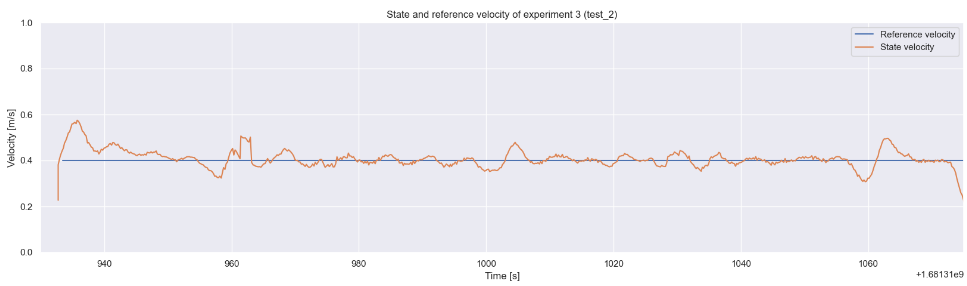


Figure 4.7: Reference and state velocity of the Tito Neri Dark Blue for the Port Call experiment (Strategy: Time, Berth available: No, Alternative: 8)

Case 2: Strategy: Emissions, Berth available: Yes

For this case, the Emissions strategy was chosen and the Tito Neri Dark Green was not at the berth location, so the berth **was** available. The chosen alternative corresponding to this is alternative 7. This means that the direct route should be chosen and an engine order of 0.8 (Table 3.1).

The results below show that the Tito Neri Dark Blue sailed the direct route at a velocity of 0.4 m/s (= max velocity · engine order = 0.5 · 0.8). Observation of the messages that were sent, showed that the correct scenario was chosen given the situation. Furthermore, the results show that the chosen scenario was successfully implemented.

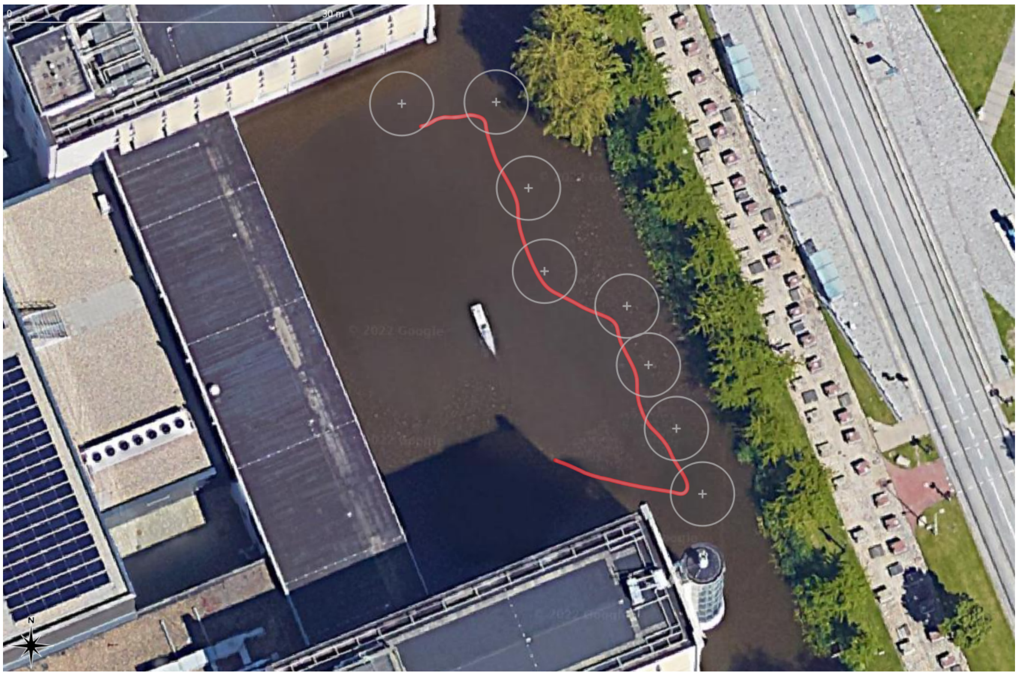


Figure 4.8: Sailed path of the Tito Neri Dark Blue during Port Call experiment (Strategy: Emissions, Berth available: Yes, Alternative: 7)

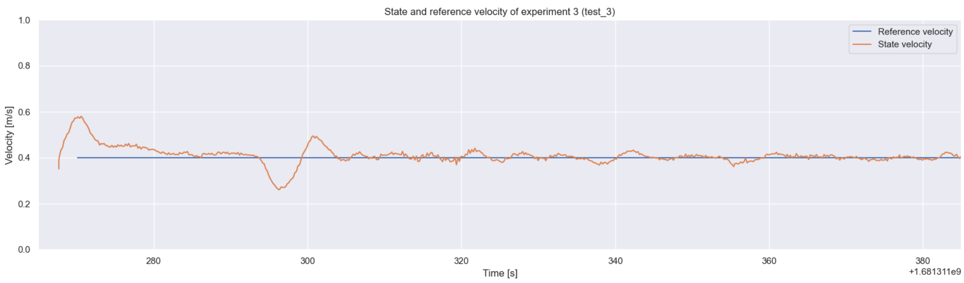


Figure 4.9: Reference and state velocity of the Tito Neri Dark Blue for the Port Call experiment (Strategy: Time, Berth available: Yes, Alternative: 7)

Case 3: Strategy: Time, Berth available: No

For this case, the Time strategy was chosen and the Tito Neri Dark Green was at the berth location, so the berth was **not** available. The chosen alternative corresponding to this is alternative 12. This means that the redirect route should be chosen and an engine order of 1.0 (Table 3.1).

The results below show that the Tito Neri Dark Blue sailed the redirect route at a velocity of 0.5 m/s (= max velocity · engine order = 0.5 · 1.0). Observation of the messages that were sent, showed that the correct scenario was chosen given the situation. Furthermore, the results show that the chosen scenario was successfully implemented.

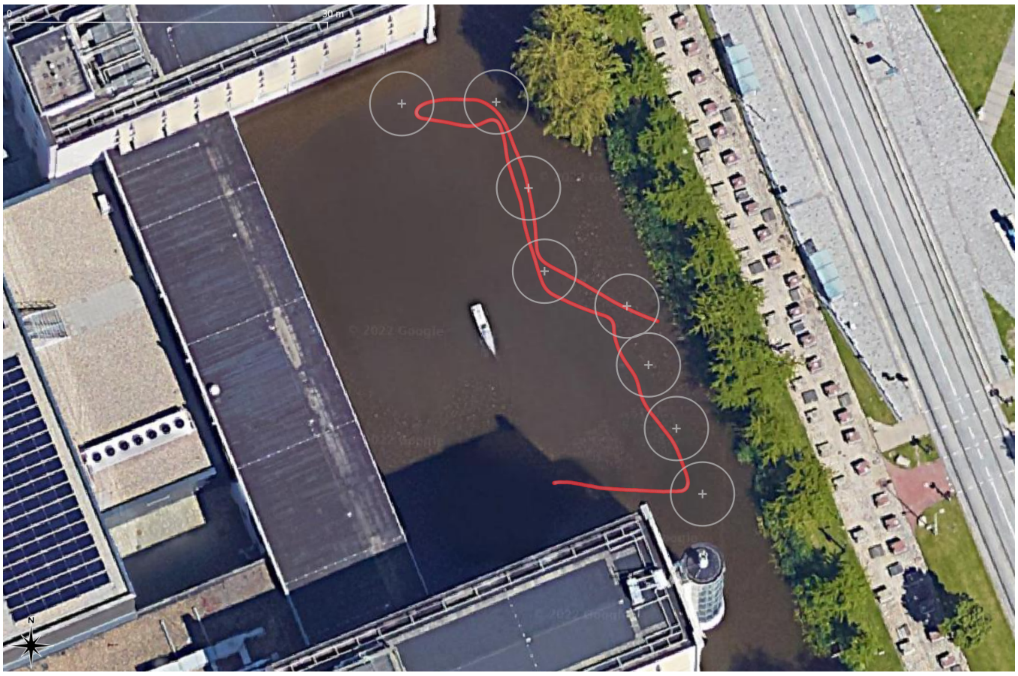


Figure 4.10: Sailed path of the Tito Neri Dark Blue during Port Call experiment (Strategy: Time, Berth available: No, Alternative: 12)

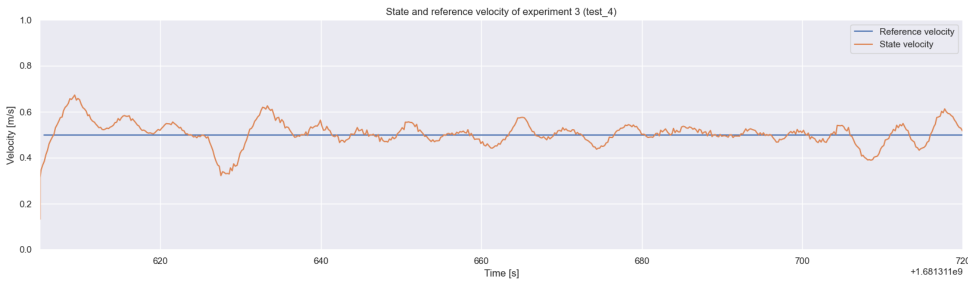


Figure 4.11: Reference and state velocity of the Tito Neri Dark Blue for the Port Call experiment (Strategy: Time, Berth available: No, Alternative: 12)

Case 4: Strategy: Time, Berth available: Yes

For this case, the Time strategy was chosen and the Tito Neri Dark Green was not at the berth location, so the berth **was** available. The chosen alternative corresponding to this is alternative 12. This means that the direct route should be chosen and an engine order of 1.0 (Table 3.1).

The results below show that the Tito Neri Dark Blue sailed the direct route at a velocity of 0.5 m/s (= max velocity · engine order = 0.5 · 1.0). Observation of the messages that were sent, showed that the correct scenario was chosen given the situation. Furthermore, the results show that the chosen scenario was successfully implemented.

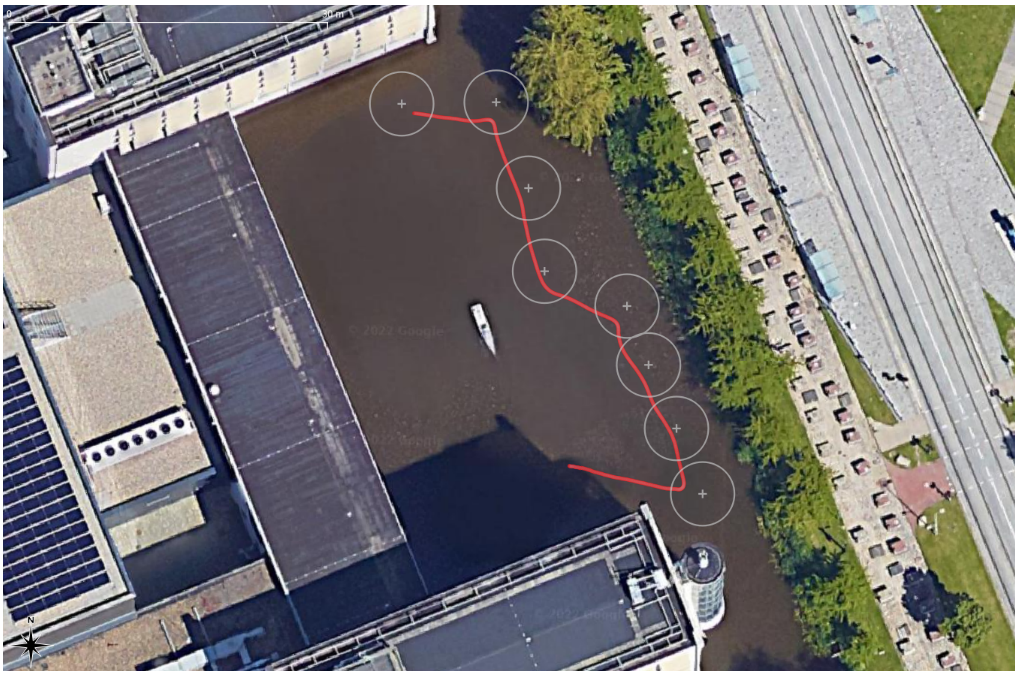


Figure 4.12: Sailed path of the Tito Neri Dark Blue during Port Call experiment (Strategy: Time, Berth available: Yes, Alternative: 11)

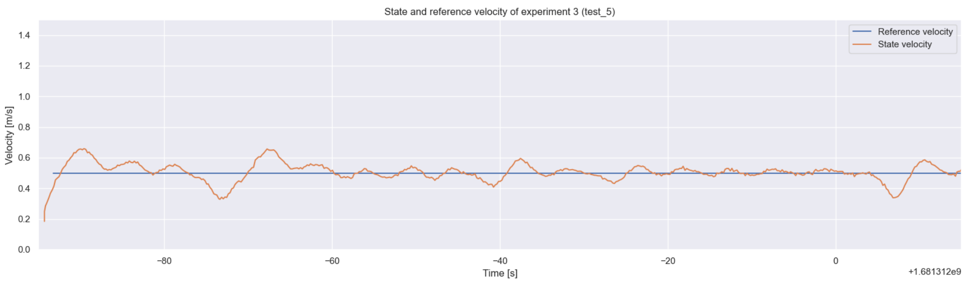


Figure 4.13: Reference and state velocity of the Tito Neri Dark Blue for the Port Call experiment (Strategy: Time, Berth available: Yes, Alternative: 11)

Additional simulation experiment: Strategy: Emissions, Berth available: No and Yes

To provide supportive proof of the adaptability of the automated response mechanism, an additional simulation experiment was conducted where the berth availability was changed during sailing. This experiment serves to prove that the vessel is capable of changing and adapting its route (and potentially velocity) during sailing. This was done by recreating Case 1 of the Port Call experiment, virtually. The difference for this simulation was that the berth availability was changed from No to Yes when the vessel was between the second and third waypoints. This was done by changing the location of the Tito Neri Dark Green from the berth location to an arbitrary, different location in the 3ME Pond. The following figure show screenshots of the Foxglove Studio application that was used to replay the recordings of the additional simulation experiment. Figure 4.14 shows the location of the Tito Neri Dark Green and the route choice for the Tito Neri Dark Blue before the change of berth availability. Figure 4.15 shows the same data after the change of berth availability.

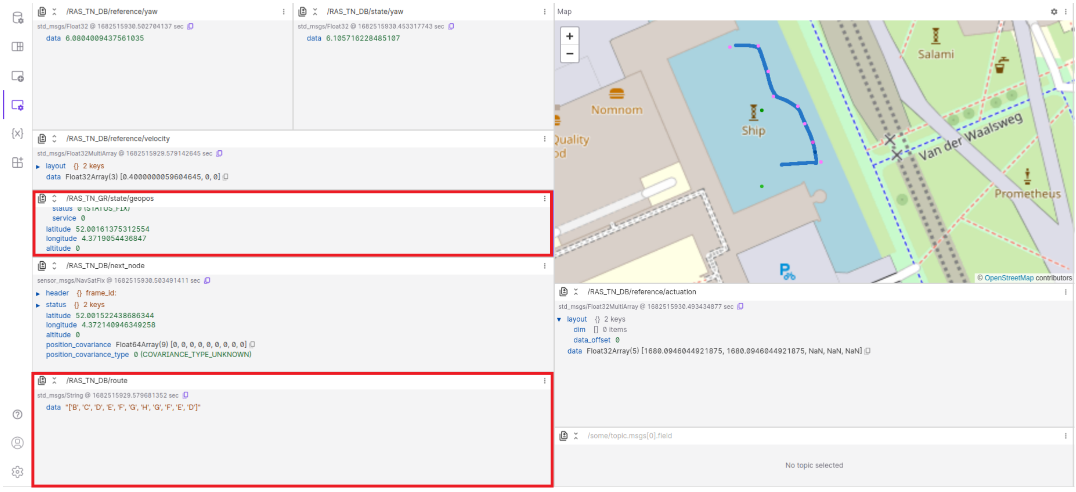


Figure 4.14: Screenshot of the Foxglove Studio application during the replaying of the recording of the additional simulation experiment. This screenshot was taken before the changing of the berth availability (note the location of the Tito Neri DG) and shows the vessel following the redirect route (note the route choice of the Tito Neri DB).

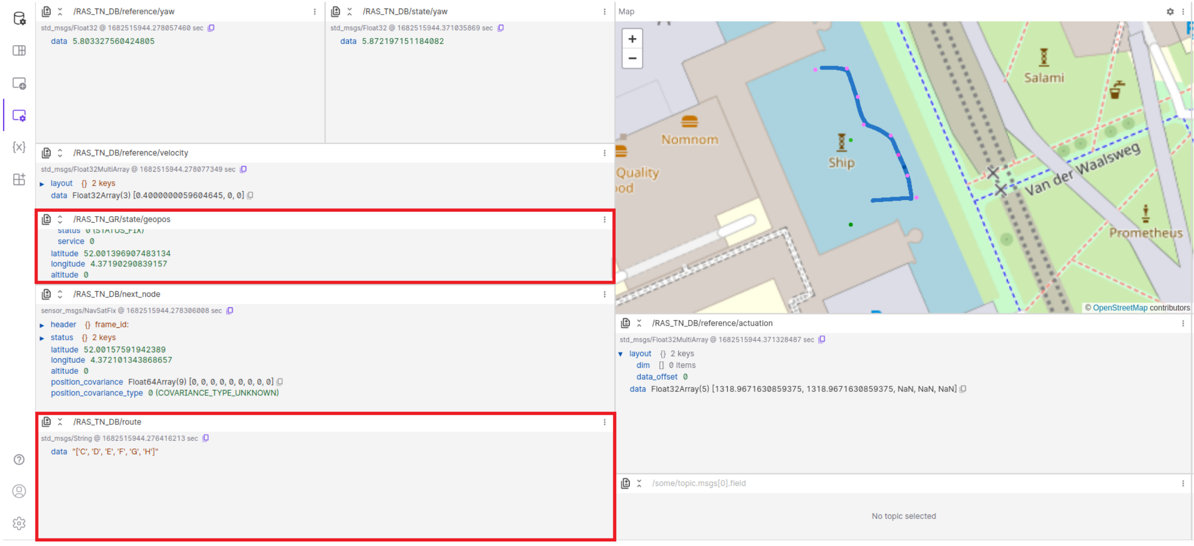


Figure 4.15: Screenshot of the Foxglove Studio application during the replaying of the recording of the additional simulation experiment. This screenshot was taken after the changing of the berth availability (note the location of the Tito Neri DG) and shows the vessel following the direct route (note the route choice of the Tito Neri DB).

4.4. Summary

This section provides a summary of this chapter and aims to answer the related research sub-question: 'How can the integration of autonomous technology and maritime logistics simulation improve the efficiency and sustainability of maritime operations?'. In chapter 4, the results of the conducted experiment were presented and analysed.

The results of Experiment Green Routing showed that a stable connection between ROS and OpenTNSim was established. Additionally, the Green Routing capability was tested successfully. The controlled vessel managed to navigate and complete a route, provided by the simulation software. Furthermore, functional limits for the vessel's RPM range were found and used in the development of a velocity control system.

The results of Experiment Green Steaming showed that a basic level of velocity control was reached by the newly developed velocity controller. The functioning of the velocity controller enables the Green Steaming capability, the objective of this experiment.

The results of Experiment Port Call showed that for a varying berth availability and chosen strategy, the system was able to determine and implement the correct simulation scenario. This meant that the vessel was able to respond automatically to varying logistic situational awareness information, the objective of the experiment.

The answer to the fourth research sub-question can be determined by the potential of the developed and tested method. The developed and tested method proves that (at lab-scale) logistic situational awareness information can serve as input for an automated system that uses simulation to determine the preferred way to respond, given a predefined strategy. In this specific research, it was shown that a lab-scale autonomous vessel was capable of applying the tactics of Green Steaming and Green Routing as a response to information on berth availability. Due to the scope and limitations of the research and the consequent experimental setup, no quantitative data on improved efficiency or sustainability was found. However, research on the applied tactics proves the potential for improved efficiency and sustainability of maritime operations. This is further discussed in chapter 5 and chapter 6.

5 Discussion

This chapter will discuss the results presented in chapter 4. First, the limitations of the study will be addressed. Then, the main results will be interpreted and finally, the practical implication of the findings will be discussed, as well as their contribution to existing knowledge.

5.1. Limitations

As for almost anything in life, this research has limitations. The limitations will be identified and acknowledged by discussing any assumptions or constraints. In this study, decisions were made regarding the used software, hardware and experimental approach. Simulations were done using OpenTNSim, communication was done through ROS, the facilities of the RAS were used and lab-scale experiments were conducted. These decisions create limitations.

5.1.1. Limitations regarding OpenTNSim

The DES software OpenTNSim was chosen because of its applicability to logistic inland shipping scenarios and the available in-house expertise. Other DES software could also have been used but would require specific modules that integrate the different software modules. However, besides this, it is expected that similar DES software can be used to create a similar system and give similar results. Also, some more specific limitations were found when using OpenTNSim.

Some assumptions and simplifications were made in the design of the software modules and the experiments and in the data analysis. The use of OpenTNSim in the software modules required some assumptions because a simulation environment had to be created. The used energy module (Baart et al., 2022) calculates quantities of emissions for the simulated logistics scenario. This method is described by Segers (2020) (Segers, 2020) and is dependent on the chosen vessel characteristics, water depth, sailed distance, sailing speed, energy consumption factors and emissions factors. The vessel characteristics can be found in Table 3.2 and the simulated water depth was 6 meters for all experiments. The energy consumption and emissions factors can be found in the energy module. The assumptions regarding the simulation environment mean that the real lab-scale vessel was represented by a virtual Large Rhine vessel. And the 3ME pond was 6 meters deep instead of the 1-1.5 meters it actually is. This means that the simulated environment bears little to no resemblance to the real environment, which means that one can not take the performance indicators from OpenTNSim and say something about the real performance. Furthermore, the route in the experiments was scaled down disproportionally to the velocity. Combining this with the disproportional vessel characteristics, it could mean that with a properly scaled experiment, the developed method could function incorrectly or at least insufficiently.

Another limiting factor can be the simulation time of five seconds. In the developed method, a simulation is done every five seconds to determine the course of action. In this study, the used model is capable of generating a simulation within a second. However current trends in logistics research show that Machine Learning (ML) models are becoming more common (Akbari & Do, 2021) and ML models vary significantly in computation time (Kumar, 2019). It is crucial that for potential developments of the developed method, this time constraint is taken into account.

5.1.2. Limitations regarding ROS

For this study, all communication between software and hardware was done through ROS. No other middleware was considered and in the context of open-source robotics middleware, ROS is the most widely used middleware. The open-source and standardized nature of ROS allows for an easy understanding of the functioning of the developed modules in this research. It is expected that this research can be adapted to the use of other middleware if necessary. However, no other middleware was studied.

5.1.3. Limitations regarding the experimental approach

For the approach of the experiments, three types were considered: simulation, lab-scale and full-scale. Full-scale experiments were not achievable given the scope and experimental nature of the research. Simulation experiments could have provided sufficient results but lacked the real-world dynamics that one experienced with practical testing. However, some limitations were found in the lab-scale testing.

The results of the conducted experiments were limited by the design of the experiment. Firstly, the simplicity of the experiments was essential to prove the potential of the developed method but it was also a limiting factor. The logistics scenario in the Port Call experiment was greatly simplified and could be deemed trivial. This is partly caused by the route generation system. Route generation was done mostly statically and in a more dynamic complex logistic scenario, this system would not be capable of showing the same results.

An assumption was also made regarding the waiting time of the Tito Neri Dark Blue vessel in the Port Call experiment, in case the berth was unavailable. OpenTNSim does not allow for non-moving vessels, so it was manually added that the berth was unavailable for 20 seconds for the scenarios with the direct route. This delay of 20 seconds was chosen to fit the use case and did not rely on any research or statistics. Due to the disproportional scaling, it would have been too complex to relate this to actual delays in inland shipping. This assumption further adds to the simplicity of the experiment.

5.1.4. Limitations regarding the research scope

Another limiting factor could be the experienced constraints in this research. Inherent to a graduation thesis, constraints were found in time, the scope of the study and facilities. Most of the above-described assumptions are a result of one of these constraints. Furthermore, additional, full-scale simulations to test and validate the potential of the developed method of improving efficiency in maritime operations were not conducted due to time constraints. These time constraints occurred due to unexpected practical issues at the research facilities.

5.2. Interpretations

The goal of this research is to support ship operators in processing and evaluating situational awareness information. This was done by developing a practical method that integrates autonomous technology and logistic simulations to respond to situational awareness information. The consequent main research question, that additionally guided this research, considers how simulation can be used to bridge the gap between strategic planning and operational decision-making in autonomous maritime logistics. Software modules were developed, and practical tests were done to reach the objective and answer this question.

The main methods of the research involve the developed software modules and lab-scale experiments. The development of the software modules resulted in an autonomous control system, operating via ROS, with the OpenTNSim simulation software in the loop. During sailing, every five seconds, twelve simulations were computed depending on the real-time position of the vessel and situational awareness information, in the form of berth availability. The simulations varied in engine order and route choices and were evaluated based on emissions, fuel and cost. Depending on a chosen strategy, the preferred simulation was chosen, resulting in an automated tactical response and corresponding operational decision-making. In this study, three experiments were conducted to test the strategy-specific behavioural response of a lab-scale autonomous vessel to logistics information.

The main findings of this study show that logistics simulation software can be used to process and evaluate situational awareness information and when added to an autonomous control system this can lead to automated strategy-specific behaviours. In this study, the evaluated situational awareness information was automatically used to control an autonomous vessel. However, instead of an automated response, the developed method can also be used to create operational decision support for ship operators. This means that the main findings show that logistics simulation software can be used to support ship operators in processing and evaluating situational awareness information.

Considering the main research question, the results of this research show a method that is able to automatically translate a predefined strategy into corresponding operational decision-making, using predefined tactics. This means that the gap between strategic planning and operational decision-making in autonomous maritime logistics can be bridged by using simulation to evaluate predetermined tactical responses with respect to predefined strategies. In this research, the applied framework for strategy, tactics and operations shows that the natural bridge between strategy and operations is tactics. Predefining and quantifying these tactics and the interfaces of these tactics with strategy and operations enables a quantifiable and deterministic method to translate strategy into operational decision-making, using simulation.

5.3. Implications

Based on the findings of this research, there are some potential practical implications. The main practical implications involve decision support for ships, operational optimization of maritime projects and 'optimal compliance' by using simulation, all with the goal to improve the efficiency and sustainability of maritime operations.

Regarding decision support for ships, the developed method could offer valuable operational decision support to ships transporting goods, by leveraging the addition of logistic situation awareness information. Currently, the sustainability of ports can be improved by bunker management and port call optimization. Both complex processes require a lot of information and extensive decision-making (European Maritime Safety Agency, 2023). With the addition of situational awareness information, the developed method could serve as decision support by processing all information and translating it into potential operational decisions, as is done in the experiments. This way the ship's crew is still responsible for the actual course of action but is supported by reducing the complexity of the process.

Regarding the operational optimization of maritime projects, the developed method could be used in projects where different maritime vessels are dependent on each other, for example in dredging. The OpenTNSim and OpenCLSim software is already being applied in the offline optimization of such projects (de Boer et al., 2022). This research has shown that OpenTNSim can be used in real-time and benefits from the addition of live logistics information. This way, it is feasible to develop a system that can operationally optimize these sorts of projects in real time, using simulation software. Besides logistic information, information on environmental conditions, fleet composition and planning should then be combined in a simulation environment.

Finally, a more ambitious practical implication could be 'optimal compliance'. Compliance refers to the act of adhering to laws, regulations, standards, and guidelines. Optimal compliance refers to complying and optimizing within the compliance boundaries. In the maritime industry, most laws, regulations, standards, and guidelines can be quantified by ship characteristics, fuel types, emission limits, and speed and route restrictions. Most of this can already be defined in the OpenTNSim software. With some additional developments, a majority of the compliance could be quantified and incorporated in a simulation environment in OpenTNSim. Using this environment to then optimize maritime operations could serve as a method to reach 'optimal compliance'. With the increasing number of (sustainability) laws, regulations, standards, and guidelines, this method could reduce complexity by using the computational power of machines.

5.3.1. Contribution to existing knowledge

This section discusses the contribution of this research to existing knowledge. First, it will be discussed how this research fits in the existing field and what gaps were addressed and potentially filled. Then, the developed method will be related to existing products to show similarities and differences.

To determine the contribution of this research to the existing research field, developments in this field have to be described. Research on the application of MASS in ports (Devaraju et al., 2018) explains that for the future of MASS in ports, many challenges have to be overcome. This was done by identifying technologies and port infrastructure for autonomous surface vessels and determining their technological readiness. This analysis shows that for autonomous technologies, computational logistic technologies and control strategies are the most important challenges that need to be addressed. It is described that current situation awareness methods should be combined with optimization models and algorithms for global planning and efficient scheduling. The technological readiness of these technologies is classified as 2, on a scale of 1-9. This means that there is a need for research that addresses computational logistics technologies and control strategies. Both of these are addressed in this research.

Liu et al. (2023) did a study in 2023 on green and intelligent inland vessels that summarizes the development status of five key technologies. Intelligent navigation is one of the considered technologies and a common architecture of autonomous control is proposed in this study to address this (Figure 5.1). The system takes inputs from ships and shore-based databases for real-time information and predicted information. Then, a decision module determines waypoints and heading angles for the control module. Furthermore, regarding energy efficiency, this study considers intelligent decision-making based on energy efficiency optimization. These optimization models can provide crew members with better suggestions on operations to achieve emissions reduction. And while this study provides several examples of the application of autonomous technologies to real vessels in experimental form, it recommends future work in the application of autonomous navigation of green and intelligent ships and green energy-efficient control of intelligent ship equipment. This research aims to address both of these recommendations.

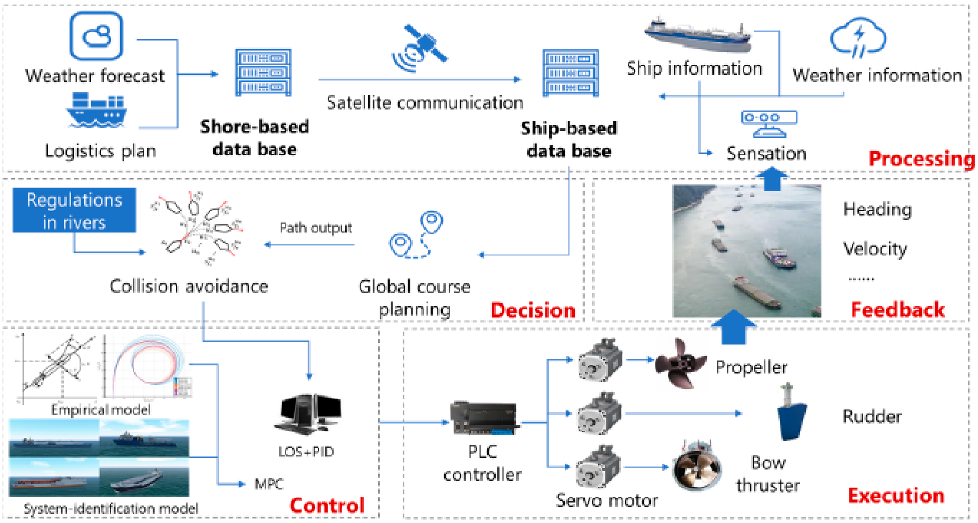


Figure 5.1: Ship control architecture (Liu et al., 2023). The diagram shows that real-time ship information can be combined with prediction information of weather and logistics to serve as input for a decision module. The decision module generates global course planning. The architecture is very similar to the architecture realized in this research. It should be noted that the architecture of this study is more advanced.

Gu et al. (2021) describe the research of autonomous shipping to be at a transition between fundamental and application. This is shown by the difference in the amount of research in the transport and logistics field when comparing autonomous shipping and autonomous vehicles. The earlier described study on MASS in ports and the Chines study confirm this transition. In this research, an effort is made to contribute to the described transition from fundamental to application, by bridging the gap between strategy and operations in maritime logistics. This research attempts to prove the application of autonomous navigation combined with green energy-efficient control by using a simulation-based model.

Besides considering this research in its research field, it is also interesting to relate it to existing products. Three examples are illustrative:

Wärtsilä Advanced Assistance Systems The Wärtsilä Advanced Assistance Systems are described as autonomy solutions ranging from smart sensors to decision support tools. Their SmartMove is a system, available to ships, that uses improved situational awareness to perform complex manoeuvres such as docking and harbour entry. The system predicts motion and provides subsequent decision support. Relating this to this research, similarities are found in the use of situational awareness to make predictions of the future and provide decision support. However, the SmartMove system makes predictions of motion whereas in this research predictions are made regarding logistics processes.

Sofar Wayfinder The Sofar WayFinder system is a dynamic voyage guidance system that provides the most efficient route and speed to your fleet by considering the vessel's performance and environmental conditions. Similarities are found in the way route and speed are dynamically evaluated to determine the optimal scenario. However, the WayFinder system is focused on optimizing a trip without considering logistics. This is where the focal point of this research is.

Awake.ai Awake.ai is a platform that aims to optimize port operations using AI. It tries to maximize port capacity, enable just-in-time arrival and improve turnaround times. Similarities can be seen in the objectives of this platform and the developed method in this research. Both systems aim to improve the efficiency of maritime operations at the interface of logistics and operations. The awake.ai system is far more advanced than the developed method from this research. However, it lacks integration with a ship's control system, which leaves most of the decision-making still in the hands of humans. It will not surprise me if the future of maritime logistics is in integrating platforms such as awake.ai into the control system of ships.

6 Conclusion

The complexity of the maritime industry is evident. Ships are having to adhere to various regulations and guidelines, and day-to-day operations are dependent on volatile market conditions and increasingly busy ports and waterways. In this dynamic and complex environment, it is becoming increasingly difficult for ship operators to efficiently process and evaluate all available situational awareness information, and use it for operational decision-making. Autonomous technology and simulation are already being used to support ship operators in complex manoeuvres and in dealing with environmental conditions. However, there still is potential for autonomous technology and simulation to support ship operators in dealing with logistic information. This study aims to fill this gap by developing and testing a method that integrates real-time maritime logistics simulation software and autonomous control systems to improve a ship's ability to respond to logistics information while taking into account predetermined strategic objectives. The objective of this study is to support ship operators in processing and evaluating logistics information and improve this alignment of operational decision-making and strategic objectives. This objective is translated into the main research question as follows:

How can simulation be used to bridge the gap between strategic planning and operational decision-making in autonomous maritime logistics?

To answer this question, four sub-questions were formulated and three experiments were conducted. The detailed answers to the sub-questions are described in the summaries of chapter 2, chapter 3 and chapter 4, and the conclusions are discussed in the following paragraphs, as well as the results of the experiments.

What is the gap between strategic planning and operational decision-making in (autonomous) maritime logistics)? The gap between strategic planning and operational decision-making in (autonomous) maritime logistics can be seen as the difference between high-level strategic objectives and low-level operational decisions. This gap is created by a difference in timeframes and the adaptability of the strategic and operational levels. For example, at the strategic level, shipping companies have to control the air emissions of a fleet, while at an operational level, ship operators are focused on the safe and efficient control of their ships. Factors that can increase or decrease this gap are information flow and technology integration. This means that improving information sharing, processing and evaluation, and integrating different technologies and onboard systems can minimize the gap between strategic planning and operational decision-making.

What are the challenges for integrating autonomous technology and maritime logistics simulation? This study investigates the potential of using simulation software to process and evaluate logistics information and use this to adapt the operations of an autonomous vessel to fit a predetermined strategy. To achieve this, autonomous technology and maritime logistics simulation had to be integrated, this posed several challenges. The experienced challenges can be divided into four general areas: software integration, hardware-software integration, model validation, and experimental reproducibility. The challenges that were experienced in the integration of software programs and software and hardware are relatively straightforward and easily overcome. This was done by using packages in Python that made it possible to communicate via ROS. The challenges with model validation are more complex. The simulation software was designed for logistics scenarios at full-scale. Aligning this with the lab-scale environment was not always possible, given the scope and time of this research. This means that the results of this study can only be used qualitatively and not quantitatively. For complex scenarios that approximate real life or significant quantitative analysis, more effort should be put into the modelling of the logistic scenario and validating this model.

How can the integration of autonomous technology and maritime logistics simulation be tested and validated in a lab-scale environment, to reach the research objective? To reach the research objective and answer the main research question, a combination of HIL and scenario-based testing was done. For scenario-based testing, it was crucial that the experiment scenarios contained the logistic essence that one aimed to test and would prove the method's potential. This was done by simplifying a common logistic process that would lay emphasis on the decision-making process following the input of logistic information. By designing a simple experiment in which an autonomous vessel was given three operational options as a response to a delay of an upstream vessel, a scenario was created where simulation could be used to support decision-making. The validation of this experiment was done by quantifying and qualifying the response options that were tested and collecting data that could prove the correct execution of these responses.

How can maritime logistics simulation improve the efficiency and sustainability of maritime operations? The results of the experiments showed that it is possible to use maritime logistics simulation to calculate the best, predetermined response option to logistics information, given a predetermined strategy. By using the computational capabilities of the simulation software, responses can be evaluated based on efficiency and sustainability, and thus these can be improved.

The first two experiments proved that it is possible to integrate an autonomous control system with maritime simulation software. The third experiment, 'The Port Call Experiment', showed a potential use case of that integrated system. A logistic scenario was scaled down to fit the lab-scale environment. Real-time simulations were done to assess different logistic scenarios in which engine order and route choices were varied. Logistic information was added in the form of berth availability. Furthermore, three different strategies—reduce emissions, reduce time, reduce costs—were determined, which the vessel had to follow. The berth availability was varied and the automated response of the vessel, generated by the simulation software, was observed.

The results of the third experiment showed that for varying berth availability and chosen strategy, the lab-scale autonomous vessel was able to adapt its sailing speed and route choice accordingly. This meant for example that the vessel sped up and sailed directly to its destination to minimize time when the berth was available. However, for the same case with an unavailable berth, the vessel's best option was to sail to a different berth first to minimise time.

To answer the research question, the gap between strategic planning and operational decision-making can be bridged using simulation. By creating an environment in which the predefined strategies and response options—or tactics—form a quantitative framework and are related. This environment can then be used to simulate and optimize operations, within the limits of this framework. And when one combines this with proper information flow and integration of different technologies, as proposed in this research, the gap between strategic planning and operational decision-making in autonomous maritime logistics can be bridged.

It can be concluded that this study shows that autonomous technology and simulation can be used to process, evaluate and respond to logistics information. By using simulation software to evaluate predetermined operational response options against strategic objectives, and choosing the preferred response, one can enable automated and strategy-specific behaviour following logistics information. And while in this research, the operational decision-making was automated, it is also possible to only provide decision support by presenting the preferred response option. This means that simulation and autonomous technology can be used to support ship operators in the complexity of current maritime logistics by providing the computational capabilities to determine optimal operational responses while also considering predetermined strategic objectives.

Considering the most recent studies on the developments and applications of intelligent vessels in inland shipping and port areas, it can be concluded that this research contributes to the described research gap. In this research, no novel software, hardware or technology is considered. However, it does provide a novel method where simulation, predetermined strategies and automated operational decision-making are used to effectively deal with logistics information. And while this research was limited in scope and conducted at a disproportional lab scale, there are some potential practical implications. Firstly, the developed method has the potential to be used in a non-autonomous ship and act as decision support for ship operators. The research has shown that simulation can be a useful tool to deal with complexity and situational information. Secondly, the proposed method could be used in the operational optimization of maritime projects, such as dredging. In these sorts of projects, even more information and quantitative objectives are known. This improves the applicability of the developed method. And finally, a more elaborate simulation environment could be used to incorporate quantifiable laws, regulations and guidelines. Therefore, creating the potential to optimally comply with them. In short, this research has humbly shown the potential of the application of computational logistics as a support tool in maritime logistics. Furthermore, it has shown that with limited resources, it was possible to create a functioning system which means that with more research and more resources, computational logistics can and will play a significant role in the (autonomous) maritime industry.

7 Recommendations

In this chapter, some recommendations are provided for the future directions of this study. These are based on the discussion and conclusion from chapter 5 and chapter 6, respectively.

1. Proportionally scaled experiments should be done to further investigate and validate the use of the OpenTNSim in the control system of an autonomous ship. More specifically, proportionally scaled experiments would allow for quantitative investigation of the improvement in efficiency and sustainability of the developed method. OpenTNSim is designed for the simulation of real-world logistic processes and ships. Scaling this to a lab-scale environment would require a detailed analysis of the factors that influence the performance in the virtual environment, and how those factors relate to the realistic environment. This could also be done vice versa by recreating the lab-scale environment in the virtual environment. This would require modelling of the lab-scale vessel, its characteristics, and the testing location to be used in the simulation environment. These studies would further develop the possibilities of creating and using a digital twin.

2. To investigate the real-world potential and feasibility of the developed method, one could collaborate with inland shipping companies. By taking historical data on shipping fleets and their logistic objectives, one could backtest the use of the simulation software as decision support. This would require locational data of vessels and logistic information on the scenario they were in. It can then be tested whether or not the addition of logistics information and the use of the simulation software could have improved operations or supported the ship operators. This research could be extended by setting up a pilot version of the system on a real version to check the live functioning of the system. This would also require live locational data, but more importantly, this would require a method the gather relevant logistics information. A method to do this would be to collaborate with 'Blauwe Gold, Verbindend', an initiative that gathers and shares real-time information on opened bridges and available berth locations.

3. The developed method could be tested in the context of a dredging project to investigate its applicability to maritime contractor projects. In these sorts of projects, the potential for operational optimization is greater because of two main reasons. Firstly, in these projects, information flow is better because this is mostly internal communication of a single company. Great information flow means that the gap between strategic planning and operational decision-making can be minimised. Secondly, in these projects, strategic and operational objectives are often very clearly formulated and quantified, which increases the applicability of simulation models. For example, in dredging, you often deal with spill windows, noise windows and emission requirements. For further research, one could collaborate with a contractor such as Van Oord to test the developed method's potential in the operational optimization of dredging projects. A proposal could be to create a case study

of one or multiple dredging vessels that work towards a common goal, while under various restrictions and requirements. Incorporating these in the simulation environment and then observing the behaviour of the vessels in dynamic logistics situations could be a valuable study. For such a study, it is recommended to make use of OpenCLSim, as well. OpenTNSim is particularly useful when analysing traffic behaviours. OpenCLSim is more useful for the scheduling of logistic activities and in-depth comparison of alternative operating strategies.

4. A more specific recommendation is to improve the routing system that is used. In this research, a route and the different route options were predefined and statically used to generate consecutive waypoints. It could be really valuable to develop a dynamic routing system that would use the ship's location, available network nodes and an algorithm to iteratively generate the best route. This is something that is already done on famous navigating systems such as Google Maps. Furthermore, one could investigate the addition of environmental routing in this system. Environmental routing focuses on dynamic route optimization that considers water depth, currents, and other environmental conditions. An example of this is a route optimization model for dynamic current developed by Van Halem (2019).

5. Finally, another way the developed method could be improved, is to use a form of AI (e.g. machine learning). In the current method, the autonomous vessel displays preferred operational behaviour based on a predefined strategy and a limited number of options to respond to situational awareness information. Instead, a system could be trained using experienced maritime specialists, such as captains. One could study and record the behaviour of the specialists in generated (or real and live) logistic scenarios while imposing different strategic objectives. This data could then be used as training data for an AI system. This method would replace the simulation aspect of the method developed in this research. And while this would require a lot of data and effort, current technological developments in this area show the great potential of AI.

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A
Python modules

The Python modules can be found on the OpenTNSim GitHub page Baart et al., 2022. One should specify the 'Afstuderen_MaxvanGijn' branch. The scripts can be found in the 'OpenTNSim/notebooks/student_notebooks/max' directory.

A.1. Experiment Green Routing module

The Experiment Green Routing module is called 'Sail2point.py'.

A.2. Tactics module

The Tactics module is called 'tactics.py'.

A.3. Experiment Port Call module

The Experiment Port Call module is called 'Sail2point-exp3.py'.

B
Additional results

B.1. Experiment Green Routing

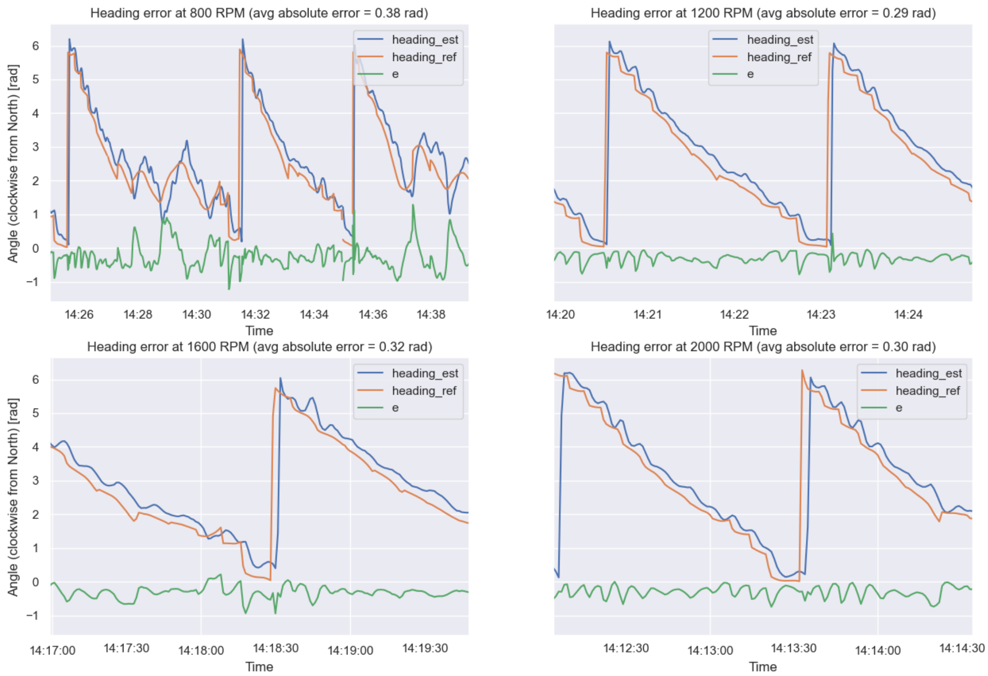

Figure B.1: Heading errors for Experiment Green Routing

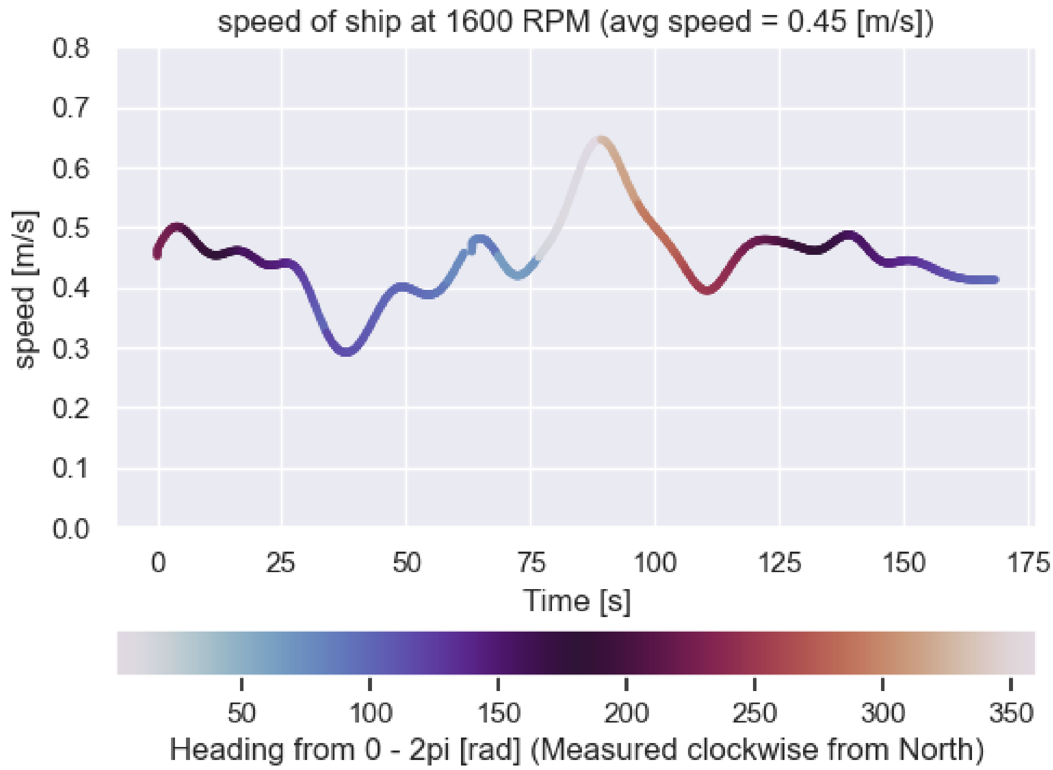

Figure B.2: Speed as function of heading for Experiment Green Routing (1600 RPM)

C

Log of experiments

The following section is a collection of notes from the conducted experiment.

C.1. Experiment Green Routing

Additional scripts that were run for this experiment:

- 'TN_Nomoto_heading_controller.m' Boogmans, 2023a

C.1.1. Test day 1 23-1-2023 (unsuccessful)

- Test 1: RPM: 2000, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: Did not receive messages back from Arduino after putting the vessel in the water. After some problem-solving we got it to work but the ship's headings were off.
- Test 2: RPM: 2000, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: Again some problems with booting up of hardware. After solving this the vessel roughly followed the path but missed some waypoints. Can be attributed to problems with the GPS data.
- Test 3: RPM: 2000, PID (heading): 0.2 0 0, Script: 'Sail2point.py', Description: Tested with different PID settings. Did not work. Was over tuned.
- Test 4: RPM: 2000, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: Did not start due to dying battery.

C.1.2. Test day 2 25-1-2023 (unsuccessful)

Overall failed test day. Various technical difficulties occurred.

C.1.3. Test day 3 30-1-2023 (successful)

- Test 1: Joystick controlled, Description: control test where the joystick was used to sail a circle to calibrate all sensors and systems.
- Test 2: RPM: 2000, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: Two completed laps. Smooth.
- Test 3: RPM: 1600, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: 1-2 laps completed. Smooth.
- Test 4: RPM: 1200, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: 1-2 laps completed. Smooth.
- Test 5: RPM: 800, PID (heading): 0.07 0 0, Script: 'Sail2point.py', Description: 1 lap completed. Very slow and instable at certain points in the circle due to wind and wind gusts.

C.2. Experiment Green Steaming

No specific notes are available from this experiment. The experiment is described in section 3.

C.3. Experiment Port Call

Additional scripts that were run for this experiment:

- ’TN_Nomoto_heading_controller.m’ Boogmans, 2023a
- ’USV_surge_velocity_controller.py’ Boogmans, 2023c
- ’USV_geopos_heading_differentiator.py’ Boogmans, 2023b

C.3.1. Test day 1 01-03-2023 (successful)

- Test 1: PID (velocity): 14000 1700 0, PID (heading): 0.07 0 0, Script: ’Sail2point-exp3.py’, Strategy: emissions, Berth: not available, Description: Successful but recording was wrong.
- Test 2: PID (velocity): 14000 1700 0, PID (heading): 0.07 0 0, Script: ’Sail2point-exp3.py’, Strategy: emissions, Berth: not available, Description: Successful.
- Test 3: PID (velocity): 14000 1700 0, PID (heading): 0.07 0 0, Script: ’Sail2point-exp3.py’, Strategy: emissions, Berth: available, Description: Successful.
- Test 4: PID (velocity): 14000 1700 0, PID (heading): 0.07 0 0, Script: ’Sail2point-exp3.py’, Strategy: duration, Berth: not available, Description: Successful.
- Test 5: PID (velocity): 14000 1700 0, PID (heading): 0.07 0 0, Script: ’Sail2point-exp3.py’, Strategy: duration, Berth: available, Description: Successful.