Application of Mixed Simulation Method to Modelling Port Traffic

Ehiagwina Omoforma Augustine

A thesis submitted in partial fulfilment of the requirements of Liverpool John Moores University for the degree of Doctor of Philosophy

March 2021

Abstract

Marine ports are the largest single business complex in the maritime sector impacting the coastal, marine, and atmospheric environment. The environmental effects of port operations mostly originate from the vessel and cargo handling operations, and maintenance. Port operations generate marine pollution in many forms (chemical, biological, solid waste, and sedimentation) and present a challenge to all port operators. Because ports are often located near urban areas, the wider impact of port operations on the environment cannot be ignored as it can potentially affect the economy of these areas as a whole. Air pollution is a significant externality for ports located close to urban areas. Around 4.5% and 6.2% of the total SO_2 and NO_X respectively, emitted by ships are due to in-port activities such as manoeuvring (approaching harbours) and hoteling (at the dock in port). A vessel consumes around 10% of fuel during slow manoeuvring. Assuming around 4.5% and 6.2% of the total SO2 and NOx emitted by ships are due to in-port activities such as manoeuvring (approaching harbours) and hoteling (at the dock in port), simplifying the traffic model hinders the ability to conduct accurate emission assessment and limits the ability to conduct an environmental assessment as a result of increased port capacity.

The research aim is to develop a multi-method simulation model of port systems to simulate port traffic for assessing various port challenges like emission, throughputs, etc. The study will develop a mixed simulation model of port systems comprising of marine traffic and associated processes using the port of Liverpool as a case study. The developed simulation model will be used to estimate emission within the case study port.

The study developed a multi-method simulation model representing individual actors and specific processes of the entire port system. The developed simulation method integrates two major modelling approaches: discrete-event simulation and agent-based simulation. Due to the complexity within the port, the study focused on the vessel and cargo handling sector of the port because manoeuvring (approaching harbours) is a significant source of pollution. The developed method adopts an object-oriented approach. Object-oriented modelling is an important aspect of the modelling methodology because it supports the reusability and scalability of the developed model as entities are represented as objects with specific characteristics based on their types. This is significant in representing vessel and cargo terminal types. Each vessel type was encapsulated with internal characteristics e.g. passage plan, speed, etc. A terminal developed to handle bulk cargoes is different from a terminal that handles container cargoes. Therefore, agents were developed to represent various cargo terminal types (such as container terminal, bulk terminal, passenger terminal, etc.), with each terminal type possessing its characteristics specific to itself.

The method was applied in the study area. AIS data was collected for the Port of Liverpool over the 12 months of 2016. The data provides information on all marine traffic (fitted with AIS) for the Port of Liverpool outer channel (Liverpool Bay) and the port inbound and outbound lanes along the River Mersey. This data set was used to design and validated the simulation model. A maximum of seven vessels was observed to be transiting through the outer waterway, four at the inner and two in the manoeuvring waterway. Vessel transit times and speed variation are observed to be influenced by the vessel traffic density within each waterway. Vessel waiting and dwell time are seen to be influenced by lock availability and the tidal condition of the port. An increase in tidal duration results in an increase in both waiting and dwell time and vice versa. The validation outcome reveals that the developed model also possesses a relative realistic speed changing behaviour when compared to real-world data. The simulation result also shows a realistic relationship with the travel time distribution from the historical data set.

The developed model represents the port as an entire system, however, the study only focussed on the vessel handling process. Previous port modelling has witnessed lots of simplification in vessel traffic models, port process models, and exclusions of external condition models over the years, but the object-oriented programme implemented in this study can help solve these issues. Therefore, the developed methodology would enable better models to be integrated.

Acknowledgements

Central to the success of research is the valued input from many sources. My highest gratitude goes to the Most Holy Trinity – God the Father, My Saviour Jesus Christ and the Holy Spirit, who has been my very present Help in time of need, who has been and is my Rock and Sustenance till this stage in life and without Whom, I would not be created, alive or able to undergo this journey.

I am very grateful to my supervisor, Prof Ian Jenkinson for his great effort to guide me on the right path on this journey. My gratitude goes to my second and third supervisors, Dr Christian Matthews and Dr Jason Kirby, for their input on this research. I am always very grateful to my family especially my Mother (who has played the role of both a Father and a Mother indeed). Their help and support are precious to me. I would like to thank my Pastor and Daddy, and my beloved Mummy, Dr Ayo Akinsanya and Mrs Morenike Akinsanya, and their family for all the prayers, support and words of encouragement. Also, I want to thank all the brethren in the body of Christ, my friends, research colleagues, and other researchers at LOOM research institute who have been supportive to me.

Thanks to the Dean of Liverpool John Moores University, DCLM Liverpool, and NIMASA for their financial assistance towards the success of this research.

List of Publication

Conference Paper

- Ehiagwina, A. Application of Mixed Simulation Methods in Modelling Port-Traffic within Congested Areas. The 33rd annual European Simulation and Modelling Conference (ESM 2019), held on 28–30 October 2019, at UIB, Palma de Mallorca, Spain.

Others: Journal Articles

- Okorie, O., Charnley, F., Ehiagwina, A., Tiwari, D. and Salonitis, K., 2020. Towards a simulation-based understanding of smart remanufacturing operations: a comparative analysis. *Journal of Remanufacturing*, pp.1-24.

Contents

List of Figures

List of Tables

Glossary

Acronyms	**Name**
APF	Artificial Potential Field
AIS	Automatic Identification System
AMVER	Automated Mutual-Assistance Vessel Rescue System
CO	Carbon Monoxide
COLREGS	Collision Regulated
DCPA	Distance of Closest Point of Approach
EEA	European environment agency
EF	Emission Factors
FIFO	First-In-First-Out
GHGs	greenhouse gases
GIS	Geographical Information System
GPS	Global Positioning System
HC	Hydrocarbons
ICOADS	International Comprehensive ocean-atmospheric data set
IMO	International Maritime Organisation
LMIS	Lloyd's Maritime Information System
MARPOL	Marine Pollution
MEPC	Marine Environment Protection Committee
MMSI	Maritime Mobile Service Identity
NAEI	National Atmospheric Emission Inventory
NM	Nautical Miles
NO_X	Nitrogen Oxides
NTSLF	National Tidal and Sea Level Facility
PID	Proportional-integral-derivative
RDRR	Range to Domain over Range Rate
SAFES	Ship Auto-navigation Fuzzy Expert System
SO_X	Sulphur Oxides
SLM	Spatial–logical mapping
TCPA	Time to Closest Point of Approach
TEU	Ton equivalent unit
UNCTAD	United Nations Conference on Trade and Development
VTS	Vessel Traffic Service
WPS	World Port Source

Chapter 1: Introduction

1.1 Background

Growth in waterborne transport is expected to increase with international trade. The United Nations Conference on Trade and Development (UNCTAD), forecast that the volume of seaborne trade transport will expand at an estimated average annual growth rate of 3.5 percent between 2019 and 2024, (UNCTAD, 2019). For many ports, this growth will result in higher traffic densities and some cases congestion. The time a vessel spends in the port is a major factor for assessing a port’s service quality (Kemme, 2020). Thus, port increased capacity to deal with higher volumes of traffic can be achieved by: (1) Improving the efficiency of the port process, and/or (2) Expanding existing port infrastructure which normally requires a large capital investment project, (Huang et al., 2016).

As freight traffic continues to grow, the question of how to ensure the sustainability of port growth is increasingly important, (UNCTAD, 2012). Globalisation has enhanced the importance of seaports as gateways to international markets, (Cullinane, 2002). Issues around economic growth are the priority of port operators (Cheon and Deakin, 2010) and social and environmental considerations are often secondary (Kotowska, 2016). This has boosted the demand for sustainable development and green management, (Hiranandani, 2014) (Chiu et al., 2014). The problem is establishing the balance between environmental concerns and economics as port traffic grows and/or changes are made within the port as a result of maintenance, investment etc, (Kuznetsov et al., 2015). Without adequate tools to assess both economic and environmental effects of changes to support port operations, planning and policy, there is a risk of imbalance and damage to the environment.

Marine ports are the largest single business complex in the maritime sector impacting the coastal, marine, and atmospheric environment, (McConnell, 2002) (Hinds, 2007) (Davydenko and Fransen, 2019). The environmental effects of port operations mostly originate from the vessel and cargo handling operations, and maintenance, (Kuznetsov et al., 2015). Port operations generate marine pollution in many forms (chemical, biological, solid waste, and sedimentation) and present a challenge to all port operators, (Adams et al., 2009). Ports are often located near urban areas so the wider impact of port operations on the environment cannot be ignored as it can potentially affect the economy of these areas as a whole (Darbra et al., 2005) (Fusco Girard, 2013). Whilst port operations have enriched some, the quality of life in urban areas is threatened with issues such as local air pollution from ships or inland transport, traffic congestion, and co-location of risky or polluting industrial facilities around ports. (Ault et al., 2009; Di Natale and Carotenuto, 2015) (Gómez et al., 2015) (Lam and Notteboom, 2014)

In the port industry, simulation has been widely used in operations analysis and planning, (Ince and Topuz, 2004). This has been largely a response to pressure to improve shipping operations in general and the need for effective integration of shipping into the logistics chain, particularly in container port operations. Most of the simulation models in the research literature are directed towards improving efficiency, predicting performance, (Bellsolà Olba et al., 2018) and supporting a cost-benefit analysis for investment appraisal including estimating the value of externalities. Ports are made up of a network of connected processes, (Davydenko and Fransen, 2019). Many of these are affected by external factors for example vessel arrivals are influenced by shipping lines and navigation through the port on weather and tides etc. Air pollution is a significant externality for ports located close to urban areas. Around 4.5% and 6.2% of the total SO_2 and NO_X emitted by ships are due to in-port activities such as manoeuvring (approaching harbours) and hoteling (at the dock in port), (Castells et al., 2014).

The result of this complexity is that most studies have focussed on modelling specific aspects of the system for example Port Capacity, Terminal Operations, or Navigation. Modellers have chosen simulation methods appropriate to the level of abstraction i.e. system dynamics, discrete event or agent-based modelling. However, this results in an oversimplification of the system, for example, the vessel arrival process may be ignored, or anchoring may be treated as a simple queue process that ignores the size of the anchorage and vessel distribution. It also limits the ability to integrate different models for example a discrete event model designed for terminal operations is not often reused as part of an integrated model with a model designed to assess navigation.

Therefore, analysing the requirement and defining problems provides a point of focus and ensures that a developed simulation model can address stated problems effectively, (Anosike and Zhang, 2000). Key requirements are developing a complete port model capable of representing the whole system at any level of detail; that can integrate specialist models developed for specific purposes for example by adding a model designed to assess navigation safety and can be updated using data generated from real-world operations for example vessel movements generated from AIS data. To meet this requirement, the developed model must be scalable to allow the integration of future changes. Developing such a simulation model will provide support for port operators to assess both the economic and environmental effects of changes resulting from the increase in port traffic and establish a balance between environmental and economic concerns.

1.2 Research aims and objectives

The research aim is to develop a multi-method simulation model of port systems to simulate port traffic for assessing various port challenges like emission, throughputs, etc. The study will develop a mixed simulation model of port systems comprising of marine traffic and associated processes using the port of Liverpool as a case study. The developed simulation model will be used to estimate emission within the case study port. The set requirement was to develop a model which: (1) Has the capability to model the whole system at any level of detail; (2) Integrate specialist models developed for specific proposes for example by adding a model designed to assess navigation safety; (3) Can be updated using data generated from real-world operations for example vessel movements generated from AIS data. To achieve this the study develops the following objectives; to

- Review the application of a simulation model to modelling the port system to identify gaps in previous model and simulation modelling approaches.
- Identify and investigate the key systems (vessels, port processes, etc.) that make up the port and assess how they can be best modelled.
- Develop a port traffic simulation model of Liverpool port using the suitable methods identified. The objective also includes data collection and analysis for the model development.
- Assess the impact of an increase in vessel traffic on vessel emission. This includes testing of the developed port traffic model using real-world data for assessing vessel traffic emission within the study port.

1.3 Port of Liverpool case study

The Port of Liverpool for the study is located in the northwest (see Figure 1.1 of England at Latitude: 53° 26' 11" N Longitude: 3° 0' 41" W and is currently owned and operated by the Mersey Docks and Harbour Company (WPS, 2020). The Port of Liverpool is one of the largest, busiest and most diverse ports in the UK, located for transatlantic trade with berths spanning both sides of the River Mersey. It sits on both banks of the River Mersey in a strategic vantage point within the northwest of England. The port is one of the busiest container ports in Britain and Northern Europe, handling almost 700,000 TEUs of containerized cargo per year, more than 4.5 million tons of dry bulk cargoes per year, and operates eight roll-on/roll-off ferry services for freight and passengers that make daily trips. The Port of Liverpool contains over 485 hectares of operational docks that handle general cargo, timber and forest products, crude oil, coal, edible oils and fats, cocoa, copper, steel, granite, aluminium and other metals, and chemicals. The Port of Liverpool is also a popular cruise ship destination and a busy ferry port for people travelling the Irish Sea.

Figure 1.1 Map of Liverpool (Thompson et al., 2020)

The port makes economic contributions to the local area and benefits from direct links to the M53, M57, M62 and M6 (M58) motorways and the rail connection within the port, (WPS, 2020). As vessel traffic grows, vessel operators seek ports positioned in close proximity to industrial and urban areas, thus exposing residents to emissions from both vessels and marine infrastructures (Castells Sanabra et al., 2014). (Gómez et al., 2015, Lam and Notteboom, 2014), (Darbra et al., 2005), (Fusco Girard, 2013). Maritime emissions from the vessels moving in and out of the port are reported to contribute approximately 9% of the total emissions within the city (see Figure 1.2), and as significant contributors to the relative increase of SO_X and NO_X (see Figure 1.3) concentrations in port-cities (Corbett et al., 2007; Lack et al., 2009; Moldanová et al., 2009).

The air emissions from this gigantic transport infrastructure could threaten the environment of the city. For example, four areas in Liverpool are found to have concerning levels of air pollution capable of affecting human health, (Williams, 2020). Owing to the geographical position and characteristics in Liverpool, vessel traffic emissions can easily affect residential areas due to the effect of sea and land breezes (Donateo et al., 2014; Jeong et al., 2017). Thus, estimating emissions resulting from vessel traffic for effective air quality improvement strategies in coastal regions is significant, making the development of a multi-method simulation more essential.

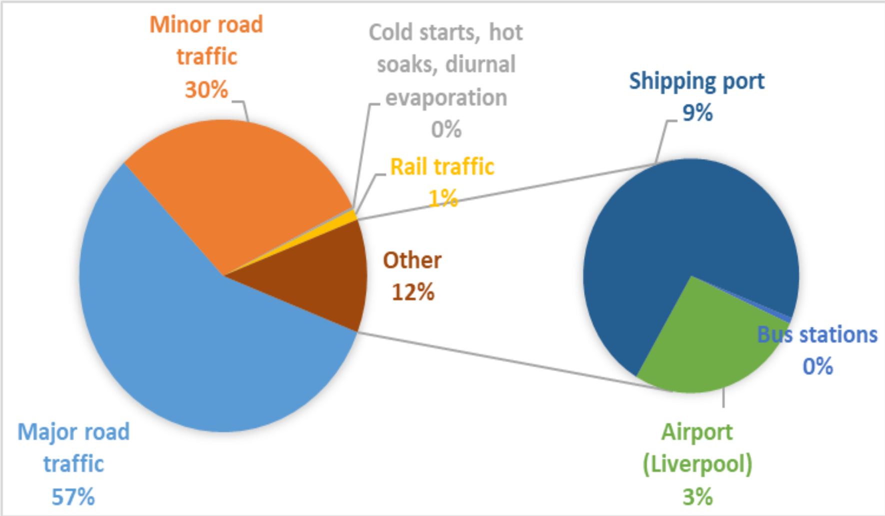


Figure 1.2: Emission percentage distribution of specific pollutants across the transportation sector city of Liverpool (Adapted from the Transport and Emissions in the Liverpool City Region Performance and Review Sub-Committee (2020)

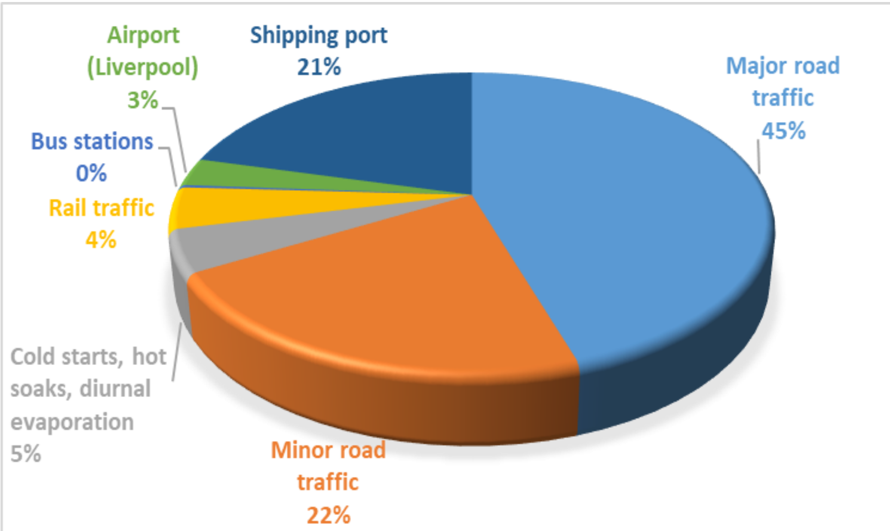


Figure 1.3: NOx emission distribution across Liverpool transport sector

1.4 Structure of Thesis

To report the research activities undertaken to deliver the various objectives of this research, the research is divided into the following chapters:

1.4.1 Chapter One: Introduction

This chapter presented an overview of the research explaining the challenges of port operators and the simplicity issues with previous simulation applications within the port and the need for a new simulation methodology for port traffic modelling by providing a problem statement, research aims, objectives, and the structure of the whole thesis.

1.4.2 Chapter Two: Literature review

This chapter reviews previous literature on three simulation models suitable for developing a good port traffic model. The chapter also reviews studies on port simulations and vessel traffic to achieve an all-round view of previous port traffic models and to identify gaps within each study

1.4.3 Chapter Three: Research Methodology and Simulation Structure

The general synopsis of the research methodology used throughout the thesis is detailed in Chapter 3. This includes the justification of the simulation method used in simulation development. The chapter also discusses the basis for which a multi-method simulation was used for this study and outline the simulation structure used in developing the port traffic simulation.

1.4.4 Chapter Four: Conceptual model development

This chapter discusses the developed design of the various parts of the port needed for constructing the port traffic simulation to achieve the aim and objectives of this research. It also highlights the study area and its structural layout. It discusses the data analysis process used in the study and results of both, vessel traffic, port process, and external conditions, which serves as input for constructing the planned simulation model and the potential output expected from the study.

1.4.5 Chapter Five: AnyLogic Model development

Following chapter three, in this chapter, the simulation models of the various port processes, the vessel models and external conditions were developed in AnyLogic. The chapter explains how each entity (anchorage, locks, cargo terminal, tide, etc.), the vessel behavioural and collision avoidance model, tidal, weather seasonal and visibility model were represented in AnyLogic and how they operate as individual entities and as a whole system.

1.4.6 Chapter Six: Verification and validation of AnyLogic Model

This chapter discusses the model application in the case study port. The chapter also discusses the model calibration and validation following a series of experimental test runs and a comparison between historical data from the study area and simulation output.

1.4.7 Chapter Seven: Application of validated AnyLogic Model in Case Study

The chapter estimates vessel emissions within the case study using the validated port traffic simulation. The simulation output from the port traffic was used to estimate vessel emission within the cases study. The emission estimate was then compared with that estimated using real-world data. The chapter also compares both results as part of the port traffic simulation model validation process and identifies key bottlenecks that need to be dealt with to enable the port to meet its goal.

1.4.8 Chapter Eight: Conclusion and Future Work

The chapter presents a summary of the research looking at various aspects of the research, the research contributions and limitations, discussions on the validity and limitation of the research. The advantages of the proposed simulation model are also presented to conclude the research and highlight future research work and suggestions.

Chapter 2: Literature Review

2.1 Introduction

This chapter analyses the up-to-date literature which has influenced this study. It reviews the background of a port-traffic system including the definition of different components of the system. It reviews the background of the three major simulation methods used in operational research. The review includes past and current trends in terms of previous simulation models and how authors have applied them in modelling the various component of the port-traffic system. The background information and work done by previous researchers concerning port-traffic simulation, such as simulating vessel traffic, simulating port processes, and how they are modelled has also been investigated and outlined in this chapter

2.2 Overview of Port Traffic System

In a port traffic processes start when a vessel arrives and requests access, Figure 2.1. The vessel traffic service (VTS) provides information about the cargo terminal availability and other conditions, such as weather and traffic conditions. Vessels with permission from the port authorities can then proceed through the waterway (channels) and navigate to their destination (allocated berth and cargo terminal). Otherwise, they must wait outside the port at the anchorage area until there is an available berth and are permitted to proceed to berth, (Bellsolà Olba et al., 2018). Vessels with specific navigation requirements or limitations will need a pilot and/or tug assistance.

Once a vessel is granted access, the vessel leaves the anchorage and navigates to its allocated berth through the waterway. For some ports, some locks divide the waterway in two, the inner and outer waterway. The waterway between the anchorage and lock is the outer waterway, while the waterway between the lock and cargo terminal is the inner waterway. Within the waterway, vessels navigate through different parts of the port having specific manoeuvring requirements such as speed reduction, etc. When the vessel arrives at the cargo terminal, its berth (stops for cargo operation). Once the berthing process is performed, cargo loading/unloading operations start. The loading/unloading operations deal with cargo movement and storage within the cargo terminal and stacking area, either from the vessel or to the vessel. When the loading/unloading operations are completed, vessels are ready to depart; they are required to ask for new permission to leave the port. The reverse navigation process occurs when they are allowed to sail towards their exit

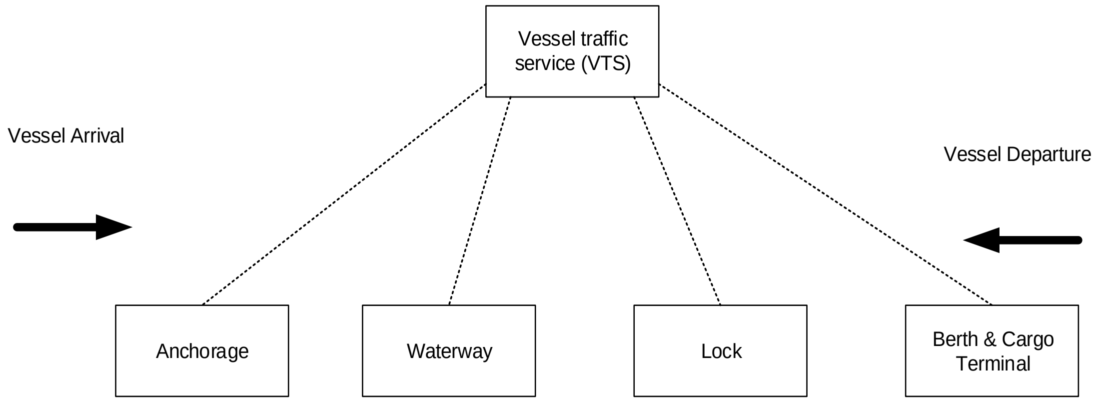


Figure 2.1: An overview of a port traffic system

Port traffic comprises two main parts, port systems and vessel navigation, Figure 2.1. The port system includes; 1) the geographical area (waterway), 2) port processes (anchorage, lock, berth, and cargo terminal processes), 3) External conditions (weather and seasonal changes). The vessel navigational consist of; vessel arrival process, fleet composition (vessel types), vessel navigational behaviour such as course choice, speed variation, collision avoidance.

2.3 Component of the port system

2.3.1 Geographical Area

The geographical area comprises waterways leading to various areas within the port such as cargo terminals, locks, etc. The waterway is made up of several areas having specific navigational characteristics and traffic rules that, lead to differences in navigational behaviour (speed changes, course changes, etc.). Due to these differences through each part of the waterway, variations in vessel movement patterns and speed arises, which are the key element in the performance of a busy port and can be analysed as they lead to variations in transit times.

2.3.2 Port processes

The port process includes the anchorage, berth and terminal, lock, pilot, and tug. The anchorage serves as a safe waiting area and a queueing process for vessels before berth allocation. Vessels wait at the anchorage until cargo terminals are available for them to berth. At least anchoring should not be considered as a simple queue process, where the influence of anchorage and vessel distribution at anchorage does not affect the port performance. Literature shows only a few recent studies were addressing this topic (Huang et al., 2011; Verstichel and Berghe, 2009). Also, only Huang et al., (2011) adapted algorithms to optimize vessel allocation in an anchorage area.

The berth is a waiting area situated alongside a cargo terminal for vessels needing cargo operations (cargo loading and unloading process). Berthing and terminal operations are relevant crucial for minimizing costs and dwell times and should be included as an independent parameter as they aim to assess port traffic performance. Studies on vessel berthing have been conducted in detail by several researchers (Alvarez et al., 2010; Arango et al., 2011; Fararoui, 1989).

The lock is a waiting area to help balance the water level between two areas. During a lock process vessels stay within the lock for the duration it takes to match both water levels, after which it proceeds to the port, and the same when leaving the port. Vessels share turns while using this process. Ports often have restrictions on navigation for several types of vessels because of their dangerous cargo or difficult manoeuvring characteristics that require assistance by tugs or a pilot to assure safe navigation inside the area. The inclusion of tugs and pilots is necessary for any port simulation model. However, the best way to do representing them within a model is not clear.

2.3.3 External conditions

External conditions include the influence of weather conditions such as tide, current, visibility, etc. These are a constraint on daily port performance as they can influence vessel time in port. For example, tidal windows have an important effect on port processes and performance resulting in delays in port operational time.

2.4 Component of Vessel Navigation

2.4.1 Traffic Rules

Traffic rules in ports usually follow the rules of the International Maritime Organization (IMO) plus their own specific rules due to their specific design characteristics. As mentioned before, VTS centres control if vessels follow these rules and that they do not initiate dangerous situations. These rules are directly related to risk and safety levels, and the more detailed they are, the better the risk assessment can be carried out. Explicit and detailed traffic rules can allow individual assessment. A control and traffic verification agent is relevant and should be considered (Xiao et al., 2013). A detailed implementation of these rules allows a more accurate analysis of the results. It might also help to identify hidden traffic management problems behind simulation results and new traffic management strategies could be implemented.

2.4.2 Fleet composition

In navigation, the behaviour of each vessel is different. Their different sizes and weights influence their movements and speeds, as well as braking times or rudder angles. Making clear groupings of vessels can lead to a more precise simulation model. The classification should be accurate and the different groups should be chosen based on their similarities in navigational behaviour.

2.4.3 Vessel Speed

During the navigation process, vessels change their speeds and their maximum and minimum speeds are different base on types due to their physical characteristics. In the simulation models, due to the computational complexity of representing these accelerations or decelerations can be done using a free speed choice and variation during sailing, the use of several specific fixed speeds according to each specific situation or port area, or sail with a unique speed. Although vessel speeds do not change instantaneously, the possibility of a model to include free speed choices and change with time fits better an accurate representation of vessel navigation in a port. In addition, the influence of the infrastructure and encounters between vessels on vessel speed should be included.

2.4.4 Vessel Navigational Behaviour

Vessel course choice, or path change, during navigation between two points, is a complex element to simulate. This path depends on several parameters, such as bridge team behaviour, port geographical topography, and external conditions. The precision of the models according to real vessel sailing behaviour is related to their manoeuvring behaviour during this process. Vessel manoeuvring behaviour can be divided into three major parts based on the port geography namely cruising, manoeuvring, and hoteling.

- ***Cruising mode***: The Cruising mode is defined as an operational mode where vessels move at their design speed that is when the propulsion engines are operating at high loads. Also, depending on external conditions (e.g. weather, other vessels), the vessel at its cruising mode alter their speed to the assigned requirement stated within the maritime collision regulations guide (rules of the road).
- ***Hoteling mode***: Hoteling mode is an operational mode associated with vessel stops. This stops areas are either anchorage, berth or other respective areas like locks. Vessel speed while hoteling is always assumed to be 0 knots as they are not expected to move. Vessels usually change from hoteling to manoeuvring state when they are moving.
- ***Manoeuvring mode****:* The manoeuvring mode is defined as an operational mode where vessels move at speed levels below their designed speed, that is when the propulsion engines are operating at lower loads due to geographical constraints like waterways, or speed reduction requirements, or traffic density or external condition. Vessel speed during this state varies.

Previous research showed that ship dynamic manoeuvring can be modelled (Sutulo et al., 2001). Moreover, the human behaviour in vessel manoeuvring can also be modelled and it makes more realistic vessel navigation (Hoogendoorn et al., 2013). Free course choice and the influence of the infrastructure or other vessels on vessel navigation is relevant to assess different situations and specific behaviours that might affect the safety of the port. The inclusion of human factors, such as bridge team behaviour, in the sailing path should be considered (Hoogendoorn et al., 2013).

2.5 Port Traffic Simulation modelling

The term simulation model means the usage of a computational model to gain additional insight into a complex system's behaviour e.g. port traffic by visualising the effects of the modelling choices, but also to evaluate designs and plans without actually bringing them into existence in the real world, (Bandini et al., 2009). The usage of these "artificial environments" is often necessary because the simulated system cannot be observed since it is being designed, and also for ethical reasons. A model is an abstract and simplified representation of a given reality, either for a planned system or an already existing one, (Bandini et al., 2009). Models are commonly defined to study and explain observed phenomena or to foresee future phenomena.

In the port industry simulation has been widely used in operations analysis and planning, in response to pressure resulting from improved shipping operations in general, and the need for effective integration of shipping into the logistics chain particularly in container port operations (Kia et al., 2002), (Dragović et al., 2005) (Angeloudis and Bell, 2011), (Dragović et al., 2017), (Petering et al., 2009), (Rashidi and Tsang, 2013), (Alessandri et al., 2007, Lehnfeld and Knust, 2014), (Cartenì et al., 2009). Most of the research literature is directed towards improving efficiency (Galatioto et al., 2015), (Parola and Sciomachen, 2005), (Sun et al., 2012), predicting performance (Kia et al., 2002), (Yun and Choi, 1999), and investment appraisal, (Demirci, 2003), (Lin et al., 2014), (Islam and Olsen, 2011, Moon and Woo, 2014). Improvements in efficiency (Bhamu and Sangwan, 2014), (Casaca, 2005) can have a positive influence on the environment by reducing CO_2 emissions for example, (Kontovas and Psaraftis, 2011) (Moon and Woo, 2014).

Three groups of researchers have recently reviewed marine traffic simulation models comprising of both port and vessel models in detail. Szlapczynski and Szlapczynska (2017) present a systematic review of the models using ship domain for whatever application purposes. However, other models, which are not based on the ship domain were not assessed. Bellsolà Olba et al. (2018) reviewed port simulation models focusing on vessel traffic from a port operations viewpoint. The underline modelling methodology and the corresponding application limitations were, not discussed in detail. The author assessed simulation models used in eighteen published studies of port operations, against the inclusion (or not) and fidelity of their port process, and vessel traffic models. Simulation models designed to support port planning, economic assessments, and/or assess capacity and efficiency were based largely on port processes and did not include detailed vessel traffic models, (Groenveld, 1983, Park and Noh, 1987, Hassan, 1993, Demirci, 2003, Yeo et al., 2007, Goerlandt and Kujala, 2011, Almaz and Altiok, 2012, Rayo, 2013, Piccoli, 2014, Uğurlu et al., 2014, Scott et al., 2016, Bellsolà Olba et al., 2017). (Zhou et al., 2019) reviewed maritime traffic models from the vessel behaviour modelling perspective. The maritime traffic models include the models for vessel traffic both at sea and in confined water areas. The author analysed the underlying modelling paradigms and assessed the extent to which maritime traffic models can represent vessel behaviour. A review of 35 traffic models (which included models of vessel movement) were assessed against the following criteria: (1) Model application area e.g. open water or confined areas with the limited navigable room; (2) Navigational behaviour based on vessel's static characteristics (vessel type, geometric sizes, and/or tonnage), and its dynamic kinetics (position, speed heading, and course); (3) External factors: (a) traffic rules, (b) encounter situations with other vessels, and (c) environmental conditions. Traffic rules governing the area include collision avoidance regulations (COLREGS), speed limit zones, and waterways usage

This chapter reviews previous literature on three simulation methods and a suitable combination of these methods to develop a good port traffic model. The scope of this review covers the simulation model of both vessel and port within the maritime industry, with the exemption of commercial model to achieve an all-round view of previous port models and to identify gaps within each study. Previous models are reviewed to determine the simulation modelling method applied and how well the systems were represented to gain more insight as to what method best capture a system.

2.6 Review of simulation methods

The three common methods used in business systems simulation are Systems Dynamics, Discrete Event and Agent-Based. System dynamics models systems in terms of aggregates (stocks, flows), and the feedback loops. Discrete-event models a system as a sequence of operations performed on entities. Agent-based models are based on individual entities interacting with each other and with the environment, (Macal and North, 2014, Borshchev and Filippov, 2004). The different simulation methods can be used to model a system depending on the level of abstraction required for the study, (Borshchev and Filippov, 2004). At a macro level where interactions between entities within the system are not considered, the system can be modelled using System Dynamics simulation. At the mid-level, the structural layout and processes that govern the systems operations are included and these processes are suitable for discrete event simulation. At the micro-level agents behave independently and their interactions with other agents are controlled based on rules from the mid-level system. For example, although vessels behave independently as they move through the port environment, where they move to (anchorage, berth, etc.), and the general path they move through (port waterway and channels) is governed by the port traffic system, which is mid-level entities. Within the port environment, vessel traffic, cargo terminal scheduling and allocation, and general operational rules, etc. are governed by the port. So, any vessel visiting a port is required to abide by the port rules whilst at the port.

2.6.1 System Dynamics

System Dynamics, (Forrester, 1994) is a well-developed approach for visualizing, analysing, and understanding complex dynamic feedbacks, (Nasirzadeh et al., 2018), (Barlas, Y. 2002). It is usually used to analyse problems from a macro and holistic-thinking perspective. The theoretical foundation of this approach is reductionism, which is a process of breaking complex phenomena, concepts, or entities into smaller constituents, (Ding et al., 2018).

System Dynamics focuses more on flows around networks than on the individual behaviour of entities. It mainly considers three main objects; stocks, flows and delays. Stocks are basic stores of objects; an example may be the number of ships in a port. Flows define the movement of items between different stocks in the system and out/into the system itself. Lastly, delays are exactly as they sound, they are the delay between the system measuring something and then acting upon that measurement, e.g. anchorage, cargo terminal, etc. The structure of system dynamic modelling contains stock (state) and flow (rate) variables. Stock variables define the accumulation within the system, flow variables define the flows which are derived from the decision-making process. The method comprises multi-loop feedback structures arranged orderly and with nonlinearity. The structures can be diagrammatically represented using stock-flow and causal loop diagrams, (Ahmad et al., 2016). The stock-flow diagrams transform ideas into simple forms (Ding et al., 2018). The causal loop diagrams can capture the feedback structures of a complex system. It can also map how a system is dynamically influenced by the various interactions of the system's variables, (Ding et al., 2018). However, system dynamics is often criticized, because a complex system cannot be fully understood by just dealing with a single discipline.

System dynamics simulation model describes vessel movement in state-space representation, expected to capture the details of vessel behaviour in port traffic. The system dynamics models are designed to present the process of vessel behaviour in a system as it is. For example, Leguit (1999) developed an operator Support System (OSS) for vessel traffic management to help traffic operators better understand the development of vessel traffic situations and in advance identification of unsafe situations. The author determined vessel behaviour at different visibilities using a proportional-integral-derivative (PID) controller considering the forces on different vessel components (i.e. hull, rudder, and propeller). Other authors like Beschnidt and Gilles, 2005 developed a system dynamic simulation focused on modelling the dynamics of vessels in the water and on generating typical sensor measurements such as radar or GPS. The author model simulated object's reactions to an external control signal (external condition) using differential equations in two-dimensional space. Lisowski, 2016 developed a deterministic sensitivity control system for sensitivity analysis implemented into a game control system of moving objects, such as ships. The structure of the game ship controlling the system in collision situations and external conditions was represented using differential equations in two-dimensional space. Fang et al., 2018 developed a more extensive collision avoidance decision-making system for non-uniformly moving ships based on the Six-Dimensional (6D) degree of motion to simulate the ship's motion using differential equations. A real-time ship manoeuvring simulation model for investigating the manoeuvring performance of large tankers in the Bosporus was developed by Sariöz and Narli, 2003, the vessel movement was represented in Six-Dimensional (6D) degree of motion using differential equations.

The method captures only the major structures of a port system (vessel, port process, etc.), and how each entity affects the others. The method also considers all entities holistically, which indicates the limitation in applying such models for an area with many different vessels, (Mallick et al. 2015). Therefore, vessel traffic in the port can be simply viewed as a stock and flow diagram, because, system dynamics aims to understand how and why system behaviour changes (Vlachos et al., 2017). Also, the system dynamics method is not scalable and visual as it does not consider bottom level interactions, because it cannot give a profound explanation of the micro-behaviours in the system. Since, the relationship between macro behaviour and micro behaviour is ignored, (Ding et al., 2018). For example, visualising vessel behaviour from place to place within the port is impossible as the method can only view vessel traffic in port from a macro level interaction using mathematical equations, e.g., number of vessels calling on port, etc.

2.6.2 Discrete-event methods

Discrete-event methods adopt a process-oriented approach, that is, the dynamics of the system are represented as a sequence of operations performed over entities, (Borshchev, 2013). Systems are modelled as networks of queues and activities where state changes in the system occur at discrete points in time, (Angeloudis and Bell, 2011, Alessandri et al., 2007, Dragović et al., 2017). The method focuses on simulating events and their relationships with the primary dynamic system (e.g. in a berth process, the relationship between the arrival of a vessel, the cargo operation, and the vessel departure), (Nasirzadeh et al., 2018). Discrete-event simulation models processes as series of discrete events. This means that entities (the general name for what is being considered, e.g. "vessels") are thought of as moving between different states as time passes. The entities enter the system and visit some of the states (not necessarily only once) before leaving the system. In discrete-event simulation models it is a common practice to model people as deterministic resources ignoring their performance variation and their pro-active behaviour. With these simplifications, it is not possible to make accurate predictions about system performance (Siebers, 2006). Discrete-event simulation model's systems as networks of queues and activities, where state changes in the system occur at discrete points of time.

A key difference between discrete-event simulation and agent-based modelling is their flexibility and efficiency in modelling different types of systems. Agent-based simulation modelling is suitable for systems with entities that interact frequently with each other and allow one to take both into account individual agent's behaviour. Discrete-event simulation has various worldviews (e.g., event scheduling, process interaction, activity scanning, state machines, and other formalisms) that vary greatly in modelling flexibility and analytical power (Kiviat 1969). The interactions in a discrete event simulation are actually among processes, e.g. arrival process, service process etc. rather than those observed in an agent-based model. Thus, the approach can be used for modelling static entities as each entity can be modelled as a process–interaction in a simulation model. In general, discrete-event simulation focuses on simulating events and their relationships of the underlying discrete-event dynamic system.

Port processes are better modelled using discrete-event simulation as these follow a sequence of operations performed on agents (vessels). Discrete event simulation modelling can adequately simulate processes and include interconnections, but not the interactions between port processes and vessels. This has resulted in studies majoring in discrete event simulation to simplify or ignore lower-level interactions between entities. For example, Groenveld, (1983) developed a simulation model of the port-system to determine the port capacity using a discrete event simulation approach. Demirci (2003) analysed and evaluated the effect of port traffic condition and prospective congestion using the Flex-SIM simulation program, which follows a process-based approach. Yeo et al. (2007) construct a simulation model to investigate the impact of port expansion on port performance using a discrete event approach. Almaz and Altiok, (2012) perform a marine assessment of port operations using FlexSim which is a discrete-event simulation tool. Piccoli, (2014) used the Flex-SIM simulation program, which follows a process-based approach to develop a simulation model which evaluates vessel arrival intervals for BOTAS Ceyhan loading terminal, Ugurlu et al. (2014) used a discrete event simulation model of port operations to assess the cost and benefits of various long wave mitigation approaches for the port Gerald-ton. Li et al., (2016) presented a hybrid simulation model that combines traffic-flow modelling and discrete-event simulation for land-side port planning to evaluate port traffic for bulk cargo ports, (Li et al., 2016). Ricci et al., (2014) also developed a sea-side operational port model to support maritime terminal operation using a discrete-event simulation approach for the port of Messina, (Ricci et al., 2014)

Also, a complete port-traffic simulation model should include micro-level interactions of vessels characteristics relevant for assessing the system. For example, in the model developed by (Almaz et al., 2006, Camci et al., 2009, Goerlandt and Kujala, 2011, Merrick et al., 2003, Piccoli, 2014, Puszcz et al., 2011, Thiers and Janssens, 1998), the details of the individual vessel behaviour (position, speed, and course) are simplified as generic movement rules for all entities. Also, the rules for different vessels are defined as the same under any circumstances. Most of the discrete-event models present the maritime traffic in one-dimensional space, with routes predefined within the models and waypoint coordinates if needed. And the vessel speed has been defined as the same for all vessels as in (Piccoli, 2014), or by vessel classification as in (Almaz et al., 2006, Camci et al., 2009, Goerlandt and Kujala, 2011, Merrick et al., 2003, Hasegawa, 1990, Hasegawa et al., 2001, Hasegawa et al., 2000)

The reviewed works of the literature reveal that no port simulation studies have included realistic traffic models with various port processes. These depend on numerous variables including the traffic conditions, the physical environment of the port, physical characteristics of the vessel, navigational rules and interactions between the vessels. In the discrete-event simulation, the difference between vessel behaviour is either ignored or simplified and the behaviour common to each vessel type based on vessel characteristics is unknown, (Zhou et al., 2019, Bellsolà Olba et al., 2018). With these simplifications, the interaction between vessels during transit and manoeuvring times cannot be accounted for and hinders the ability to capture location-aware and situation-dependent behaviours and to conduct accurate fuel consumption and emission assessment.

2.6.3 Agent-based methods

Agent-Based simulation modelling is a bottom-up approach that represents the spatial or social interactions between individuals and their environment (Ding et al., 2018, Railsback and Grimm, 2019). Agent-based simulation models are characterized by the presence of agents performing some kind of behaviour in a shared environment. The approach aims at describing the behaviour of a complex system by characterizing the behaviours, interactions and sociality among entities, (Liao et al., 2008). In an agent-based simulation, systems are modelled as a collection of independent decision-making entities called agents (Bonabeau, 2002). For example, complex problems are broken down into smaller problems, which are then assigned to agents with the best ability to solve such problems. Each agent separately considers its condition and decides based on a set of rules. Although each agent has its own goal, assigning help to solve the more complex issue. For example, problems with regards to a vessel like speed changing can be assigned to a vessel agent, while that of a port process like berth allocation can be assigned to another. Each agent separately considers its condition and decides based on a set of rules. Agents may execute various behaviours appropriate for the system they represent. The decision processes of simulated agents are explicitly described at the micro-level, (Bonabeau, 2002). The overall behaviour of the system emerges at the macro level as a result of the actions of the agents, and their interactions with other agents and the environment, (Siebers and Aickelin, 2008).

The notion of an agent, however, is controversial (Franklin and Graesser 1997), and the most commonly adopted definition of an agent by (Wooldridge and Jennings 1995) specifies a set of properties that must characterize an entity to effectively call it an agent. These properties include autonomy (the ability to possess a certain degree of control over its state), social ability (the ability to interact with other agents using a communication language), reactivity (the ability to perceive an environment in which it is situated and respond changes) and pro-activeness (the ability to take the initiative, starting some activity according to internal goals rather than as a reaction to an external stimulus).

In agent-based modelling, agents and their behaviours are not the only modelled things; but also the actions and interactions between these multiple agents (as individual entities or collective ones such as organizations or groups) can be simulated through the environment. Thus Agent-based modelling focuses explicitly on modelling the micro-level entities and dynamics of the real system to be modelled (e.g., individual characteristics and behaviours, actions and interactions between the entities and the environment, etc.)

According to (Michel et al., 2018), an agent is always in a cyclic three-phase process (as shown in Figure. 1.): perception – deliberation – action. These phases work assumes that:

a. Firstly from the current state of the environment, agents have perception receive knowledge perception is obtained by the agent. The obtained knowledge might be a simple raw data structure or a more complex one.

b. Secondly, a deliberation (memorization) function starts its process in which the agent makes its internals progress and renew its representation of the world using the perception obtained before. In this process, a specification of the core part of the behaviour of an agent and its architecture (reactive or cognitive) is defined. In such, a situation as the memorization process is not needed, and perceptions are harmonized directly to actions, the deliberation process is skipped.

c. Finally, an action is taken by the agent base on its new internal state and its current perception. The result of the taken action is immediately noticed in the agent adaptation within the environment.

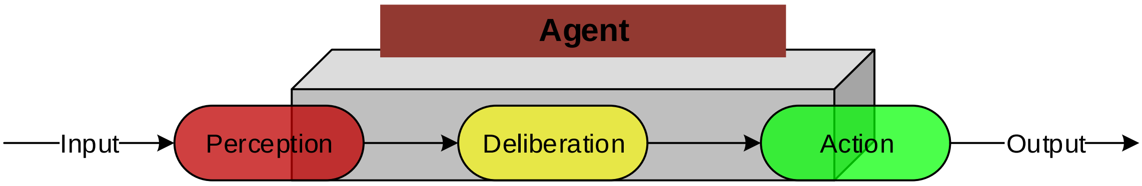


Figure 2.2: An agent as a three-phase process

2.6.3.1 Comparison between Discrete-event and Agent-based Simulation Modelling

Following Table 2.1 and Table 2.2, the main difference between discrete-event and Agent-based is that discrete-event focuses on the process flow while Agent-based focuses on the individual entities in the system and their interactions, which is the focus of this research, (Angeloudis and Bell, 2011, Alessandri et al., 2007, Dragović et al., 2017). Pugh (2006) in a quantitative comparison between discrete-event and agent-based models stated that model construction is easier using discrete-event models compared to agent-based. Yu et al. (2007) looking into the model characteristics added that more model blocks are required for discrete-event modelling; while Agent-based require less class. Nonetheless, looking at adaptability (movement) which is a huge part of this research, discrete-event does not reflect the true flexibility contained in the real system appropriately, and proactive behaviours can only be modelled using an agent-based model, (Majid, Aickelin, and Siebers, 2009).

2.6.3.2 Comparison between System-Dynamics and Agent-based simulation modelling.

Following Table 2.1 and 2.2, agent-based models show how the interaction among individual decision-making and learning may generate complex aggregate behaviour, but the system-dynamic approach aims at reducing emerging aggregate, and often puzzling, behaviours into underlying feedback causal structures. Consequently, system-dynamics models typically aggregate agents into a relatively small number of states assuming their perfect mixing and homogeneity (Rahmandad and Sterman, 2008). On the other hand, the Agent-based model preserves heterogeneity and individual attributes at the risk of relinquishing robustness and parsimony. Concerning this research, system dynamics has two main limitations, first, individuals are modelled in terms of probabilities, and no attempt is made to justify these in terms of individual preferences, decisions, and plans. It also requires large computational power to run such a simulation model. Second, each simulated person is considered individually without regard to its interaction with others. This indicates a great limitation in applying system dynamics simulation modelling to an area with a large number of different vessels.

Table 2.1: Comparisons between Simulation Models, (Behdani, 2012)

System Dynamics (Lansdowne)	Discrete-event Simulation (DES)	Agent-based Simulation
System-oriented; the focus is on modelling the system observables	Process-oriented; the focus is on modelling the system in detail	Individual-oriented; the focus is on modelling the entities and interactions between them
Homogenized entities; all entities are assumed to have similar features; working with average values	Heterogeneous entities	Heterogeneous entities
No representation of micro-level entities	Micro-level entities are passive 'objects' (with no intelligence or decision-making capability) that move through a system in a pre-specified process	Micro-level entities are active entities (agents) that can sense the environment, interact with others and make autonomous decisions
The driver for the dynamic behaviour of a system is "feedback loops".	The driver for the dynamic behaviour of a system is "event occurrence".	Driver for the dynamic behaviour of the system is "agents' decisions and interactions".
Mathematical formalization of the system is in "Stock and Flow"	Mathematical formalization of the system is with "Event, Activity and Process".	Mathematical formalization of the system is by "Agent and Environment"
handling of time is continuous (and discrete)	handling of time is discrete	handling of time is discrete
Experimentation by changing the system structure	Experimentation by changing the process structure	Experimentation by changing the agent rules (internal/interaction rules) and system structure
The system structure is fixed	The process is fixed	The system structure is not fixed

Table 2.2: Comparison of Simulation for Port-Traffic Modelling, (Behdani, 2012)

	System Dynamics (Lansdowne)	Discrete-event Simulation (DES)	Agent-based Simulation
Numerousness and heterogeneity	No distinctive entities; working with average system observables (homogenous entities)	distinctive and heterogeneous entities at the technical level	distinctive and heterogeneous entities at both technical and social level
Local Interactions	The average value for interactions	Interactions at the technical level	Interactions at both social and technical level
Traffic Network	Hard to present	Not usually presented	Straightforward to present
Adaptiveness	No adaptiveness at the individual level	No adaptiveness at the individual level	Adaptiveness as agent property

Emergence	Debatable because of lack of modelling more than one system level	Debatable because of predesigned system properties	Capable to capture because of the modelling system in two distinctive levels
Self-organization	Hard to capture due to lack of modelling the individual decision making	Hard to capture due to lack of modelling the individual decision making	Capable to capture because of modelling autonomous agents
Co-evolution	Hard to capture because the system structure is fixed	Hard to capture because processes are fixed	Capable to capture because network structure is modified by agent's interactions
Path dependency	Debatable because of no explicit consideration of history to determine the future state	Debatable because of no explicit consideration of history to determine the future state	Capable to capture because current and future state can be explicitly defined based on system history

Four major agent-based simulation approaches have been adapted in modelling vessel traffic in port by the previous author. These are Cellular Automata, Artificial Potential Field and rule-based model, which comprises generic and specific rule-based models.

2.6.3.3 Cellular Automata

The Cellular Automata model is a specific type of rule-based model. It is discrete both in time and space to describe the discrete movement of vessels through grids of cells. The waterway or traffic route is discretized into cells with a predefined size. The vessels are assigned a certain number of cells according to their length. The states of cells are assumed to be either available or occupied. For all cellular automata models, the decision of vessel behaviour depends on the status of neighbouring cells. However, the moving direction and the moving speed differ according to the rules defined in different models. The position of the vessel is updated at each time step. Vessel speed is modelled generally in two ways; either constant or dependent on vessel type, (Liu et al., 2010) (Blokus-Roszkowska and Smolarek, 2014). Alternatively, the speed of the vessels is decided by rules of following behaviour (Feng, 2013, Qi et al., 2017b, Qu and Meng, 2012, van de Ruit et al., 2010). However, cellular automata models present the dynamics of traffic flow based on vessel speed and position in cells, the detailed behaviour of vessels can hardly be simulated. The impacts of external factors were also simplified.

Authors have applied this method in port traffic modelling. For example, (Liu et al., 2010) developed a cellular automata model of a waterway traffic flow to verify the rationality of statistics and prediction to help solve the problems of complexity and non-linearity in port traffic control and management. The model constitutes of different classes of vessels, safe distance between vessels as collision avoidance guidance, a ship arriving law and berths processes. The dynamics of traffic flow are based on vessel speed and position in cells, the detailed behaviour of vessels can hardly be simulated.

Blokus-Roszkowska and Smolarek, 2014 developed a cellular automaton model for safety analysis of waterways' crossings in the restricted area. The model describes different types of vessels and introduced rules of vessels movement and collision avoidance manoeuvre. The author considers the relative course of the other vessel to determine the reacting behaviour, which could be acceleration or course change. Similarly, the dynamics of traffic flow are based on vessel speed and position in cells, the detailed behaviour of vessels can hardly be simulated. Feng, 2013, developed cellular automata combined with a numerical simulation model with an integrated bridge system for partial reduction waterway traffic. The model is used to analyse the effect on waterway transit capacity by precautionary area length and ship arrival rate. The dynamics of traffic flow are based on vessel speed and position in cells, the detailed behaviour of vessels can hardly be simulated. Qi et al., 2017b, developed a cellular automata model for ship traffic flow, called a spatial–logical mapping (SLM) model, which studies the vessel traffic flow and improves marine transportation efficiency and safety. The author included a spatial discretization rule using the mapping rule, and vessel dynamics are simulated by updating the rules within the model. However, the dynamics of traffic flow were based on vessel speed and position in cells, the detailed behaviour of vessels was hardly be simulated.

Regarding the external impacts, Qu and Meng, 2012, Qi et al., 2017a adopt random variables to represent the impacts of weather and sea state on vessel speed. The interactions with other vessels are considered by defining deceleration rules when another vessel is within a distance of safety (Feng, 2013, Qi et al., 2017a). Blokus-Roszkowska and Smolarek (2014) consider the relative course of the other vessel to determine the reacting behaviour, which could be acceleration or course change. Qu and Meng (2012) define crossing rules for vessels about to enter the main traffic route from the branch waterways and rules for overtaking situations.

2.6.3.4 Generic rule-based Models

Generic rule-based models assume the details of the individual vessel behaviour (position, speed, and course) are simplified as generic movement rules for all agents. In such models, the rules for different vessels are defined as the same under any circumstances. The differences in unhindered behaviour among different vessels and the external impacts under different circumstances cannot be presented in the generic rule-based models. When applying for macroscopic statistical analysis for a large area as presented in the referenced papers, the models are well applicable. Authors who have applied this model include;

Almaz et al., 2006 develop a functional simulation model for the maritime transit traffic in the Strait of Istanbul to investigate the effects of type and frequency of transit demand within the strait. The study used a realistic and practical environment to analyse and evaluate the effects of policies, resource availabilities, possible transit vessel profiles and environmental conditions, based on past transit vessel and environmental conditions data. The author presents the maritime traffic in one-dimensional space, i.e. the lateral position of vessels in the waterway is not included. The routes were predefined with waypoint. Vessels were modelled as agents, and the behavioural rule of agents follow the routes and turn instantly at the waypoints. The vessel speed was dependent on the classification.

Camci et al., 2009 developed a simulation model, which aims to relax some assumptions made by previous studies for marine traffic in Istanbul Strait. The author also presents the maritime traffic in one-dimensional space. The routes were predefined with waypoint. The behaviour rule of the agents is to follow the routes and turn instantly at the waypoints. The vessel speed was dependent on the classification.

Goerlandt and Kujala, 2011 developed a simulation model to determine the expected number of accidents, the locations and the time when they are most likely to occur while providing input for models concerned with the expected consequences. The author presented the maritime traffic in one-dimensional space. The routes were predefined with waypoint. The behaviour rule of the agents is to follow the routes and turn instantly at the waypoints. The vessel speed was dependent on the classification. Merrick et al., 2003 developed a simulation model to estimate the number of vessel interactions in the San Francisco Bay area. The model output shows the level of congestion within the study area. The study area was represented in one-dimensional space. The routes were predefined with waypoint. The behaviour rule of the agents is to follow the routes and turn instantly at the waypoints. The vessel speed was dependent on the classification. Piccoli, 2014 develop a simulation model using the port of Jebel Dhanna/Ruwais as a case study to assess marine operations performance. The model was presented in one-dimensional space and the routes were predefined with waypoint. The behaviour rule of the agents is to follow the routes and turn instantly at the waypoints and vessel speed was defined as the same for all vessel types.

Puszcz et al., 2011 presented a probabilistic model of vessel traffic in Southern Baltic on chosen areas to understand traffic behaviour. Vessel traffic was analysed through statistical methods with the use of historical AIS data. The study area was represented in one-dimensional space with the routes predefined using waypoint. The behaviour rule of the agents is to follow the routes and turn instantly at the waypoints. The vessel speed was generated from historical distribution. Thiers and Janssens, 1998 developed a simulation model of port traffic consisting of navigation logic, tides and lock planning to investigate hindrances in the port Antwerp. The author presented the maritime traffic in one-dimensional space. Vessel speed is determined for each waterway segment allowing vessels to change their speed immediately they enter a new segment.

Hasegawa, 1990 used a Ship Auto-navigation Fuzzy Expert System (SAFES) to simulate and evaluate port traffic in Japan. The system SAFES is a simulation tool with navigational capabilities such as course keeping, collision avoidance, etc. The author model basic features of the navigational system using fuzzy reasoning or control. The study area was represented in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data. The vessel speed was dependent on the classification. Hasegawa et al., 2000 applied AIS into SAFES to develop an intelligent transport system for marine traffic in Japan. The study area was represented in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data. The vessel speed was dependent on the classification For re-configuration or re-design of the marine traffic system, Hasegawa et al., 2001, developed an intelligent marine traffic simulator. The simulation model was used to evaluate marine traffic for configuration of sea area, lanes and traffic conditions. The modelling includes the behaviour of human operators to account for human error. The simulated area was represented in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data. The vessel speed was dependent on the classification. Xu et al., 2015 developed a simulation model for simulating vessel traffic in the inland multi-bridge waterway. The simulated area was represented in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data. The vessel speed was generated from historical distribution.

The conditions of external environmental factors are considered by defining different vessel speeds (Almaz et al., 2006, Camci et al., 2009, Merrick et al., 2003, Puszcz et al., 2011), or generating vessels according to the tidal window (Piccoli, 2014, Thiers and Janssens, 1998). Qu and Meng, 2012, Xu et al., 2015 define the rules of overtaking by a distance of safety. None of the models defines detailed behaviour rules for collision avoidance during other encounters. However, the Distance of the Closest Point of Approach (DCPA) and Time to the Closest Point of Approach (TCPA) are calculated for risk analysis (Goerlandt and Kujala, 2011, Hasegawa et al., 2001). The traffic rules regarding speed limit or overtaking prohibition are also included for all vessels (Qu and Meng, 2012, Thiers and Janssens, 1998, Xu et al., 2015).

2.6.3.5 Specific rule-based models

Similar to generic rule-based models, the dynamic vessel behaviour (position, speed, course, and heading) is assumed to be described by a set of rules. However, the specific rule-based models consider the differences between vessels and the possible interaction between vessels and the circumstances. The unhindered behaviour of different vessels is usually distinguished. The impacts of the geographical layout can also be included by defining behaviour rules. The vessel behaviour during an encounter can be determined according to a situation-based calculation. The specific rule-based models represent the interaction between vessels better than the aforementioned two approaches. However, in most of the pre-defined rules, the safety distance or other parameter value to trigger the evasive manoeuvre for collision avoidance is subjectively determined by the user for a specific area during model development. It limits the applicability of models in other areas. The impact of environmental external factors is not included yet. To present such impacts on different vessels by specific rules, detailed manoeuvring particulars for specific vessels may be needed.

Aarsæther (2011) developed a simulation model composed of autonomous agents and efficient time-domain to undertake preliminary simulation studies of marine traffic to deliver estimates, or for screening procedures before undertaking the more expensive simulations with a human operator. The vessel course was not designed to follow the route. The author defines vessel behaviour as a first-order model between the current and desired speed. . But the influence of external conditions was not included. Miyake et al., 2015 developed a port traffic simulation model with the inclusion of a collision avoidance algorithm. The rules for basic behaviour and vessel course were designed following the route and vessel to turn at the waypoints. The speed of the vessels was fixed throughout the voyage. . Nevertheless the influence of external conditions was not included. Watanabe et al., 2008 used the Marine traffic simulator developed at Osaka University to simulate marine traffic flow based on the “Ship Auto Navigation Fuzzy Expert System” (SAFES). Each modelled vessel has its characteristics (principal particulars, speed, manoeuvring parameters, OD (origin and destination) and waypoints). The rules for basic behaviour and vessel course were designed following the route and vessel to turn at the waypoints. The speed of the vessels was fixed throughout the voyage. The author assumes the waterway bank to be a virtual agent with the same speed parallel to the vessel agent or in the opposite direction.

Davis et al., 1980 developed a simulation model of ship behaviour using the concept of a domain and an evasion area, called an arena, which determines when a ship takes avoiding action. The rules for basic behaviour and vessel course were designed following the route and vessel to turn at the waypoints. The speed of the vessels was based on distributions derived from historical data. Colley et al., 1984, developed a simulation model using a range to the domain over range rate (RDRR) criterion to simulate traffic flow and collision avoidance through the main south-west bound lane of the Dover Strait traffic separation scheme. Vessels are modelled as a separate object possessing given attributes with behavioural rules designed following the waterways. The speed of the vessels was based on distributions derived from historical data. Huang et al., 2013 presented a simulation model covering the waterway network with flexibility in defining traffic flow patterns. The author modelled vessels as separate objects possessing given attributes with behavioural rules designed following the waterways. Vessels speeds were based on distribution derived from historical data. Li, 2013, developed a model called Marine Traffic Conflict Simulation System, to evaluate measures for conflict detection and resolution using the seaport of Singapore as a case study. The rules for basic behaviour and vessel course were designed following the route and vessel to turn at the waypoints. The speed of the vessels was based on distributions derived from historical data.

Xu et al., 2013 developed a simulation model to help reduce accidents in waterway areas having bridges. The author modelled vessels as separate objects possessing given attributes with behavioural rules designed following the waterways. Vessels speeds were based on distribution derived from historical data. Vessel interactions with other vessels during encounters or the influence of external conditions were not included.

Rayo, 2013 developed a simulation model to assess access into the waterway for the Taman Seaport in Russia. The model assesses the type and widths of different waterway access. Vessels are modelled as a separate object possessing given attributes with behavioural rules designed following the waterways. The speed of the vessels was based on distributions derived from historical data. Huang et al., 2016 developed a model to simulate a large number of interacting vessels while reflecting the navigational behaviours of various vessel types. The author modelled vessels as separate objects possessing given attributes with behavioural rules designed following the waterways. Vessels speeds were based on distribution derived from historical data. Nevertheless, the influence of external conditions was not included. Gucma et al., 2017 presents a simulation validation of a vessel traffic stream model using real-world data of vessel delays in Świnoujście — Szczecin waterway. The model is based on the Monte Carlo methodology. Vessels are modelled as a separate object possessing given attributes with behavioural rules designed following the waterways. The speed of the vessels was based on a specific distribution. Nevertheless, the influence of external conditions and collision avoidance behaviour was not included. Shu et al. (2015) developed a port simulation model for predicting vessel behaviour within the ports and waterways. The model was calibrated with AIS data to minimize the difference between vessel course by comparing vessel route from AIS data and predicted model route. Vessel interactions with other vessels during encounters or the influence of external conditions were not included.

Regarding the impacts of external environmental factors, only two models include the corresponding behaviour rules. For the impact of the Riverbank, Davis et al. (1980) define the domain of bank, while the vessels will change course to sail parallel to the bank and decelerate. Watanabe et al. (2008) assume the waterway bank to be a virtual agent with the same speed parallel to the vessel agent or in the opposite direction.

Nearly all models include the interactions between vessels for collision avoidance, except for Xu et al. (2013). Rayo, 2013, Gucma et al., 2017 only define a distance of safety to determine whether a vessel should decelerate or not, in which course change is not considered in the one-dimensional space. The remaining models adopt different criteria to judge the encounter situation between vessels and calculate DCPA and TCPA to trigger the evasive actions. Aarsæther (2011) only defines a distance of safety as the only criterion. Davis et al. (1980) adopt the ship domain to indicate the timing when the domain is infringed by the other vessel, in which the size is decided by statistical data. Colley et al. (1984) further considers the relative speed of the other vessel and defines the concept of range to the domain over range rate (RDRR) in the calculation. This way, the three types of encounters can be distinguished. The behaviour rule during a dangerous head-on situation (starboard-to-starboard) is also defined. Li, 2013, Miyake et al., 2015 trigger the collision avoidance behaviour with an increase of DCPA and TCPA. Watanabe et al. (2008) adopt the concept of CR by Hasegawa et al. (2001) to judge the situation and calculate the timing for the vessel to turn back to the original route. Huang et al. (2016) use DCPA and the Separating Axis Theorem (Eberly, 2001) to detect the collision candidate. All of them assign the responsibility of taking actions among vessels in encounters based on the rules of COLREGs. The resulting evasive behaviour is mainly to change course or to change both course and speed. The magnitude of the behaviour is decided to best decrease DCPA and TCPA.

In the models by Davis et al., 1982, Colley et al., 1984, Miyake et al., 2015, the multi-vessel encounter situation is assumed to be a series of two-vessel encounters. The most dangerous vessel to avoid collision first is chosen with the earliest TCPA. In this case, if the most dangerous vessel is the give-way vessel, and she does not take evasive actions within a certain time, the stand-on vessel at liberty should take action by a round turn. During the collision avoidance, DCPA and TCPA are calculated at each time step to judge the situation.

2.6.3.6 Artificial potential field models

An Artificial Potential Field (APF), also known as artificial force field are a method of an agent-based simulation designed to calculate the potential and forces to decide the speed and course at each time step. The approach has been implemented in three maritime traffic models for different types of water areas. In these models, vessels are defined as agents, and an artificial potential field was used to subject vessel course to a force that is derived from the sum of the attractive potential and the repulsive forces. All models by artificial potential field present the vessel behaviour in two-dimensional continuous space. The models are designed to calculate the potential and forces to decide the speed and course at each time step. Artificial potential field shows its potential in modelling the course choice under the external impacts from sailing boundaries or other encountering vessels. It can be expected that the method could represent the impacts of external factors as repulsive potential based on the hydro dynamical calculation or sufficient data analysis to calibrate the parameters in the function. However, the method of artificial potential field APF itself hardly simulates the unhindered vessel speed, which is so far derived from historical data or modelled separately.

Xiao (2014) developed a simulation model to provide detailed vessel behavioural information of vessels in a specific navigational environment, on both the vessel traffic level and the individual vessel level, for safety analysis, decision making, planning of ports and waterways, and design of mitigation measures. The author adopts an artificial potential field to simulate the impacts of banks and encounters (head-on and overtaking situation) on vessel behaviour in straight waterways. Vessel behaviour was modelled using the Nomoto model (Kawaguchi et al., 2004) based on basic manoeuvrability, and the impact of wind and current were indicated by variations in vessel course and heading, without influencing the vessel speed. However, the model does not consider the different fleet compositions and vessel dynamic behaviour (speed variations).

Rong et al. (2014) developed a model of vessel navigation in a restricted waterway. The author adopted a Monte Carlo simulation technique to simulate marine traffic based on AIS (Automatic Identification System) data. The developed simulation model consists of a ship collision avoidance model based on the artificial potential field method. Traffic lane boundaries are represented by a series of points with the repulsive potential to the vessels. Vessel speed changes only during an encounter with other vessels or obstacles. Otherwise, vessels keep a constant speed determined when generating the vessel in the beginning. The impact of external conditions, e.g. wind or current, were excluded from the model.

Cheng et al. (2017) propose an approach to simulate maritime traffic flow based on historical data and Agent-based models. The author combined the agent-based simulation artificial potential field method to develop collision potential fields of different obstacles. The impacts from fixed obstacles in the multi-bridge area are simulated using an artificial potential field. The repulsive potential field around fixed obstacles is assumed to be a rectangle or circle with three layers, in which the most inside layer is set with the largest repulsive potential. The potential of the three layers is defined separately as a function of distance, speed, and course, while the potential within each layer is the same. Vessel speed changes only during an encounter with other vessels or obstacles. Otherwise, vessels keep a constant speed determined when generating the vessel in the beginning. The impact of external conditions, e.g. wind or current, were excluded from the model.

2.7 Discussion on reviewed literature

The literature review reveals that several approaches have been adopted by previous researchers to represent port traffic. Amongst others, discrete-event, system dynamics and agent-based simulation is the core approach utilised. The review, therefore, studied the different methods and their application in simulating port traffic. Port traffic is composed of three aspects; port processes, the impact of external conditions and vessel traffic. Models tend to focus on ether port process or vessel traffic modelling partly because of the different knowledge and skill sets required and the constraints of the simulation methods used. Being able to re-use and integrate process and traffic models would be an advance in port modelling.

Each aspect has been represented by several authors using a different simulation method, discrete-event, system-dynamics, and agent-based simulation. The literature review reveals that both port processes and vessel traffic have been simplified by previous authors to suit their research purpose. For example, although many studies have included all of the relevant port processes, most have not fully modelled the associated processes. For example, Park and Noh (1987) applied a discrete event simulation approach to creating a user-oriented port expansion model, which determines the economic future of port capacity to meet the projected demand, (Park and Noh, 1987). However, processes like anchorage and berthing were simplified: the anchorage process was considered a queuing system, while the berthing process was considered a simple dwell time. Similarly, studies by (Hassan, 1993, Thiers and Janssens, 1998, Demirci, 2003, Yeo et al., 2007, Almaz and Altiok, 2012, Piccoli, 2014, Uğurlu et al., 2014, Scott et al., 2016, Bellsolà Olba et al., 2017) have adopted the same approach.

None of the studies has aimed at developing a complete port-traffic model that adequately represents port processes and vessel traffic. However, the authors have modelled each aspect to some degree of detail. Each aspect of port traffic and the simulation approaches used by previous authors to model them was reviewed. The outcome of the review shows that port processes are static meso-level/intermediate/mid-level structures composed of interactive operational processes. Authors representing port processes major on modelling the various operational processes like anchorages, berth etc. but ignore the interaction between each process

For example, in the model created by Hassan, (1993) to simulate a complex port, the relationship between each port process (e.g. the relationship between berth and anchorage) were not represented but were just linked as a sequence of events. In the model developed by Yeo et al. (2007) to evaluate marine traffic congestion in Busan port, the cargo operation (cargo loading/unloading) phase, that is, when a vessel is at berth was not included. In the model developed by Piccoli (2014), to assess port marine operational performance both the vessel berthing process and cargo operation phase were modelled as one. Uğurlu et al., (2014) developed a model to determine the handling capacity and usability of a port terminal where the anchorage process was represented as a simple queue. In the study conducted by Bellsolà Olba et al., (2017) to estimate the network capacity of vessel traffic, marine infrastructures like anchorage, berthing manoeuvring, terminal operations were excluded. This resulted in the vast use of discrete-event simulation or other process related models in representing port processes, since modelling the interaction between entities is a challenge. In dealing with this challenge the review also found out that representing a complete port process would require a combination of approaches. Thus, a mixed simulation approach composed of agent-based and discrete-event simulation modelling was considered because the agent-based model can simulate the interactions between entities during port processes and also allows the integration of different simulation modelling techniques and computer programming approaches. With the discrete-event simulation representing the static properties and individual operation of the port processes, the agent-based simulation models the interactions between each entity. This can better represent port processes and the diverse communication between processes, thereby increasing the model scalability, and to date, no study has adopted a mixed simulation method to represent port processes.

For vessel traffic, the review study the behaviour of vessel traffic and approaches used by several authors. The outcome shows that several simplifications have been made in simulating vessel navigational behaviours. For example, vessels moved at fixed or randomly selected speeds, and the effects of vessel-to-vessel encounters, where vessels must adjust course and speed, were excluded. Only models developed specifically to assess traffic capacity and risk during vessel navigation included modelling of vessel behaviour during navigation. These, therefore, did not include port-marine and terminal process models.

Some of these are simulating navigation as a sequence of events using discrete-event simulation modelling which ignores certain factors like transit time, environmental condition, vessel types and speed, etc. Also, some model has focused on a specific aspect of navigational behaviour, like the impact of environmental conditions on current using system-dynamic simulation to implement mathematical calculation. Some also using agent-based simulation to ignore the impact of environmental conditions on vessel behaviour and the interactions between vessels. For example, Hasegawa et al. (2001), developed a free navigational model in Osaka Bay. The navigational model was designed to reconfigure and evaluate marine traffic systems for any configuration of sea area, lanes and traffic conditions. Although it reproduces vessel navigational behaviour, the model does not include external conditions and their impact on vessel movement. Goerlandt and Kujala (2011) developed a simulation model to assess the probability of vessels collision. The model created several waypoints using AIS data but doesn't consider their dynamic properties and navigational behaviour, (Goerlandt and Kujala, 2011). Huang et al. (2013) developed a model using AIS data to simulate the navigational network, traffic flows and complex navigational behaviours of vessels within the port. The study models vessel behaviour without taking considering the environmental influence on vessel navigation and the speed of each vessel, (Huang et al., 2013).

Most studies applying the agent-based simulation approach came closest in representing vessel navigational behaviour. For example, Xiao et al. (2013) developed a multi-agent traffic simulation model calibrated to simulate dynamic ship manoeuvring for assessing maritime safety. The model includes waterway infrastructure and external influence but does not consider the different fleet compositions and vessel dynamic behaviour (speed variations). Shu et al. (2015) developed a port simulation model for predicting vessel behaviour within the ports and waterways. The model was calibrated with AIS data to minimize the difference between vessel course by comparing vessel route from AIS data and predicted model route. Vessel interactions with other vessels during encounters or the influence of external conditions were not included. Xu et al., (2015) simulate vessel traffic flows in inland multi-bridge waterways. The model structure is divided into three parts: a vessel generating model, a routing model and a vessel behaviour model. The first model generates the vessel distributions based on historical AIS data using a Monte Carlo method, and it considers different distributions for vessel types, vessel sizes, vessel arrivals and vessel velocities, (Xu et al., 2015). The routing model generates the position of the waypoints for each vessel route. The vessel behaviour model considers different sailing restrictions for specific traffic situations: free flow, overtaking or following. However, the port processes like anchorages and different speeds changing the behaviour of vessels were not included.

Since port traffic is composed of two aspects; port processes and vessel traffic, none of the reviewed models represented a complete port-traffic model encompassing navigational behaviour, the impact of the external condition and port processes. Hence comparison between each simulation approach was conducted. The comparison is aimed at investigating the ability of each simulation approach to effectively represent a complete scalable port-traffic simulation model. Research agrees that the differentiation in simulation approaches stems from key issues such as the level of abstraction, which is the level of details required when a model is applied.

The result shows that system dynamics is used for studies requiring high abstraction of details, while discrete-event simulation modelling is used for studies requiring less abstraction range. But agent-based simulation modelling cuts across all abstraction levels, meaning agent-based simulation can model systems at any level of abstraction. Thus, this approach can be used to model vessel traffic where each entity within the model represents an agent. However, considering how different simulation methods correspond to abstraction to simulating port-traffic;

- The navigational behaviour of individual vessels (e.g. response to a change in visibility) cannot be clearly defined using discrete-event or system dynamics, except agent-based simulation.
- Port processes are complex. The discrete event can be used to separate static processes, while the agent-based simulation can be used to describe multiple interactions.
- Activities are arguably a more natural way of describing a system than processes; therefore port processes and vessel traffic activities are best to describe using Agent-based simulation.
- Entities behaviour is stochastic. Points of randomness can be applied strategically within agent-based models, as opposed to arbitrarily within aggregate equations.

Analysing the requirement and defining problems provides a point of focus and ensures that a developed simulation method can address stated problems effectively, (Anosike and Zhang, 2000). Hence, to integrate both port processes and vessel traffic a multi-method simulation is required. A complete port model must be capable of integrating process models and agent-based traffic models. The solution is to adopt a multi-method simulation approach composed of both agent-based and discrete-event simulation models. While there have been several studies on port traffic in literature, there are few that position the adopting of a multi-method simulation in representing port traffic. Discrete-event simulation models the processes associated with each part of the port process, while agent-based simulation models the interaction between entities within a process and between processes. For example, the interaction between vessels as they travel from the anchorage process to the lock-gates process. Or an entity manoeuvring from the lock gate to the berth.

2.8 Conclusions

While many studies have focused on modelling and simulating aspects of the port system few have investigated the development of systems modelling and simulation methodologies that can be applied to model every aspect of the system. Where studies have developed a more realistic simulation of vessel traffic they have not been integrated with a complete model of port processes. The difference in vessel behaviour is generally simplified because they are mainly modelled using process-related approaches such as discrete-event simulation. The differences between vessel behaviour are either ignored or simplified. With these simplifications, the interaction between vessels during transit and manoeuvring times cannot be accounted for. A vessel consumes around 10 per cent of its fuel use during slow manoeuvring. Assuming around 4.5% and 6.2% of the total SO_2 and NO_x emitted by ships are due to in-port activities such as manoeuvring (approaching harbours) and hoteling (at the dock in port), simplifying the traffic model hinders the ability to conduct accurate emission assessment and limits the ability to conduct an environmental assessment as a result of increased port capacity.

Chapter 3: Research Methodology and Simulation Structure

3.1 Introduction

A major concern when developing a simulation model is retaining the relationship knowledge between the real system and the simulation model (Frankel, 1987, Dragović et al., 2005). Also, a challenge in port traffic simulation modelling is being able to re-use and integrate process and traffic models (Frankel, 1989, Demirci, 2003). Hence, this study adopted a multimethod simulation comprising discrete-event and agent-based simulation as discussed in Section 2.7. This chapter provides the outline of the research methodology adopted in the study including the structure of the developed port traffic simulation model. The chapter discusses multi-method simulation and its application in this study. The chapter also outlines the structure of the developed model which include the simulation objectives, purpose, simulation environment, underline assumptions, simulation verification and validation, and the working principles. The structural application of these techniques and the steps required for the case studies are also discussed. The application of these techniques and the steps required for the case studies are given in Chapters 4, the development in AnyLogic is presented in Chapter 5, while the validation and verification are presented in Chapter 6.

3.2 Research Methodology Overview

This section outlines the approach on how the simulation model development, validation and application are tied up together to develop a multi-method simulation model of port systems to simulate port traffic for assessing various port challenges like emission. Models and frameworks developed for the main chapters including Chapter 4: Conceptual model development, Chapter 5: AnyLogic Model development, Chapter 6: Verification and Validation of AnyLogic Model, and Chapter 7: Application of Validated AnyLogic Model in Case Study. Figure 3-1 shows the framework overview and how the technical chapters are linked.

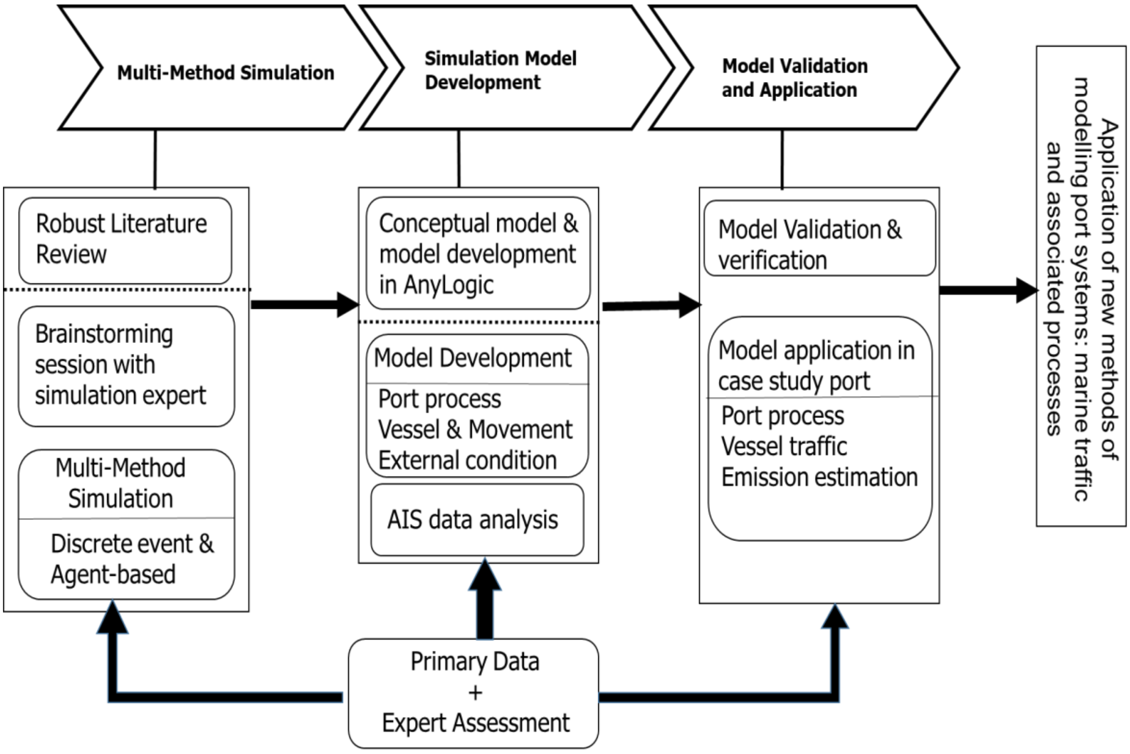


Figure 3.1: Overview of the research framework

Chapter 4 is the initial technical chapter and serves as the preliminary assessment chapter for the model development, validation and application. The chapter reveals the conceptual model of the developed port traffic simulation. The identified key systems that make up the port will be further investigated and designed based on the simulation methodology discussed in Chapter 2 in this chapter. The chapter discusses major themes such as the overview of the port traffic, conceptual model design, and the different model layer. The conceptual model design and working process follow the model structure presented in this chapter. The chapter also presents the historical AIS data analysis which serves as model input.

The conceptual model developed in chapter 4 is then integrated into AnyLogic to develop the model in Chapter 5. The various systems are represented based on the simulation method discuss in Chapter 2 and the design in Chapter. For example, port processes are represented as processes using the discrete-event simulation method in AnyLogic. The developed port traffic simulation model in AnyLogic uses the historical AIS data analysis in chapter 4 as input. The developed port traffic simulation model is then run for verification of the simulation performance, and validation using real-world data in Chapter 6. The simulation output of the validated port traffic simulation model in AnyLogic is then used to estimate the emission of the case study in Chapter 7.

3.3 Multi-Method simulation modelling

Multi-Method architectures can also be defined by combining two or more different models. A major purpose of multi-method simulation is to complement simulation methods. The complementarity of methods presumably mitigates assumptions prescribed within methods that allow for shaping more flexible research approaches. The reasons for combinations of methods and the need for hybrid methodologies given by respondents is to move away from the perception that one method fits all a need for a holistic view of the complex interconnected systems, and a need to include dynamic elements.

The combination of discrete-event and agent-based simulation approaches is highly suitable for distributed problem solving as they offer the possibility to divide the main task into small subtasks (Smith & Davis, 1981). One of the first papers dedicated to a combination of two approaches in the field of transportation was published by Gambardella et al. in 2002 (Gambardella, Rizzoli, & Funk, 2016). The authors developed the agent-based discrete-event simulation model of the flow of intermodal terminal units among the inland intermodal terminals using the MODSIM III simulation platform. They modelled the operation of the intermodal terminal with different modes of transport such as road and rail. However, the authors have not considered a probability distribution for the random variable to simulate different operations such as the arrival of vehicle, loading & unloading operations, etc. It could potentially reduce the accuracy of the results.

Ongo & Karatas constructed the agent-based model of maritime search and rescue and patrol operations (Onggo & Karatas, 2015). The model of the MASSIM simulation platform consists of two agents such as searcher and target. The main objective of the searcher is to detect the target. According to their behaviour, targets can be classified into three groups: a cooperative target that wishes to be detected by the searcher (e.g. the victims in a search and rescue operation), a non-cooperative or evading target that is willing to hide or escape from the searcher (e.g. a refugee trying to reach his/her destination without being detected by the coast guard), and a non-cooperative target that wishes to be as close as possible to the searcher without being detected (e.g. a hostile submarine trying to approach surface ships as close as its effective torpedo range). Nevertheless, the scale of the proposed model is closely designed at mid-level which is not correlated with microsimulation that is associated with agent-based discrete-event simulation.

Abourraja et al. developed a multi-agent simulation model for rail–rail transhipment yard at Le Havre Port to solve the problem of gantry crane scheduling by using the AnyLogic simulation platform (Abourraja et al., 2017). The authors proposed such agents as operational planner agent who takes short-time planning decisions on incoming freight trains, determining the resource allocation and handling or departure operations with freight trains; a tactical planner agent which schedules intra-port container transfer activities (medium-time planning decisions) by determining the required number of shuttles and considering containers characteristics (such as size, type, origin, target terminal and date of arrival at maritime terminals; transport service provider agent, who creates long freight trains and plans their arrival and departure dates from the multimodal terminal by representing rail transportation actors and coordinating container routing to and from Le Havre seaport over its hinterland. Still, the authors have not represented the vehicles and handling equipment as the agents, which could simplify the visibility of the developed model and interaction between agents. Furthermore, the authors have not represented the process flowcharts developed in the internal environment of the agents, since they applied Agent Library, State Chart, Rail Library and Process Modelling Library of the AnyLogic simulation platform.

(Varol and Gunal, 2013) presented a simulation-based analysis tool to understand the relationship between naval forces deployment and piracy. The author adopted a hybrid method comprising of discrete-event simulation and an Agent-based simulation model. Our conceptual model is created using event graphs and the model is implemented using SharpSim discrete event simulation library. The behaviour of entities, the interaction between entities, and the autonomy properties of entities was modelled using agent-based, while event scheduling was modelled using discrete event simulation. The simulation environment was represented with a Geographic Information System (GIS) map.

Frazzon et al. developed a smart port-hinterland integration concept based on the application of a simulation DES model to analyse the port processes and micro-simulation technique to investigate the behaviour of urban road networks or other congested sites (Frazzon et al., 2019). The authors used two software: Aimsun and SimPy. The Aimsun hybrid simulator provided the macroscopic modelling and simulation of the travel demand was implemented to identify the bottlenecks of the road network. The SimPy discrete-event simulation software was applied to analyse numerically the queues in the gatehouses of the Brazilian ports. However, the application of two software is time-consuming, since the authors solved the technical problems of the port operations. Furthermore, it loses the visibility of the developed simulation models.

Collectively these studies have advanced agent-based discrete event modelling of the logistic facilities operation. However, they cannot adequately capture certain aspects in the real-world transportation environment, for example, operation uncertainty and disturbances, which are reducing the applicability of these methodologies. Furthermore, these studies are dedicated to solving separate issues such as operations management, scheduling, and facility location. Finally, most authors applied different simulation platforms instead of

AnyLogic simulation which consists of three simulation paradigms as agent-based, system dynamics and discrete event simulation.

3.4 Application of Mixed-method simulation in this study

The plan multi-method simulation will combine models representing individual actors and specific processes. Vessel traffic can be modelled by agent-based models which reflect movement characteristics of individual agents and interactions between them such as collision avoidance. These interactions are sometimes deficient in many existing vessel traffic simulation models, (Burmeister et al., 1997). Port processes are better modelled using discrete-event simulation as these follow a sequence of operations performed on agents. However, the operations of both simulation methods differ. The agent-based simulation focuses on modelling individual behaviour, while a discrete-event simulation is process-based. Hence, it is difficult to coordinate interactions between both simulation methods. This situation is made more difficult by the fact that interfaces are developed to enable communication amongst the entities modelled by these methods. With a range of available simulation tools, adequate interfacing that would facilitate coordination between these methods is usually too difficult or impractical, (Zhang et al., 2006). What is needed is a unified decision support framework that can integrate both simulation methods and coordinated interactions within the model.

Vessels and their interactions within the system can be captured using an agent-based simulation approach. Interactions within the system exist across all entities (vessels, port, and the environment), but the constraint that governs the interaction exists within the mid-level entities. The port traffic is governed and structured by different processes existing in the mid-level layer. This layer coordinates how micro-level objects move and interact within the system. Realistically, objects do not move randomly, they move across processes and interact with entities along each process. A vessel arriving at the port moves to the anchorage, then through the locks to its allocated cargo terminal. This sequence governs the movement of vessels, i.e. from one process to another. This mid-level stage also contains the waterway layout controlling the path a vessel takes from one process to another. So, capturing the mid-level entities is essential to modelling the port traffic system, hence a discrete-event simulation approach is needed.

Using the discrete event simulation modelling, an anchorage is represented as a waiting process built up with discrete entities reflecting relevant factors of the process (e.g. berth allocation, contact to tug and pilot, a queue of arrived vessels awaiting berth, etc.). While the agent-based simulation governs the mechanism of how, when, and why each entity communicates with the others. For example, when a vessel arrives at the anchorage, it joins the queue of arrived vessels in the waiting process using the discrete event model. But communicates as an agent with the port while in the waiting process for berth availability, tug and pilot operations, lock availability, etc.

Using agent-based simulation, a vessel can be modelled as an agent with its behaviour e.g. speed changing. An entire population of vessels (vessel types: container vessels, tankers, passenger vessels, etc.) can be represented as a collection of independent decision-making entities called agents, where each agent executes various behaviours appropriate for the system they represent. For example, the behaviour of a container vessel at a particular position within the waterway may differ from that of a tanker due to the different locations of their allocated cargo terminal. Interaction of the system's elements is central in generating behaviour (e.g. vessel to vessel interaction results in changes in speed, course, etc.). Each vessel interacts according to locally defined rules. Vessel movement patterns can be examined (based on vessel types) and represented using statecharts. A statechart is a formal and logical representation of states and transitions that may occur during the dynamic performance of the system under consideration. A state is the condition of an object in which it performs some activity or waits for an event. A transition denotes a switch from one state to another. Transitions are relationships between states, drawn as arrows, optionally labelled by a trigger that causes actions. Transitions may be triggered by user-defined conditions (timeouts or rates, messages received by the state-chart, and Boolean conditions). Combining both states and transition, a state chart represents the different contexts in which system behaviours occur. Event- and time-driven behaviour of an entity is controlled using a state-chart.

Port traffic control schemes are often designed based on the analysis of AIS data. (S. Wang et al., 2013; Y. Wang et al., 2013; Zhang et al., 2015; Coello et al., 2015; Goldsworthy and Goldsworthy, 2015). Research studies based on AIS data, frequently focus on: the optimization of shipping routes (S. Wang et al., 2013; Y. Wang et al., 2013); improving the efficiency of port operations (e.g., Nishimura et al., 2005; Petering, 2009); or modelling ship traffic behaviour (trajectories, speed profiles etc.) in high or low traffic densities (Xiao et al, 2015).

Compared to other transport sectors, studies combining analysis of both the geographic location, dynamic information (speed, heading etc.), and object characteristics (type, length etc.) of ship traffic are scarce. Geographical Information Systems (GIS) are used to map and capture movements relevant to a geographical area (Bury et al., 2014). An appreciation of these dynamics is required to visualise and effectively represent vessel activities and travels within the port to achieve sustainable development, (Paraskevadakis et al., 2016). However, few studies combine analysis of both the geographic location, kinetic dynamic information (speed, heading etc.), and vessel characteristics (type, length etc.) contained with the AIS data sets. This analysis shows the relationships and impact of vessel behaviour across a geographical location. For example, Willems et al. (2009) develop a decision-support model for ship traffic control by visualizing vessel traffic patterns across a geographical location using a GIS system. Tsou (2010) also created visuals of vessel trajectory and density maps using ArcGIS. Aarsaether and Moan (2009) obtain vessel traffic statistics and estimate navigation patterns in the restricted waters. Zhang, Meng, and Fwa, (2017) presented spatial distribution hotspot areas in Singapore Strait, by analysing ship traffic demand and the spatial-temporal dynamics of ship traffic.

Though AIS data analysis provides insight into vessel traffic and forms the basis of the simulation model, currently, research analysing both the geographic location, dynamic information (speed, heading etc.), and vessel characteristics (type, length etc.) to develop a multi-method simulation is scarce.

3.5 Profile of the developed port-traffic model

3.5.1 Simulation Objective

To develop a port traffic simulation model of Liverpool port using multi-method simulation. This objective aims to,

- Model vessels and their characteristics using agent-based simulation.
- Model individual navigational and collision avoidance behaviour of vessels using agent-based simulation
- Model each port process as an agent associated with processes represented using discrete-event simulation modelling, with interactions with other processes modelled with agent-based simulation.
- Model-specific external conditions e.g. tide, using agent-based simulation.
- Develop a digital simulation environment with dynamic abilities (zoom in and out).
- Maintain scalability (that is, allowing for model extension and re-usability) and update using data generated from real-world operations.

3.5.2 Simulation Purpose

The developed simulation model (**see Figure**) will simulate vessel, external condition, and port processes to be used to estimate emission within the case study port. The developed simulation model includes models of the vessel, external condition, and port process.

3.5.2.1 Vessel Model:

Model various vessels as an agent with behavioural characteristics based on vessel types, port rules and IMO COLREGs. The various part of this model for each agent include;

- Vessel Agent: A part of the vessel model that represents objects with vessel characteristics (e.g. speed) based on vessel types (e.g. container, general cargo, etc.).
- Vessel behaviour: A part of the vessel model that represents the vessel agent's behaviour (movement and collision avoidance).

3.5.2.2 Port Process model:

Comprise of the various port processes model as an agent to simulate the various port associated processes base on vessel types (e.g. container, tanker, etc.). The processes represented within each port process agent are;

- Anchorage process model: This simulates the waiting process vessel undergo as they arrive in the port and before them berthing at the cargo terminal.
- Lock: This simulates the waiting period vessel undergo when entering or leaving the berth and cargo terminal area.
- Berth & Cargo terminal: Simulate the berth and cargo operation process the vessel undergoes at the cargo terminal.

3.5.2.3 External Condition:

Comprises of tidal and visibility model to simulate the external conditions affecting vessel and port processes within the study area

- Tide: model the tidal rotation and height of water in the port
- Visibility: Represent the visibility condition within the study area.

3.5.2.4 Port Geographical Area:

Represent the marine environment of the study area created using a digital map to capture the port waterways, location of port processes, etc.

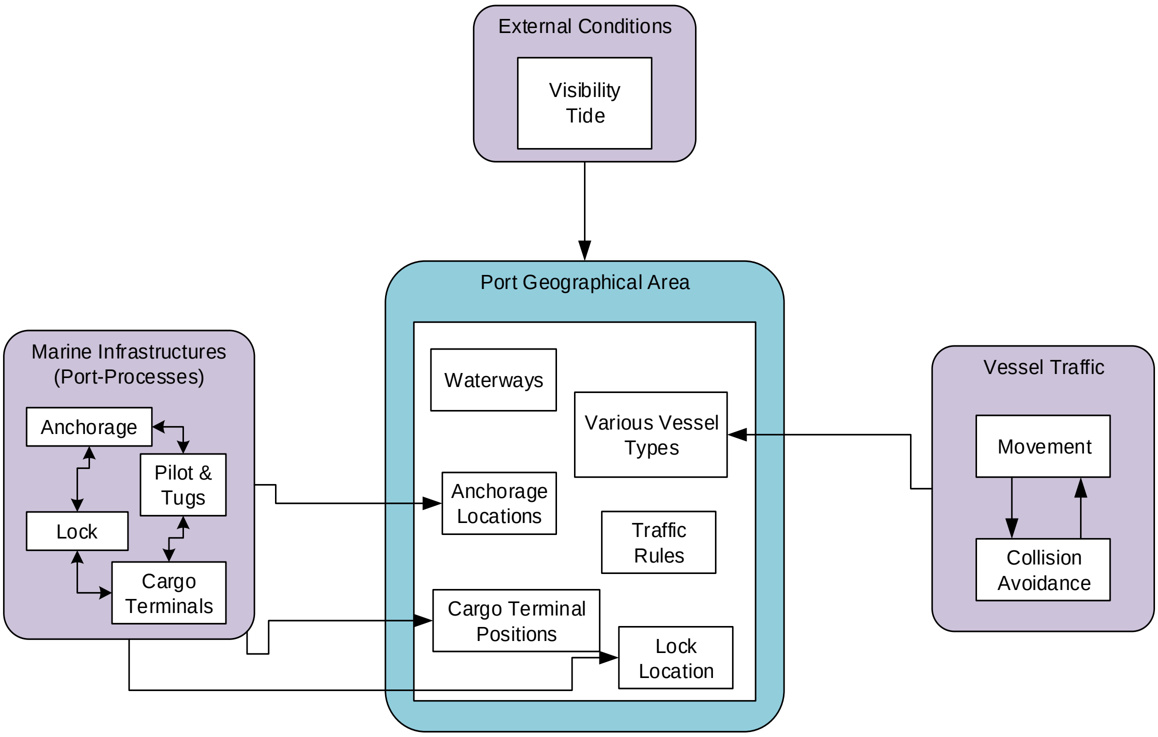


Figure 3.2: Component of the developed simulation model

3.5.3 Simulation environment

Complex hybrid system modelling may require distributed simulation due to system complexity, performance and interoperability requirements, etc. The developed simulation interoperates components simulated with both discrete event and agent-based simulation. Thus, using a more standard tool capable of simulating both methods is essential to avoid the creation of distributed simulations, where components are run on different machines and different platforms.

Agent-based models are often written in object-oriented languages like Java or C++ because agents can be viewed as an extension to objects. When developing a multi-agent simulation, it makes sense to use a helper package designed for this purpose, because multi-method simulation can be facilitated using simulation toolkits, which provide reliable templates for the model design, implementation and visualisation. (Tobias and Hofmann, 2004; Railsback et al., in press). This is because the important part of such a system is the accuracy of the model parameters and behaviour, and a helper package can abstract the design of the model from its programming. This allows the modeller to focus on tweaking the model rather than solving unrelated coding issues.

There are several tools, commercial and academic, capable of modelling and simulating systems with mixed discrete and agent-based (also called hybrid systems), (Abar et al., 2017). Although there are many systems available for developing agent-based models, eight were initially identified based on:

- Their ability to simulate agents and their technical improvements;
- Usability in agent-based simulation and their user community;
- User-friendly structure and in most cases they are accompanied by a variety of demonstration models with the model's programming script or source code is available;
- They are capable of developing spatially explicit models, possibly via the integration of GIS functionality

These tools are Swarm, MASON Repast, StarLogo, NetLogo, OBEUS, AgentSheets and AnyLogic.

Swarm is an open-source simulation system designed specifically for the development of multi-agent simulations of complex adaptive systems (Swarm, 2006). Swarm was designed to study biological systems; attempting to infer mechanisms observable in biological phenomena (Minar et al., 1996). Swarm has also been used in the field of anthropology, computer science, ecology, economics, geography, and political sciences. Useful examples of spatially explicit models include the simulation of pedestrians in the urban centres (Schelhorn et al., 1999 and Haklay et al., 2001); and the examination of crowd congestion at London's Notting Hill carnival (Batty et al., 2003). Although agent-based models can easily be developed using Swarm, another simulation tool capable of simulating discrete processes will be required to simulate the port processes.

MASON (Multi-Agent Simulation of Neighbourhood) was developed by the Evolutionary Computation Laboratory (ECLab) and the Centre for Social Complexity at George Mason University. MASON does not provide functionality for dynamically charting (e.g. histograms, line graphs, pie charts, etc.) model output during a simulation, or allow GIS data to be imported/exported (Luke et al., 2004). Therefore, lacking the ability to output dynamic results (e.g. vessel speed) is needed within this study.

The Recursive Porous Agent Simulation Toolkit (Repast) originally developed at the University of Chicago is currently maintained by Argonne National Laboratory and managed by the Repast Organisation for Architecture and Development (ROAD). Repast caters for the implementation of models in three programming languages: Python (RepastPy); Java (RepastJ); and Microsoft.Net (Repast.Net) and Repast Simphony (RepastS) which is the core functionality of RepastJ or Repast.Net, although limited to implementation in Java. Repast has an agent analyst extension that allows users to create, edit, and run Repast models from within ArcGIS (Redlands Institute, 2006). Useful examples of spatially explicit models created using Repast include the studying of segregation, and residential and firm location (Crooks, 2006) and the evacuation of pedestrians from within an underground station (Castle, 2006). Although agent-based models with spatial abilities (using GIS maps) can easily be developed, another simulation tool capable of simulating discrete processes will be required to simulate the port processes.

StarLogo is a shareware modelling system developed at the Media Laboratory, Massachusetts Institute of Technology (MIT). Unlike the other six agent-based simulations discussed in this section, both StarLogo and NetLogo models are programmed procedurally, opposed to an object-oriented nature. Thus, models developed with StarLogo do not benefit from the similarity in abstraction shared between the agent-based and object-oriented paradigms.

NetLogo (originally named StarLogoT) is a variant of StarLogo, originally developed at the Centre for Connected Learning and Computer-Based Modelling at north-western University, to allow StarLogo models to be developed on computers using the Macintosh operating system. NetLogo is specifically designed for the deployment of models over the internet (NetLogo, 2006). Both NetLogo and StarLogo provide the functionality to import image files, which can be used to define the agent's environment, thus facilitating the development of spatial models. Similar to Repast, NetLogo and StarLogo are mainly agent-based simulation tools and the process models would require a discrete-event simulation tool.

OBEUS (Object-Based Environment for Urban Simulation - Table 3) was developed at Tel Aviv University, Israel. OBEUS is implemented in the Microsoft.NET framework but relies on several third-party components (Microsoft.NET Framework, Borland C# compiler, etc.), which must be installed to operate the system. OBEUS provides a graphical user interface to develop the structure of a model, although the behaviour and interaction rules of agents must be programmed using one of the Micorsoft.NET languages (e.g. C#, C++, or Visual Basic, etc.). Consequently, moderate to strong programming skills are required). Although agent-based models can easily be developed using OBEUS, another simulation tool capable of simulating discrete processes will be required to simulate the port processes.

Agent-Sheets is a modelling system that allows modellers with limited programming experience to develop an agent-based model because models are developed through a graphical user interface (Repenning et al., 2000). Carvalho (2000) has used Agent-Sheets extensively to teach undergraduate students, the author comments that it is easy to use the system to develop models quickly, providing students with hands-on experience of ABM without the need to learn a programming language. However, the author notes models created with Agent-Sheets are limited in their sophistication (e.g. the complexity of agent behaviour and interaction). Furthermore, the system lacks functionality to dynamically chart simulation output, and agents are limited to movement within a two-dimensional cell-based environment. Thus, the method cannot be used in this study.

AnyLogic is a multimethod simulation modelling tool developed by The AnyLogic Company (former XJ Technologies). From its name AnyLogic, the simulation tool supports all three well-known modelling methods: agent-based, discrete event, and system dynamics simulation methodologies, and it's a cross-platform simulation software that works on

Windows, macOS and Linux. AnyLogic allows the users to combine these simulation approaches within the same model. For example, using agent-based simulation to model vessel movement and discrete event simulation to model port processes as intended in this study. AnyLogic also incorporates a range of functionality for the development of agent-based models. For example, models can dynamically read and write data to spreadsheets or databases during a simulation run, as well as dynamically chart model output. Furthermore, external programmes can be initiated from within an AnyLogic model for dynamic. AnyLogic also supports the use of a GIS spatial environment as required in this study.

The study plans to model vessels as agents with behavioural characteristics and port processes as an agent with embedded processes operating within a geographical environment represented with GIS map. To model such systems successfully and to get accurate and reliable results from simulation experiments one needs an executable language naturally describing hybrid behaviour, and a simulation engine capable of simulating discrete events interleaved with an agent-based model. Hence, the multi-method modelling tool used in this study is AnyLogic. AnyLogic is a simulation tool that permits the use of both agent-based and discrete event simulation. It also has the capability of integrating a GIS map into the model. This enables the development of a more realistic and multi-functional model of port traffic, (vadlamudi, 2016).

3.5.4 Underlying assumptions:

1) The major actors are the vessel and their movement in and out of the port.
2) Cargo operation (loading and unloading process) is represented as a delay process
3) Tug and pilot operations are represented as a specific duration attached to the anchorage process
4) Vessel collision avoidance actions are represented as speed changing actions.
5) The lock process is represented as a delay process.

3.5.5 Simulation verification and Validation

Despite the similarities, some researchers (e.g. Ormerod and Rosewell 2006, Windrum et al. 2007, Klugl 2008, Duong 2010) have noted that model validation in agent-based simulation is especially challenging and identified some common challenges. First, representing agent's behaviours and the interactions between agents using a set of logical rules. It is challenging to extract this information from social and intelligent agents, such as people and organisations, especially if the agents do not want to be exposed (such as pirates or human traffickers). Furthermore, real-world agents are often heterogeneous. Hence, it is challenging to validate whether the rules used in an agent-based simulation model represent the rules used by most real-world agents and whether we have represented the heterogeneity of real-world agents correctly. Secondly, there is a need to validate agent-based simulation models at various levels (agent/micro level, system/macro level and intermediate/meso levels). It is challenging to validate behaviour at the system level based solely on knowledge of the behaviours of individual agents. For example, Duong (2010) explains that emergence does not exist before a simulation is run (it might not even exist in the modeller's mind); hence, techniques such as structured walkthrough to analyse emergence from a model without running it would be virtually impossible. Even if we can generate traces during a simulation run, it is still a great challenge to explain how behaviour at a lower level can cause emergence at a higher level. Finally, an agent-based simulation model often requires high-fidelity data. Although the collection of high-fidelity data has become very common, qualitative behavioural data from heterogeneous agents in a population are rarely available. Hence, empirical validation may not be possible. The difficulty in validating an agent-based simulation model is reflected somewhat in the survey done by Heath et al. (2009). They surveyed 279 research articles and found that only 35 per cent of the models were validated both conceptually (white box) and operationally (black box). Windrum et al. (2007) conduct an interesting discussion about the methodological issues surrounding the empirical validation of agent-based simulation. Hence, the challenge is not simply one of data availability, it is also methodological.

Given these challenges, (Xiang et al., 2005) presented some validation techniques relevant for agent-based simulation models. These include,

Face validity is asking the domain experts whether the model behaves reasonably and makes subjective judgments on whether a model is sufficiently accurate. There are two ways to allow the experts to give the correct judgments easily:

- ***Animation*** is the graphical display of the behaviour of the model over time. Some simulation software, such as Swarm and Repast, have built-in features for animation and can even track the individual's properties while the simulation is running.
- ***Graphical Representation*** is representing the model's output data (mean, distribution, and time series of a variable) with various graphs. These graphs can help in making subjective judgments.

Model developers also use *Animation* and *Graphical Representation* for code verification in the model implementation process. Face validity is the first step of the three-step approach formulated by Naylor and Finger and is widely followed in industrial and systems engineering.

Tracing is a technique similar to *Animation*. The behaviour of entities in the model is followed to determine if the logic of the model is correct. Although tracing is extremely useful in isolating the strange behaviour of the model, it causes considerable additional processing overhead.

Internal Validity involves comparing the results of several replications of a stochastic simulation model using different random seeds. If the random seeds used for the random number generators cause the inconsistency (large variability) of the sample points, the model is questionable either in the programming model or the conceptual model.

Historical Data Validation is used when historical data exists (or if data is collected on a system for building or testing the model). Part of the data (the training sets) is used to build the model and the remaining data (test sets) is used to determine if the model behaves as the system does.

Parameter Variability - Sensitivity Analysis is a validation technique where one changes the values of the input and internal parameters of a model to determine the effect upon the model and its output. The same relationship should occur in the model as in the real system. Those parameters that are sensitive, i.e., cause significant changes in the model's behaviour, should be made sufficiently accurate before using the model.

Predictive Validation is used to compare the model's prediction with actual system behaviour. The system data may come from an operational system or specific experiments. For instance, the data may come from laboratory or field experiments. To perform *Turing Tests*, experts of a system are given both real system and model outputs and asked if they can discriminate between the real system output and the model outputs.

The historical data method was used to validate the developed simulation model, while the internal validity technique was used to verify the model. This method was adopted because it best fit the study as part of the historical data were used as the modelling dataset to build and train the developed model. The other part was used to validate the model by running a few tests. The test was mainly run for a week due to computational complexity and limited dataset vessel agent behaviour and interactions exist more during dense traffic, which mostly occurs around mid-week. Also, the internal validity was used as the simulation is expected to give some logical outcome related to the internal logic and the model input. For example, the model input for berth time is set to follow an exponential distribution, hence, the model output is expected to follow an exponential distribution.

To accomplish this task AIS data was collected for the Port of Liverpool over the 12 months of 2016. The data provides information on all marine traffic (fitted with AIS) for the Port of Liverpool outer channel (Liverpool Bay) and the port inbound and outbound lanes along the River Mersey. This data set was used to train and validate the simulation model. The historical data method is implemented by dividing the collected data into a modelling set and a validation set to evaluate the model and validate results, respectively. It provides the basis for distributions of vessel types, inter-arrival times, transit speeds, hoteling times, anchorage times and transit times used within the model. The data also provides the information needed to validate the state-space models used to control agent behaviour within the model.

The data set was first classified by ship type. For example, data classified as containerships was generated by 93 vessels which created around 23,984 data entries. However, not all data entries are complete, or they are complete but contain errors. These entries therefore must be removed or corrected. Once the data sets had been prepared, they were plotted and visualised using a GIS map. Historic AIS data of vessel trajectories were plotted to visualise and extract relevant information of vessel movement patterns and lane positions for both inbound and outbound vessels. These plots were used to gain an understanding of ship positions at a given point in time and ship movements across any given time window by manually analysing vessel trajectories. Then the data were used to generate distributions applied within the model, e.g. arrival intervals and location, passage speed and time, etc. Which were also used to verify the developed simulation model.

3.5.6 Classification

1) Hybrid simulation model. Composed of discrete-event and agent-based simulation. Port processes are modelled as agent-based on vessel type (e.g. container, tanker, etc.) while their associated processes (anchorage, cargo terminal, etc.) are embedded within the agent port process modelled as discrete time-stepped model implemented in a discrete-event simulation system, the model component executes one-time step after each other. Vessel agents are modelled as an agent with behavioural characteristics represent using a state machine. In the context of the port traffic simulation, the one-time step of simulation time corresponded to 1 hour in physical time.
2) Model variables are represented in different units.
   Vessel speed: in Knots
   Positions: in Latitude and Longitude
   Time: in hours
   Distance: in Nautical Miles
3) The model component makes use of stochastic variables. Given the initial state and the same set of parameter values (e.g. initial starting positions, speed distributions, for vessels, location for port processes) and initial conditions as inputs, the vessel agents randomly select their initial start point and speed. Also, vessel agent changes their speed depending on the condition, which is either as a response to a collision situation or based on the area they are within the port.

3.5.7 Interfaces of the port traffic model

AnyLogic windows-based development environment includes a graphical model editor and code generator that maps the model into Java code. The figure shows the architecture of AnyLogic for model runs on any Java platform on the top of the AnyLogic hybrid engine. A running model exposes an interface to control its execution and retrieve information via a text-based protocol. That interface is used by Viewer and Debugger that runs on Java platforms as well. The model supports the connection of multiple clients from arbitrary (e.g. remote) locations.

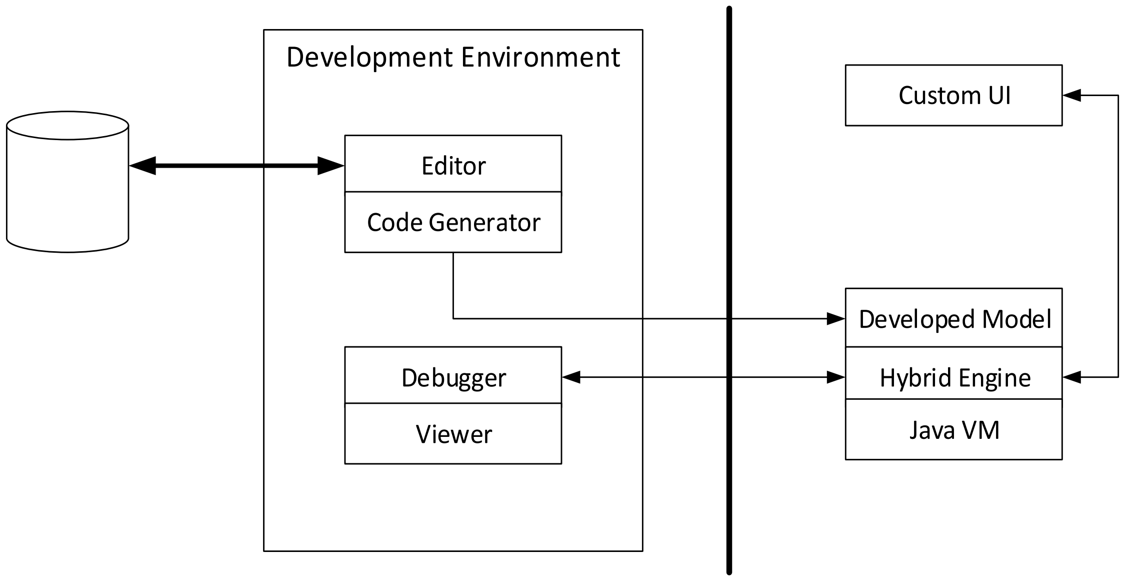


Figure 3.3: Architecture of AnyLogic simulation environment.

A subset of UML was used for real-time as a modelling language and extended to incorporate continuous behaviour. The language supports two types of UML diagrams: collaboration diagrams and state-chart (state machines). The main building block of a hybrid model is called an active object. The object interface elements can be of two types: ports and variables. Objects interact by passing messages through ports, or by exposing continuous-time variables one to another. The object may encapsulate other objects, and so on to any depth. Encapsulated objects can export ports and variables to the container interface, see Figure 3.4. An object may have multiple concurrent activities that share object local data and object interface. Activities can be created and destroyed at any moment of the model execution. An activity can be described by a Java function or by a state-chart.

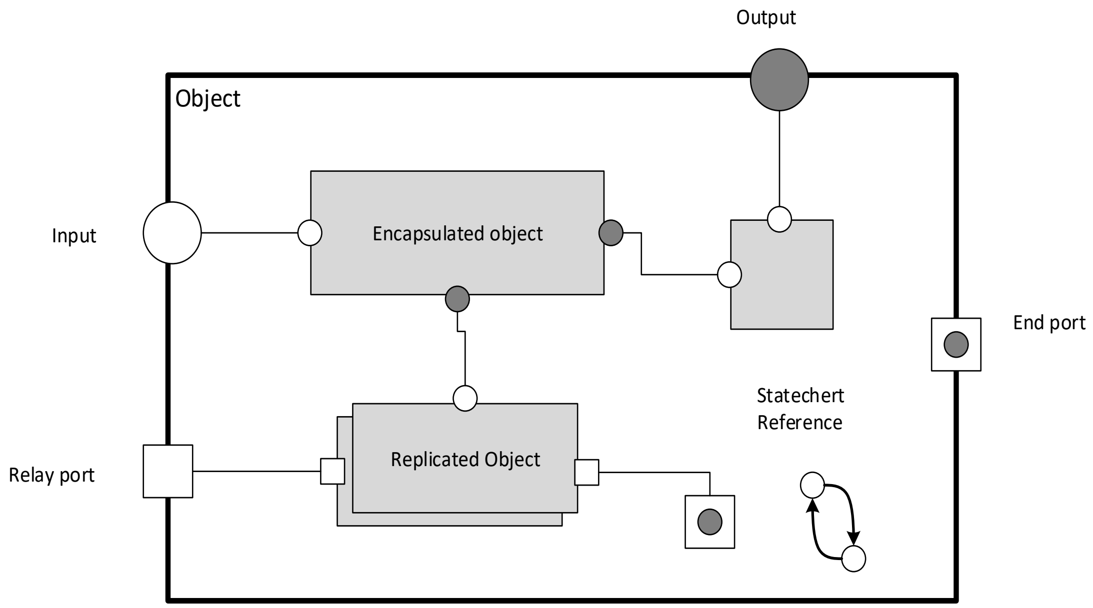


Figure 3.4: AnyLogic structure diagram extending UML-RT (UML for real-time) with continuous connections

3.5.8 Working principles of the port traffic simulation model

Traffic processes in a port start when a vessel is injected into the model, as shown in Figure 4.2. The injected vessel is considered an arrived vessel and immediately receives information on traffic and weather conditions within the port. The arrived vessel then wait at the port anchorage area until permission is given to proceed to berth. Vessels are to proceed with the assistance of a pilot and/or tug, and vessels with permission from the port authorities can proceed to their allocated cargo terminal after tug and pilot arrival. Once a vessel can enter the port, it sails to its allocated berth through the approach channel or entrance waterway. Vessels sail within the channel lanes of the port waterway to avoid groundings. Then the vessel goes through the lock gates before it arrives at the berth. On arrival at the vessel's allocated terminal, the berthing process is performed, and loading/unloading operations start. When the loading/unloading operations are completed, vessels are ready to depart; they are required to ask for new permission to leave the port. The reverse navigation process occurs as they depart from the port.

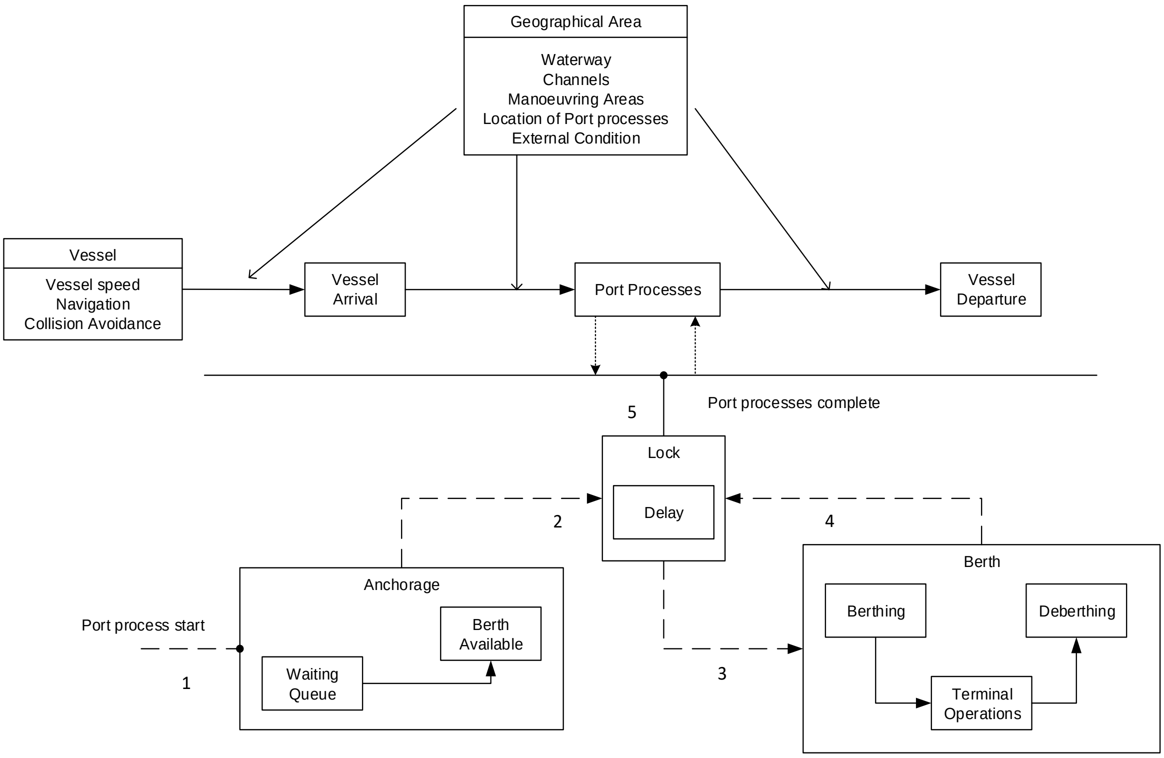


Figure 3.5: Working process of the developed simulation model

3.5.8.1 Working principle of port processes

As explained earlier in section 3.5.8, once a vessel arrives at the anchorage area, the anchorage process commences with the vessel entering into a waiting queue. Immediately the vessel receives a queue number, and the vessel waits until it is assigned to a specific berth and for the arrival of its designated pilot and tug. Following the arrival of the vessel, the port immediately enquires for an available terminal to berth the vessel (based on the vessel type). Where there is an available terminal to berth the vessel, the terminal is booked and allocated to the waiting vessel in the queue based on type and queue position (using a first-in-first-out (FIFO) method). Once a vessel is assigned to a berth, the port pilot and tugs are contacted, and until their arrival, the vessel will remain at the anchorage. Contacting tugs and pilot are represented using a delay process, which stops only when vessels are assigned to a berth and immediately collects details regarding allocated berth (e.g. location) and other information needed by the pilot. But the waiting time for tugs and pilots to arrive is represented by a period. Then the lock operator is contacted and the vessel joins a queue of arriving vessels awaiting lock availability. Once the tug and pilot waiting time is complete, the vessel informs the lock of its readiness to proceed. The lock-in response requests the allocated terminal and vessel details. Based on this information, the lock contacts the terminal for security purposes. Then depending on the tidal conditions, the pilot is asked to proceed to lock. Then the pilot notifies the traffic control of the incoming vessel and the vessel is released from the waiting process. The duration from vessel arrival to anchorage area, to its release from the waiting process is the vessel waiting time.

Vessels requesting to use the locks are initially added to a queue once the lock operators are contacted. The awaiting vessel is allocated a queue number and when the number is reached the vessel is notified. The lock process begins when a vessel arrives at the lock system. The vessel stays within the process for a while, after which it proceeds to the port, and the same when leaving the port. Vessels share turns while using the lock, and a vessel reaches its turn when its allocated queue number is arrived at.

The berth process begins once the vessel arrives at its allocated berth. Upon arrival and berthing, the cargo operation process commences which is represented as a period depending on vessel types. On completion of the cargo processes, the vessel's departing process commences and the port pilot and tugs are contacted, and until their arrival, the vessel will remain at the berth. The waiting time for tugs and pilots to arrive is represented by a period. Then the lock operator is contacted and the vessel joins a queue of departing vessels awaiting lock availability. Once the tug and pilot waiting time is complete, the vessel is in turn to use the lock service, the vessel informs the lock of its readiness to proceed. Then depending on the tidal conditions, the pilot is asked to proceed to lock. Then the pilot notifies the traffic control of the outgoing vessel and the vessel is released from the waiting process.

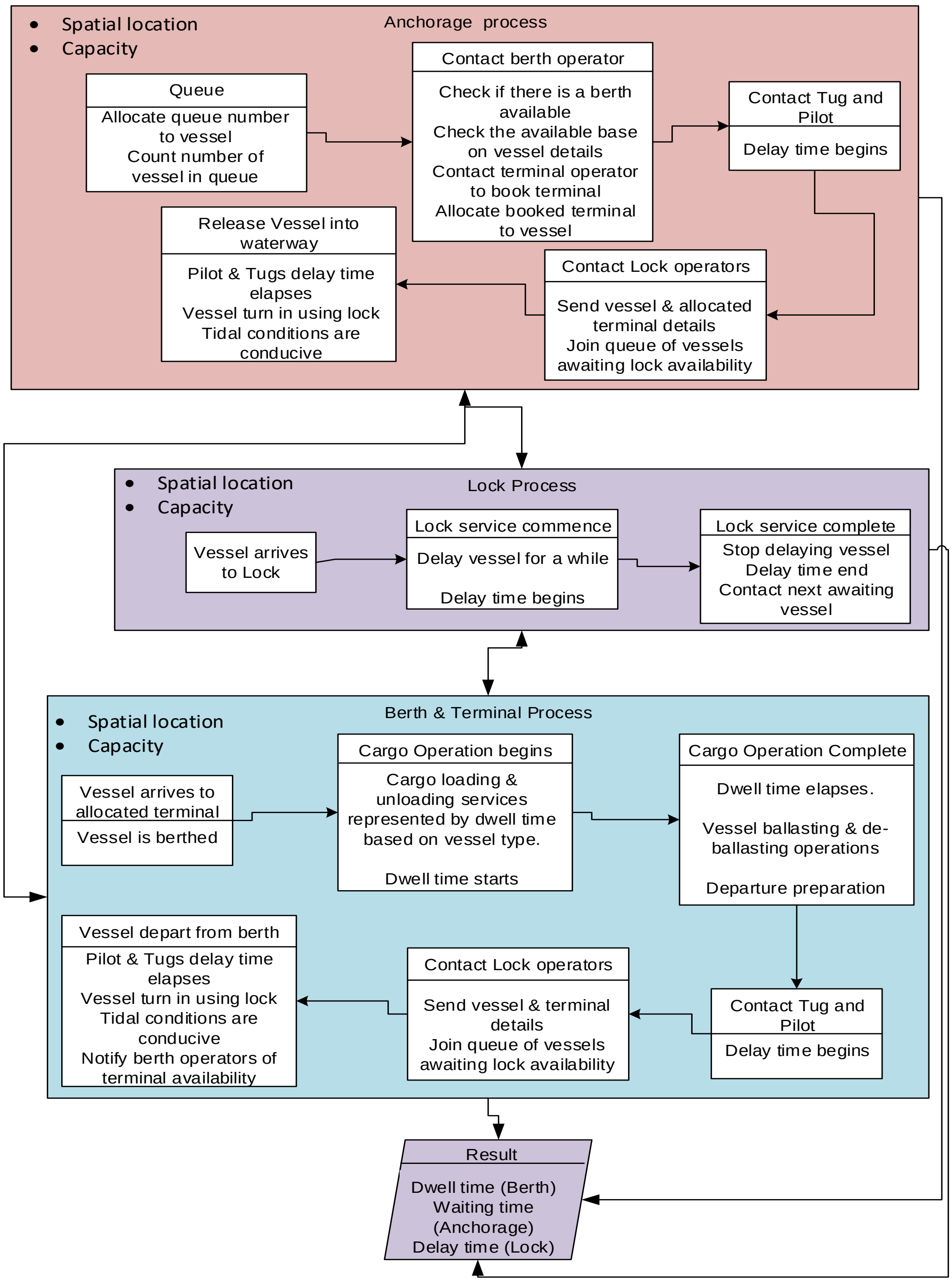


Figure 3.6: Working process of port process systems within the developed simulation model

3.5.8.2 Working principles of Vessel movement within the port

Vessels are allocated characteristics based on vessel type, static characteristics include: Name, Size, etc. and kinematic dynamic characteristics include speed, positions, etc. Vessels enter the model with initial positions, heading and speed values. Each vessel's passage plan is based on its type and terminal destination within the port. Vessels of the same type have similar passage plans but modify their speed, heading, and position depending on the weather and traffic condition. For example, in poor weather conditions, vessel operators reduce vessel speed.

Vessel behaviour outside the waterway is different from that inside the waterway as shown in Error! Reference source not found.. The outside waterways are areas with a wider navigational room where vessels anchor. Vessel behaviour is restricted by traffic volume and as such, collision avoidance manoeuvres including speed changes are required. The inside waterways are narrow channels with a limited navigational room. They are composed of inbound and outbound lanes. Inbound and outbound are specific expressions for the direction of ship passages. A vessel with an inbound direction means that the vessel is coming into the channel from the outside waterway, while an outbound vessel is sailing towards the outside waterway from the inside channel. Vessel collisions avoidance actions are restricted to just speed reduction as vessels are required to navigate within their lane (either inbound or outbound). The time taken for an inbound vessel to travel from the port entrance to the anchorage is the outer transit time, and from the anchorage areas to the lock area is called the inner transit time, while the time taken to travel from the lock areas to the vessel's allocated terminal is the manoeuvring time.

The model is expected to experience the following features:

- Autonomy: vessel agents encapsulate some state (that is not accessible to other ships based on ship type) and make decisions about what to do based on this state, without the direct intervention of humans or others. For example, in crossing situations, where two shipping lanes intersect, ships we make a decision based on the traffic rules encapsulated in the state they are.

- Reactivity: agents are situated in an environment (e.g. ships in port). These agents can perceive the environment and respond in a timely fashion to changes that occur in it. For example, using AIS trajectories in creating ship routes within the port, and ships can locate places like anchorage and detect weather changes and other vessels along the route.

- Pro-Activeness: agents do not simply act in response to their environment, they can exhibit goal-directed behaviour by taking the initiative, and thus, instead of using a general traffic-flow model, traffic becomes an emergent property of the interaction between agents.

- Social Ability: agents interact with other agents via some kind of agent-communication language (e.g. ship-to-ship interaction via traffic rules), and typically can engage in social activities to achieve their goals (e.g. ship-to-port interaction), hence, making the model flexible.

The most convenient way of developing a hybrid system modelling is to specify agent behaviour as a set of the state within a state machine. When a state changes as a result of some discrete event, the behaviour of the agent may also change depending on the embedded action within the state. In turn, a condition specified on continuously changing variables could trigger a state machine transition. State machines run within objects that communicate discretely, e.g. by message passing, as well as by sharing continuous-time variables over unidirectional connections. Vessel movements are divided into several states that are automated by independent behaviour rules. This enables the scalability of the agent's functionality without any modifications to the existing behaviours**.** The agent's environment is created using a GIS map and the waterway network is marked up using GIS-target-line (see Figure 4.5 and Figure 4.6). The behavioural state-chart consists of several states linked to a GIS-target line. In cases where modification is needed, for example, within the agent environment, a lot of unexpected events can happen (change in weather conditions, etc.) and the agent must deal with many different situations (e.g. collision scenarios). Where agent behavioural modification is needed, only the agent behavioural rules might need to be adapted or expanded. Agents have four major behaviours:

- Emergence: As vessels manoeuvre through the port from one target area to another, they produce emergent behaviours as they draw closer to different areas within the port, which result in speed changes throughout the waterway. For example, as vessels proceed to the Anchorage area, they decelerate, till they come to a stop.
- Adaptation: A simple adaptive behaviour built into the simulation is that the ship can always adapt its heading according to the geographical shape of the waterway. The model was built on a GIS space. Shipping routes were not created. Ships are expected to adapt to the directional changes as they proceed to their next target area within the GIS space.
- Sensing: The vessels can sense their environment along the waterway for other ships and specific areas using embedded rules. For example, vessels can observe the tidal conditions, and they immediately proceed to an anchorage point on arrival at the port once the tide is below the average high-water mark.
- Interactions: There are three kinds of interactions. One is the vessel's behaviour between one GIS-target line and another, creating their paths, and changing their speed as they manoeuvre through the port. Second is the vessel to port interaction, with tidal conditions, available berth and locks facilities. The third is the vessel to vessel collision avoidance interaction.

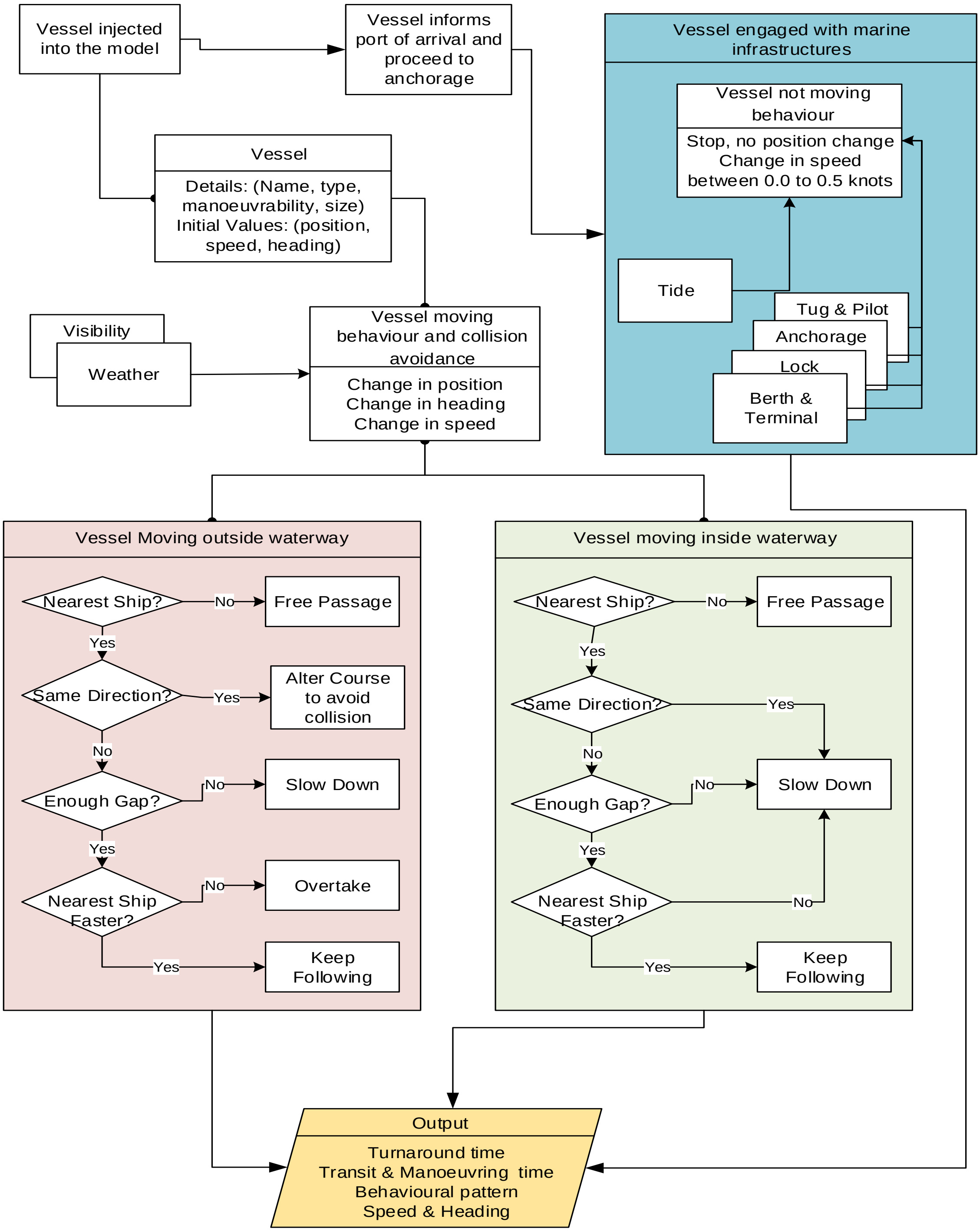


Figure 3.7: Working process of vessel model within the developed simulation model

Chapter 4: Conceptual model development

4.1 Introduction

A port is a connected system of port systems, Vessel-Traffic and External conditions operating within a geographic area. These systems operate connectively and their activities are influenced by interactions between entities e.g. vessel-to-vessel, vessel-to-port, vessel-to-weather etc. which affect overall performance. For example, tidal changes may increase the waiting time of vessels at anchorage, and increase dwell time for a vessel at the terminal. Vessel movement patterns and interactions during collision avoidance etc. influence transit time, fuel consumption, and traffic density. These contribute to increases in vessel turnaround time which affects port performance.

The component of a port follows a hierarchy made up of these systems, their entities, characteristics and operations, as shown in Figure 4.1. The hierarchy consists of entities operating within their various systems. For example, anchorage, lock, and berth are entities under the marine infrastructure system. The characteristics and method of operation of each entity vary. For example, anchorage operates as a queue process, berth operates as a delay process, while vessel operates as a dynamic object moving from one process to another. However, the individual operations executed within each system makes it difficult for coordinated interactions to exist amongst them. This situation is made more difficult by the fact that interfaces are developed to enable communication amongst the entities that make up these systems. Hence, a unified decision support framework (AnyLogic) was used that facilitates the coexisting of different simulation methods and coordinates interactions of decisions across different levels

This chapter explains the development of the port simulation including models of:

- Geographic area
- Processes i.e. availability anchorages, locks, and berths,
- Vessel traffic;
- Environment (currents, tides and weather).
- Interaction between vessels, the environment, and port;

The model systems are represented as agents composed of their associated processes and interaction mechanisms. Discrete event simulation is used for modelling port processes, while vessels and their movements are modelled using agents-based simulation models. External conditions are modelled as an agent with dynamic rotation of events, while the port geographical area is represented with a dynamic map using a GIS map.

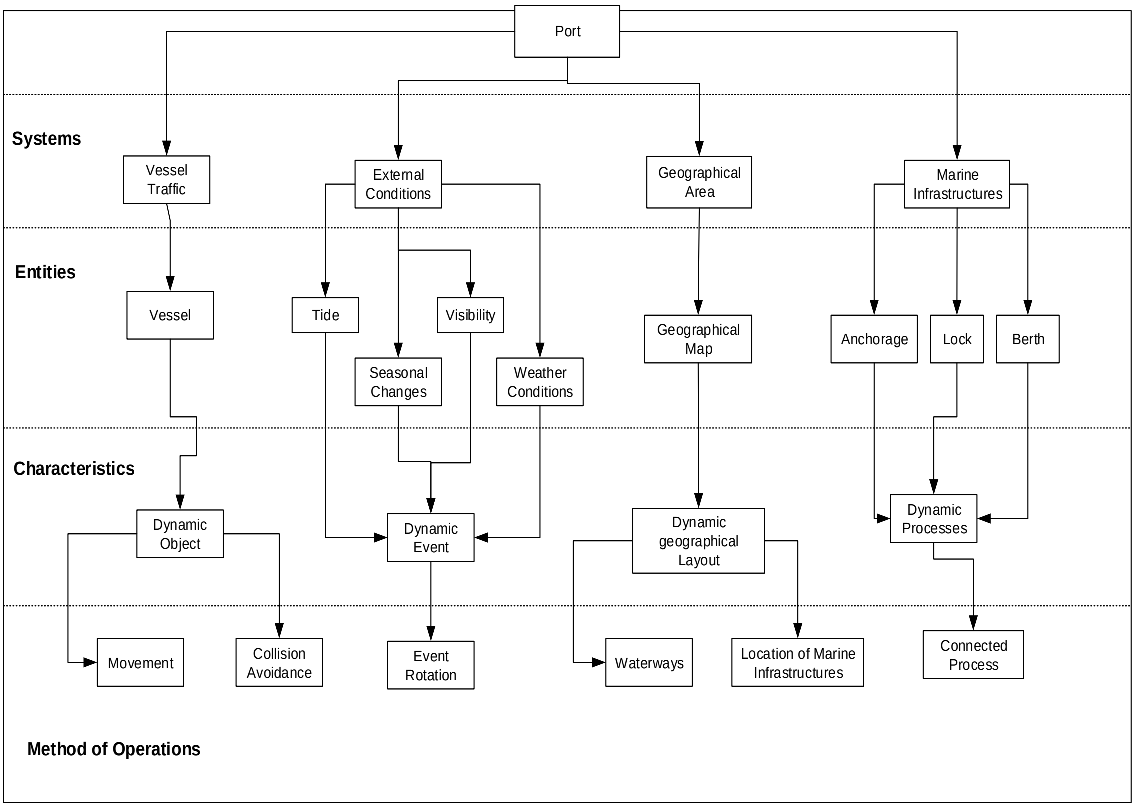


Figure 4.1: Component of Port traffic system

4.2 Overview of the port traffic simulation model

Traffic processes in a port start when a vessel arrives, as shown in Figure 4.2. The arrived vessel immediately informs the port of its arrival and receives information on traffic and weather conditions from the port. The vessel traffic service (VTS) provides information on traffic conditions, the meteorological team provides weather information, and tidal information is provided by the port. The port operators notify the vessel of the allocated berth. Vessels with permission from the port authorities can proceed to their allocated cargo terminal after tug and pilot arrival (depending on the port rules). Otherwise, they wait at the port anchorage area until permission is given. Vessels with specific navigation requirements or limitations will need a pilot and/or tug assistance. Vessels with permission from the port authorities can proceed to their allocated cargo terminal after tug and pilot arrival

Once a vessel can enter the port, it sails to its allocated berth through the approach channel or entrance waterway. Until it arrives at the berthing area, each vessel will sail through different parts of the port, such as turning basins, crossings or inner basins depending on their allocated berth. Each of these areas has specific sailing requirements and manoeuvring behaviours depends on the vessel characteristics. Vessels can sail at any position within the channel lanes of the port waterway to avoid groundings. For a port having locks, the vessel goes through the lock gates before it arrives at the berth. On arrival at the vessel's allocated terminal, the berthing process is performed, and loading/unloading operations start. The loading/unloading operations deal with cargo movement and storage within the terminal and stacking area, either from the ship-to-shore or shore-to-ship. When the loading/unloading operations are completed, vessels are ready to depart; they are required to ask for new permission to leave the port. The reverse navigation process occurs as they depart from the port.

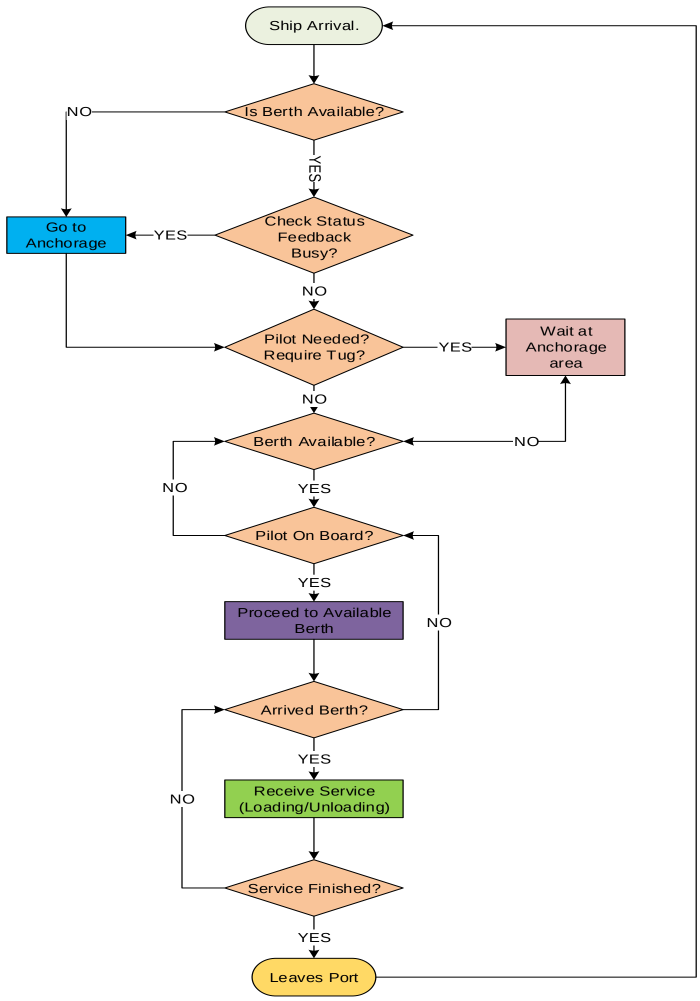


Figure 4.2: Vessel traffic logic within the port

As discussed in the previous chapter, the port traffic simulation models are developed to simulate vessel, external conditions, and port processes to estimate emission within the case study port. Thus, the model is developed with certain scope to fit this specific purpose. The characteristics of the model and its underlying assumptions were discussed in Chapter 3, and they provide details required for the simulation model evaluation. Hence, for this research, a simulation model that includes port processes and traffic characteristics with individual vessel navigation behaviour (movement, speed, etc.) influenced by environmental conditions (tide, visibility, etc.) that affect navigation, is used to replicate port traffic system within the port of Liverpool.

For a realistic representation of vessel traffic, the model simulates individual vessels as an agent with specific characteristics, where different vessel types have specific traffic rules and sailing limitations. The model includes individual vessel information (e.g. type) and allows the calculation of the desired indicators. The main parameters already identified will be calculated using the model and validate using historical data. Moreover, individual results for each water area of the port are calculated to verify the model.

4.3 Conceptual design of developed port traffic simulation

The developed port-traffic simulation model is built using the AnyLogic simulation tool. The simulation model is an object-oriented simulation. The interface port model developed in AnyLogic is used to set up the input data for the different systems, run the model and generate the output results. The main processes represented by the model are the vessel agent with navigational characteristics, port processes (anchorage, berth and lock), port waterways and channel, manoeuvring areas and berthing areas (see Figure 4.3), with detailed speed changing the behaviour of vessels. Speed variations in each section are due to vessel position within the waterway, and collision avoidance situations. The model reproduces properly all the port operations to be considered within a port traffic system to meet the required qualifications for this research purpose.

The first step was to build the case study area and arrange the input necessary for the simulation model. The historical AIS data and geographical data was collected for the port of Liverpool and it includes: 1) terminal location, waterway dimensions, 2) water depths across the port, 3) vessel arrivals distribution 4) service times for all the terminals, 5) sailing rules per vessel class in each port area, such as vessel minimum and maximum speeds, encountering limitations, safety distances and manoeuvrability restrictions in each port area, and 6) external conditions (tide and visibility).

An assumption done in this research is that vessels arrive with stochastic arrivals. The Port of Liverpool schedules vessel arrivals with a minimum of 24 hours in advance, with that, their waiting times are negligible at arrival, since they already informed the navigators when they should arrive, so they adjust their sailing speed to make it on a specific time. However, since this is not the case for many ports, stochastic arrivals will be used for this research.

The input is grouped into four main components, which are port layout, port calls (vessel arrival and traffic composition), external conditions and port control (see Figure 4.3). The port calls, which comprises vessel arrival and the traffic composition represented by the vessel state chart includes the information related to the vessel flows inside the port in an origin and destination matrix. It also includes the interaction with the various port process which determine the cargo terminals for each vessel berth. Since vessels have different sailing requirements and restrictions in different layouts, the port layout describes the different port spatial areas that represent different navigational situations within a port designed using a GIS map within AnyLogic. When looking at vessel traffic, actions like stops at the anchorage are included due to traffic restrictions due to either the combination or single external conditions (visibility and tide), spatial designs (lock area) and traffic compositions (traffic density) in specific areas of a port that do not allow certain vessels to sail. The tidal window is a limiting factor, where vessel arrivals are constrained to certain hours where there is high tide and the water depth is enough for the vessel draughts. The port control includes the international laws and regulations, as well as specific regulations which are needed for the case study. The input can be divided into fixed and variable input. The fixed components are the port layout and the port control, while the traffic composition (vessel behavioural state chart), port calls (vessel arrivals), and external conditions are variable and thus their input values for each run are different to create a diversity of scenarios due to the use of statistical distributions (see Figure 4.4).

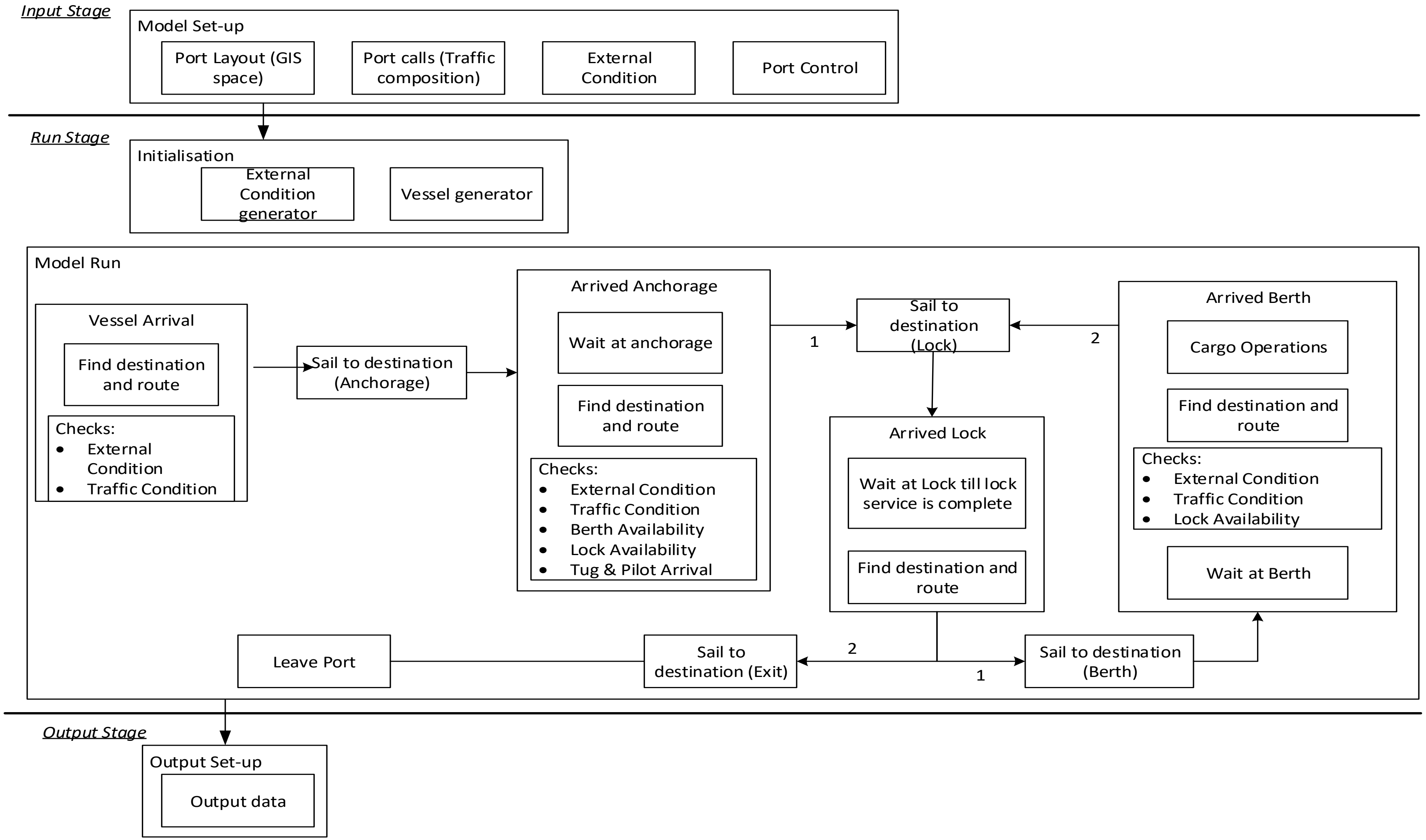


Figure 4.3: Conceptual design of the developed port traffic simulation

The developed simulation model is an object-oriented simulation that is built under the AnyLogic platform. The simulation model implemented the operational flow vessel and port processes in Figure 4.4, which shows the simplified operational flow of vessel movement within the developed port traffic model. In the model, the component systems are defined as three classes of objects (i.e. agents): SHIP (vessels), PORT (Marine Infrastructure), and ENVIRONMENT (External conditions). Agents operate within the geographic port area which is modelled as a GIS map. Associated with each agent (object) are rules which define how they interact with other agents i.e. SHIP agents within the geographic area can interact with PORT and ENVIRONMENT agents, and PORT agents can operate with the ENVIRONMENT. PORT agents are sited at locations in the GIS map. Encapsulated within these agents are processes for example anchorage processes, tug and pilot, berth scheduling and allocation etc. Processes are modelled using discrete-event simulations interacting with agents. ENVIRONMENT agents are associated with rules relating to tide, and weather. For example, tidal rules relating water height to tidal state.

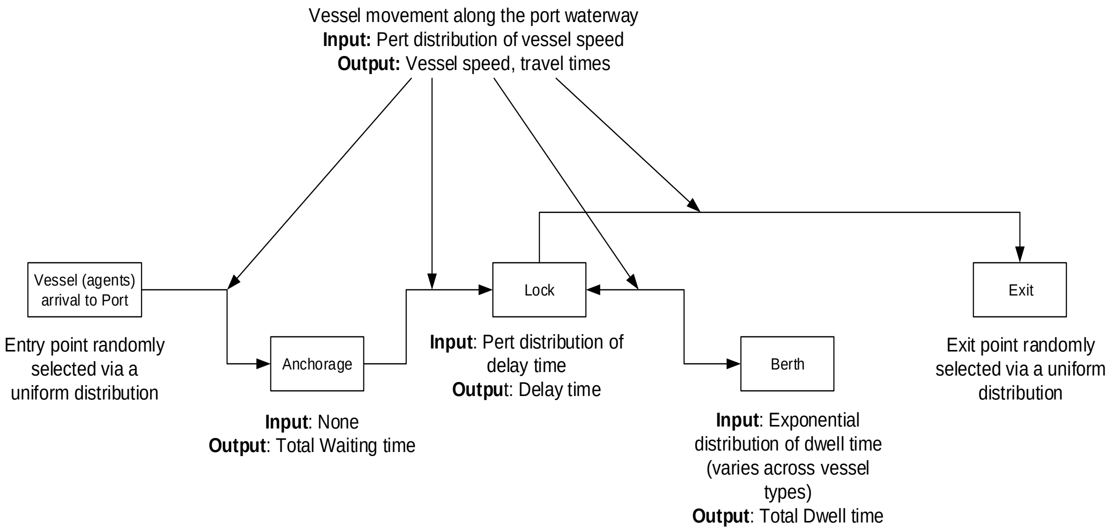


Figure 4.4: Summary view of operational flow vessel and port processes including inputs and expected output within the developed port traffic simulation

Vessel (SHIP agents) types (container, bulk carrier, tanker, etc.) and arrivals into the model are based on distributions generated using historic AIS data. Vessel initial speed varies according to type, and their entry position determines their initial heading. The vessel initial entry point is selected using a uniform discrete distribution between ranges of all three zones. When a vessel arrives in the port area it informs the port of its arrival. The vessel is directed to anchorage or proceeds to an available berth based on the response from the port traffic control. A vessel moving within the port heads towards a series of GIS-target lines. During movement, it follows port rules and IMO rules of the road controlled by a behavioural state-chart, and a collision avoidance state-chart. The behavioural state-chart is linked to a GIS-target line and governs vessel movement patterns**.** The state charts were developed using the movement pattern observed from the analysed AIS data via a trajectory plot, interpreted using "a stop and move" approach, (Spaccapietra et al., 2008).

The multi-method simulation is developed to implement three structural layers based on the behaviour of each system, namely; the static layer, the process layer and the interactive layer. The static layer consists of constructing the fixed components of the modelled port geographical area, and the various external conditions that influence port operations. The fixed or static component of the port includes the port waterways, berth and cargo terminal locations, lock, and anchorage areas. Although, the port area is modelled using a GIS map making it dynamic (zoom in and out), the location and dimension of these components within the port are fixed. The external conditions include models of the tide, weather, visibility and seasonal changes. The input to this layer is the map features and locational data of the geographical area, and the development of the various external conditions. The process layer defines the mechanisms of port operational activities such as anchorage, berth and cargo terminal, and lock processes. Input to this layer includes the development of the various port processes and the inclusion of the duration of each process from the AIS data (mainly for lock, and berth and terminal processes).

While the interactive layer consists of vessel movement and interaction mechanism, the movement mechanism consists of vessel movement and speed changing behaviour within the port, while the interaction mechanism deals with vessel collision avoidance and speed changing behaviour within the port. The input for this layer includes the development of a behavioural state-chart for vessel movement and a collision avoidance state-chart for vessel interaction with other vessels. The state-chart logic for vessel movement contains the input of the port waterway from the static layer and vessel speed at each part of the waterway from the AIS data. While the collision avoidance contains input of vessel speed changes for collision avoidance as per advice by COLREGs, and a developed collision avoidance process based on COLREGs and the port traffic rules.

4.4 Static Layer (Geographic area)

As mentioned earlier the static layer consists of constructing the geographical area for the model. The port geographical area is divided into an outer waterway (Figure 4.5) and an inner waterway (Figure 4.6). The wider channel prior to a ship anchoring (the Liverpool Bay region) is referred to as the outer waterway, while the narrow channel including the locks area is called the inner waterway. An inbound vessel comes into the waterway from the open sea and moves through the inbound traffic lane, and an outbound vessel is sailing to the sea using the outbound traffic lane. The waterways were divided into zones. The outer waterway comprises zone 1-5 separated by -0.2 degrees of longitude, while the inner waterway comprises zone 7-10 divided by speed ranges within areas situated at <-3.0 degrees of longitude.

The spatial environment for the model was created using spatial data from digital charts of the marine area and imported into AnyLogic in shape-file format. The downloaded data contained sea area, bathymetry, and shoreline, wreck areas, landmarks, obstructions and navigational buoys used to identify navigable and non-navigable zones within the port environment. The navigational network is shown on a marine chart of the study area in Figure 4.5 and Figure 4.6**.** The network is made up of waypoints created as GIS-target lines and control features which are usually part of the network signifying specific areas like anchorage area and berth or cargo terminal. The waterway is divided into zones. Each zone is represented by a sequence of GIS-Target lines. Each GIS-Target line is a waypoint in the navigation network representing a section of the waterway. Each corner and length of a GIS-Target line is defined by the observed traffic density from the AIS data analysis. The set of all GIS-Target lines defines the movement area of all vessels within the simulation model.

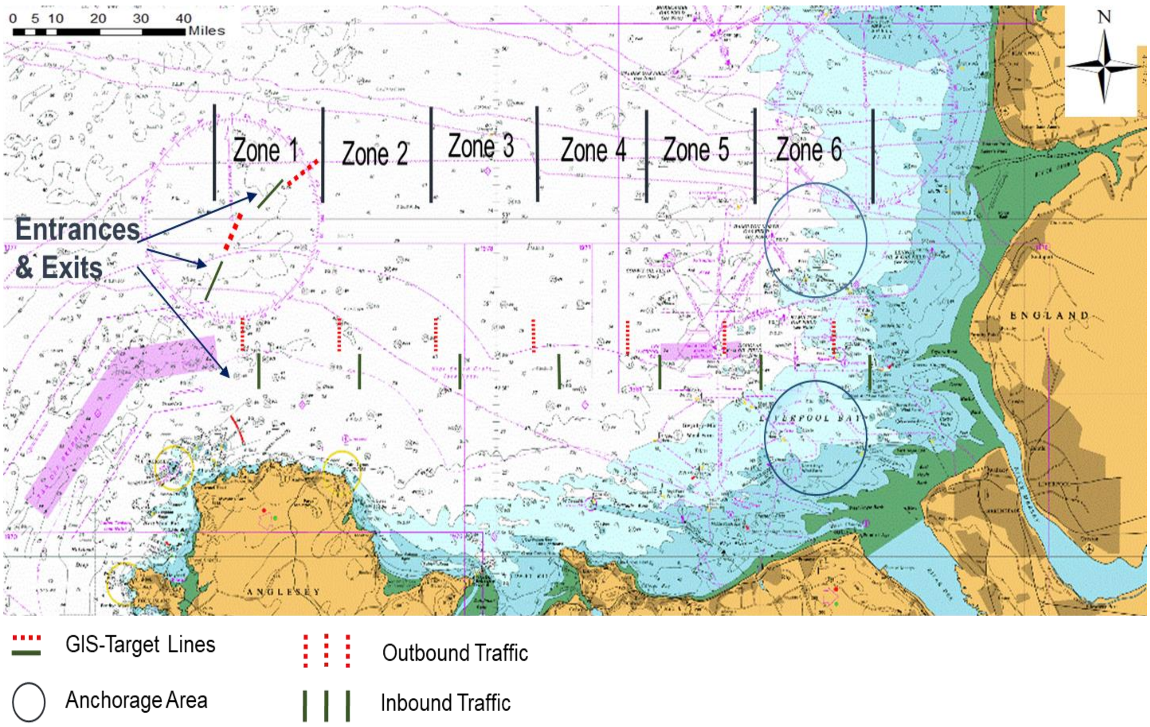


Figure 4.5: Outer Waterway description and navigational network layout

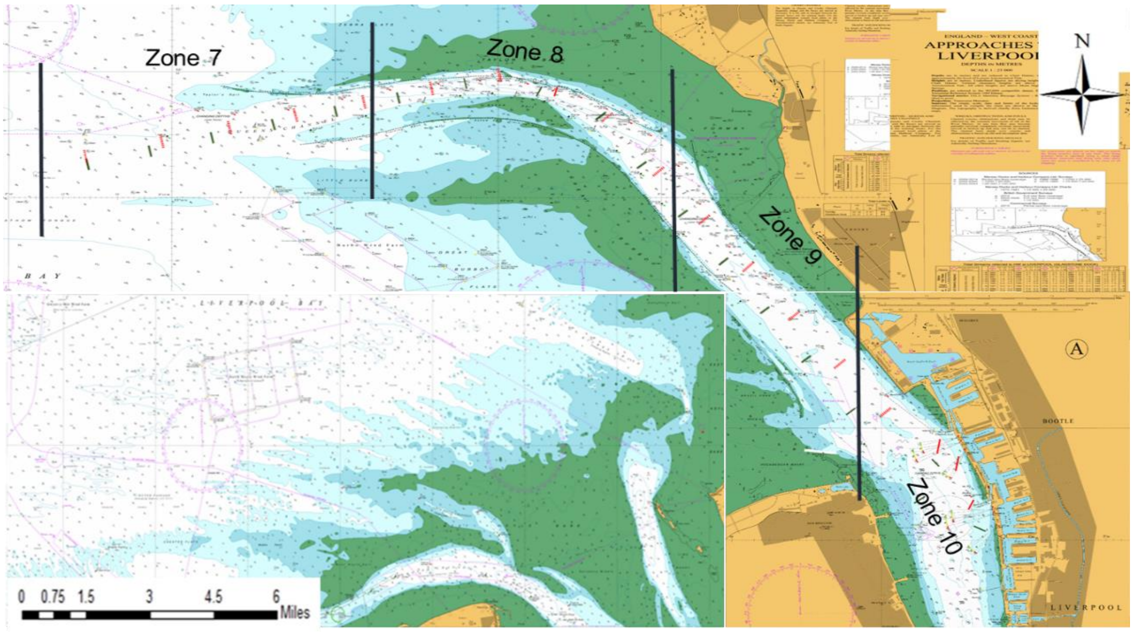


Figure 4.6: Inner Waterway description and navigational network layout

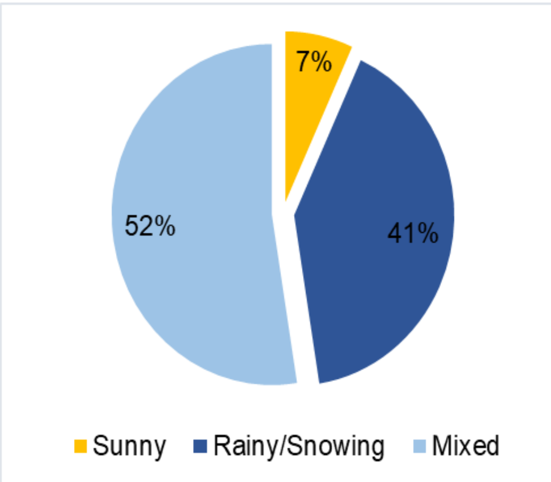
Vessels move along the waterway from one GIS-target line to another keeping to the assigned lane. Each GIS-target line is connected to the vessel state chart. The route-following behaviour also influences the agent's speed. Allowing vessels to accelerate and decelerate when needed. Vessel movement and behaviours also include:

- Intersection or changing directions: When a vessel approaches an intersection, its speed is reduced, and based on its passage plan it turns (alters its course) in the direction that leads to its destination.
- Speed limit zone: Some ports have speed restricted areas. Agent's check if there are existing rules within their present environment and for speed limit zone, they respond by reducing their speed as required by the rule.
- Agent following: Especially in the inner waterway, agent-following behaviour restricts overtaking and improves traffic safety by limiting collision possibilities. When a vessel is in front of another vessel, the vessel behind reduces its speed to keep a safe distance from the vessel ahead.
- Overtaking: this is related to the route-following behaviour. When the vessel ahead is moving at a lower speed when compared to a vessel behind in the outside waterway, the vessel behind might decide to overtake the one ahead. This decision depends on the velocity difference between both vessels and the navigable room in front and at the port side of the vessel being overtaken according to IMO COLREG.

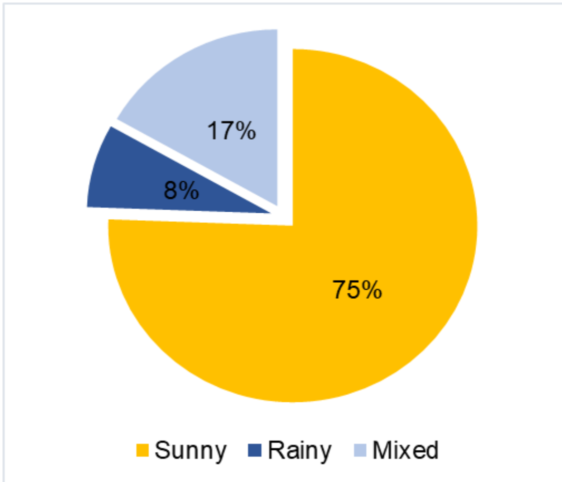
4.5 Static Layer (External Conditions)

4.5.1 Weather

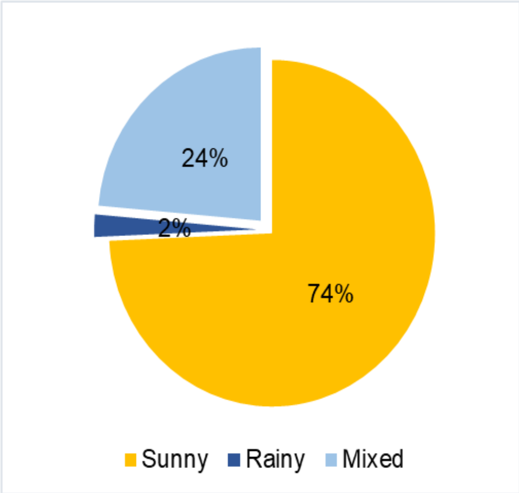
Weather influences vessel speed, as vessels reduce their speed during poor or moderate visibility. The weather model is based on monthly weather statistics. The model gives one of three visibility values: Good, Poor or Moderate (that is, 50% poor or 50% good), which are linked to the weather status. The monthly weather data was collected from Time and Date website (Time and Date, 2020). The data contains details of daily weather status which include temperature, wind, humidity, etc. The weather statistics were calculated for four seasons (winter, summer, autumn and spring). The weather status was simplified into sunny (absolutely dry), rainy/snowy (Heavily wet) and mixed weather (slightly wet and dry). Figure 4.7 shows the weather approximated distribution during each season. For example, during winter there is a higher chance for the weather status to be slightly wet or dry, than it being absolutely wet or completely dry. However, this is different for the other seasons. In winter the chances of the weather status being sunny, rainy/snowy or mixed are randomly distributed using the seasonal distribution. For example, the chances of a mixed weather status are 56%, 7% for sunny and 41% for rainy/snowy (see Figure 4.7 (a)).



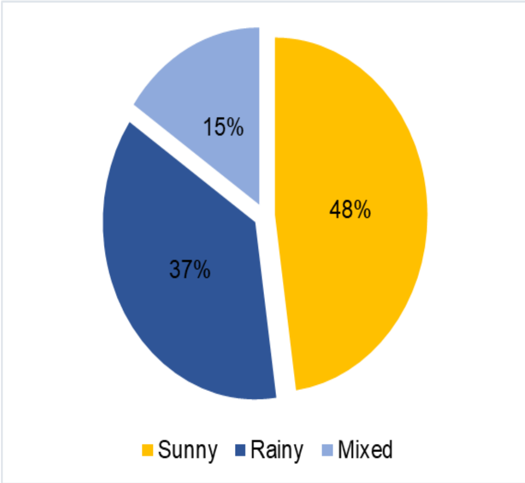
Winter



Summer



Spring



Autumn

Figure 4.7: Distribution and categorisation of weather status for all seasons

The seasonal changes were represented using a state chart. Each state represents a particular season and daily estimate of the weather status. The seasonal changes were uniformly distributed between a minimum of 89.5, and a maximum of 91.5 days for all seasons respectively.

4.5.2 Visibility

Visibility is the distance one can see and it is determined by light and weather conditions. Weather conditions that affect visibility are fog, mist and smog. These weather conditions are determined by weather status (sunny, rainy/snowy, and mixed weather (slightly wet and dry)), (Deng et al., 2016). These weather conditions are simply made from water droplets suspended in the air mostly observed during mixed weather status, meaning poor visibility conditions are most likely to occur during mixed weather status. According to (Deng et al., 2016), visibility decreases with increases in relative humidity (mainly when relative humidity reaches 80% or above). This only occurs during winter and autumn in the UK as shown in Figure 4.8

Thus, during winter and autumn, the chances of a day's visibility being poor are assumed to be 30% each if the weather status is either sunny or rainy respectively (that is, 30% for sunny and 30% for rainy), and 40% in mixed weather. The chances that the visibility is good are 40% each if the weather status is sunny or rainy weather respectively, and 20% if mixed weather. The chances that the visibility is moderate (that is, 50% poor or 50% good) is 30% each if the weather status is either sunny or rainy respectively, and 40% in mixed weather during winter and autumn seasons. Visibility is assumed to be generally good during spring and summer.

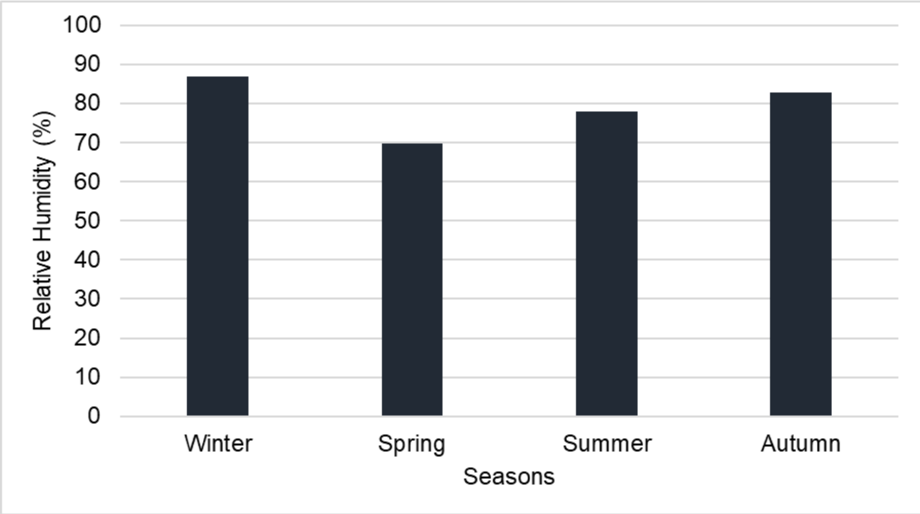


Figure 4.8: Relative humidity for different seasons

4.5.3 Tidal model

Tides are a constraint in vessel scheduling. A vessel cannot proceed to the cargo terminal if the tide is too low. Tides cause an increase in waiting and dwell time. The tide model determines the tidal height of water suitable for a vessel to navigate in and out of the port. The tidal model is developed using a state chart, where each state predicts tidal height values ranging from low to high. At low tide, vessels wait at the anchorage or berth (thus, increasing waiting and dwell time), and move from one point to another as the tidal height increases.

The data supplied by the National Tidal and Sea Level Facility (NTSLF) tidal monitoring station at Gladstone Lock was analysed and used to predict the tidal height, and pattern for the port waterway. The result in Figure 4.9 shows the level of high and low tides and their pattern for the first 30 days. The tidal levels from this data set were relative to the ordinance datum, which accounts for the height of the chart datum. The standard chart datum value for the port of Liverpool is –4.93 m (National Tidal and sea level facility, 2020). Thus, if the tidal height is for example 10m above the chart datum, the relative ordinance datum value is 10m + (–4.93m), which is 5.07m. This is because the ordinance datum is always higher than the chart datum.

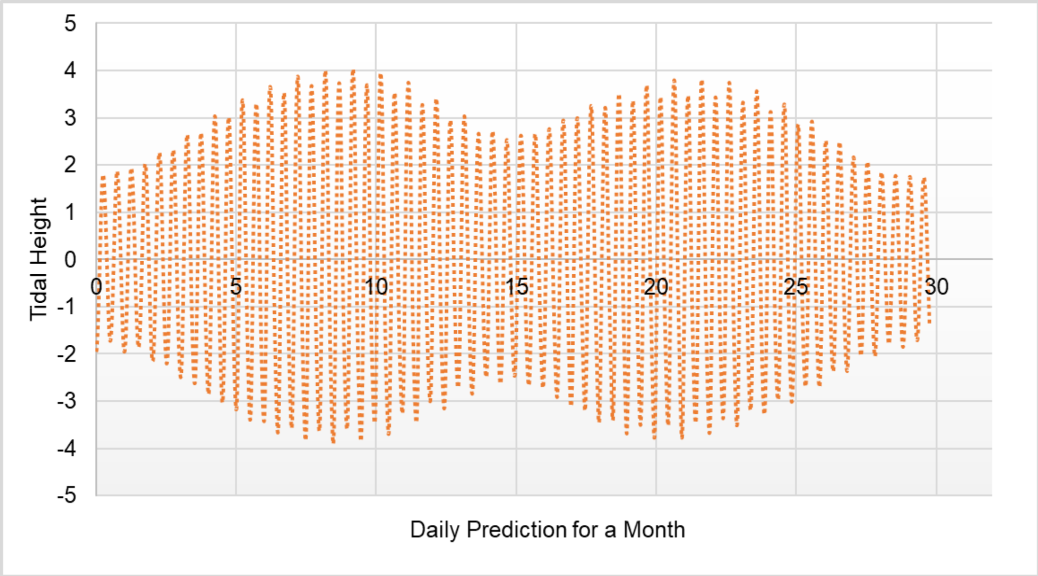


Figure 4.9: Periodic tidal plot for a month

The Tidal data was further studied for trends and it was observed that the tidal height pattern changes after seven days (see Figure 4.10). To accommodate for this, sample analysis was done by applying the rule of the 12th method.

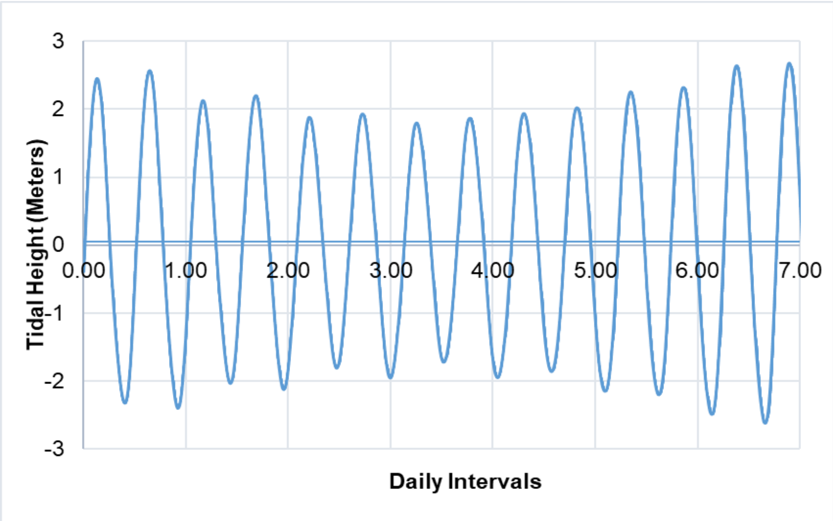


Figure 4.10: Periodic tidal plot for a week

The rule of 12th as explained is used to calculate the expected water level, (Werner, 2020). This rule states that in the 1st hour after low tide the water level will rise by 1/12 of the predicted tidal range in any given area. In the 2nd hour, it will rise 2/12, and in the 3rd hour, it will rise 3/12. In the 4th hour, it will also rise 3/12, in the 5th, it will rise 2/12, and in the 6th hour, it will rise 1/12 as shown in Figure 4.11 using an example of a 4.9-metre tidal height.

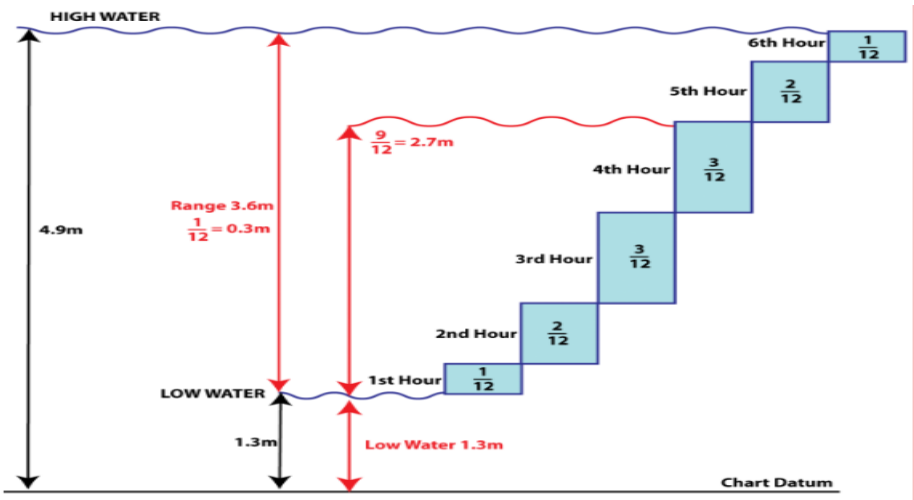


Figure 4.11: The rule of 12ths for calculating expected tidal range (R, 2021)

The rule was applied to examine its ability to estimate tidal height and suitability in simulating tidal height. The analysis was done using a forecast tidal prediction for November 2020 and the 2016 historical tidal data supplied by the National Tidal and Sea Level Facility (NTSLF). And the results were compared to see if there are similarities. The values were first analysed by calculating the average high water and low water values as shown in Table 4.1**.**

Table 4.1: Tidal Parameters

Parameters	Date	Average HW (AHW)	Average LW (ALW)
current 2020 tidal prediction	15/11/2020	10.05	0.93
Sample from Historical dataset	15/11/2016	10.23	0.62

Using the 12th rule, the estimated tidal heights are calculated as shown in Table 4.2**.** At stage seven, a new high water value is attained. The other values are calculated in descending order using the rule of 12th by subtracting at each stage. In stage 13, the values are switched back using equation 1, and the process is repeated for a day cycle. The result is presented in Figure 4.12 and proof that the rule of 12th is suitable for simulating tidal height.

$$stage\ 13 = \left(stage\ 12 - \left(\frac{1}{12} * New\ HW\right) + second\ LW\right)$$ ……………………..Equation 1

Table 4.2: Predicted Tidal values

Stages	Formula	2020 prediction data output	2016 Historical data
1	LW	0.93	0.62
2	LW + (1/12 x AHW)	1.77	1.47
3	Stage 2 + (2/12 x AHW)	3.45	3.18
4	Stage 3 + (3/12 x AHW)	5.96	5.74
5	Stage 4 + (3/12 x AHW)	8.47	8.3
6	Stage 5 + (2/12 x AHW)	9.99	10.01
7	Stage 6 + (1/12 x AHW)	10.83	10.86
8	Stage 7 - (1/12 x AHW)	9.99	9.96

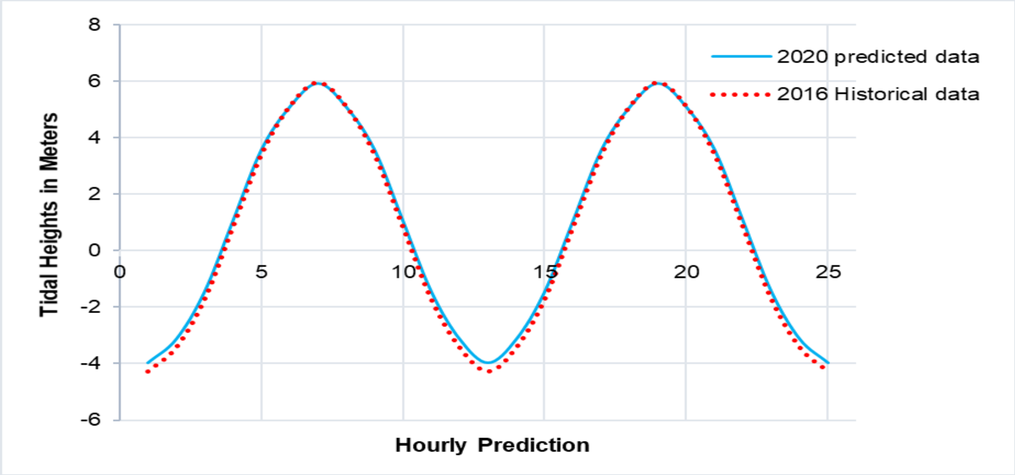


Figure 4.12: Sample Analysis using the rule of 12th to determine the tidal height

4.6 Process layer (Port processes)

As mentioned earlier the process layer defines mechanisms of port operational activities situated within the static layer. At the process layer, basic port processes associated with vessel handling operations are modelled as processes embedded with a port process agent based on vessel type (e.g. container, tanker, etc.). For example, Figure 4.13 show a sample of the container port process agent with its associated processes. The container port process agent dynamics is static (that's is they don't move) but composed of two associated processes (anchorage and cargo terminal), embedded within the port process agent and interact with the locking process outside the container port process agent. The port process agent has two main parameters, location and type, which determines the location of each process and the vessel type they handle.

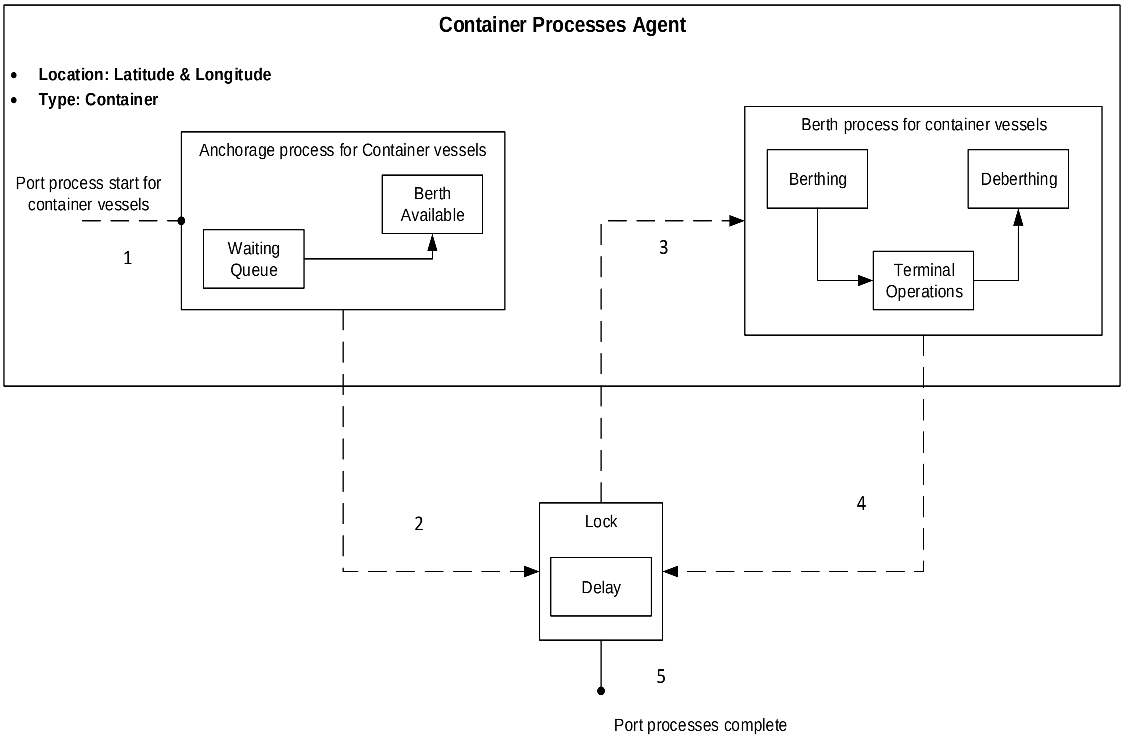


Figure 4.13: Design of a port process agent with its associated process embedded

Generally, port processes include anchorage, lock, and berth. Anchorage and berth processes are modelled to handle specific vessel types because real-world cargo terminals are designed to handle vessels based on cargo types, hence a tanker vessel cannot berth at a container terminal. Also, these processes are interconnected (see Figure 4.13), for example, (berth and anchorage) when there is an available berth, the waiting vessel at the anchorage is notified, and the vessel leaves the anchorage area depending on the environmental conditions. The anchorage serves as a waiting area for arriving vessels before berthing (see Figure 4.5). The Berth and terminal process deals with the cargo operations process of the port. Cargo operations mean loading or offloading cargoes from or to the vessel. The lock process is a stop area where vessels are delayed for a while to balance their draft from the outer waterway to that of their designated port area (see Figure 4.14). In extreme weather conditions or during low tide or if a port lock is not available (for ports having locks), vessels are required to remain at anchorage or berth depending on their position at that time (berth–lock, anchorage–lock). Each process is vital for the effective running of the port and the duration of each process affects vessel turnaround time. For example, vessel waiting time is dependent on the anchorage process, the vessel delay time is dependent on the locking process, and vessel dwell time is dependent on the berth and terminal process.

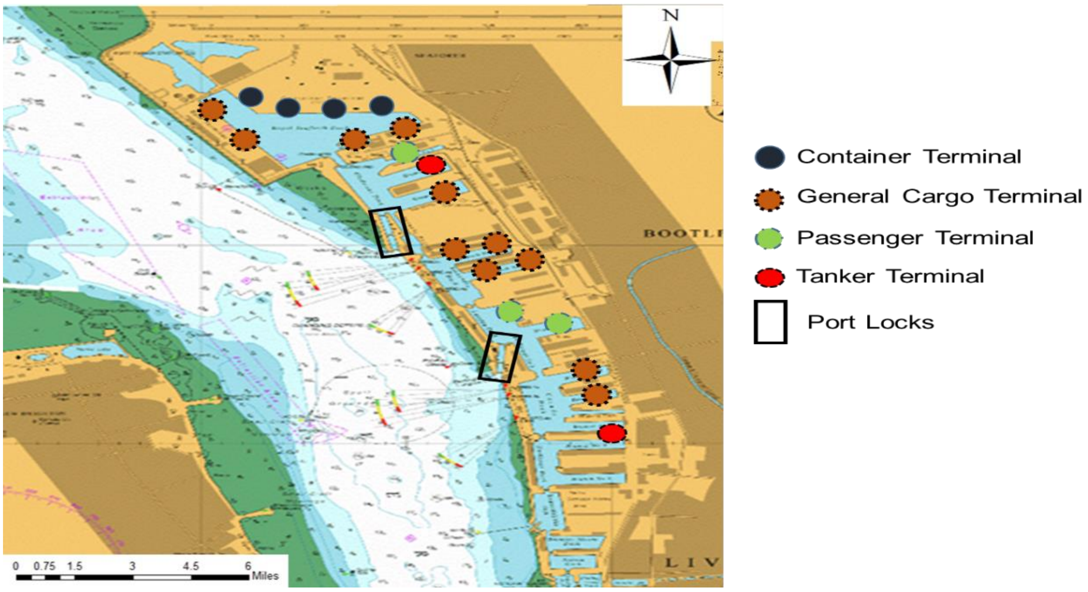


Figure 4.14: Port Locks and Terminal Area

4.6.1 Anchorage process on vessel arrival

To capture vessel time at lock, the delay time distributions are approximated using a PERT distribution as explained above. The result as shown in Figure 4.15 reveals that the average lock time is 41 minutes, 30 seconds, with a minimum time of 31 minutes, a maximum time of 51 minutes, and a mode of 42 minutes.

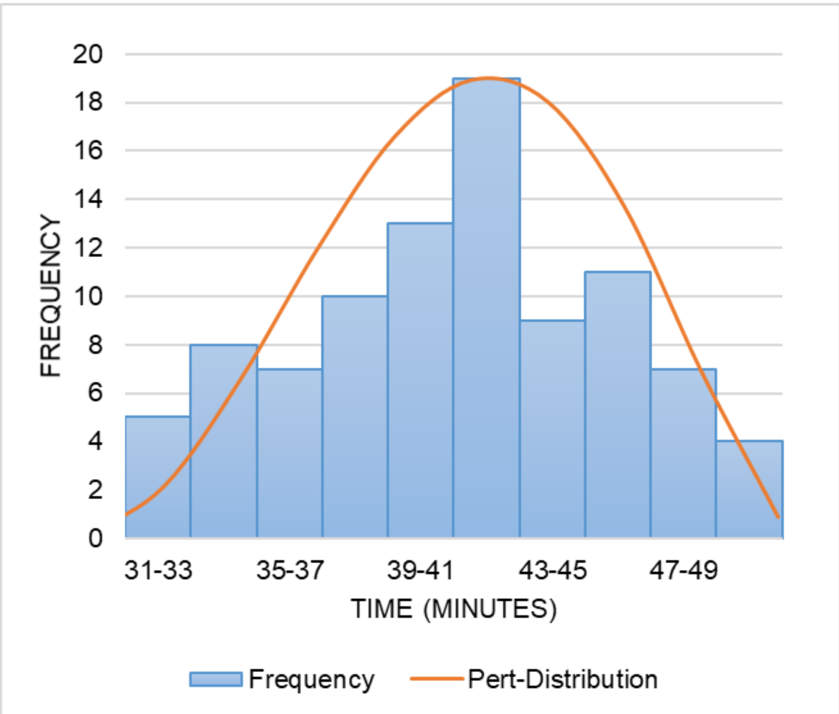


Figure 4.15: Pert distribution of Lock duration

4.6.2 Data analysis of model input: Berth and terminal processes

The duration from vessel arrival to berth, to its release from the berthing process is the vessel dwell time. The dwell time is affected by many factors, such as weather conditions, ship's loading conditions, the fluctuation of port handling efficiency, the variations of cargo storage volume and its transportation, and so on. Since dwell time measures the time a vessel spends at the berth from vessel arrival till departure from the berth. From the historical AIS data, it was difficult to observe the different dwell times as dwell time differs across vessels. Therefore, average dwell time was distributed using an exponential distribution formula below;

$$f = \lambda e^{-\lambda t}$$

Where, t denotes the dwell time in hours, $\lambda = 1/\mu$ is the arrival rate, and μ = denotes the average waiting time in hours.

Exponential distribution measures the length of time between events. For example, Figure 4.16 shows an exponential distribution for the dwell time of container vessels, with an average of 24 hours 10 minutes.

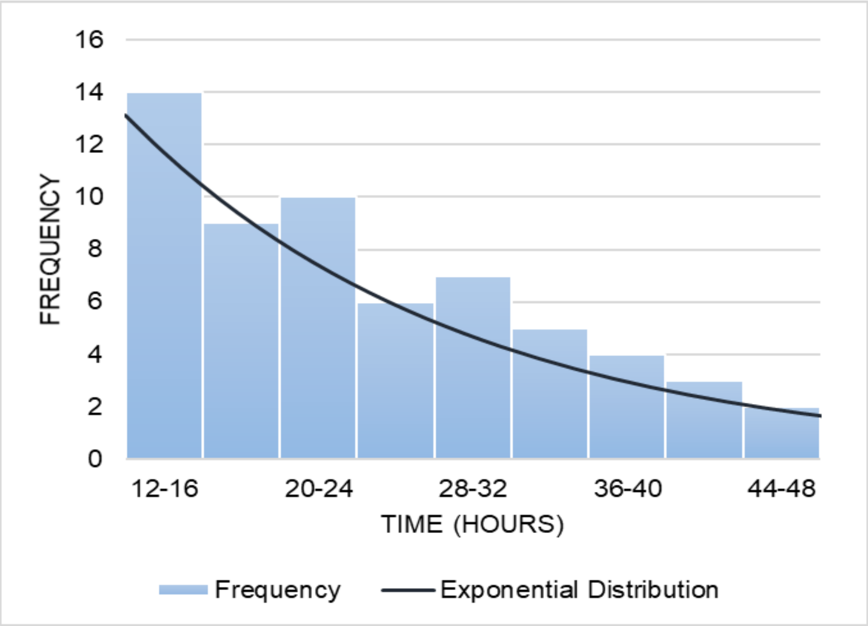


Figure 4.16: Exponential distribution of container vessel dwell time.

4.7 Interactive Layer (Vessel Traffic)

Vessel agents are created with the ability to interlink with other vessel agents regardless of type to make them aware of other agents within the environment. These agents are modelled with behavioural characteristics based on vessel type static characteristics include: Name, Identification, etc. and dynamic characteristics include speed, headings, positions, etc. Vessel agent dynamics are influenced by the agent's destination, location, external condition, and collision avoidance situations due to traffic density. For example, the position of a vessel will determine its speed. If a vessel is within the outer waterway it can accelerate more than when within the inner waterway. Vessels agents are injected into the model with initial positions, heading and speed values based on their state logic. Each vessel's passage plan is based on its type and terminal destination structured by its state machine. Vessels of the same type have similar passage plans because their cargo terminals (berth) are situated nearby. However, vessel agent modifies their speed, heading, and position depending on the weather and traffic condition. For example, in poor weather conditions, vessel operators reduce vessel speed.

The vessel state chart follows a logic connected to the GIS target lines which marked up the agent's environment. Vessel movements are divided into several states embedded with different behaviour rules based on the GIS target lines they are connected to. Each state contains a destination needed by a vessel agent as a part of its passage plan. An arrived destination is regarded as a vessels origin. Vessel behaviour is restricted by traffic volume and as such vessel checks the traffic density and makes collision avoidance manoeuvres such as speed changes where required.

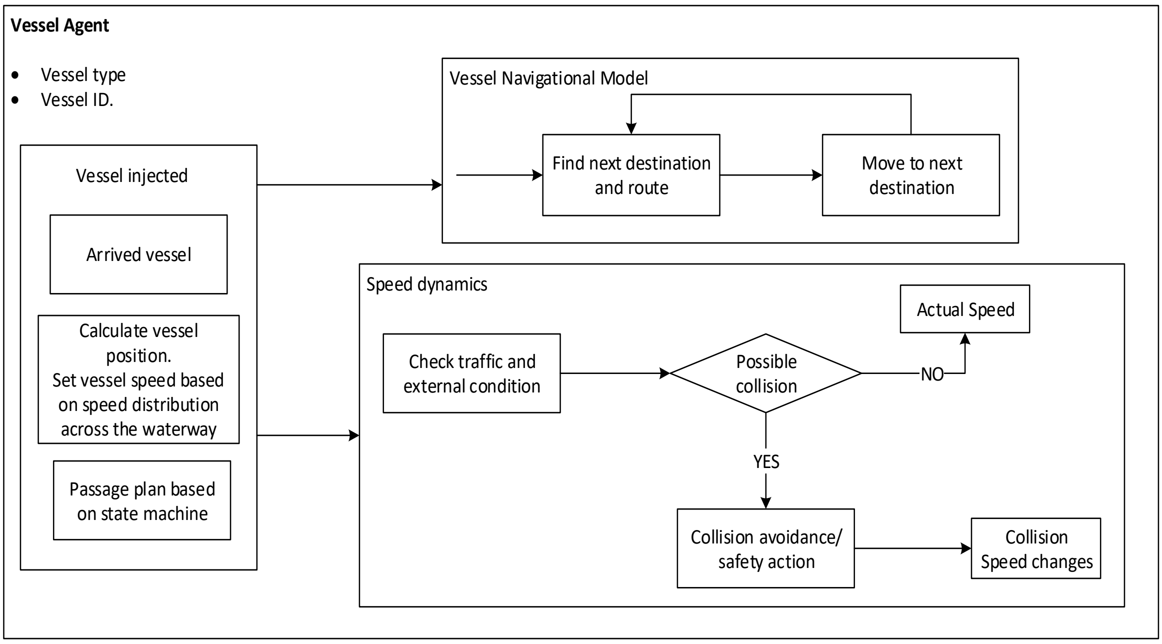


Figure 4.17: Design of a vessel agent with its embedded state logic details

4.7.1 Vessel Arrival Distribution

Vessel arrival point varies as shown in Figure 4.5, and the average number of vessels per day was calculated for three separate quarters of the year. The arrival frequency reveals the average number of vessels arriving each day of the week for each quarter. The weekly inter-arrival frequency for container vessels is shown in Figure 4.18, general cargo Figure 4.19, Tankers, Figure 4.20, Passenger's vessels, Figure 4.21. The result reveals that a minimum of one, a maximum of three, and an average of two container vessels are expected daily. For general cargo, a minimum of one, maximum of three and average of two. For passenger's vessels, a minimum of two, a maximum of six, and an average of four vessels are expected daily. For tankers, an average of one ship per day is expected.

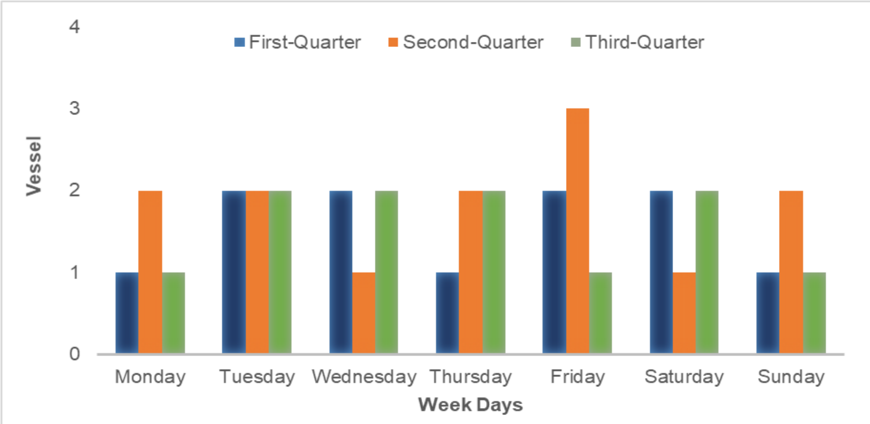


Figure 4.18: Containership arrival rate

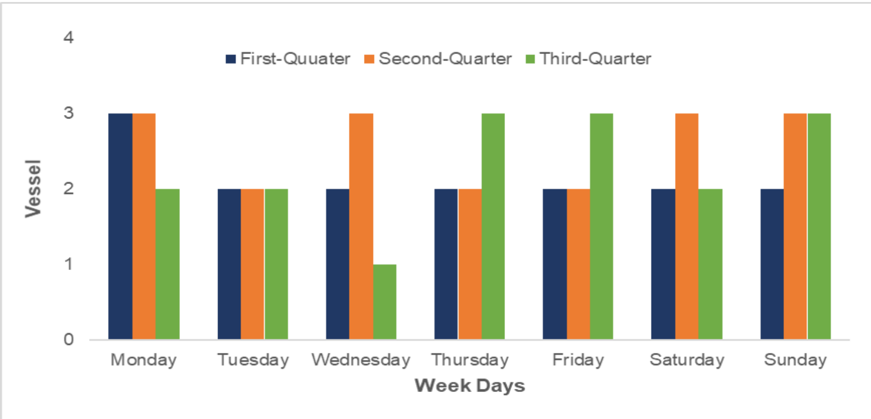


Figure 4.19: General Cargo arrival rate

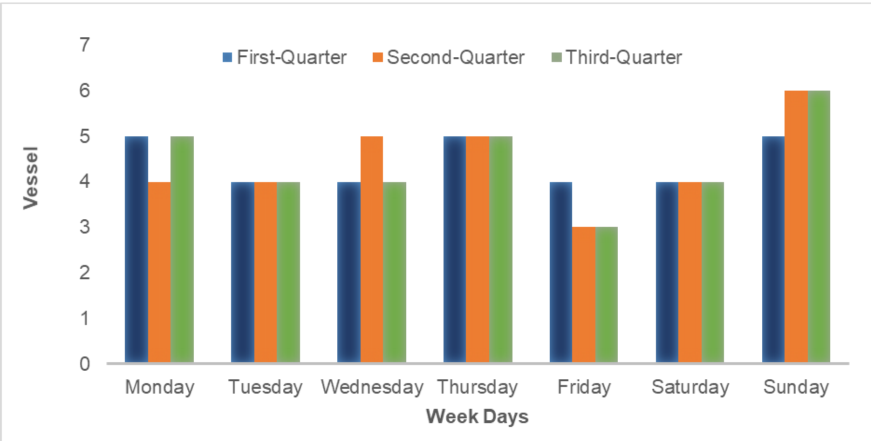


Figure 4.20: Passenger vessels arrival rate

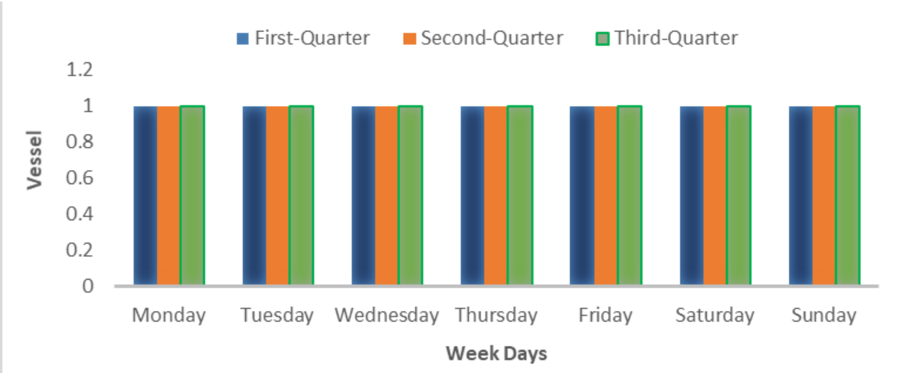


Figure 4.21: Tanker vessels arrival rate

The inter-arrival time of vessels varies by vessel type. For example, the minimum and maximum time interval between consecutive arrivals of general cargo are approximately 04 minutes, and 2 days 21 hours 40 minutes, respectively, with a mode of approximately seven hours.

Since the yearly arrival rate is known for the various vessel types. For example, container vessel has a maximum of three vessels, minimum of one and a mode of two vessels, the arrival rate of each vessel can be estimated using a three-point estimation technique (meaning a distribution technique that estimates the values of a variable using its minimum, mode, and maximum value) e.g. triangular distribution beta-pert distribution, etc. This method was chosen because the majority of the data are around the mode. The beta-pert distribution was used for this study. This is because the triangular distribution only considers the three estimated points (minimum, mode and maximum values) as a fixed triangle, but the PERT method allows us to convert the three-point estimate into a bell-shaped, nearly normally distributed curve, (see sample in Figure 4.22) (Sebastian, 2020), making it more useful for calculating the probabilities of ranges of expected arrivals.

The maximum estimate represents the best-case scenario. The minimum point represents the worst-case scenario. Both minimum and maximum estimates are the extreme range of expected outcomes. The mode represents the most likely case, it is the estimation deemed to be the most realistic.

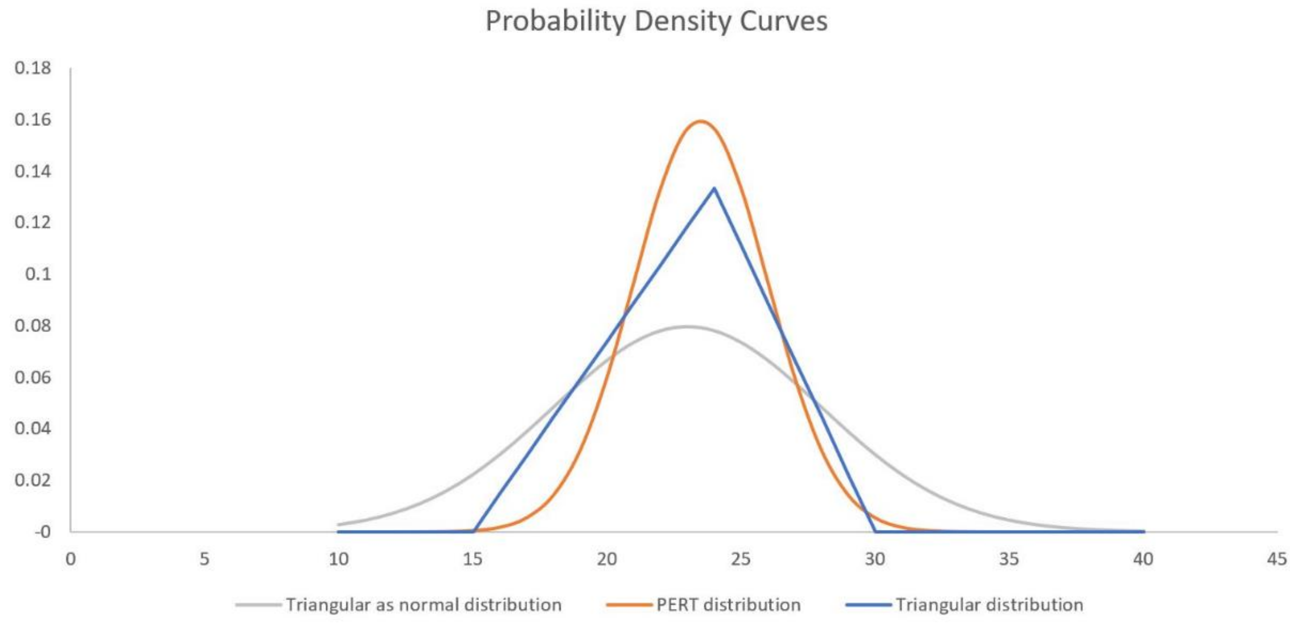


Figure 4.22: Comparison between a triangular distribution and beta-Pert distribution

Source: (Sebastian, 2020)

The inter-arrival time is estimated based on the vessel arrival rate. The beta-Pert distribution requires three factors to comfortably estimate the inter-arrival time value of a certain variable. These parameters are:

- The minimum value: is the assumed worst-case scenario of daily arrivals in a year. For example, the minimum arrival of container vessels is one vessel per day.
- The maximum value: is the assumed best-case scenario of daily arrivals in a year. For example, the maximum arrival rate of a container vessel is three per day in a year.
- The mode value: is the most occurring daily arrivals in a year.

This approach was used across all vessel types. Figure 4.23 shows a sample of the probability curve of the daily arrival rate of container vessels, with an average of two vessels per day. The average time was calculated using Equation 3.

Average $\mu = \frac{\alpha + 4m + \beta}{6}$ Equation 3

$\boldsymbol{\alpha}$ = Minimum daily arrivals in a year, $\boldsymbol{\beta}$ = Maximum vessel daily arrivals in a year, and

$\boldsymbol{m}$ = Mode (most occurring daily arrivals in a year).

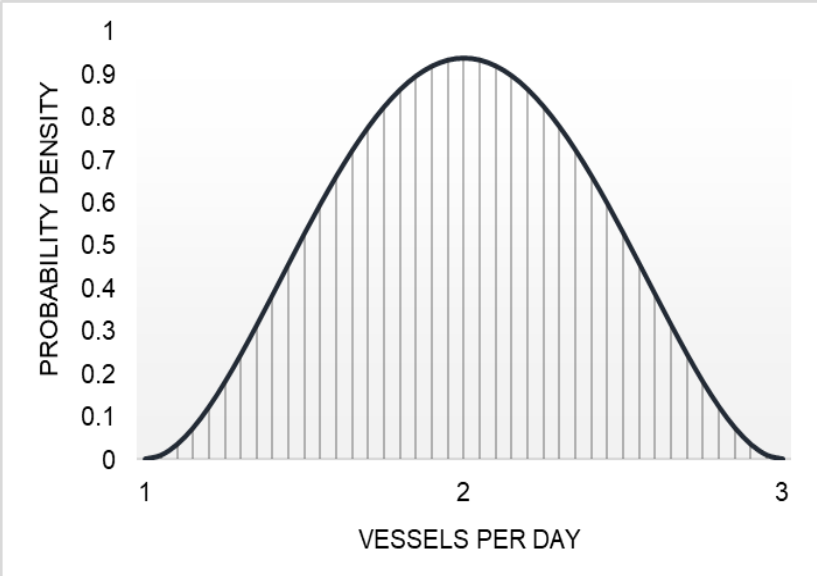


Figure 4.23: The Pert-Probability curve of the daily rate of arrival for container vessels

4.7.2 Vessel movement analysis for model construction

The 2016 AIS data for Port of Liverpool was used for conducting this analysis. The database contains vessel tracks with the status of vessel's (dimension, position, speed, heading, etc.) but lacked information like vessel type which had to be added manually by looking up the vessel using its MMSI, and IMO numbers. The AIS data were divided into vessel types and terminals used during cargo operations as shown in Table 4.3. For example, cargo operations for both bulk carriers and general cargo vessels were observed to be conducted at the same cargo terminal from the AIS data. Thus, they are grouped as general cargo vessels. This is also similar for ro-ro and passenger vessels.

Table 4.3: Categorisation of Vessel types

Vessel type	Grouping
Tanker	Tanker
Bulk Carrier	General Cargo
General Cargo	
Container Ship	Container vessel
Passenger	
Ro-Ro vessel	Passenger Vessel

Trajectory data is analysed using "a stop and move" approach (Spaccapietra et al., 2008) i.e. the sequence of moves going from one stop to the next**.** Vessel positions across the port were plotted and visualised using ArcGIS. All data points were joined together to reveal the vessel trajectory. The sequence of time-stamped locations visited by a moving object formed that object trajectory, where the trajectory represents the path taken by that object together with the time instants at which the object was at any position along the path, (Vazirgiannis and Wolfson, 2001). Trajectories (t) and speed profiles of vessels were plotted and manually interpreted using the stop and move approach. The extracted result from trajectory analysis was interpreted using a state-chart by examining vessel behaviour (changes in speed, course, and position) toward the specific area represented as (T). These specific areas are: Entry point (T-begin), anchorage area (T1), Entrance to channel (T2 and 6), locks (T3 and 5), berth or cargo terminal (T4), and exit point (T-end) (see Figure 4.24).

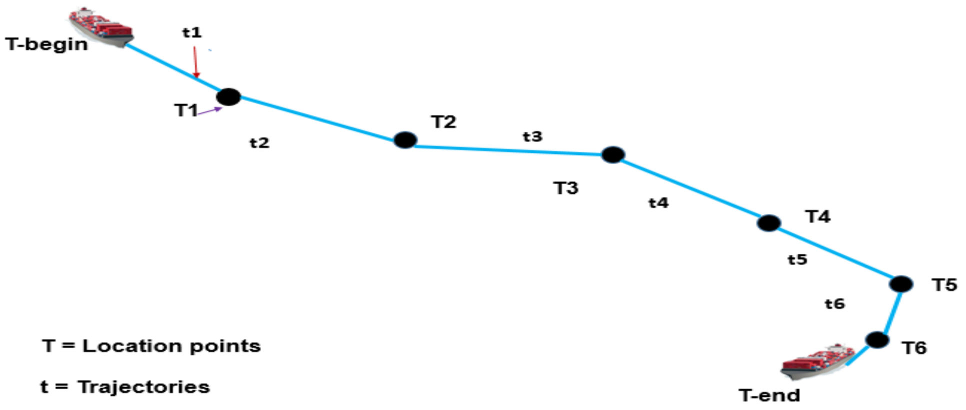


Figure 4.24: Vessel course divided into fixed location points T1-6 and speed segments t1-6

The interpretation is shown in Table 4.4. The ship trajectory component is “move” if the shipping speed is greater than 0.5 knots, and “stop" if the shipping speed is less than 0.5 knots. The trajectories (t) represents the direction of movement. For t-3 and -5, and t-2 and -6, t-3,-2, denotes an inbound movement, while t-5,-6, is an outbound movement.

Table 4.4: Analysis interpretation for state-chart creation using Descriptive approach

State		**Meaning**	**Trajectory component**
Arrived	**T-begin**	Denotes a ship arrived at the port	Move
To Anchorage	**t-1**	The ship is manoeuvring to an anchorage area	Move
At Anchorage	**T1**	A ship speed is less than 0.5 knots and its position is constant outside the port over time	Stop
Leaving Anchorage	**t-2**	A change in speed and position of a ship At Anchorage	Move
Approaching Narrow channel	**t-2 & t-6**	A ship GIS point denotes that a ship is moving towards the port-channel after leaving the anchorage for t-2 and after leaving the lock for t-6.	Move
Manoeuvring in channel	**t-3**	GIS point from the trajectory visualization shows that the ship is within the port narrow channel with continuous speed reduction.	Move
At Channel Entrance	**T-2 & T-6**	When a ship speed in-state “Approaching Narrow channel” for t-2 and “Leaving Narrow channel” for t-6 is less than 16 knots and its subsequent speed keeps decreasing	Move
Approaching Lock	**t-3 & t-5**	When a ship speed in-state “Manoeuvring in the channel” for t-3 and “Leaving berth” for t-5 is less than 4 knots and its subsequent speed values are below 4 knots	Move
Entering Lock	**t-3 & t-5**	when a ship speed in-state “Manoeuvring in the channel” for t-3 and “Leaving berth” for t-5 is less than 2 knots and when the next speed range is less than 1.0 knots	Move

In Lock	**T3 & T5**	when a ship is in the port lock and the speed value is less than 0.5 knots and at a particular location over time	Stop
Leaving Lock	**t-3 & t-5**	When a ship speed "In Lock" increases by about 0.5 knot, and the visualisation map denotes a change in position.	Move
Approaching berth	**t-4**	when a ship speed in-state "Leaving Lock" is less than 3 knots and the subsequent speed value falls below 2 knots	Move
At Berth	**T-4**	When a ship arrives at its final destination and is visually identified as the point where the inbound and outbound trajectory meet, and the ship speed value is less than 0.5 knots	Stop
Leaving berth	**t-5**	when a ship speed in-state "At Berth" increases by about 2-3 knot, and the visualisation map denotes a change in position	Move
Leaving Narrow channel	**t-6**	when a ship speed in-state "Leaving Lock" gradually increases over 10 knots, with a change in a position towards the outer channel	Move
Leaving Port	**tend**	Denotes a ship is out of the narrow channel and is moving away from the port channel.	Move
Collision Avoidance		Denotes a drastic decrease in ship speed is in the state "Approaching narrow channel" (Outer Channel), and less than 1.0 knots when a ship is within the narrow channel.	Move

4.7.3 Vessel speed analysis for model input

The AIS data provides a lot of information for analysis. From the results, there exist similarities and differences in vessel traffic characteristics across vessel types. Regarding similarities, vessel speed, and time intervals conform to certain distributions, which can be used to describe the vessel traffic. The PERT distribution triangular distribution fits vessel speed with maximum, mode, and minimum speed values across zones allowing us to calculate the mean speed across the waterway and better simulate vessel speed. The PERT distribution was chosen for two reasons; first, there is a large variation of vessel speeds. Different ships will manoeuvre with a different speed based on their location and the traffic density, for example, Figure 4.25 shows the speed profile of four samples from each vessel type from their entrance to departure from the port. Thus, vessel speeds were analysed based on zonal separation as discussed in section 3.4.

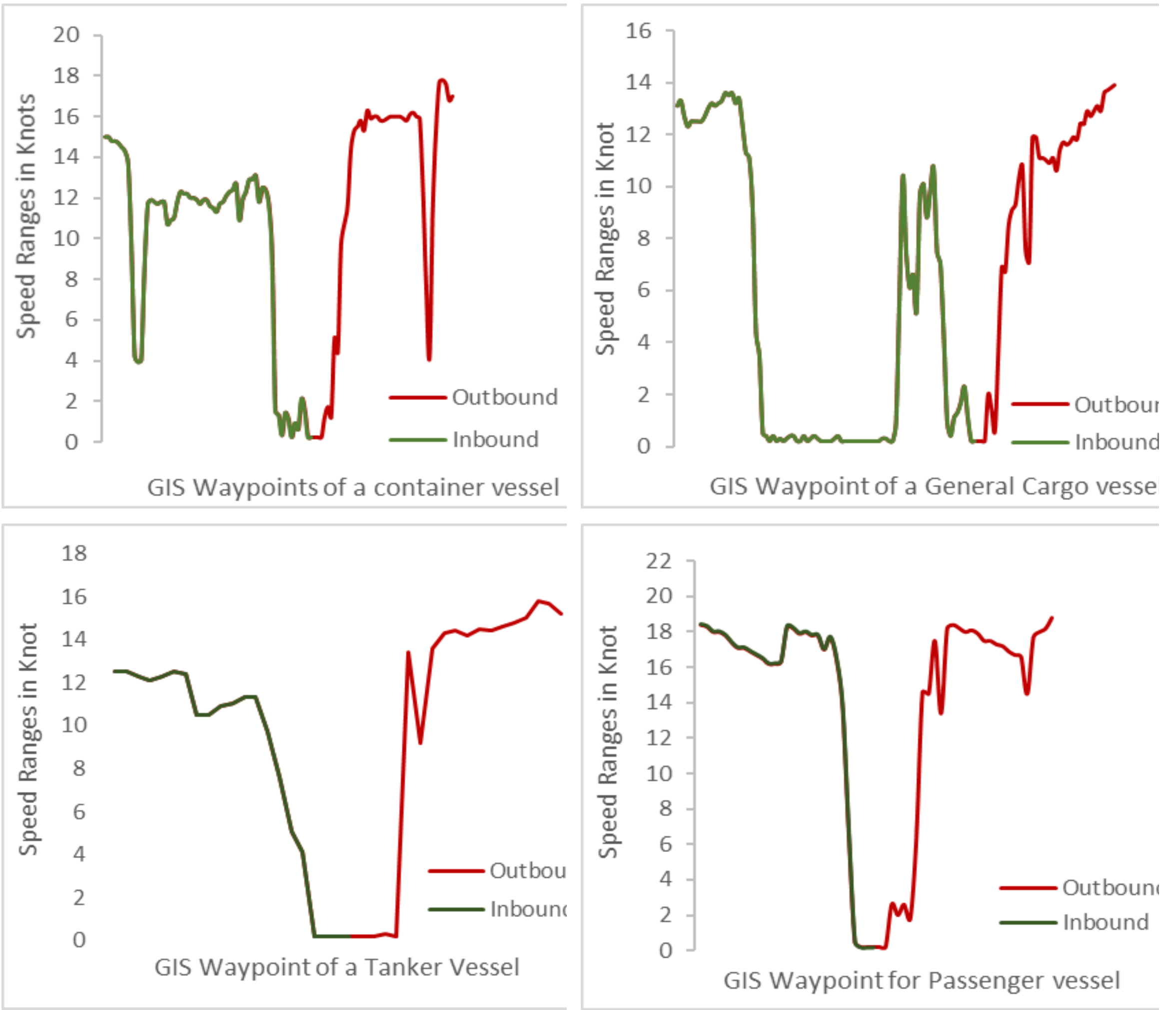


Figure 4.25: Sample speed profile of various vessel types

Secondly, the majority of the speed data were seen to be represented around the mode across zones. Vessel speeds for each zone were collected separately for different vessel types and the distributions approximated using a PERT distribution: maximum, minimum and mode speed value observed in the data set within a zone.

The maximum and mode value of vessel types were collected directly from the AIS dataset, while the minimum speed was realistically assumed from the dataset based on the actual speed at which vessels are expected to be operating across each zone. For example, in zone one, vessel speed was approximated across types (see Figure 4.26). Table 4.5 shows a summary of the different speed variables of vessel types across zones, while the speed distributions of the various vessel types for all zones are shown in Appendix A

Table 4.5: Model input for vessel speed across zones

		Zone									
Vessel type	Pert parameters	1	2	3	4	5	6	7	8	9	10
Container	Max (knots)	23.5	23.3	22.9	23.1	22.8	21.4	20.6	19.9	9.9	4.9
	Min (knots)	10	9.5	9	8.5	8	7.5	7	10	5.0	0.5
	Mode (knots)	12.2	16.8	16.6	16.5	12.4	16.1	13.3	10.5	8.2	0.5

[redacted]											
Tanker	Max (knots)	24.2	17.6	17.2	17.5	16.7	16.5	28.3	28.3	9.9	4.9
	Min (knots)	10	9.5	9	8.5	8	7.5	7	10	5.0	0.5
	Mode (knots)	12.3	10.7	11.1	11.6	12.4	12.4	10.2	10.6	9.9	0.5
[redacted]											
General Cargo	Max (knots)	19.6	20.4	20.8	22.5	21.5	22.6	22.9	20.7	9.9	4.9
	Min (knots)	10	9.5	9	8.5	8	7.5	7	10	5.0	0.5
	Mode (knots)	10.7	10.7	11	11	9.8	9.7	10.5	10.6	9.9	0.5
[redacted]											
Passengers	Max (knots)	23	22.9	22.2	22.4	25.1	26.1	25.3	22.7	9.9	4.9
	Min (knots)	10	9.5	9	8.5	8	7.5	7	10	5.0	0.5
	Mode (knots)	19	18	18.8	17	18.1	18	17.3	15.4	6.0	2

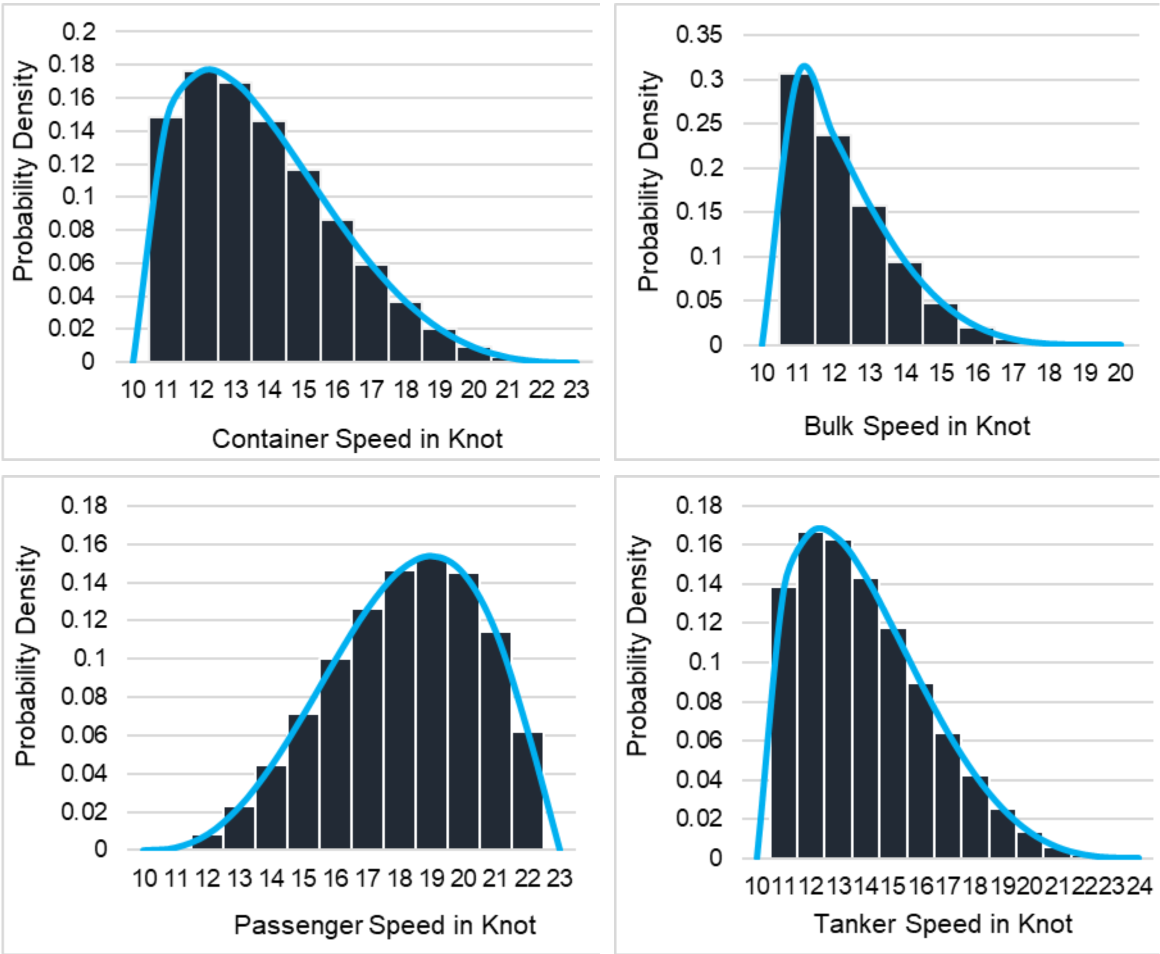


Figure 4.26: Sample Zone One speed distributions

4.7.4 Collision avoidance

Collision regulations (COLREGS) govern how vessels take avoiding action. Implementation is open to interpretation. The decision of one vessel might not be clear to the other and this becomes an even greater problem when more than two vessels are involved, (Lorenzon et al., 2017).

The collision avoidance depends on the ship operation mode of the vessel i.e. cruising or manoeuvring. Outside a narrow channel, the vessel can operate in cruising mode. The

COLREGS require it to alter course to a safe position if possible, when overtaking, crossing or in a head-on situation. Within a narrow channel, vessels are required to reduce their speed to the safest possible limit to avoid the collision. The Cruising algorithm calculates a new manoeuvring position, while the manoeuvring algorithm reduces speed. The collision avoidance speed inputs are shown in Table 4.6. The maximum, minimum and mode values of vessel types were realistically assumed from the data set and from the assumed minimum speed value vessels are expected to be operating across each zone within the model.

Table 4.6: Model input for vessel collision avoidance speed across zones

		Zone									
Vessel type	Pert parameters	1	2	3	4	5	6	7	8	9	10
All	Max (knots)	10	9.5	9	8.5	8	7.5	7	10	5.0	0.5
	Min (knots)	4.0	3.5	3.0	2.5	2.0	1.5	1.0	2.0	1.0	0.2
	Mode (knots)	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	0.2

The avoidance algorithm (Figure 4.27) was constructed within the model for each agent using a state chart. This decides the action an agent's vessel takes based on its operational mode. Actions include changing the speed at specific locations such as stopping at anchorage, changes of course and speed during collision avoidance. An agent can get its position, calculate its speed, identify other vessels and their position and speed, the environmental condition and its next position along its planned route (waypoint). From this information, it makes its decision to move from one point to another and at what speed depending on the agent’s state and if the environment stays the same.

The model is linked to physical geography. Vessel positions and headings are calculated using real latitude and longitude from the port area map. The model receives input of ships within the port area using an AnyLogic link property. This connects agents within the environment allowing them to be detected using a detection range. In this case, the maximum range radar can pick another vessel. Using the collision detection range, each ship autonomously keeps a lookout for possible collision situations looking at ships nearby as it moves within the simulation space.

Safe passage ranges were used around each ship, to easily observe avoidance action taking during possible collision risks. The safe passage range is the minimum distance required by ships to comply with COLREGS while in navigable water:

- 0.3 NM (nautical miles) + 6 x Vessel length + 500 m, when on the starboard side; and
- Vessel length + 500 m when on the port side.

The safety range is the minimum distance between two ships where a collision-avoidance action must be taken. This is 3 NM during poor visibility, and 6 NM in good visibility. The safety range in practice is dependent on the ship navigator’s decision. In this model, it was set at a constant of 1 NM. Once a ship is detected (within 3 NM), the collision avoidance state machine becomes active. The avoidance process (preparation stage) starts running only when the ship receives a message signifying there is another vessel within its safety range (1 NM). Collision avoidance action is triggered when the nearest agent (previously within 1 NM (safety range)) is within the safe passage distance (500 meters).

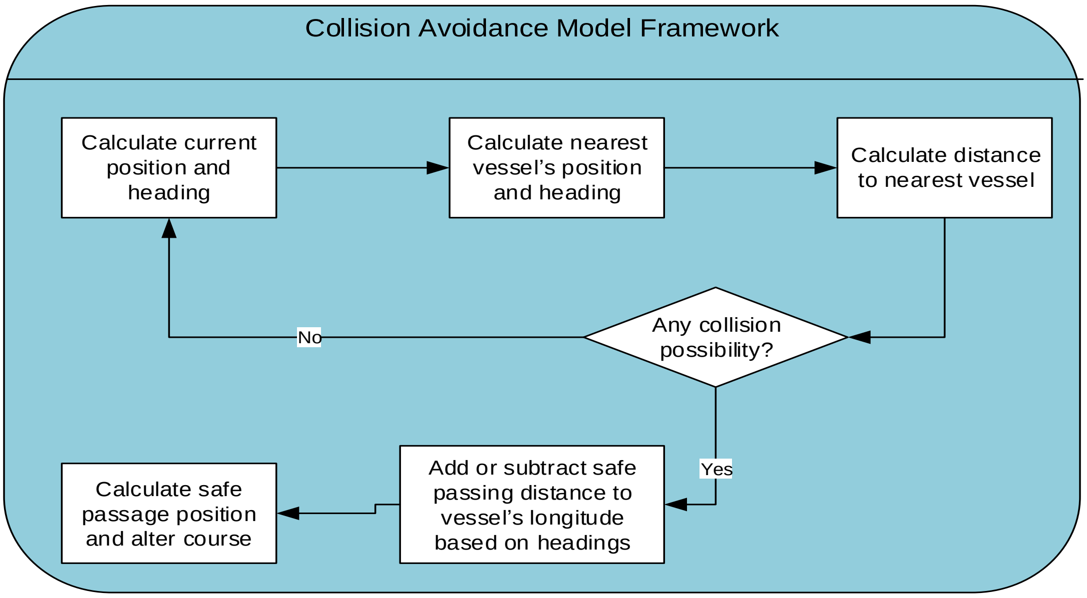


Figure 4.27: Collision Avoidance model

4.8 Model output and validation

The historical data method is implemented by dividing the collected data into a modelling set and a verification set to evaluate the model and verify results, respectively. The model parameters are calibrated using the historical AIS data. The data are divided into vessel types and were used to calibrate vessel movement patterns, speed changes, vessel and port times (transit, delay, dwell, etc.), arrival intervals and quantity based on vessel type, etc. The model output values of speed patterns (changes in speed overtime), inter-arrival time, distributions and positions, durational distribution (transit time, manoeuvring time, waiting time etc.) are calibrated to fit reality. Figure 4.28 shows the times at which each step of a ship's port operation starts and stops as documented in the port, allowing for the calculation of a variety of parameters (or indicators) that the shipping industry uses to calculate performance. Port time is the time duration between a ship's arrival at the entrance buoy and the ship's departure from the same buoy.

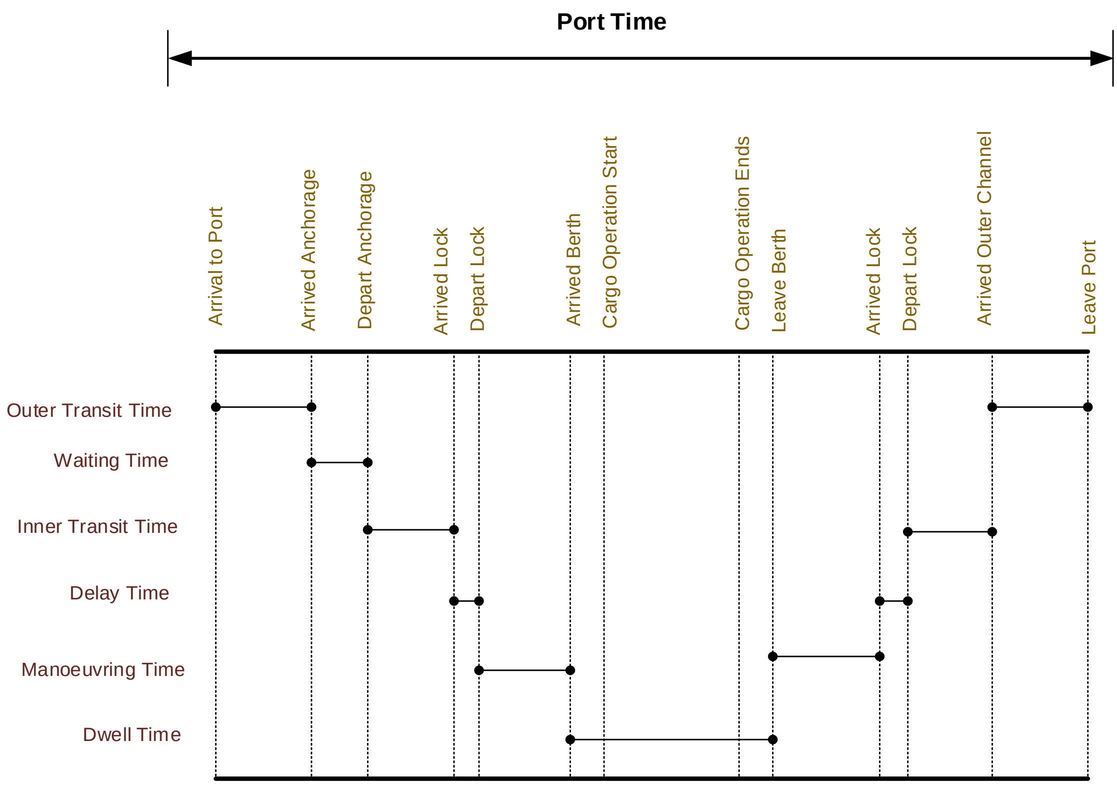


Figure 4.28: Breakdown of ship's time in port

4.8.1 Transit Time

Transit time is divided into two: outer waterway transit time (outer transit time), and inner waterway transit time (inner transit time). The outer waterway transit time is the period from a vessel arrival at zone 6 (anchorage) and vice versa. Though there are various anchorage areas in the port, however, zone 6 was chosen as it is the most used anchorage area by vessels and it is between the inner and outer waterway. The inner waterway transit is the period between the vessel's departure from anchorage (zone 6) to the lock and vice versa. Estimating a vessel's transit time from the historical AIS data was difficult since the transit times between two vessels varies, hence, a histogram was used to group the frequencies of 60 sample vessels across the minimum and maximum observed time. The histogram was fitted with a normal distribution using the average transit time and the standard deviation for both waterways across vessel types as shown in appendix 2. The average transit times for the different vessel types are listed in Table 4.7. The results reflect the difference in vessel speed as vessels navigate through each zone as observed in section 4.7 and appendix B and C.

4.8.2 Manoeuvring Time

The manoeuvring time is the period of vessel movement from the lock to their allocated berth or vice versa. It varies between vessels due to the different location of cargo terminals from the lock and the vessel's manoeuvring speed. Similar to transit time, vessel manoeuvring time from different vessels was difficult to capture, hence a histogram was used to group the frequencies of vessels across the minimum and maximum observed time. The histogram was fitted with a normal distribution using the average manoeuvring time and the standard deviation of the waterways across vessel types as shown in Appendix D. Table 4.7 shows the average manoeuvring times of various vessel types.

Table 4.7: Average Travel times according to vessel types from historical AIS data.

Travel Time	Vessel Type	Average Time	Standard Deviation
Outer Transit	Container	01 hours: 50 minutes (1.84 hours)	0.18
	General Cargo	02 hours: 58 minutes (2.97 hours)	0.47
	Passenger	01 hours: 41 minutes (1.68 hours)	0.1
	Tankers	02 hours: 06 minutes (2.09 hours)	0.26
Inner Transit	Container	01 hours: 47 minutes (1.78 hours)	0.24
	General Cargo	02 hours: 37 minutes (2.61 hours)	0.16
	Passenger	01 hours: 26 minutes (1.36 hours)	0.31
	Tankers	01 hours: 56 minutes (1.93 hours)	0.16
Manoeuvring Time	Container	36 minutes (0.56 hours)	0.05
	General Cargo	48 minutes (0.79 hours)	0.19
	Passenger	42 minutes (0.7 hours)	0.09
	Tankers	38 minutes (0.63 hours)	0.05

4.8.3 Waiting Time

Vessel waiting time is the period between vessel arrival at the anchorage area and its departure from it. The waiting time of vessels at anchorage varies across types, meaning regardless of a vessel arrival time if there is no cargo terminal available for that type, vessels of other types that arrive later can proceed to berth. Hence, there is no specific waiting time realistically. As a result, the waiting time is not used as an input to the model, but for validation purposes. Therefore, the average waiting time for all vessel types was calculated from the historical AIS dataset as shown in Table 4.8.

Table 4.8: average waiting time for all vessel types from the historical AIS dataset

Vessel Type	Average Waiting Time
Container	10 hours: 32 minutes
General Cargo	17 hours, 53 minutes
Passenger	04 hours: 16 minutes
Tankers	02 hours:52 minutes

4.9 Conclusions

This chapter focused on discussing the port model construction. Details on the development of the port geographical area comprising of the outer and inner waterway, the traffic network, and the various location of marine infrastructures (anchorage, locks and berth (cargo terminals)) were discussed in sections 3.3 and 3.4. Explanation of the various port process, their input and expected output data was discussed in section 3.5. A detailed explanation of the vessel model comprising of vessel types, arrivals rate, and speed. Also, vessel movement and collision avoidance models were discussed in section 3.5, while vessel transit and manoeuvring times are discussed in section 3.7. Vessel times at the various processes are discussed in section 3.4

The chapter also contains details of external conditions (seasonal changes, weather, visibility, and tide) considered in this study and the model input in section 3.6. The Data analysis was conducted using Microsoft Excel and the results were used as input to the developed port model in AnyLogic. The description of the port model in this chapter (Section 3.2) forms the building blocks of the developed port model as discussed in Chapters 4 and 5

Chapter 5: AnyLogic Model development

5.1 Introduction

The methodology as described in Chapter 3: Chapter 1: is applied to the case study. The case study aims to show the application of the methodology as well as assess the environmental impact of vessel traffic in the port. The proposed multi-method simulation was implemented in AnyLogic to develop the discussed port traffic model. The various port systems and their entities were modelled using a combination of agent-based simulation and discrete-event simulation. Entities were modelled based on their system operation as discussed in Chapter 2: and Chapter 4: This Chapter discusses the simulation development in AnyLogic for the case study. The conceptual model design applied in AnyLogic is novel, hence the chapter also explains how the entities within each system are modelled.

5.2 The design of the developed port traffic simulation model in AnyLogic

The port traffic simulation model was developed with a similar design to a realistic port system as shown in Figure 5.1. To ensure the modelling reflects reality, the developed port model must include the following systems:

i. Port process: Vessel Traffic Control, Arrival and anchorage, Lock, Berth and Terminal;
ii. External conditions (tides, weather and visibility).
iii. Vessel traffic and Interaction between vessels, the environment, and port;
iv. Geographic area

The simulation design for the port model is shown in Figure 5.1. The design reveals the connection of the various port systems within the simulation models. The simulated design also shows the entities embedded within each system. The various systems within the simulation model in AnyLogic are, the user interface provides visual feedback, the model environments representing the geographical area (in connection to Figure 5.1) containing the simulated agents. The simulated design also includes the simulation controller, the vessel agent's types (container, tanker, passenger and general cargo), port agents (comprising of various cargo terminal types as agents, anchorages, cargo terminal allocation, intercommunication systems), the tidal agent, and weather and visibility agent.

The simulation controller is the simulation timer used to start, pause or stop a simulation run. It is also used to keep track of the elapsed time and initialise the order events within the simulation. The model environment consists of a dynamic map of the geographical area with routes and waterways areas mapped out using spatial data sets, and, the location of various static agents (e.g. cargo terminal, lock and anchorage areas). The model environment provides visuals of all agents (port, vessel, and external conditions) and vessel agent movement and changes in behaviour (speed, position, and heading).

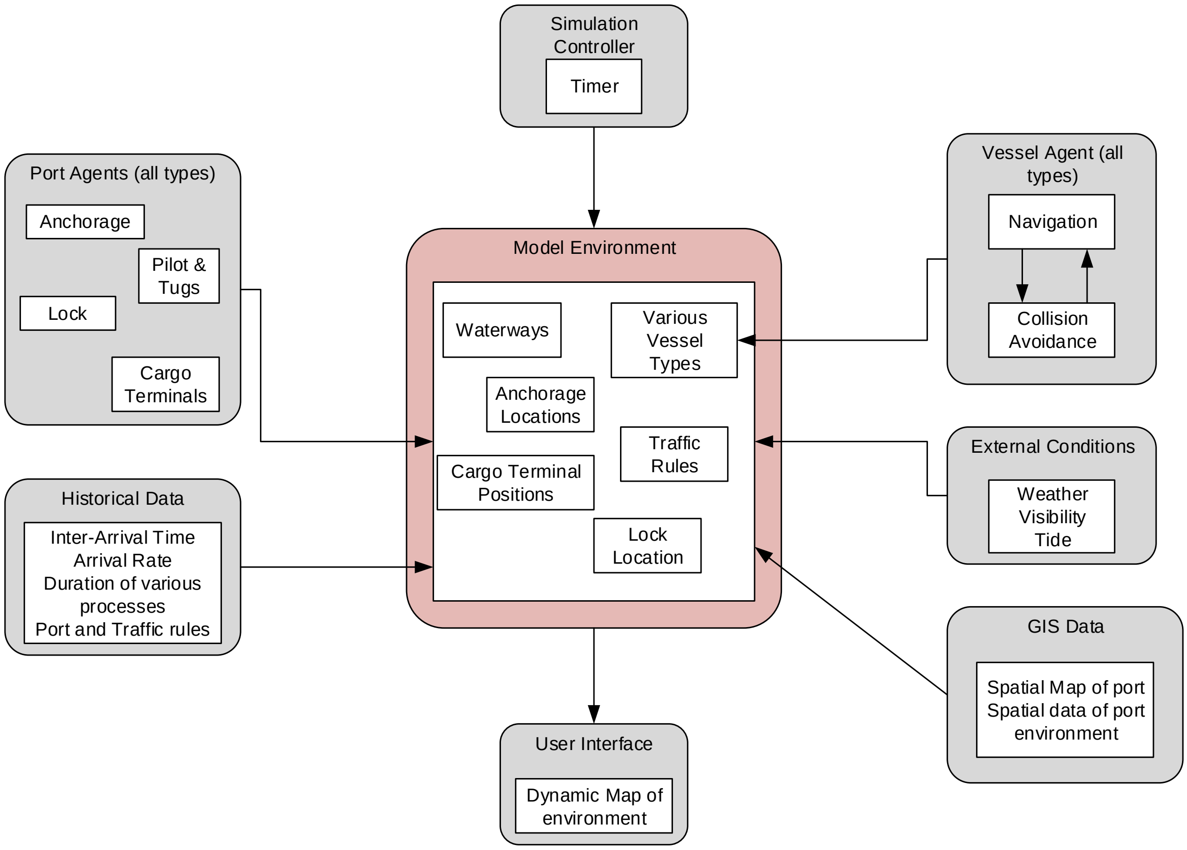


Figure 5.1: Simulation design in AnyLogic

5.3 Port Process models

The various entities within the port processes are modelled as agents associated with processes represented using discrete-event simulation in AnyLogic. The modelling design of each entity supports the inclusion of various aspects of the process difficult to model. It explicitly represents the entire process and allows the inclusion of relevant inter-communication between processes within the entire system. Where editing is required, the process block can easily be identified. The modelling structure supports scalability and can be integrated into other systems. The approach can also be used in other fields of research, like real manufacturing, etc. and processes can easily be validated. The modelling design of each entity and the purpose of each building block are discussed as follows;

5.3.1 Anchorage Model

Once a vessel agent is injected into the model, the vessel agent immediately navigates to the anchorage area. When the vessel reaches the anchorage area, it enters the anchorage process. The anchorage process is modelled as an independent entity within the port process. Anchorage processes are represented as agents associated with processes based on vessel types (container anchorage process, general cargo anchorage process, etc.). Each process exists and operates independently from other anchorage processes, but communicates with other general processes like the Lock process, and processes specific to the vessel type they handle, like berth. For example, when a container vessel agent arrives at the anchorage area, within the visual model the agent joins previously arrived agents regardless of vessel type at the anchorage area, but technically, the agent joins the anchorage processes based on container vessels. By joining the container vessel anchorage process, the container vessel agent only depends on the availability of a container berth, the queue length of other waiting container vessels (first in first out), the external conditions (tide and weather), and the lock processes. The waiting time of the container vessel is not dependent on the arrival of other vessel types. The approach captures reality, as in the real world, vessel waiting time at anchorage is only determined by the berth availability for that vessel type, queue position between related vessel type, lock availability and external conditions (weather and tide). Hence, the approach allows a realistic prediction of the agent waiting time

The anchorage process consists of two stages. The first stage focuses on checking for an available terminal by contacting the berth operator. Figure 5.2 shows the process for a container vessel. While the second stage contacts the lock, pilot and tug operators and a sample of this process for container vessels are shown in Figure 5.4. Details for each stage are explained below.

Stage 1

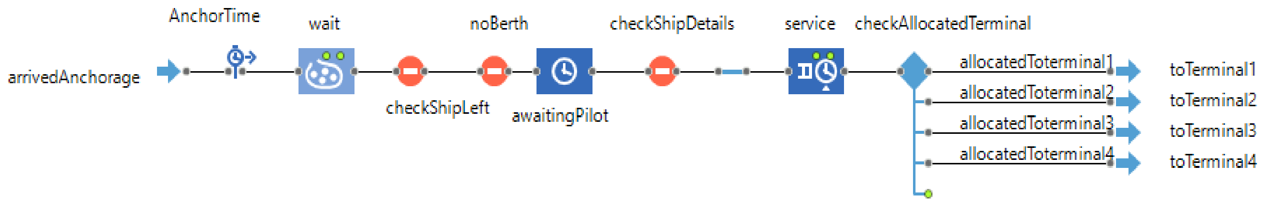


Figure 5.2: Stage One of Anchorage Process

- Enter object: The vessel (Agent) arrives at the start of the anchorage process
- Time Measure Start: Measures the time a ship agent enters its anchoring state.
- Wait: Serve as queue system for vessels within the port anchorage area. Also, allocates queue number to them and stores their details.
- Hold: Block or unblock the process flow based on lock and berth availability and external conditions e.g. Tide.
- Delay Object: Delays ships at anchorage until a berth is available.

- The Service Object: Contact berth operator for available cargo terminal based on vessel type. Figure 5.3 shows the communication process for container vessels. The communication flow was structured using a state chart. Each state affects a specific action and communication between states are connected by several conditions. For example, in the communication process for container vessels, the system checks for container terminal availability. The process commences with a message (“Check”). Then based on the condition sets (i.e. terminal numbers, numbered from 1 – 4 for container vessels), the process conducts its checks for an available berth. These conditions were represented by a Boolean variable (see Figure 5.3) called berth check. When a berth is occupied, the berth check variable for that berth is set at false. Or true if the berth is available. When the variable is true, the terminal is allocated to a vessel (next in the queue). When the berth is allocated, the variable becomes false, as the berth is no longer available.
- SelectOutput5: Release vessel to stage two after berth allocation
- Exit Object: Vessel leaves the first stage of the anchorage process: end of the process

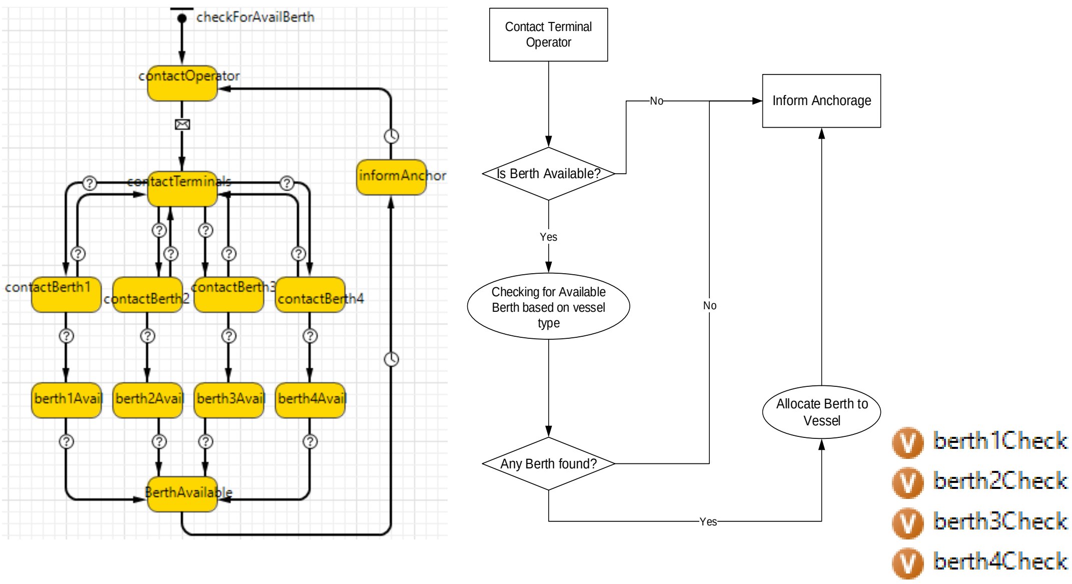


Figure 5.3: Anchorage-Berth Intercommunication

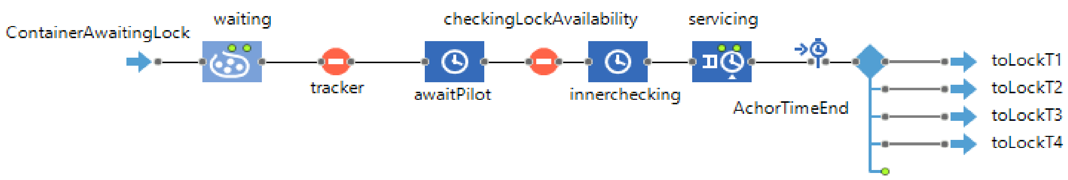


Figure 5.4: Stage Two of Anchorage Process

- Enter object: The vessel (Agent) already allocated to a terminal begins stage two of the anchorage process
- Time Measure Ends Measures the time a ship agent leaves the anchorage point.

- Wait: Serve as queue system for vessel agents already allocated to a berth but awaiting lock, pilot and tug operations. Also, it allocates a queue number to vessel agents regardless of type.
- Hold: Block or unblock the process flow based on lock and external conditions e.g. Tide.
- Delay Object: Delays vessel agent at anchorage until pilot and tug arrive. In the model, pilot and tug boat arrival times are an assumed duration approximated between a minimum of one hour and a maximum of two hours
- The Service Object: Contact the lock operator for lock availability. Figure 5.5 shows the communication process for container vessels. The communication flow was structured using a state chart. Each state affects a specific action and communication between states are connected by several conditions. For example, in the communication process for container vessels, the system checks for lock availability. The process commences with a message ("waiting"). Then based on the condition sets (i.e. terminal numbers, numbered from 1 – 4 for container vessels), the process conducts its checks for lock availability.
  The conditions were represented by variables (see Figure 5.5) called Term. These variables inform the locking process of the cargo terminal location a vessel is intending to berth. Based on this information a specific lock is observed. When the lock is available, the vessel agent is allowed to leave the anchorage and proceed to the lock.
- SelectOutput5: Release vessel to allocated berth after tug and pilot arrival and access to lock is confirmed
- Exit Object: The vessel leaves the anchorage process technically, but does not leave the anchorage area visually: end of the process

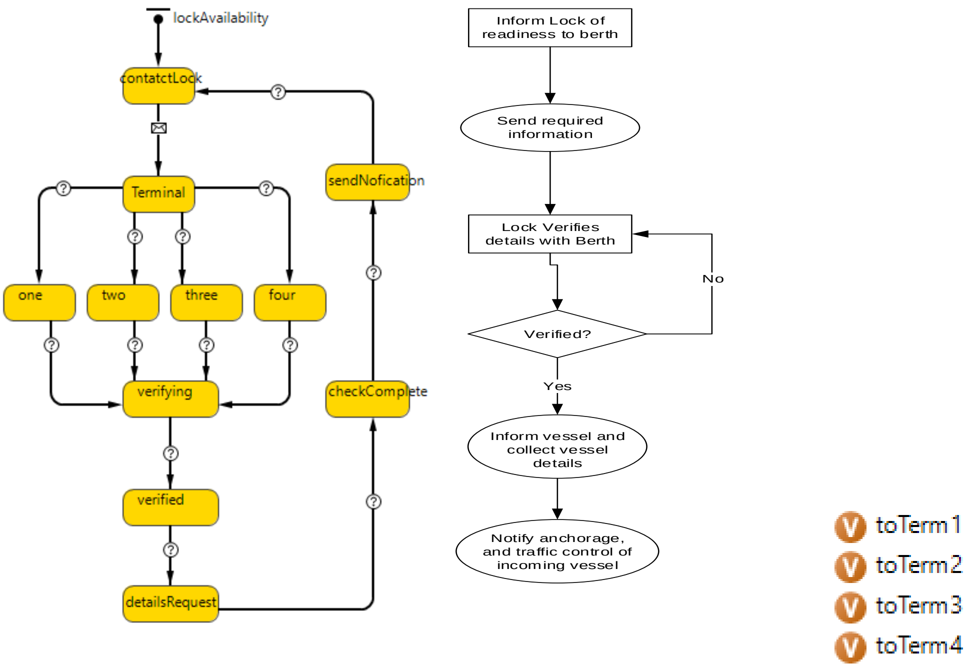


Figure 5.5: Anchorage-Lock Intercommunication

5.3.2 Lock Process

The lock process is modelled as an independent entity within the port process. Lock processes are represented as agents with associated processes independent of vessel types (that is, it accepts all vessel types). The Lock process plays a major role between the anchorage and berth processes. For example, when vessel agents leave the anchorage for their allocated berth, they must go through the lock. Similarly, as vessel agents depart from their allocated berth to leave the port, they must also use the lock. To accommodate for this, the locking process has two directions of flow (entering and departing) as shown in Figure 5.6. Entering denotes the vessel agent is proceeding to berth while departing refers to vessel departing from the berth.

The lock process was developed to admit one vessel at a time regardless of vessel types as in the real world. This was done by developing two additional processes within the locking agent namely arriving (Figure 5.7) and departing process (Figure 5.8). The arriving process is a queueing process containing all vessels intending to use the lock from the anchorage process (stage two), regardless of vessel types, following a first-in-first-out basis. Departing is also a queueing process containing all vessels intending to use the lock from the birthing process, regardless of vessel types, on a first-in-first-out basis.

The usage of the locking process is coordinated by a Boolean variable called Berth. When an arriving vessel is using the lock, the variable is declared true, and when the variable leaves the lock, the variable is declared False. When the variable is declared false, the vessels from the departing process are allowed to use the lock. When a departing vessel is using the lock, the variable is declared false and when the vessel leaves the lock the variable is declared true, allowing arriving vessels to use the Lock.

Vessels are granted access to the lock when the tidal conditions are good. The lock checks the tidal condition using the lock intercommunication link in Figure 5.9. This link stops or allows vessels within the arriving and departing process from proceeding to the lock area visually or remaining at their initial location. The link makes a decision based on the tidal condition. When the tidal status is at low water, vessels are hindered from leaving their initial position but are allowed when the tidal status is above low water. This is done by triggering a block in both processes when the tidal status is at low water and unblock when the tidal status is above low water.

Details of the process are discussed below.

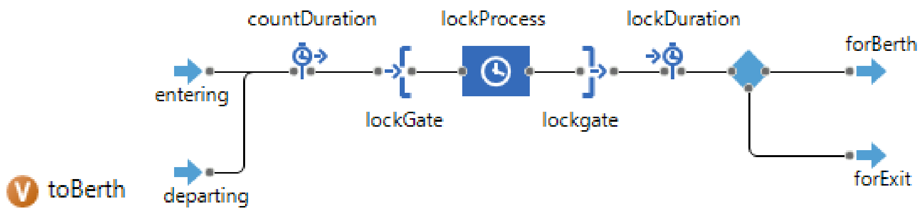


Figure 5.6: Lock process

- Enter object: The vessel (Agent) arrives at the lock area, and the locking process begins. Vessel arrival at the lock area is from two directions. The first (entering) is for vessels arriving from anchorage, while the second (departing) is for vessels arriving from the berth.
- Time Measure Start: Measures the time a ship agent enters its lock process.
- Time Measure Ends Measures the time a ship agent leaves the lock process point.
- Restricted area start and end: Restrict the number of vessels using the lock at a time, and it is set to a capacity of one vessel agent at a time.
- Delay Object: Delays vessel agent at the lock for some time. The duration for which a vessel is delayed is called the delay time. The input time value is the average delay time discussed in section 3.4.3. The delay time is distributed by a PERT distribution covering the minimum, mode, and maximum time.
- Select Output: Release vessel based on their arrival location

  Exit Object: Vessels leave the locking process based on their destination (e.g. vessel using the entering block is destined for a berth): end of the process.

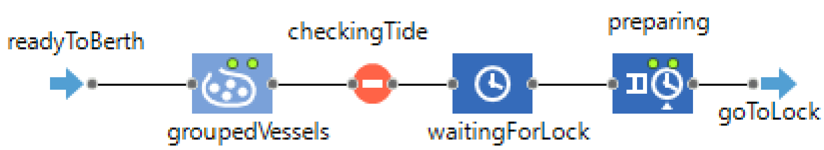


Figure 5.7: Arriving process from Anchorage

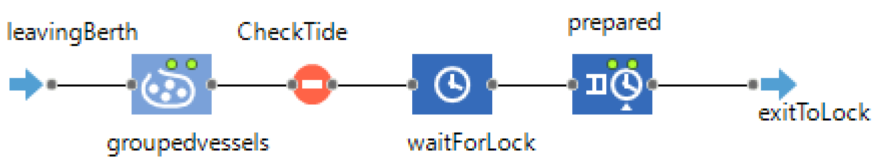


Figure 5.8: Departing process from Berth

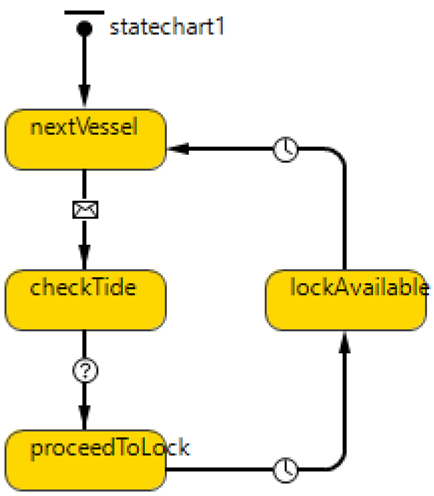


Figure 5.9: Intercommunication Link between Lock Processes

5.3.3 Berth and terminal

The berth and terminal process is modelled as an entity within the port process. Berth processes are represented as agents associated with processes based on vessel types (container terminal, general cargo terminal, etc.). Each process exists based on vessel type, but operates independently from other berth processes, and communicates with other general processes like the Lock process. For example, container terminals consist of four separate cargo terminals. They exist based on vessel type as a container terminal, meaning they only berth container vessels, but they operate independently as an agent. Hence, the dwell time of a vessel is dependent on cargo operation duration within the cargo terminal in which it is berthed regardless of the time it arrived. This means that although vessel A might be berthed before Vessel B, Vessel B can depart before vessel A. This approach is significant as it captures reality and allows vessel dwell time to be realistically predicted.

The berth and terminal consist of two processes. The terminal operation process and the lock availability process. The terminal operation process focuses on cargo operation, while lock availability focuses on the post-cargo operation process. Cargo terminals differ in type, and each type has got several terminals. Figure 5.10 and Figure 5.12 shows a container terminal sample, which is also used to explain the terminal processes.

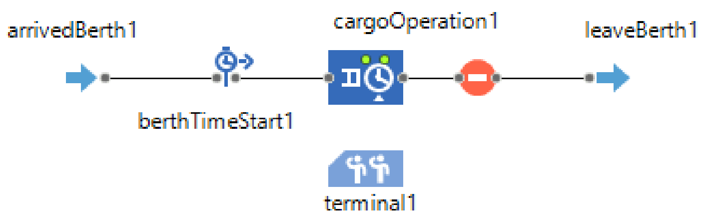


Figure 5.10: Terminal Operation process

-  Enter Object: The vessel agent arrives at the allocated berth.

- The Service Object: The block represents the cargo operation stage, that is, the period a vessel waits at the cargo terminal for cargo loading and unloading. The cargo operation begins and ends when the dwell time elapses. The period the vessel spends is determined using a PERT distribution of average dwell time values from historical data. During this period the block seizes a terminal and the required resource units for the vessels, delays it for a period, and releases the seized units. The resource unit refers to the terminal equipment required for cargo operation.
- Resource pool Object: Provides resource units that are seized and released by agents. In the berth-system process, this is the resource unit seized by the service block. It represents a particular container terminal and its cargo equipment required for port operation. It is connected to the service object representing the *cargoOperation*.
- Hold: Block or unblock vessel departure from cargo terminal following the completion of all cargo operations.
- Exit Object: Allows incoming vessel for berth operation to proceed to the departure process
- Time Measure Start: this object pairs with the Time Measure End block to measure the dwell time a vessel agent spends while at the cargo terminal. Specifically, it measures the time a vessel agent arrives at its assigned cargo terminal, thus accounting for the idle time.

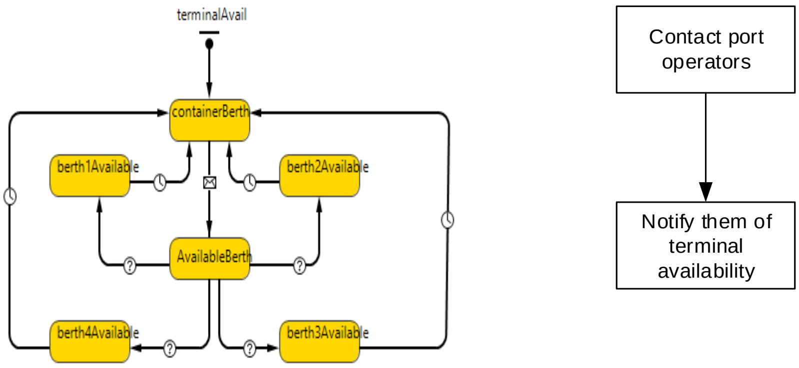


Figure 5.11: Terminal availability notification

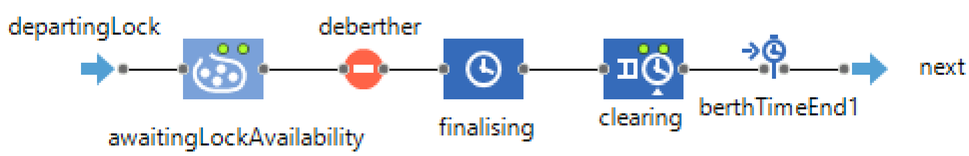


Figure 5.12: Lock availability Process for departing vessel

- Enter object: The vessel (Agent) already allocated to a terminal begins stage two of the anchorage process
- Time Measure Ends Measures the time a vessel agent leaves the berth.

- Wait: Serve as queue system for vessel agents already preparing to leave the berth but awaiting lock, pilot and tug operations. Also, it allocates a queue number to vessel agents regardless of type.
- Hold: Block or unblock the process flow based on lock and external conditions e.g. Tide.
- Delay Object: Delays vessel agent at berth until pilot and tug arrive. In the model pilot and tug boat arrival times are an assumed duration approximated between a minimum of 30 minutes and a maximum of one hour
- The Service Object: Contact the lock operator for lock availability. Figure 5.13 shows the communication process for container vessels. The communication flow was structured using a state chart. Each state affects a specific action and communication between states are connected by several conditions. For example, in the communication process for container vessels, the system checks for lock availability. The process commences with a message ("conTermPrep"). Then based on the set condition (i.e. vessel numbers, numbered from 1 – 4 for container vessels) the process conducts its checks for lock availability.
- The conditions were represented by variables (see Figure 5.13) called to Vess representing vessels. These variables inform the locking process of the cargo terminal location a vessel is intending to depart from. Based on this information a specific lock is observed. When the lock is available, the vessel agent is allowed to leave the cargo terminal and proceed to the lock.
- Exit Object: Allows incoming vessel for berth operation to leave a particular berth, thus marking the end of the berth-system process. It also notifies the anchorage of the berth availability using the notification state chart shown in Figure 5.11. The notification process begins immediately after the vessel leaves the cargo terminal. The process is triggered by the message "Berth available". Base on the terminal number the berth check the Boolean variable for that terminal becomes true.

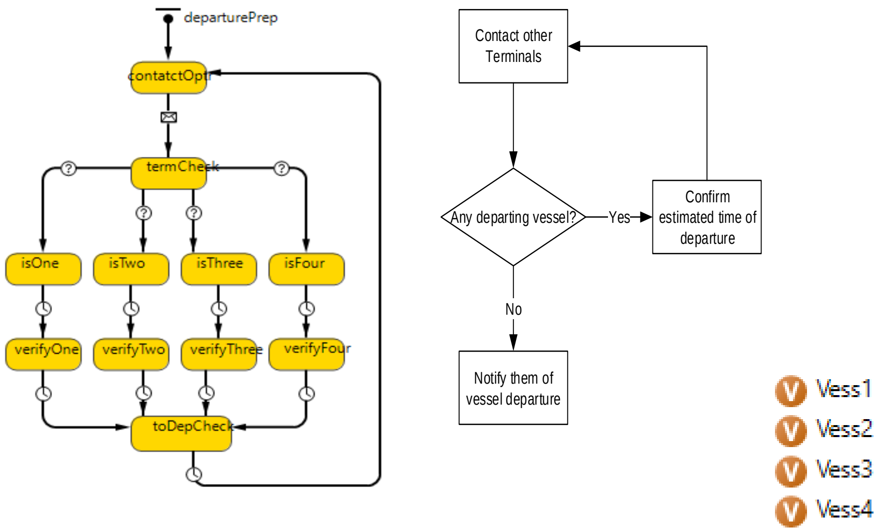


Figure 5.13: Departure preparation

5.4 External Conditions models

Entities within the external condition system are modelled using agent-based simulation in AnyLogic. The modelling structure of each entity is designed using a state-chart, and the purpose of each building block is discussed as follows;

5.4.1 Tides

The tidal model is constructed as discussed in section 3.6.3. The tide model (Figure 5.14) determines the tidal height of water suitable for a vessel to navigate in and out of the port. The tidal model is developed using a state chart, where each state predicts a tidal height value ranging from low to high. At low tide, vessels wait at the anchorage or berth (thus, increasing waiting and dwell time), and move from one point to another as the tidal height increases.

The model structure is designed to follow a real-world tidal flow pattern. Since the earth rotates through two tidal "bulges" every lunar day, coastal areas experience two high and two low tides every 24 hours and 50 minutes (24.83 hours). High tides occur 12 hours and 25 minutes apart (12.42). It takes 6.21 hours for the water at the shore to go from high to low, or from low to high. The tidal model created using a state chart is constructed to represent a realistic tidal process (see Figure 5.14). The initial starting point of the state chart was chosen based on the 2016 historical data start point which commenced approximately three (3) hours before high water (as shown in Figure 5.15**).** The time interval between high and low water is 6.21 hours. So, the inter-tidal change time between each tidal state is approximately 1.02 hours (6.21 hours divided by 6). For example, the inter-tidal time between high tide and *fallingHigh* is 1.02 hours. Following the tidal analysis in **Section 4**, the rule of 12ths, is used to estimate the expected water level

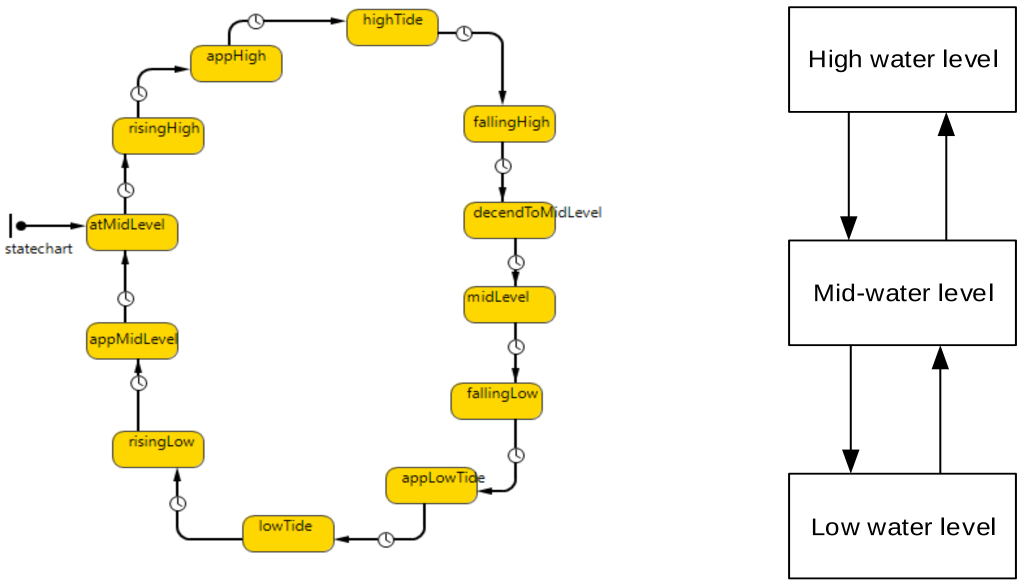


Figure 5.14: Tidal Simulation State-Chart Structure

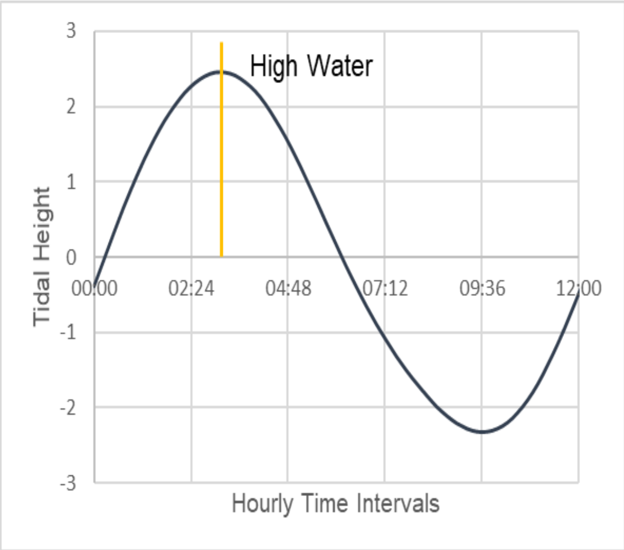


Figure 5.15: First Tidal cycle for January 2016

5.4.2 Seasonal, Weather and Visibility

The seasonal, weather and visibility models are designed as discussed in section 3.6.2. The seasonal model (see Figure 5.16) is developed using an agent-based state chart to regulate the seasonal changes and their influence on the weather condition. The created seasonal model starts from the winter season than spring, summer, and autumn. The cycle is structured based on the collected data input. Each seasonal period concludes once the seasonal duration is elapsed. Each seasonal duration is uniformly distributed between a minimum of 89.5, and a maximum of 91.5 days for all seasons respectively as discussed in section 3.6.1

The weather model (see Figure 5.16) regulates the daily weather condition within the model. The weather conditions are directly influenced by the seasonal conditions. A daily weather status within the model is decided based on the seasonal condition. For example, in winter, more rain and snow is expected compared to summer as discussed in section 3.6.1 and 3.19a. The weather conditions are divided into three, rainy, sunny, and mixed (both rainy and sunny). Daily visibility and influenced by weather conditions. The weather conditions affect the behaviour of vessels in and out of the port. For example, vessels reduce their speed when it rains because their visibility is highly affected.

The visibility model as shown in Figure 5.17 regulates the daily visibility condition based on the daily weather conditions. The visibility conditions are either poor, good or moderate. Each condition is triggered as discussed in section 3.6.1.

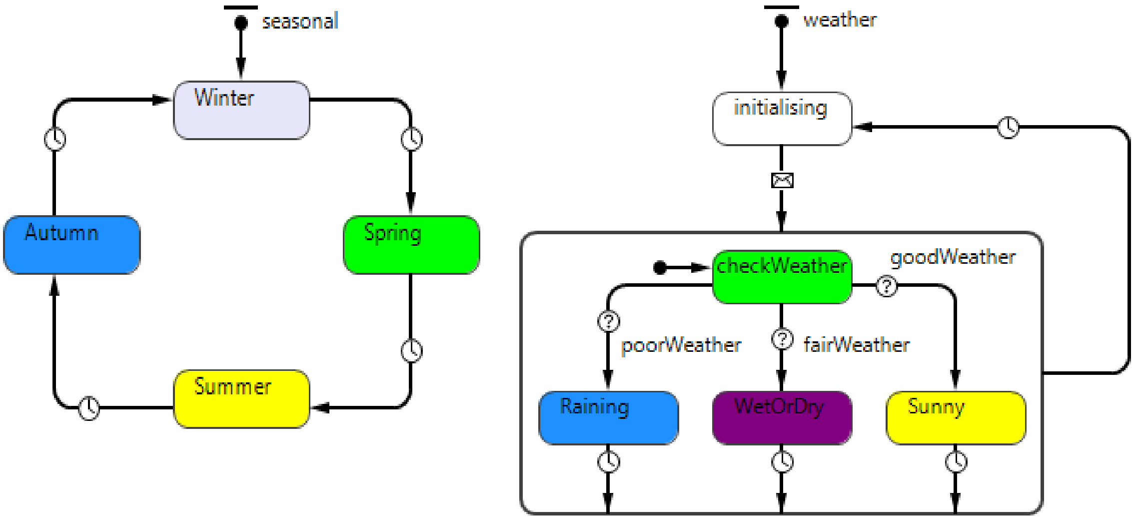


Figure 5.16: Weather and Seasonal Model

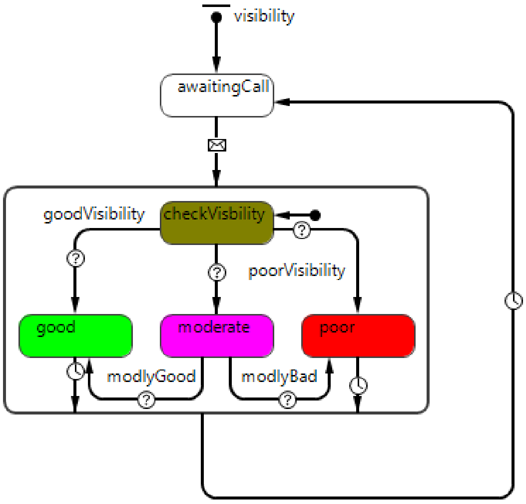


Figure 5.17: Visibility

5.5 Model of Vessel Traffic

The vessel model comprising of vessel movement and collision avoidance is modelled using agent-based simulation. The framework of each model is designed using statecharts. Advantages and disadvantages of this structure are;

Advantages

- The design structure allows the behaviour of vessels to be explicitly represented, which allows the inclusion of micro-behaviours within the entire system.
- Where editing is required, the state can easily be identified.
- The modelling structure supports scalability and can be integrated into other systems.
- The approach can also be used in other traffic and behavioural studies, like road, air, human behaviour, etc.

Disadvantage

- Modelling complexity, as a large number of variables and states are required to build the model.

The model structure of each entity is discussed below.

5.5.1 Vessel Injection into the model

Vessels are injected into the model using the AnyLogic event object (see Figure 5.18). The arrival rate was set based on the historical AIS data analysis results for different vessel types. For example, Figure 5.18 shows the arrival settings for container vessels, which reflects the AIS inter-arrival time analysis discussed in section 3.7.

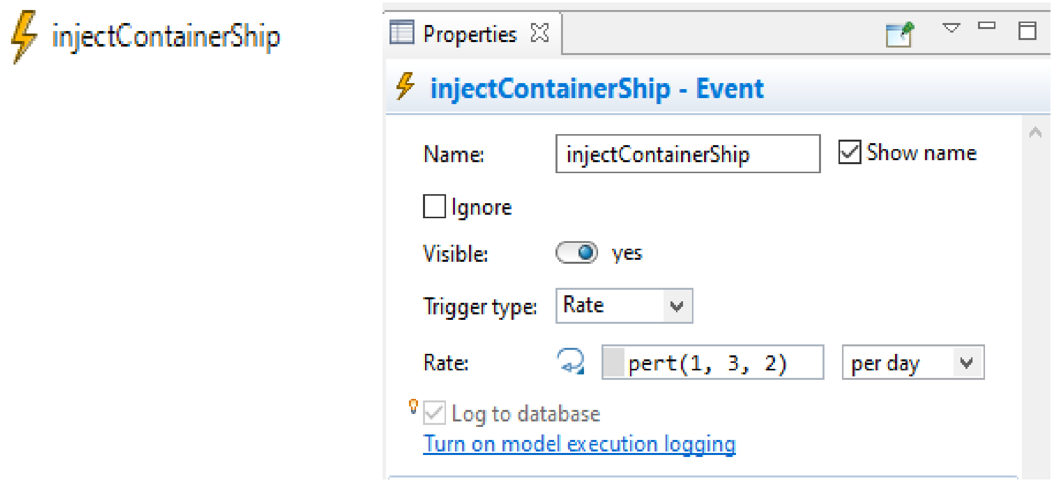


Figure 5.18: Vessel Arrival Rate

5.5.2 Vessel Characteristics:

Vessels agents are modelled as an animated objects with static characteristics: Name, ID, etc. and kinematic dynamic characteristics: speed, positions, etc. based on vessel types. Vessels are injected into the model as discussed in section 4.1. Vessel agent enters the model at an initial position, heading and speed values based on their entrance zone and vessel type. A vessel initial speed value is defined using a PERT distribution as discussed in section 3. The vessel enters the model with the ability to connect with other vessels within the marine environment. For example, Figure 5.19 shows the connection link for container vessels. The link was created using the AnyLogic connection tool, which allows agents to connect. When a vessel agent is injected into the model, it immediately connects with other vessel types including its type. This allows a vessel agent to detect the closest agent to them, get their dynamic details (speed, heading, position) in the event of a possible collision. Each agent passage plan is based on its type and terminal destination within the port as explained in section 3.

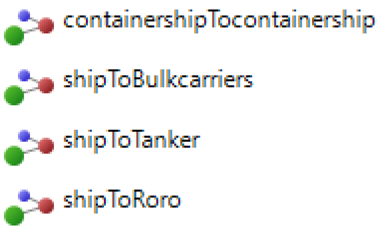


Figure 5.19: Container vessel connection links to other vessel types.

5.5.3 Vessel course

Traffic flow along the waterway can be either inbound or outbound. A vessel travel pattern consists of both a major and minor trip. Major trips are vessel movements between two major locations for example from the entrance to anchorage, or from lock to the cargo terminal, or lock to the anchorage and vice versa. A major trip consists of both inbound and outbound traffic flow. There are three major trips within the model and their periods of completion differ. The first major trip is from the entrance to the anchorage and vice versa and the time a vessel takes to complete it is called the outer transit time. While the second major trip is from anchorage to lock and vice versa and the time taken to complete it is called the inner transit time. The time taken to complete the third major trip, which is from the lock to berth and vice versa, is the vessel's manoeuvring time.

The minor trips take place between GIS-target lines (see Figure 5.20). Each GIS-Target line represents an origin or a destination along the waterway for traffic. The GIS-Target lines a vessel travels through are captured within its behavioural state-chart. The combination of both major and minor trip components form the traffic network. When a vessel is generated it is at one of the entry points of the traffic network. The vessel follows the travel pattern designed using the state machine.

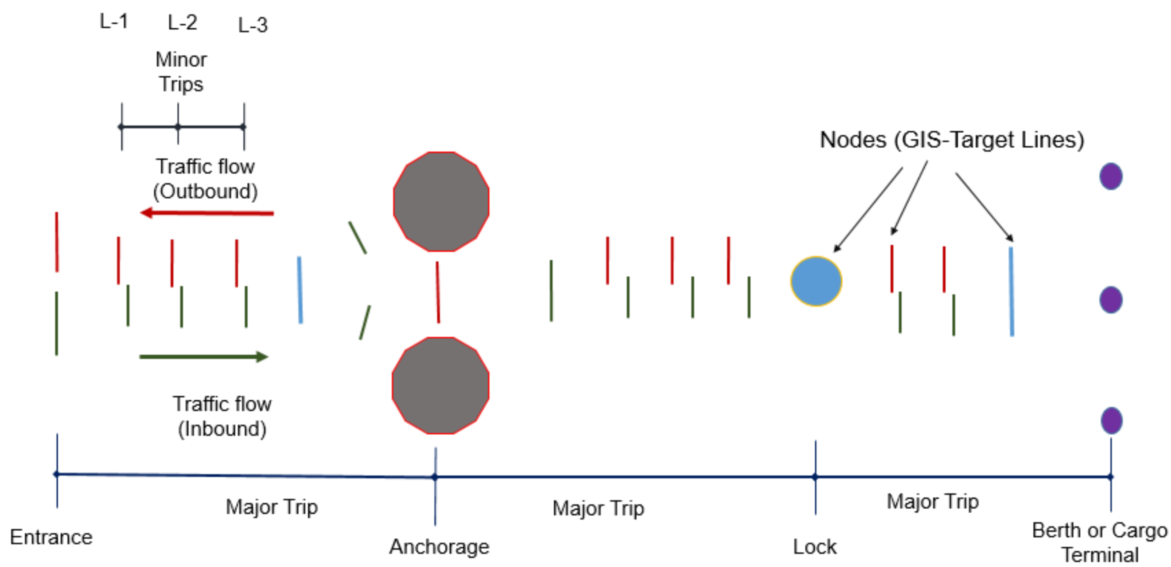


Figure 5.20: Vessel traffic flow and waterway layout

Travel patterns depend on the vessel type. A vessel visiting a port may take a major trip from the entrance point to the lock, then another major trip to the cargo terminal. Vessel course and heading are based on the traffic direction a vessel is heading (inbound or outbound) and their destination within the port. For ports with compulsory pilotage or anchorage, the vessel needs to wait at an anchorage before approaching the locks before berthing at the cargo terminal. Each travel pattern starts from an origin followed by one or more destinations (GIS-Target line) that the vessel will visit before exiting from the traffic network.

5.5.4 Vessel movement

Vessel agent movement and interaction with other vessels within the model is controlled by the agent-behavioural and the collision avoidance state-chart. The behavioural state-chart constitute several states linked to a GIS-target line. The state-chart was developed using the movement pattern observed from the analysed AIS data via trajectory plot, interpreted using the "a stop and move" approach described in Section 4. The behavioural state-chart is different for each vessel type. For example, Figure 5.21 shows the behavioural state-chart of container vessels. The state-chart structure for all vessel types follows the designed travel pattern framework structure shown in Figure 5.21**.** It contains extra states that account for a vessel's interactions with the port infrastructure and other external factors.

The behavioural state chart is made up of two types of states, a complex state and a single state. The single state represents agent interaction with the port agent. The agent interacts first with the anchorage process, then lock, and berth. The single states for agent interaction with each process (anchorage, lock, etc.) are connected to the port processes by a series of java codes. The complex state coordinates agent movement and speed changing behaviour across each GIS-Target line. A sample of a complex state detailing the operations of each part of the complex state is shown in Figure 5.22. Each complex state effect changes on vessel speed, position and heading. Vessel speeds are distributed across each zone using a PERT distribution as discussed in section 3**.**3. The outer waterway is made up of five zones, with each zone containing a minimum of three GIS-Target lines, except the fourth and fifth zone containing just two and one respectively. This is because there are three entry points to the port and one into the inner channel and the anchorage area. The inner channel contains more complex states than others because of the number of GIS-Target lines within the zones due to the geographical layout of the port. The numbers of GIS-Target lines are dependent on the port layout and are editable for different ports.

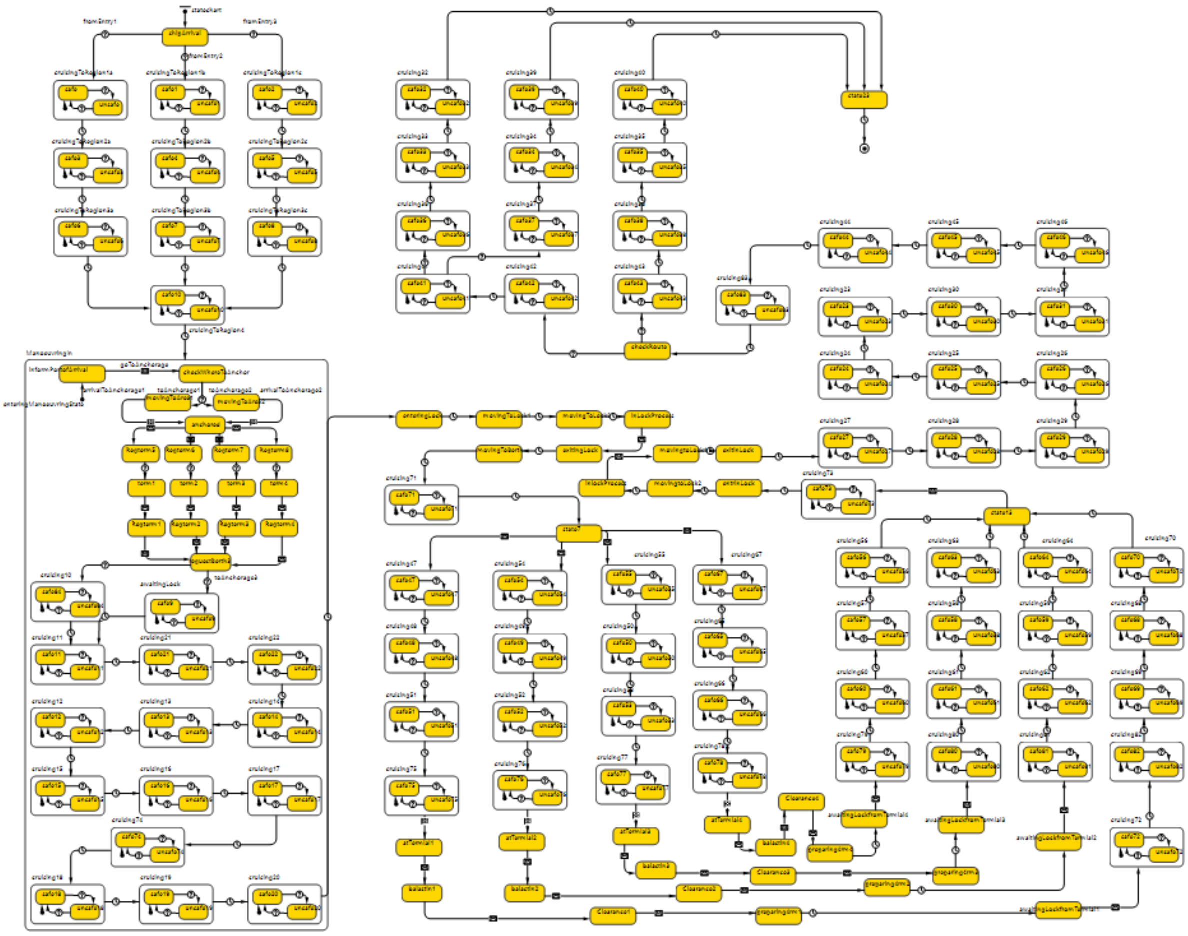


Figure 5.21: A sample of the vessel behavioural state-chart of container vessel agent.

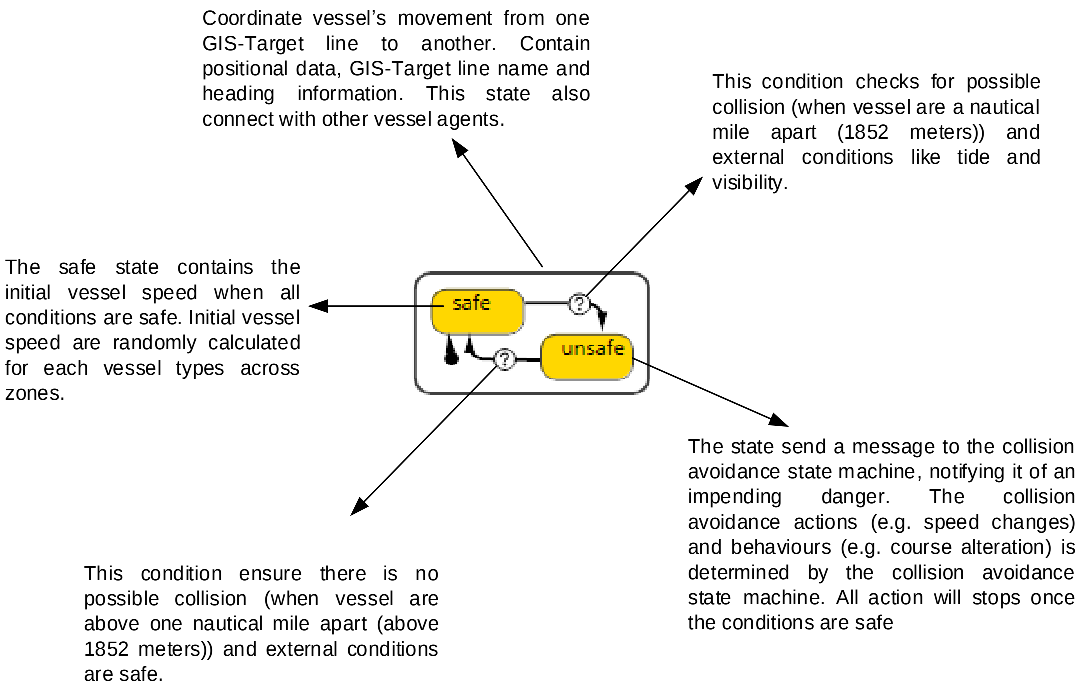


Figure 5.22: Sample description of a complex state

Each vessel follows its designated travel pattern until it reaches its destination by moving through each zone in its path. To move through a zone, the vessel travels from one GIS-Target to another. A vessel moves from one GIS-Target line to another following a series of java codes embedded within each state. The position the vessel decides to move towards on each GIS-Target line is chosen independently by that vessel in its planning process. This is done automatically by the AnyLogic tool, which allows an agent to choose the shortest distance to their destination. The time between each state is normally distributed using the average time and standard deviation of the port area (inner, outer or manoeuvring) for that vessel type (Section 3.7). For example, the time between each state in the outer waterway for container vessels is shared across zones using the average time observed from the AIS data analysis in section 3.7.1 for the outer, inner and manoeuvring areas respectively. For vessel types and water areas where calibration is necessary, simple fine-tuning of the time values is done by adjusting the time between specific target lines to fit reality.

In the advent of poor visibility or weather condition, vessels are expected to reduce their speed to avoid any collision. When a potential crossing conflict is detected, the rule of right-of-way is applied. This rule says a vessel should give way to another vessel on its right at the point of conflict. This rule specifies which vessel will take action to resolve the potential conflict. The actions to take include adjusting its speed, either to slow down or speed up. It can only do so between a minimum speed and a maximum speed. The values of the minimum and maximum speeds depend on the vessel type and what zone the vessel is in. The zonal divisions were used to keep vessels aware of their location and to specify the vessel’s permissible speed range.

5.5.5 Collision Avoidance

The agent collision avoidance state-chart is shown in Figure 5.23. The action a vessel takes depends on what operational mode they are in. Actions include changing the speed at specific locations such as stopping at anchorage, changes of course and speed during collision avoidance. The statechart is divided into two sections: the cruising and the manoeuvring. With the cruising section, (on the left-hand side) agents can alter both their heading and speed as discussed in section 3.5.3. While in the manoeuvring section vessels only reduce their speed. The cruising section is triggered when the vessel is at the outer waterway, and the initiation processes are the same as explained in section 3.5.3. The manoeuvring section is triggered when a vessel is at the inner waterway, and the operational process of the state-chart are the same as discussed in section 3.5.3.

Agents’ actions within the collision avoidance state-chart are implemented using java code embedded within each state. Agents use their connection (section 5.1) to identify vessels nearest to them. Also, the collision detection range explained in section 3.5.3 is used by each vessel to keeps a lookout for possible collision situations as it moves within the simulation space. An agent can get its position, calculate its speed, identify other vessels and their position and speed, the environmental condition and its next position along its planned route (waypoint). From this information, the agent makes its decision to move from one point to another and at what speed depending on the agent's state and if external conditions stay the same. In cases of tidal effect, each agent responds to the environmental changes by complying with the port rule generated by the port model requesting vessels to remain at anchorage.

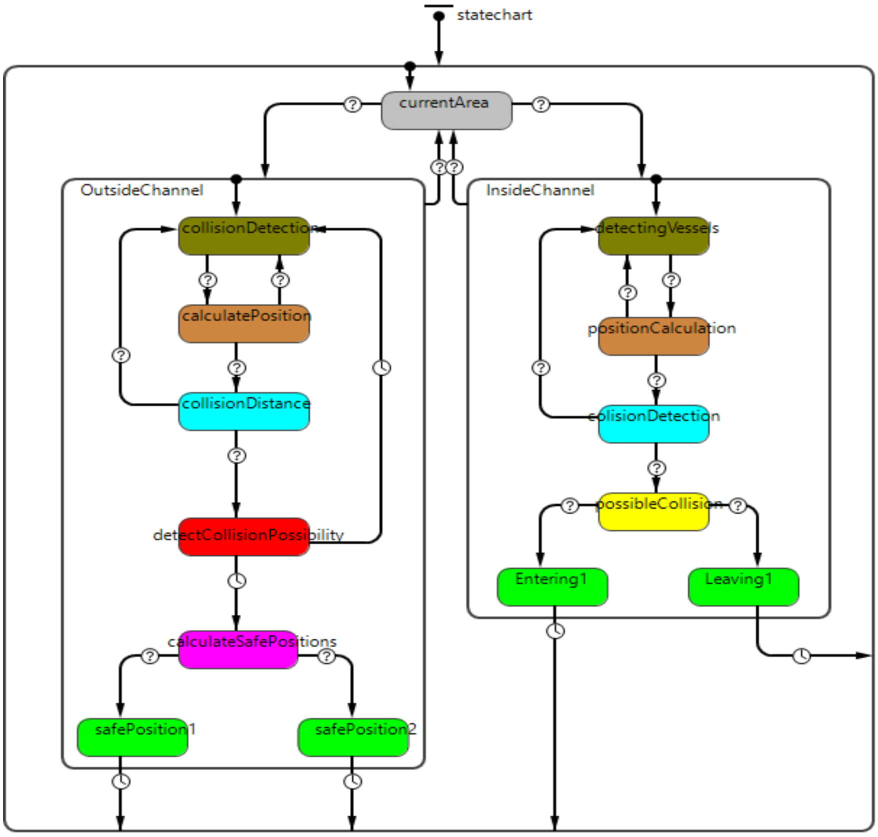


Figure 5.23: Collision avoidance state chart

The created ship collision avoidance model consists of seven states representing the different collision avoidance logic, and Table 5.1**,** defines the variables used in the collision avoidance algorithm. The collision avoidance states are, Collision Detection, Calculate Positions, Collision Distance, Calculate Collision point, detect a possible collision, calculate safe position, Safe position. The approach follows the steps used by (Oh et al., 2014).

Table 5.1: List of variable and Description

Variables	**Description**
Agent 1 Latitude and Longitude	The current latitude and longitude coordinate of the particular ship is taken into consideration and is referred to as Agent 1
Agent 2 Latitude and Longitude	The Nearest ship to Agent 1 latitude and longitude coordinate is referred to as Agent 2
Target Latitude and Longitude	The latitude and longitude coordinate of any agent next / final waypoint

Safe passing distance	The safe passing distance between two agents (set at 500 Metres for outer waterway, 200 for inner)
Detection Range	The required distance to trigger the avoidance state-machine (3 Nautical Miles for outer waterway and inner) (Maximum radar range in practice)
Safety Range	The minimum safety distance required to trigger the collision-avoidance action (1 NM for outer waterway, 500 Metres for inner) (between 6-3 NM in practice)
Point X and Y	The calculated collision avoidance position

5.5.6 Collision Detection:

This section focuses on agents observing other agents nearest to them (see Figure 5.24). In the port, ships are required to keep a regular lookout. In practice, when keeping a regular lookout, ships can be observed by the officers of the watch at different distances away. Using the ship's radar, vessels can be observed from the ship navigational room (bridge), and collision avoidance planning is made when a vessel is nearby. Similarly, a detection range was used to identify situations when two ships are nearby. Within the collision detection state, a ship is assumed to keep a regular lookout of all vessels nearest to it. The state receives information of all ships within the port environment, from the ship behavioural state-chart (ship voyage model), which accounts for good seamanship watch-keeping practices as in real-world situations. A distance detection range of 3 nautical miles is used (for testing purposes), and when a ship within 3 nautical miles is detected, an alert message that triggers the collision process is sent by the agent unsafe state. When the nearest ship within 3 nautical miles at any time moves outside the detection range, the detection state immediately sends a safety message, which stops the collision avoidance process. Thus, this state can be referred to as the seafarers' watch-keeping stage.

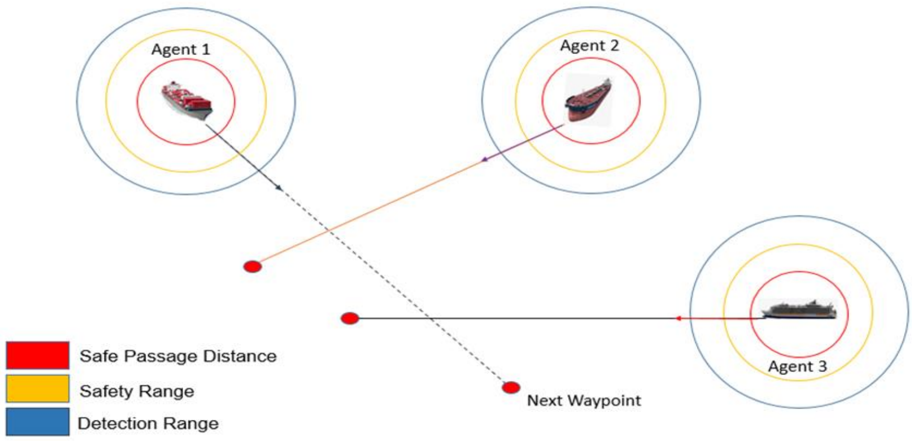


Figure 5.24: Vessel Ranges

5.5.7 Calculate Position:

This is the first triggered state when a collision alert is sent and can be referred to the collision avoidance planning stage. In this state the ship gets information of its current position, target position, and speed using a created shipCalc() method within the AnyLogic

Software. The method contains five different codes within the anylogic software, which retrieve these pieces of information as shown below;

```
for (Ship ship : main.ships){
Ownlat = ship.getLatitude();
Ownlon = ship.getLongitude();
Tlon = ship.getTargetLon();
Tlat = ship.getTargetLat();
shipSpeed = ship.getSpeed();}
```

Also, the distance between the Agent 1 and Agent 2 is immediately and continuously calculated every three (3) minutes using an event parameter containing a distance calculation method using the following code;

A 3 minutes time duration was used because the AIS reporting time for ships within a port environment is every three (3) minutes. If the distance between both agents exceeds the safety range, then the collision distance state is triggered as there could be a possible collision,

5.5.8 Collision Distance:

This state is considered a key aspect of the collision avoidance state machine. It focuses on calculating the relative distance from Agent 1 to the nearest Agent using their current positions. The relative distance is calculated in AnyLogic using a geometric method as shown below.

Relative Distance = $\sqrt{(Agent1Lat - Agent2Lat)^2 + (Agent1Lon - Agent2Lon)^2}$

If the Relative Distance is greater than the safety range then there is no collision threat, and the collision detection state is triggered again. Otherwise, there is a collision possibility, and the detect collision possibility state is triggered

5.5.9 Detect collision possibility

This state focuses on calculating the distance between both ships using the same formula as above. It performs the same duty as the possible collision state in the inner waterway collision avoidance. If the Relative Distance is greater than the safe passing distance, then there is no need for course alteration action, but the detection state is triggered again. But if it's less, then the necessary collision action is taking by triggering the calculated safe Position state.

5.5.10 Calculate the safe position

When the calculate-safe position is triggered, the agent heading will be changed. Considering the IMO COLREGS, the agent needs to manoeuvre to the starboard side of the nearest agent. We calculated the safe position by calculating the point of tangency. We assume the safe-passage-distance (SPD) to be a radius around the ship. From the agent to the nearest agent SPD, there will be two tangent points. We used the structure of the code below to calculate the agent safe passing position, where agent-longitude and latitude stand for the agent's current longitude and latitude. The starboard side can be either point X1, Y1 or X2, Y2 (longitude and latitudes) depending on the vessel direction (inbound or outbound).

PointX1 = Agent longitude + Safe Passing Distance (in degrees);
PointY1 = Agent latitude - Safe Passing Distance;
PointX2 = Agent longitude - Safe Passing Distance;
PointY2 = Agent latitude + Safe Passing Distance;

To determine the starboard side, a Boolean variable is used to determine if a vessel is inbound or outbound. When a vessel is inbound, the variable is true, and when it's outbound the variable is false. Based on this condition the agent decides on their direction to turn and head towards the safe position.

5.5.11 Entering and Leaving states

For vessels within the inner waterway, the entering and leaving states are used. The entering state refers to inbound agents, while the left refers to outbound vessels. When a possible collision is detected, that is, a vessel is within the safe passing distance, the decision a vessel agent makes is dependent on the entering and leaving states. When an outbound vessel agent detects an inbound vessel agent, both vessels reduce their speed, but when an outbound vessel detects another outbound vessel agent, both vessel positions are calculated. Based on the vessel's position, the vessel agent behind reduces its speed, while the vessel ahead continues on its path.

5.6 Summary

This chapter discussed the implementation of the proposed multi-method simulation for developing a port model in AnyLogic. This chapter majored in port processes and external condition systems. The chapter explains the building blocks of each modelled entity. The entity of each system was modelled based on their system operation. For the port process, discrete-event simulation was used, while the agent-based simulation was used for external conditions. The design structure of each entity is novel and details of the structural process were explained theoretically for some and diagrammatically for others. The chapter also majored in describing how vessel movement and interaction are modelled within AnyLogic. The vessel model comprising of vessel movement and collision avoidance are modelled using agent-based simulation. The framework of each model is designed using statecharts.

The design structure is novel and details of the structure are explained theoretically and diagrammatically for others. The next chapter focuses on the model application in the case study port.

Chapter 6: Verification and Validation of AnyLogic Model

6.1 Introduction

The previous chapter discussed the developed conceptual model in AnyLogic. The developed method was applied in the study port to simulate vessel traffic, port processes, and external conditions within the developed GIS space. The output was validated using a historical data method. This chapter discusses the model implementation within the study area and validation of the developed port traffic simulation model. It also provides detail of the validation process, which was done by comparing the model result with historical data**.** The historical data method was implemented in two ways: historical validation and internal validation. The historical data was divided into a modelling set (used in the model build-up phase) and a validation set to evaluate the model and verify results, respectively. The model parameters were validated using the validation dataset. The parameters validated are vessel speed changing, transit times, waiting time at anchorage, manoeuvring time, dwell time at berth, and delay time at lock.

6.2 Distributions

Agents' parameters were set using the analysed modelling set discussed in chapter 3. Vessel speed along the waterway was determined by zone. The speed in each zone is determined from a PERT distribution in Table 4.5 and Table 4.6, which is based on the vessel type. The values were inputted in AnyLogic following the format (PERT (min, max, mode). The time spent in the lock is determined by a PERT distribution, and the values were inputted using the same format as the speed, based on the parameters in Table 6.1. The vessel dwell-time (time between arrival at and departure from cargo terminal) is calculated from the distribution based on the parameters in Table 6.1. The values were inputted in AnyLogic using the format exponential (λ, min (hours)). The tidal model, the weather model, and visibility model were simulated as discussed in sections 3.4 and 4.4

Table 6.1: Model input distribution for vessel arrival, dwell and delay time

Parameters	Vessel Type	Simulation Input
Arrival rate	Container	$pert(1,3,2)$/day
	General Cargo	$pert(1,3,2)$/day
	Passenger	$pert(1,6,4)$/day
	Tanker	$pert(1,1,1)$/day
Dwell Time (Hours)	Container	$exponential(0.04, 0.5\ )$
	General Cargo	$exponential(0.03, 0.5\ )$
	Passenger	$exponential(0.18, 0.13)$
	Tanker	$exponential(0.04, 0.5)$
Delay time for the lock system	All vessel types	$pert(31, 51, 42,)$

6.3 Simulation model validation and verification techniques

The simulation model was validated using a historical data validation for vessel speed and verified using an internal validity technique for vessel and port times. The historical validation method is used when a part of the historical data is used as a modelling dataset, and the rest is used as the validation dataset (Xiang et al., 2005). The approach compares the simulation output with the historical data (validation dataset) of vessel speed. The objective is to determine if the model behaves like a real-world system. This is vital because, an error in these parameters will result in an error in the simulated vessel transit and manoeuvring times, which are essential for the model validation. Before the model validation, where errors were noticed within vessel speed and durations between GIS target lines during the pre-validation run, manual adjustments were made to fine-tune the model to ensure similarities with the modelling data set

Internal validation is a form of historical validation that focuses on comparing the simulation output of several replications and representing the mean and time series using graphs. Comparisons between vessel parameters (transit, and manoeuvring time) and port parameters (waiting, delay, and dwell time) from the simulation model and those from the historical data were made to ensure the model simulating vessel traffic and the model simulating port processes, within the multi-method simulation of the port, behave realistically. The data comparison was done using Microsoft Excel. Microsoft Excel was used because it was the only accessible tool during this study.

6.3.1 Verification of vessel travel times and Port Process times

As stated in section 5.3, the internal validation focuses on comparing the simulation output of several replications and representing the mean time distribution and time series using graphs. Since the time interval between each agent behaviour state is normally distributed using the average time and standard deviation across zones for each vessel type. The time interval for a vessel agent to travel between two GIS-Target lines (time between two states) is different when compared to other agents of the same type, making the agent movement time stochastic. This is so because the variation in vessel's speed and the distance a vessel travels while transiting via the outer waterway depend on their point of entry or exit, that is, the direction they enter or exit port (which is either point one, two or three). The direction a vessel takes while exiting or arriving is based on its next port of call. Whereas the distance travelled by vessels manoeuvring and transiting through the inner waterway depends on the location of the various cargo terminals. Vessel transit time is divided into two: outer waterway transit time, and inner waterway transit time.

Also, the historical data set shows that the duration to complete a major trip (from entry to anchorage, anchorage to lock, lock berth and vice versa) varies across vessels and types, and there is no exact manoeuvring, inner or outer transit time. This is due to factors including the location of terminals, traffic density and speed. Therefore, the internal validity of the model was conducted by comparing the simulation output distribution to the model input from the AIS data. The objective is to ensure that vessel travel time follows the same distribution as the input data and there are clear similarities between both distributions. Similarities between both distributions give internal validation to the vessel model within the multi-method simulation of the port. To achieve this, the calibrated model was run for two months and the 60 vessel agents' travel times were collected. The collected simulation output was grouped in ranges using a histogram. A normal distribution curve was fitted using the average times and standard deviation for the vessel travel times (inner transit, outer transit and manoeuvring) across vessel types. If the result follows a normal distribution as the input, the simulation model is said to be credible, otherwise, there is an error within the model.

6.3.2 Inner Transit Time

The inner waterway transit is the period between the vessel's departure from anchorage (zone 6) to the lock and vice versa. Table 6.2 shows the calculated averages from the simulation output and comparisons with historical data, and appendix F shows the time distribution. Compared to the model input, the simulation output is credible as it reflects a similar distribution to the input. For further observation, the average inner transit time across the various vessel types was calculated for both the historical data set and the simulation output. The average inner transit time from the model was compared with the average inner transit time generated from the validation data. The comparison reveals a clear similarity between both averages and standard deviations.

The percentage difference between both averages was calculated using the formula below:

$$\text{Percentage Difference } = 100\% \text{ X } \frac{(\text{average time in simulation data} - \text{average time in historical data})}{\text{average time in historical data}}$$

6.3.3 Outer Transit time

The outer waterway transit time is the period from a vessel entrance to zone 6 (anchorage) and vice versa. Though there are various anchorage areas in the port, however, this was chosen as it is the one most used by vessels and is closer to the inbound and outbound waterway. Table 6.2 shows the calculated averages from the simulation output, and Appendix E shows the simulation distribution. Compared to the model input, the simulation output is credible as it reflects a similar distribution to the input. For further observation, the average outer transit time across the various vessel types was calculated for both the historical data set and the simulation output. The average outer transit time from the model was compared with the average outer transit time generated from the validation data. The comparison reveals a clear similarity between both averages and standard deviations.

Table 6.2: Average Time comparison between simulation output and historical data

Travel Time	Vessel Type	Simulation Transit Average Time	Standard Deviation	Historical Transit Average Time	Standard Deviation
Outer Transit	Container	01 hours: 52 minutes (1.87 hours)	0.16	01 hours: 50 minutes (1.84 hours)	0.18
	General Cargo	02 hours: 50 minutes (2.83 hours)	0.57	02 hours: 58 minutes 2.97	0.47
	Passenger	01 hours: 45 minutes (1.75 hours)	0.1	01 hours: 41 minutes 1.68	0.1
	Tankers	02 hours: 12 minutes (2.19 hours)	0.25	02 hours: 06 minutes 2.09	0.26
Inner Transit	Container	01 hours: 49 minutes (1.82 hours)	0.21	01 hours: 47 minutes (1.78 hours)	0.24
	General Cargo	02 hours: 55 minutes (2.91 hours)	0.27	02 hours: 37 minutes (2.61 hours)	0.16
	Passenger	01 hours: 28 minutes (1.47 hours)	0.34	01 hours: 26 minutes (1.36 hours)	0.31
	Tankers	01 hours: 58 minutes (1.97 hours)	0.13	01 hours: 56 minutes (1.93 hours)	0.16
Manoeuvring	Container	53 minutes (0.88 hours)	0.16	36 minutes (0.6 hours)	0.05
	General Cargo	51 minutes (0.85 hours)	0.17	48 minutes (0.79 hours)	0.19
	Passenger	46 minutes (0.77 hours)	0.11	42 minutes (0.7 hours)	0.09
	Tankers	48 minutes (0.79 hours)	0.1	38 minutes (0.63 hours)	0.05

6.3.4 Manoeuvring Time

The manoeuvring time is the duration between vessel departure from the lock to its arrival at the berth and vice versa. Table 6.2 shows the calculated averages from the simulation output, and appendix G shows the simulation distribution. Compared to the model input, the simulation output is credible because it reflects a similar distribution to the input. For further observation, the average manoeuvring time across the various vessel types was calculated for both the historical data set and the simulation output. The average manoeuvring time from the model was compared with the average manoeuvring time generated from the validation data. The comparison reveals a clear similarity between both averages and standard deviations.

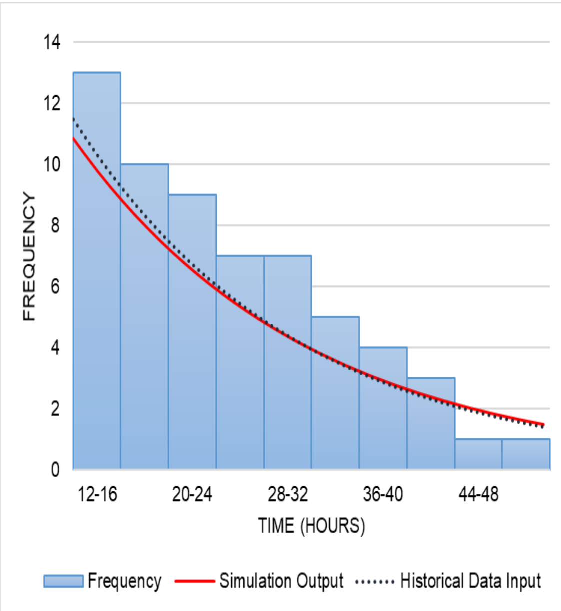
6.3.5 Port Processes

Internal validity of the port processes was conducted by comparing the simulation output distribution to the model input data. The objective is to ensure that the process times follow the same distribution as the input data and there are clear similarities between both distribution curves. Similarities between both distributions give internal validation to the various port process models within the multi-method simulation of the port. To achieve this, the calibrated model was run for two months and the 60 vessel agents' times within the various processes were collected. The collected simulation output was grouped in ranges using a histogram. The various distributions used in each process were compared to the simulation output. If the result follows the same distribution as the input, the simulation model is said to be credible, otherwise, there is an error within the model

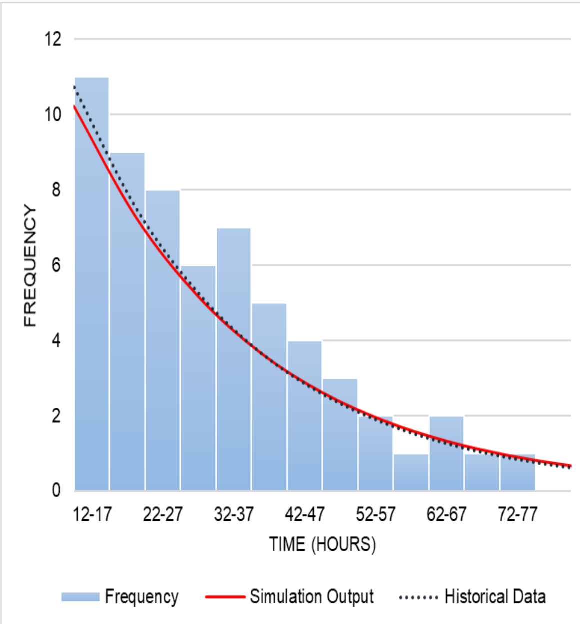
6.3.6 Vessel dwell time

The dwell time is calculated from the vessel arrival time at the cargo terminal (berth) till when it departs.

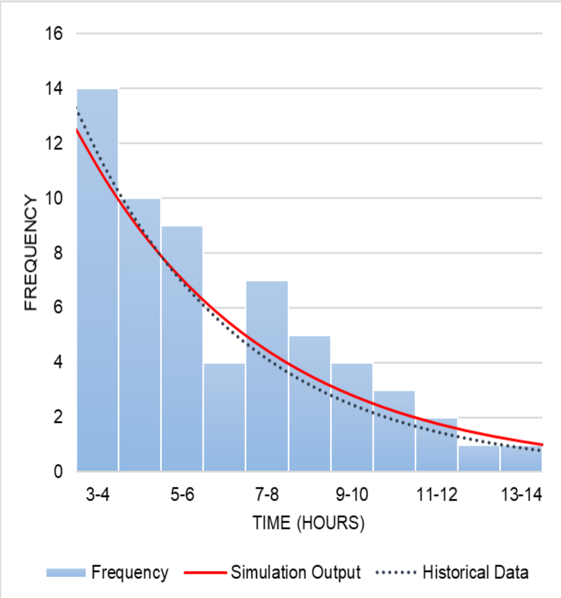
Table 6.3 shows the calculated averages from the simulation output and the percentage differences between both averages. The percentage difference between both averages was calculated using. Figure 6.1 shows the average distribution curve comparisons. Compared to the model input, the simulation output shows credible distribution similarities to the input. For further observation, the average dwell time across the various vessel types was calculated for both the historical data set and the simulation output. The average dwell time from the model was compared with the average dwell time generated from the validation data. The comparison reveals a clear similarity between both averages

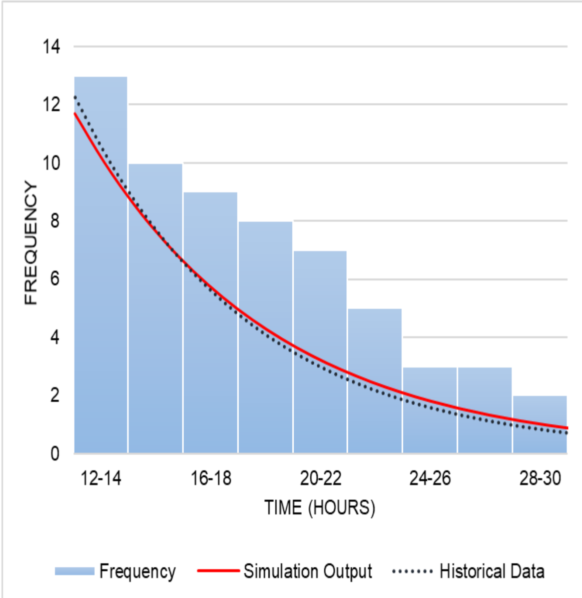


Container Vessel



General Cargo Vessel





Passenger Vessel Tanker Vessel

Figure 6.1: Dwell time distribution from the simulation model and average comparisons between simulation and historical data.

6.3.7 Anchorage Waiting Time

As discussed in the session in Chapters 3 and 4, the anchorage process is designed as a queue process to keep vessels until certain port conditions are met (e.g. cargo terminal is available, the lock is available, tidal conditions are suitable, etc.). Hence, there were no initial inputs to the model as waiting time, except the assumed pilot and tug waiting time, which is uniformly distributed between a minimum of one hour and a maximum of two hours. The period a vessel spends at the anchorage is calculated from the period the vessel arrives at the anchorage till when it leaves the anchorage. Although the waiting periods are less at the start of the model, once the traffic density matches reality (after three days), the modelled anchorage process seems to mimic reality.

Table 6.3 shows the calculated averages from the simulation output and the percentage differences between both averages. The percentage difference between both averages was calculated using the equation 5:

6.3.8 Lock Delay time.

As explained in section 3.4.3, the locking process begins when a vessel arrives at the lock system. The arrived vessel stays within the process for a period, after which it proceeds to the port, and the same when leaving the port. Since the lock was created to accept all vessels regardless of type, the input values were the same for all vessels, the simulation outputs are expected to follow similar distribution regardless of vessel type. The input parameters were distributed using a PERT distribution consisting of a minimum time of 31 minutes, a maximum time of 51 minutes, and a mode of 42 minutes (section 3.4.3). The historical average time is 41 minutes, 30 seconds.

Table 6.3 shows the calculated averages from the simulation output, and Figure 6.2 shows the simulation distribution. Compared to the model input, the simulation output shows a credible similarity with the input distribution, with an average delay time of 43 minutes 30 seconds. The average delay time from the model was compared with the average dwell time from the historical data. The percentage difference between both averages was calculated using Equation 5. The difference between simulation output and historical data for the various vessel types is 4.8%. Hence, the result shows a clear similarity between the historical data and the simulation output.

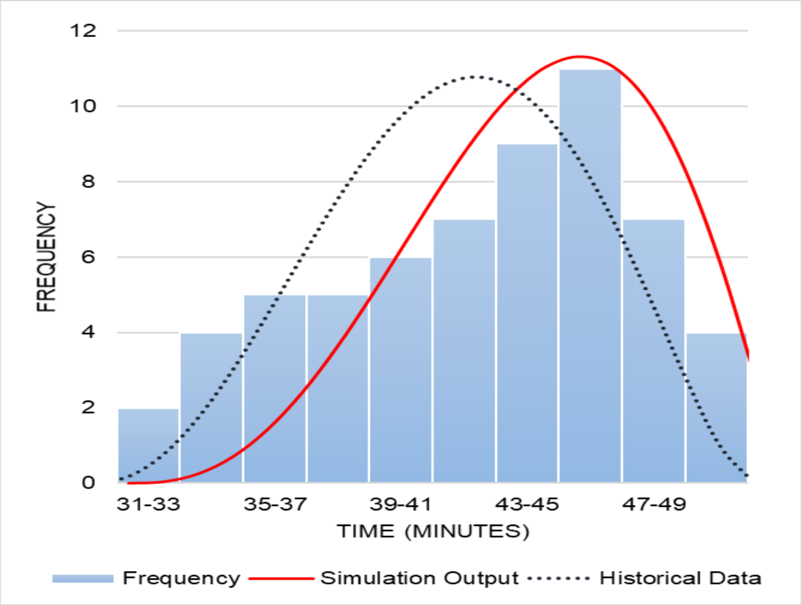


Figure 6.2: Delay time distribution from the simulation model and average comparisons between simulation and historical data.

Table 6.3: Summary of all Parameters

Parameter	Vessel Type	Simulation	Historical data	Percentage Difference
Inner Transit	Container	01:49	01:47	2.2%
	General Cargo	02:55	02:37	11.5%
	Passenger	01:28	01:26	2.8%
	Tanker	01:58	01:56	2.1%
Manoeuvring	Container	00:53	00:36	46.7%
	General Cargo	00:51	00:48	6.2%
	Passenger	00:46	00:42	10.0%
	Tanker	00:48	00:38	27.0%

Dwell	Container	25:34	24:10	5.8%
	General Cargo	35:12	33:35	4.8%
	Passenger	06:24	05:32	15.7%
	Tanker	25:41	23:31	9.2%
Waiting	Container	11:44	10:32	11.1%
	General Cargo	18:24	17:53	5.0%
	Passenger	04:05	04:16	-4.4%
	Tanker	03:43	02:52	29.3%
Delay	All Vessel	00:45:50	00:41:30	10.1%
Outer Transit	Container	01:52	01:50	2.2%
	General Cargo	02:50	02:58	-4.7%
	Passenger	01:45	01:41	4.2%
	Tanker	02:12	02:06	4.8%

6.3.9 Validation of vessel speed

Vessels sample data for a week was collected from the validation data set and inputted into the model. A week data was collected due to memory capacity as the data file was large, and there was enough traffic movement to validate the model (over 60 vessels). The data collected for each vessel include initial starting point, arrival time, destination (berth), and exit points. The model was run for one week and the speed data were collected every 10 minutes. The objective is to ensure vessel speed changes dynamically as in real-world situations. Dynamic changes in vessel speed give validation to the vessel movement model and collision avoidance model.

The simulation speed profiles summary was compared with that of the real-world data. Figure 6.3 shows the summary result of container vessels' speed profile for a week. The time intervals count the data collection every 10 minutes, that is, at zero the interval is one, then after 10 minutes is two, and so on. The same approach was used for other vessel types. The results reveal similar speed profile patterns between both data sets, however, for clarification, the data collection time intervals for the simulation output seem to be more than those of the real-world data. So, the model data collection time was fine-tuned to achieve a better view.

In fine-tuning the collection time interval, the simulation speed collection time was increased to 15 minutes, and historical data of individual vessels were compared to their simulated output. Vessels arriving on Wednesday and Thursday were observed. This was done because the simulated traffic condition during these days is expected to be closer to the real-world situation, compared to other days. Also, during the simulation runtime, vessels are seen to arrive at different daily rates (see Table 6.1), but the quantity of vessels moving through the waterway at the same time differs across the waterway area (outer and inner) as shown in Table 6.4. More vessels are moving in the outer waterway at one time because there are no movement restrictions. Whereas for the inner waterway (comprising of both inner and manoeuvring waterway), lock and berth availability are the controlling factors, as there are two locks in the port and each accepts a vessel at a time.

Table 6.4: Vessel movement along the waterway during the model run

Waterway area	Beginning of the model run		2 days after the model start run	
	Minimum Vessel	Maximum Vessel	Minimum Vessel	Maximum Vessel
Outer	3	4	4	7
Inner	1	2	2	4
Manoeuvring	1	1	1	2

The validation data of individual vessels were compared to their simulated output. Figure 6.4 and Figure 6.5, shows the result of general cargo and a container vessel sample. The result shows that the vessel agent speed profile behaves dynamically like a real-world system, with variation in vessel's speed resulting from collision avoidance action and influence of external conditions

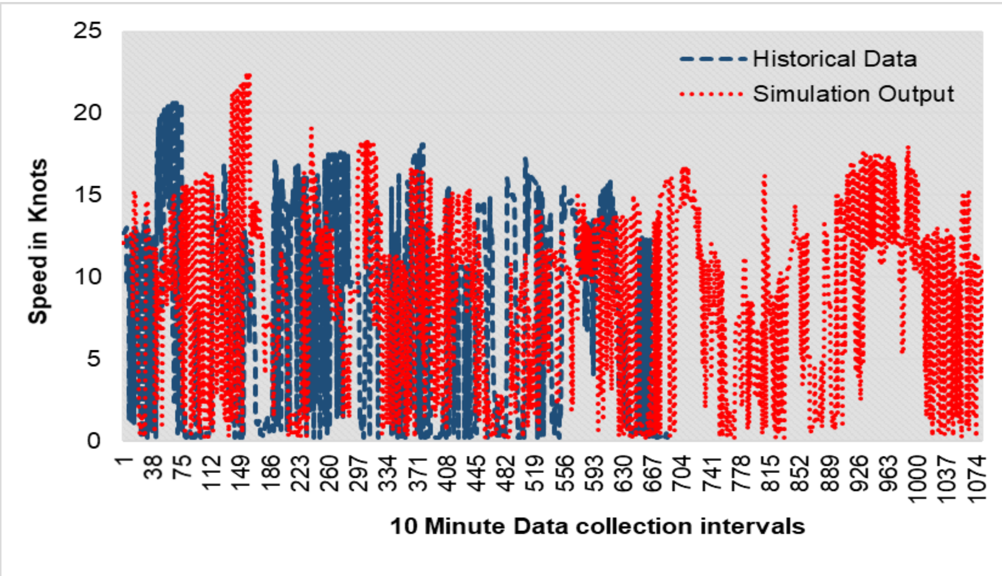


Figure 6.3: Speed profiles for a week for both Historical data and Simulation Output

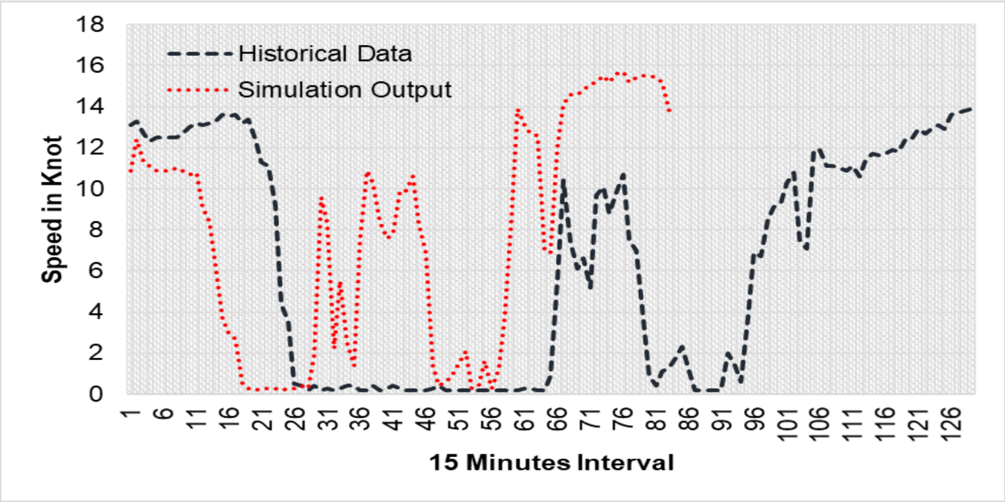


Figure 6.4: A general cargo vessel speed changes comparison between simulation output and historical data

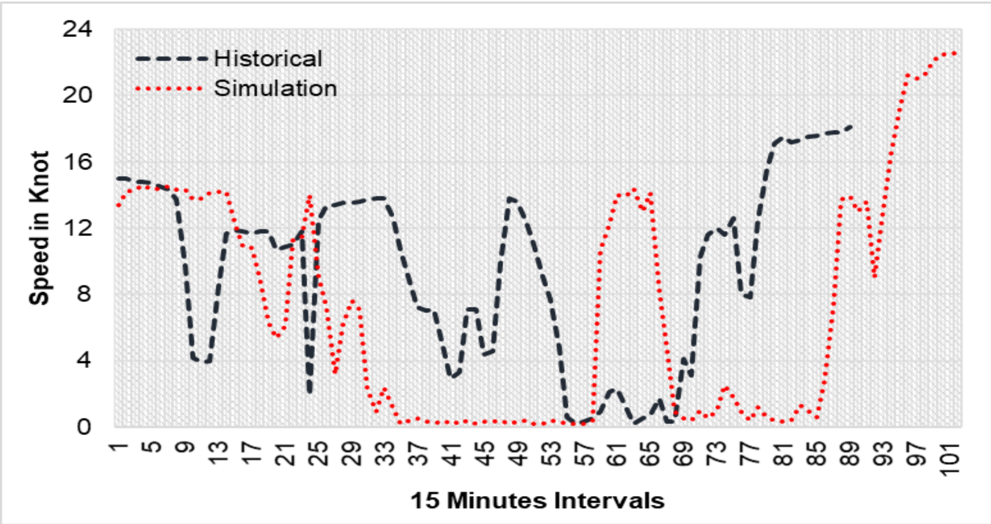
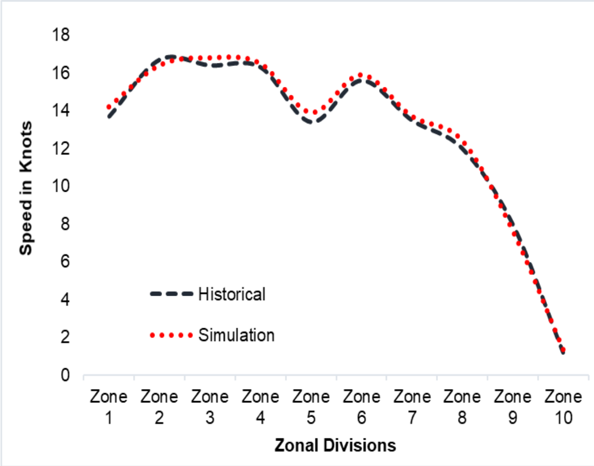
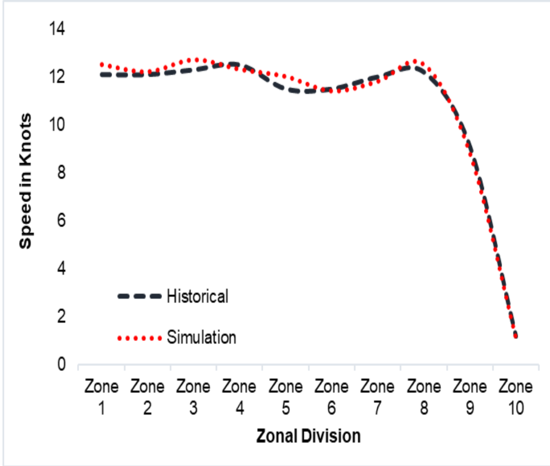


Figure 6.5: A container vessel speed changes comparison between simulation output and historical data

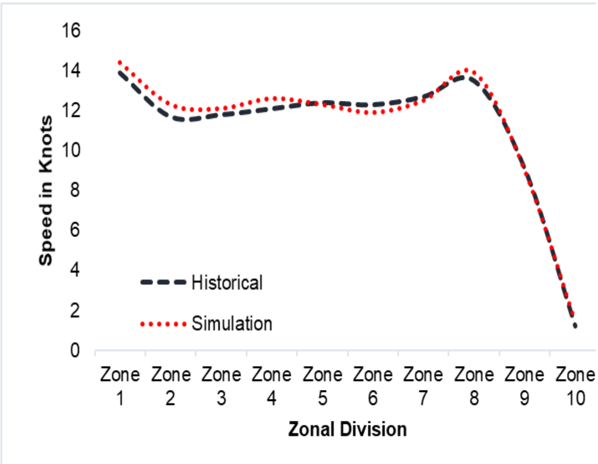
Furthermore, to observe the speed profile pattern across zones for the various vessel types, the average vessel speed was calculated for both the historical data set and the simulation output. The average vessel speed over each zone from the model was compared with the average speed over the same zones generated from the validation data as shown in Table 6.5. Shows the data comparisons for the various vessel types across zones. The comparison reveals a clear similarity between the speed pattern of the average vessel speed from the validation data set and the simulation output.



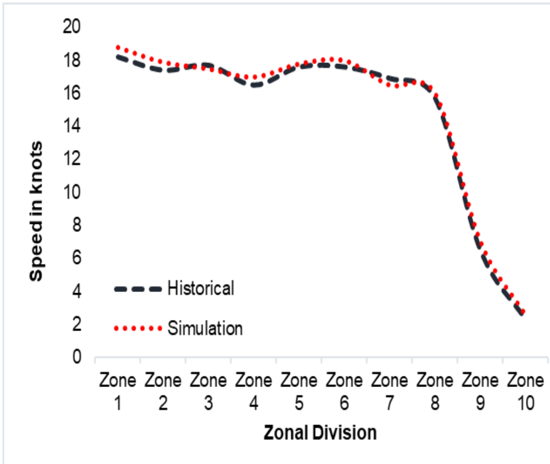
Container Vessels



General Vessel



Tanker Vessel



Passenger Vessel

Figure 6.6: Comparisons of average speed of historical data and simulation model across zones for the various vessel types

The percentage difference between simulated average speed and historical average speed is calculated using the formula below:

$$\text{Percentage Difference } = 100\% \text{ X } \frac{(\text{average speed in simulation data} - \text{average speed in historical data})}{\text{average speed in historical data}}$$

The differences between simulation output and historical data for the various vessel types is seen to be below 10% and -10% as shown in Figure 6.7. Hence, the result shows a clear similarity between the historical data and the simulation output.

Table 6.5: Summary of vessel speed comparisons.

		Zone speed average									
Vessel type	Parameters	1	2	3	4	5	6	7	8	9	10
Container	Historical	13.7	16.7	16.4	16.3	13.4	15.6	13.5	12	8	1.2
	Simulation	14.2	16.4	16.8	16.5	13.9	15.9	13.7	12.4	7.6	1.3
	Percentage Differences	4%	-1%	1%	1%	3%	1%	1%	3%	-4%	8%
Tanker	Historical	13.9	11.7	11.8	12.1	12.4	12.3	12.7	13.5	9.1	1.2
	Simulation	14.4	12.3	12.1	12.6	12.3	11.9	12.5	13.9	9	1.3
	Percentage Differences	4%	5%	3%	4%	-1%	-3%	-2%	3%	-1%	8%
General Cargo	Historical	12.1	12.1	12.3	12.5	11.5	11.5	12	12.2	9.1	1.2
	Simulation	12.5	12.2	12.7	12.3	12	11.4	11.8	12.5	8.8	1.1
	Percentage Differences	3%	1%	3%	-2%	4%	-1%	-2%	2%	-3%	-8%
Passengers	Historical	18.2	17.4	17.7	16.5	17.6	17.6	16.9	15.7	6.5	2.3
	Simulation	18.8	17.9	17.5	17	17.8	18	16.5	16	7	2.5
	Percentage Differences	3%	3%	-1%	3%	1%	2%	-2%	2%	8%	9%

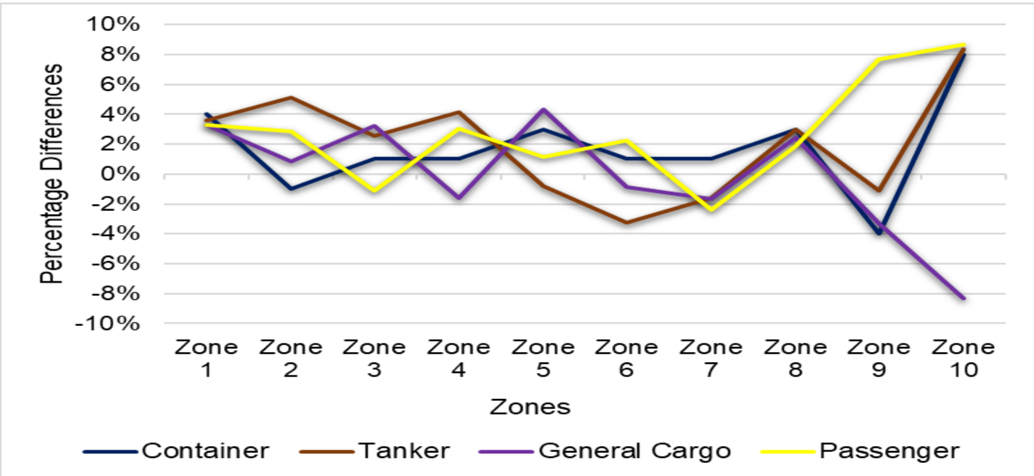


Figure 6.7: Percentage differences of average vessel speed across zones for different vessel types

6.4 Discussion

Applying the developed simulation model within the study area for model validation reveals significant information regarding the vessel handling sector of the port. First, vessel traffic within the port follows a specific pattern, which is, from vessel arrival to the anchorage, then to the lock, and thereafter berth, before departing. Vessels transit through three waterway areas (outer, inner, and manoeuvring) from their arrival to their departure (section 6.3.1). Vessel agent speed across the various waterways differs due to the navigable room present at each waterway. Vessels were observed to move at higher speeds at the outer waterway than anywhere else. Using zonal division, the average speed comparisons across zones between simulation output and historical data shows a clear match between both data sets Figure 6.6 and

Table 6.5). The percentage difference of vessel speed between the simulation output and historical data set is between 10% and -10%.

Also, as reflected by the speed profiles of individual vessel agents, speed variations were predominantly noticed for vessels within the outer waterway (Figure 6.4 and Figure 6.5). This is largely due to the traffic density within the waterway, as more vessels are seen within the outer waterway than in other waterways (see Table 6.4), and slightly due to external conditions (visibility and weather). Vessel traffic within the inner (inner and manoeuvring) waterway is observed to be influenced by lock and berth availability. Since there are two locks in the port and each accepts a vessel at a time, a maximum of four vessels (two inbounds and two outbound) were observed within the inner waterway, and a maximum of two (one inbound and one outbound) were seen within the manoeuvring waterway.

The dynamic changes in vessel speed are observed to influence the travel times of vessels regardless of type, allowing vessel agents to travel at an independent time. The average travel time comparison for vessel agents in section 5.3.2 is aimed at ensuring vessel travel time follows the same distribution as the input data and there are clear similarities between both distributions and values. Where there are huge dissimilarities the model is said to be faulty. However, the results as shown in

Table 6.5 and appendix 2, reveal that the simulation output reflecting the internal structure of the model captures reality with a maximum percentage difference of 46% and -5% for all vessels.

Vessel duration at the anchorage, berth and lock varies across vessel types. From the model, waiting time is observed to increase with the increase in vessel traffic and decrease in berth availability. The average waiting time comparisons in

Table 6.3 shows that the percentage difference between both data (simulation output and historical) is less than 12% and -5% across vessel types. The lock and berth time varies following the time distribution input. The average comparison between both data sets for lock and berth duration is observed to exhibit similar distribution, with a percentage difference of 10.1% for lock, and between -4.4% and 29.3% for the berth.

A major observation from the model is that the entire vessel handling sector of the study port is influenced by the tidal conditions. During high water, vessel agents are allowed to navigate in and out of the port but remain either at the anchorage (regardless of berth or lock availability) or berth during low water. The tidal conditions only hinder vessel movement within the inner and manoeuvring waterways and not the outer waterway, meaning arriving vessels can still proceed to the anchorage area till it is suitable for them to berth. This however increases both vessels waiting time at the anchorage and dwelling time at berth.

6.5 Summary

The chapter discussed the model calibration and validation of the developed multi-method simulation using the case study port. It also provides details of the calibration and validation process, which was done by comparing the model result with historical data. The calibration phase was focused on vessel speed and time intervals between each vessel movement state (Section 6.3). The validation phase was focused on vessel speed changing, transit times, waiting time at anchorage, manoeuvring time, dwell time at berth, and delay time at lock. The objective is to determine if the model behaves as the real-world system and if the model input produces the intended output.

Table 6.3 shows a summary of the validated parameters and their comparisons. The results show that the multimethod model exhibits similar behaviour to the real-world data.

Chapter 7: Application of Validated AnyLogic Model in Case Study

7.1 Introduction

The previous chapter discussed the application of the developed multi-method simulation in the case study port, and the validation process using the vessel speed and duration at various port processes. With that completed, a key stage in simulation development is the model implementation. This chapter discusses the application of the developed model for estimating vessel emission within the study area. The objective is to test the model's ability to simulate reality, output relevant results and predict future occurrences. Five major emission pollutants were considered, and emission output from various vessel types was also examined.

7.2 Port emission

Port traffic contributes a significant proportion of air emissions into the atmospheric environment. Concerns on emissions in the maritime sector have recently become significant and have resulted in the implementation of several preventive measures (MEPC, 2008; Skjølsvik et al., 2000) (IMO, 2017)., which has pressed policy makers and environmental scientists to develop a regulatory framework based on activity-based emissions for regional air quality management in port-cities, reduction of external cost and ecological/human health impacts, (Tichavska and Tovar, 2015) (McCollum and Yang, 2009; Tichavska and Tovar, 2015; Tichavska et al., 2017; Villalba and Gemechu, 2011).

Environmental issues as regards air emissions from ships have brought a new perspective to vessel speed. All vessels are required to be environmentally friendly as regards air emissions. This general goal is true for all vessels. But it is even more for high-speed vessels, because of the non-linear relationship between speed and fuel consumption. A ship that goes more slowly will emit much less than the same ship going faster. Gases emitted from ships can be classified into several categories. Green House Gases (GHGs) include carbon dioxide (CO_2), methane (CH4), and nitrous oxide (N_2O), among others. Non-Green House Gases include mainly sulphur oxides (SO_X) and nitrogen oxides (NO_X). Various other pollutants, such as particulate matter volatile organic compounds (VOC), black carbon, and others, are also emitted, (Chen et al.). The effects of all of the above gases on global climate are diverse and most are considered negative if not kept under control. Among other effects, GHGs contribute to global warming, SO_X cause acid rain and deforestation, and NO_X cause undesirable health effects.

Vessel speed influences ship emissions. Vessel emissions are closely associated with engine load, which generally varies by the cube of speed according to the Propeller Law; hence, emissions of pollutants are strongly speed-dependent (PSMAF, 2007). Vessel speed varies in different operational modes, including (i) cruising (at sea), (ii) slow cruising (in reduced speed zone), (iii) manoeuvring (to berth), and (iv) hoteling (at berth) (Corbett and Koehler, 2003). Concerning vessel speed, some inventory studies applied an average speed value (or engine load factor) for each operational mode or assumed the same value as the speed limit in the harbour (CARB, 2005; Winther, 2008; Tzannatos, 2010). Although the assumption is reasonable for the regional-scale emission inventory, it may not be detailed enough for the local scale, (Chen et al.).

Therefore connecting vessel speed profiles to the Tier 3 emission method will provide a detailed emission inventory of the port. This will be done first by using vessel speed profiles across types from historical AIS data to estimate the vessel emissions for different pollutants (*i.e.*, NO_x, CO, HC, CO_2, SO_2, and PM_{10}). Then a similar approach will be used on the vessel speed profile from the simulation model. The result of both (historical and simulation) data will be compared to validate the simulation model

7.3 Estimation method of vessel traffic emissions

Numerous studies have analysed applicable estimation logic to figure out the impact of maritime emissions on relevant coastal air qualities (Chen et al., 2016; Maragkogianni et al., 2016; Miola and Ciuffo, 2011; Viana et al., 2014). One of the well-known guidelines for marine vessel emission estimation, 'Air pollutant emission inventory guidebook', published by the European Environment Agency (EEA) provides technical approaches to design atmospheric emission inventories for effective air emission management. This guidebook introduced the different levels of estimation methods, Tier 1, Tier 2 and Tier 3 as described in Table 7.1. It could be found that detailed vessel information, engine profile, pollutant emission factors (EFs), fuel consumption by different fuel type (e.g. bunker fuel oil, marine diesel oil (MDO)/marine gas oil (MGO), gasoline), as well as the phase of trips (e.g. hoteling-, manoeuvring- and cruising modes) are important considerations for designing vessel emission estimation logic. The Tier 1 approach is a simple methodology that only applies the fuel consumption and defaults EFs. Although this method can be broadly adapted for estimating maritime air emissions, especially in developing countries, potential limitations such as accuracy and complexity still exist. In USEPA, the first federal standards (Tier 1) have been adopted for non-road diesel engines in 1994 and U.S.EPA (1999) also developed the Tier 2 method as the replacement of default EFs to the country-specific EFs as a part of an emission control program. However, these top-down approaches (Tier 1 and Tier 2 methods) were still not good enough, because the movement of vessels, i.e. activity information was still not considered. Tier 3 methodology, known as bottom-up approach or activity-based method requires the movement information for individual ships, EFs provided by different types of engine/fuel and operation status (e.g. a phase of vessel activity, operating hours and place of the vessel).

Table 7.1: Different level of emission estimation methods

Tiers	Formulas		Variable
Tier 1	$E_i = \sum_m (FC_m \times EF_{i,m})$	where, E_i FC_m $EF_{i,m}$ i m	 $= emission\ of\ pollution\ i\ in\ kilograms$ $= mass\ of\ fuel\ sold\ [tonnes]$ $= fuel\ consumption\ specific\ EF$ $of\ pollutant\ i\ and\ fuel\ type\ m$ $= pollutant$ $= fuel\ type$
Tier 2	$E_i = \sum_m \left(\sum_j FC_{mj} \times EF_{i,mj}\right)$	where, E_i $FC_{m,j}$ $EF_{i,m,j}$ i j m	 $= annual\ emission\ [tonnes]$ $= mass\ of\ fuel\ type\ m\ used\ by$ $vessel\ with\ engine\ type\ j$ $= average\ EF\ for\ pollutant\ i\ by\ vessel$ $with\ engine\ type\ j\ using\ fuel\ type\ m$ $= pollutant$ $= engine\ type$ $= fuel\ type$
Tier 3	*Total Inventory* $E_{trip} = E_{Hotelling} + E_{Manoeuvring} + E_{Cruising}$ *Fuel consumption for each phase is available* $E_{Trip,i,j,m} = \sum_p (FC_{j,m,p} \times EF_{ij,m,p})$ *Fuel consumption for each phase is unavailable* $E_{Trip,i,j,m} = \sum_p \left[T_p \sum_e (P_e \times LF_e \times EF_{e,ij,m,p})\right]$	where, E_{trip} FC EF LF P T e i j m p	 $= emissions\ over\ a\ complete\ trip$ $= fuel\ consumption\ [tonnes]$ =*EF depending on vessel type* $= engine\ load\ factor\ [\%]$ $= engine\ nominal\ power\ [kW]$ $= vessel\ activity\ time\ [hours]$ $= engine\ category$ $= engine\ type$ $= pollutant$ $= engine\ type$ $= the\ difference\ phase\ of\ trip$ $(hotelling, manoeuvering, cruising)$

7.4 Vessel Traffic Emission Estimation Approach

The Tier 3 emission estimation method, which is an activity-based approach was used in this study, because, there is a large variance between fuel-based and activity-based approaches due to the different scope of estimation. Research has proved that vessel emissions from the activity-based approach are generally 3.3 to 3.9 times bigger than the fuel-based approach. A major advantage of the activity-based method is the ability to capture possible variations in actual vessel speed. This is crucial as actual speed change can be used to estimate vessel emissions during the vessel manoeuvring phase as emission factors could increase as the load decreases, (Jalkanen et al., 2009). The port traffic simulation model was designed to exhibit these behaviours at such the method is suitable for this research.

Using an activity-based approach, vessel emissions are estimated using either fuel consumption or engine power. To estimate emission using engine power (see Figure 7.1), the data required the engine profile for each vessel (engine power, maximum and cruising speed), the phase of vessel activity, EFs from the technical literature reviews (Entec, 2002). Detailed information e.g. ship registration (nationality and company), construction information, size and engine profile are available from the LMIS database, the vessel movement information including travel distance and total activation hours is available to access from historical AIS data. Using the data emissions can be estimated based on vessel activities as shown in Figure 7.1 using the formula below;

$$E_{Trip,i,j,m} = \sum_{p} \left[T_p \sum_{e} \left(P_e \times LF_e \times EF_{e,ij,m,p} \right) \right]$$

The main engine load factor is expressed as the ratio of power output to the maximum continuous rated power of a ship at a given speed. The engine load factor was estimated by the Propeller Law based on the following equation

$$LF = (AS/MS)^3$$

Where,

LF $= engine\ load\ factor$ [%]

AS =*actual speed in knots*

MS =*maximum speed in knots*

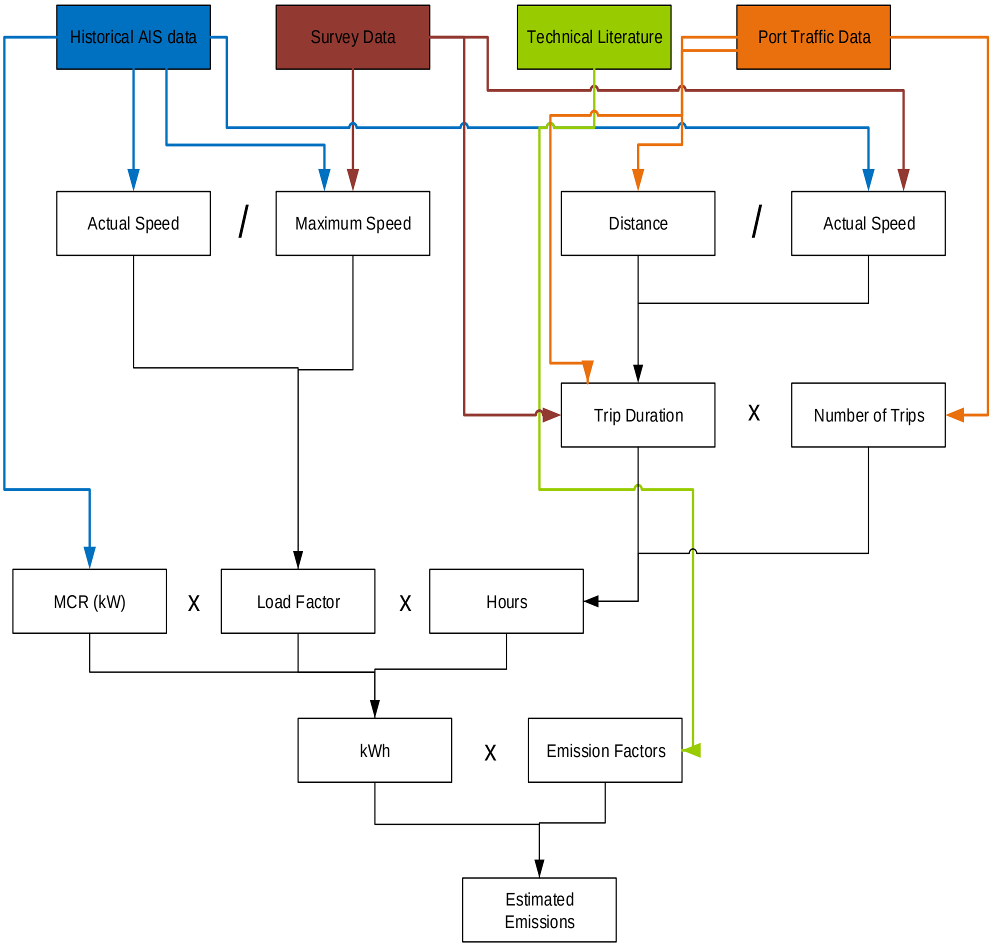


Figure 7.1: Activity-based approach for vessel emission estimate Adapted from (Port of LA (2005)

To simplify the vessel emissions in this study, the Tier 3 fuel consumption method is adopted, Figure 7.2. Using the validated port traffic simulation in Chapter 6, vessel emission can be easily estimated using fuel consumption. The fuel consumption method is used to calculate vessel emission for each phase (hoteling, manoeuvring and cruising). The emission data input for each vessel type at each phase is collected from (Entec, 2002), and corrected for the Port of Liverpool using the analysed AIS data results in Chapter 4. The simulated emission output is then calculated using the Simulation output in Chapter 6. The total emission inventory for the port based on historical and simulation data is calculated using the formula below;

$$E_{trip} = E_{Hotelling} + E_{Manoeuvring} + E_{Cruising}$$

$$E_{Trip,i,j,m} = \sum_{p} \left(FC_{j,m,p} \times EF_{ij,m,p}\right)$$

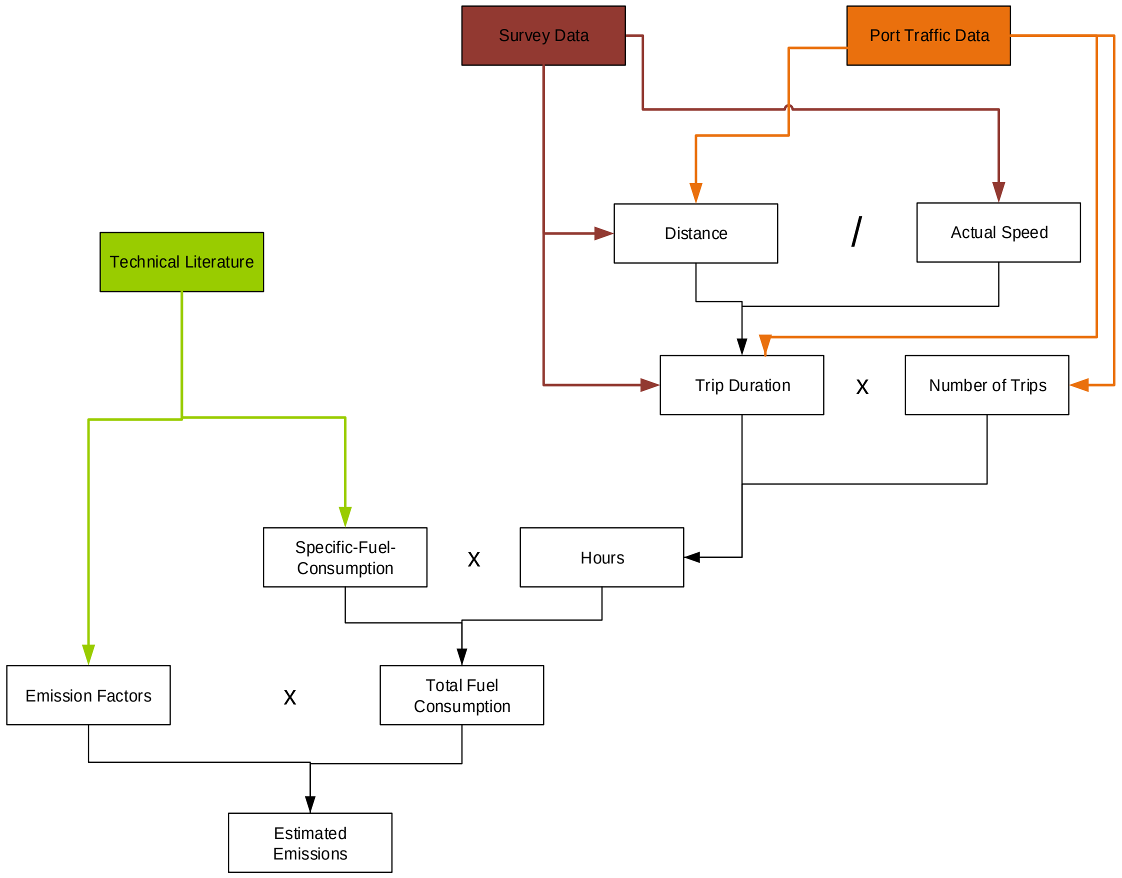


Figure 7.2: Tier III Fuel-based emission estimate approach

The diagram in Figure 7.2 shows the approach used for emission estimation in this study. The average vessel speed profile was obtained from Chapter 4 as described above and applied to the actual speed (*AS*) in Equation 7. Vessel transits, manoeuvring, dwell, waiting and delay time, have been calculated in Chapters 4 and 6 for both Historical and model data. Each time has been categorised to various operation modes as shown in Table 7.2 and their input value are the validation summary from

Table 6.3 for both simulation and historical data.

Table 7.2: Vessel time categorization by operational mode

Vessel Time	Details	Operational Mode
Outer Transit	Moving to & from anchorage area	Cruising
Inner Transit	Moving to & from Lock	Manoeuvring
Manoeuvring	Moving to & from the cargo terminal	Manoeuvring
Waiting	Waiting at anchorage	Hoteling
Delay	Stopped at Lock	Hoteling
Dwell	Time spent at cargo terminal (berth)	Hoteling

7.5 Emission Input Data

Emissions factors are used in conjunction with energy or fuel consumption to estimate emissions and can vary by pollutant, engine type, duty cycle and fuel. Emissions tests are used to develop emission factors in g/kWh and are converted to fuel-based emissions factors (grams pollutant per gram of fuel consumed) by dividing by the brake-specific fuel consumption (BSFC) or specific fuel oil consumption (SFOC) corresponding to the test associated with the emissions factors. Emissions factors vary by engine type (main, auxiliary, auxiliary boilers); engine rating (slow speed diesel (SSD), medium-speed diesel (MSD), high-speed diesel (HSD); whether engines are pre-IMO Tier I, or meet IMO Tier I or II requirements; and type of service (duty cycle) in which they operate (propulsion or auxiliary). Emissions factors are adjusted further for fuel type (HFO, MDO) and the sulphur content of the fuel being burned. Finally, engine load variability is incorporated into the factors used for estimating emissions.

All these variables were taken into account in estimating emissions as identified by IMO (2015) and emissions factors were collected based on vessel types for the following GHGs and pollutants

carbon dioxide, CO_2	oxides of nitrogen, NO_x
particulate matter, PM	sulphur oxides, SO_x
non-methane volatile organic compounds, NMVOC	

Some emission factors are dependent on how an engine is run, for example idling and rapid load changes give rise to more pollutants associated with incomplete combustion (CO, NMVOC, and PM). Thus indirectly, the type of ship operation will affect the demands on the engine and thereby emissions. In general, one can identify three-ship operational modes; Cruising (where the main engine are at ca. 80% of maximum load and auxiliary engine emissions are relatively insignificant), manoeuvring (where main engine emissions also dominate but at lower and varying loads), hoteling (where MEs are off and the emissions arise from auxiliary engines at ca. 50% of maximum load).

Specific fuel consumption (SFOC) and emission factor for each vessel category were collected from ENTEC 2002 for each operational mode as shown in Table 7.3**.** The total specific fuel consumption was calculated for individual vessel phases (shown in Table 7.3) and the overall fuel consumption is calculated by the summation of all phases. Multiplying the specific fuel consumption as shown in Figure 7.2 with their corresponding emission factor produces the emission estimates for that operational mode.

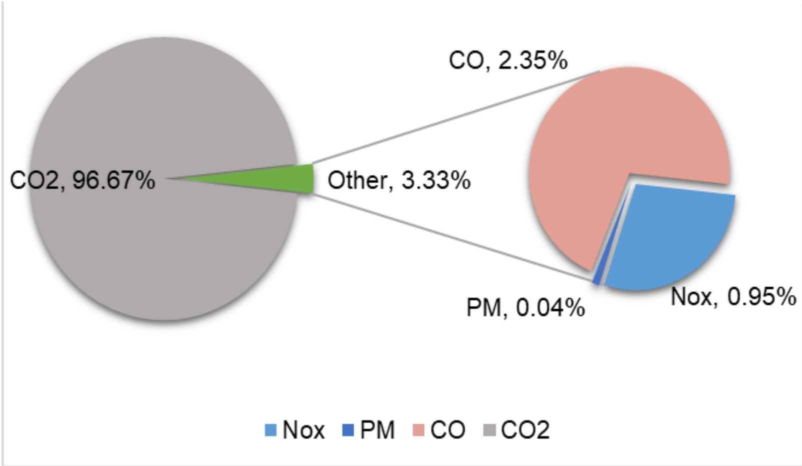
Table 7.3: Emission Factor of various pollutants and fuel consumption at each operational mode adapted from (Entec, 2002).

	Cruising					
	NOx (g/kWh)	SO2 (g/kWh)	CO2 (g/kWh)	NMVOC (g/kWh)	PM (g/kWh)	SFOC (g/kWh)
General Cargo	16.3	10.9	644	0.6	N/A	203
Container	17.5	10.7	631	0.6	N/A	199
Passenger	13.2	11.7	696	0.5	N/A	219
Oil Tankers	14.9	11.7	689	0.5	N/A	217
	Manoeuvring					
	NOx (g/kWh)	SO2 (g/kWh)	CO2 (g/kWh)	NMVOC (g/kWh)	PM (g/kWh)	SFOC (g/kWh)
General Cargo	13.3	12.1	716	0.9	1.5	225
Container	13.7	12.1	710	1	1.5	223
Passenger	11.6	12.6	750	1	1.8	236
Oil Tankers	12.1	12.8	754	1.4	2.2	237
	Hoteling					
	NOx (g/kWh)	SO2 (g/kWh)	CO2 (g/kWh)	NMVOC (g/kWh)	PM (g/kWh)	SFOC (g/kWh)
General Cargo	13.1	12	709	1.6	2.3	223
Container	14	11.8	696	1.6	2.3	219
Passenger	10.7	12.9	764	1.4	2.3	240
Oil Tankers	12	12.8	754	1.4	2.3	237

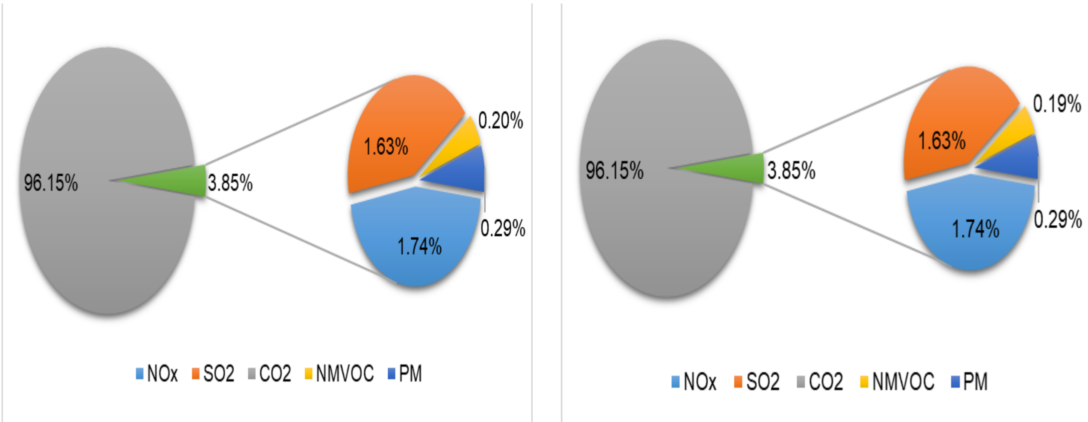
The marine emission database was compiled by Entec (2002) based on IVL and Lloyds Register Engineering Services data. Data of emission factors for NOx, SO2, HC, PM and CO2 were sorted and filtered for five different engine types, three different fuel types, where possible, and the different vessel operational modes of the ships. Data of various vessel categories (container, passengers, Tankers, etc.), were examined from the LMIS database. Then the weighted emission factor was calculated for each operating mode for each vessel category.

7.6 Emission Estimate Result

The overall emission output calculated from both the Historical AIS data and Simulation output was calculated for each pollutant and the results were compared to the emission estimate for vessels in Liverpool (see Figure 7.3). The result shows a clear similarity across pollutants with CO2 accounting for over 96% of the total emissions in the port while the remaining less than 4% is shared by other pollutants from all data sets. This implies that the developed multi-method simulation model is capable of capturing reality.



(a)



(b) (c)

Figure 7.3: Comparison of overall emissions. (a) Liverpool Vessels Emission output, (b) Emission Estimate from Historical AIS data, (c) Emission Estimate from Simulation Model

Percentage distribution of emissions across the port was carried out using the various vessel times capturing the different operational modes for both historical and simulation data (see Figure 7.4 and Figure 7.5). The result shows that vessels emit over 90% of their emission (across all emission pollutants) when in proximity to land (see Figure 7.6). These emissions mainly occur during vessel waiting and dwelling time (see Figure 7.4 and Figure 7.5). Comparing emission output across operational modes, Figure 7.7 shows that over 80% of all pollutants are released during vessels' hoteling mode than during any other. This implies that vessels emit more emissions when they are not moving. This is a delicate issue as vessels stoppage areas are in very close proximity to residential areas, and with over 80% of all pollutants emitted, the health condition of the people living in this area is at risk.

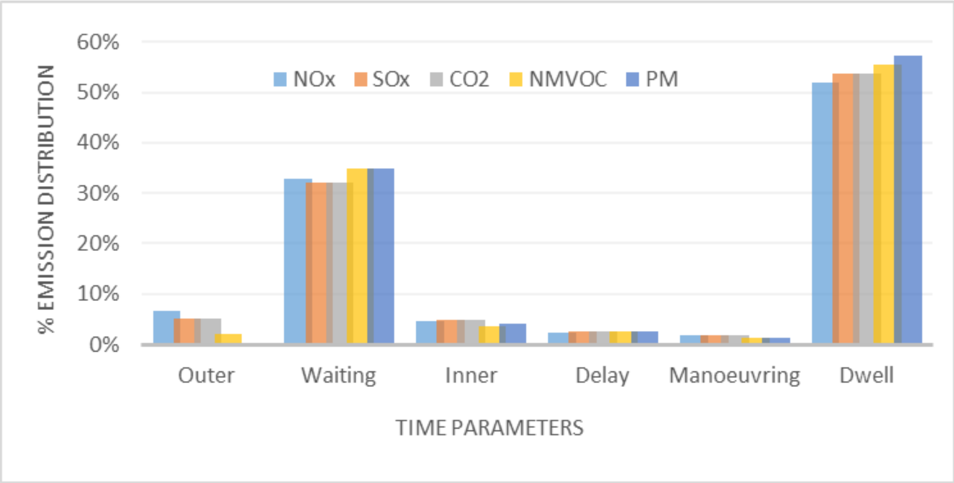


Figure 7.4: Percentage Emission distribution of all pollutants across the port of Liverpool using Historical AIS data

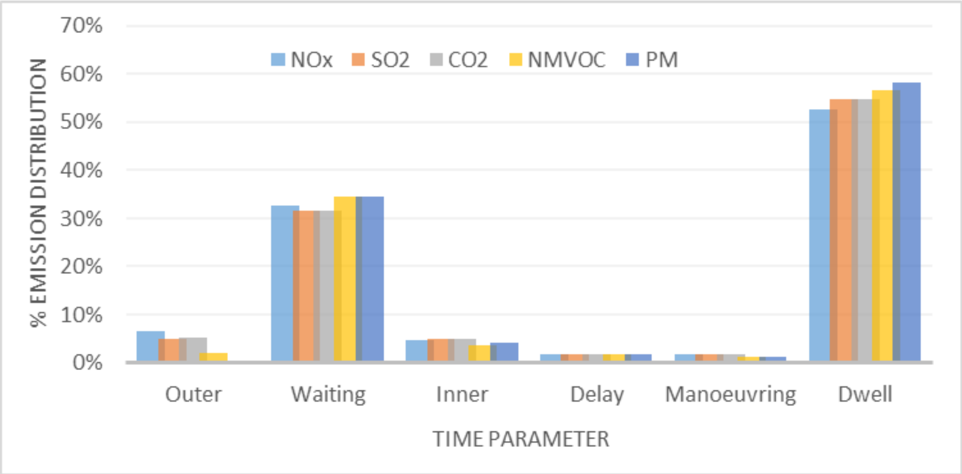


Figure 7.5: Percentage Emission distribution of all pollutants across the port of Liverpool using Simulation Output

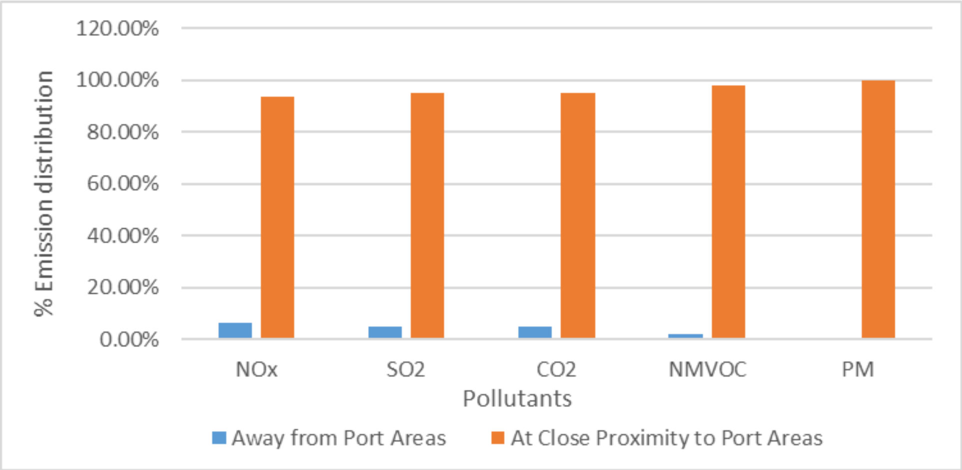


Figure 7.6: Emission distribution based on the distance to Port Areas

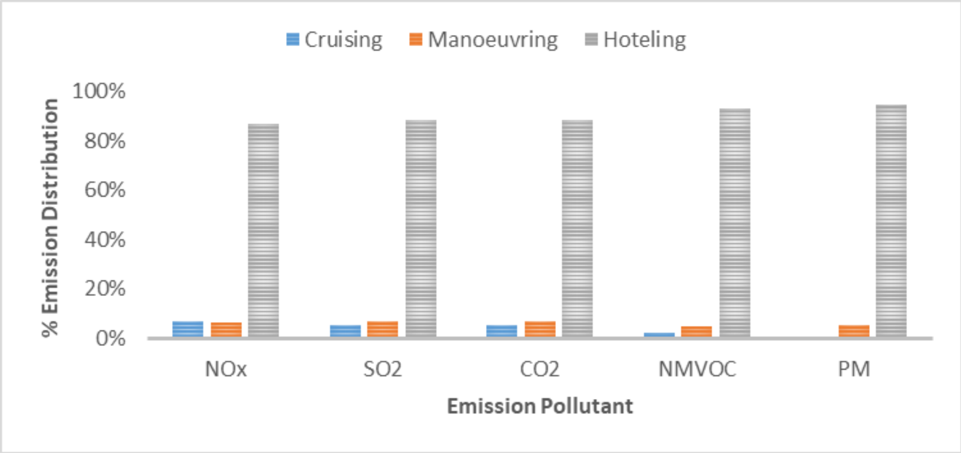


Figure 7.7: Vessel Emission at different operational mode

Emission output across various vessel types was also conducted. The result in Figure 7.8 shows that General cargo vessels emit more emissions when compared to other vessel types. Tankers and container vessels contribute 26% and 25% respectively, while passenger's vessels are the lowest contributors. This implies that with the development of the Liverpool2 container terminals, more container vessels are expected within the port. Combining this with issues raised above, regarding external conditions and predicted growth in vessel traffic, an increase in container vessel traffic, which is of economic importance to the port of Liverpool will also result in a significant increase in emission output within the port of Liverpool.

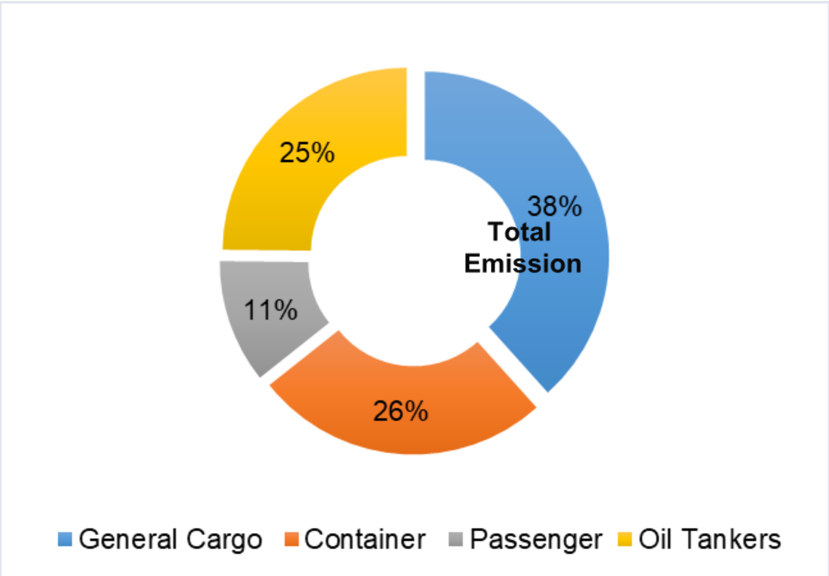


Figure 7.8: Emission distribution across various vessel types

7.7 Model Predictive Ability

Using the simulation model, the emissions in the case study port were estimated under two basic assumptions: that the traffic increases by 20% and 40% across all vessel types causing the arrival rate to grow as shown in Table 7.4. The simulation was run for two months and the averages of the various time parameters were collected as shown in

Table 7.5

Table 7.4: Input parameter value for both scenarios

Parameters	Vessel Type	Simulation Input
Arrival rate Initial condition	Container	$pert(1,3,2)$/day
	General Cargo	$pert(1,3,2)$/day
	Passenger	$pert(1,6,4)$/day
	Tanker	$pert(1,1,1)$/day
Arrival rate (20% Increase)	Container	$pert(1,4,2)$/day
	General Cargo	$pert(1,4,2)$/day
	Passenger	$pert(1,7,4)$/day
	Tanker	$pert(1,2,1)$/day
Arrival rate (40% Increase)	Container	$pert(1,5,3)$/day
	General Cargo	$pert(1,5,3)$/day
	Passenger	$pert(1,8,5)$/day
	Tanker	$pert(1,3,2)$/day

Table 7.5: Model Output for both scenarios

Parameter	Vessel Type	20% increase	40% increase
Inner Transit	Container	1.87	1.91
	General Cargo	3.01	3.07
	Passenger	1.51	1.54
	Tanker	2.03	2.07
Manoeuvring	Container	0.89	0.90
	General Cargo	0.86	0.87
	Passenger	0.78	0.79
	Tanker	0.81	0.82
Dwell	Container	26.85	28.127
	General Cargo	36.96	38.72
	Passenger	6.72	7.04
	Tanker	26.96	28.248
Waiting	Container	13.81	16.15
	General Cargo	21.71	25.39
	Passenger	4.81	5.63
	Tanker	4.38	5.12
Delay	All Vessel	0.77	0.78
Outer Transit	Container	1.93	1.96
	General Cargo	2.91	2.97
	Passenger	1.80	1.84
	Tanker	2.27	2.31

The emission estimates are shown in Figure 7.9 using a stacked area graph. The result shows that with a 20% and 40% increase in port traffic, emissions rise at a different pace in various parts of the port. There is a gradual rise at the outer and inner waterways due to the rise in vessel traffic, but a significant increase in emission at the anchorage (waiting) and berth (dwell) area resulting from an increase in waiting and dwell times.

Following the predicted growth in seaborne trade, vessel emissions within the port might see a significant rise in percentage. The main factor to this rise is not just due to the rise of vessel traffic, but also due to the impact of external factors like the tide, which directly affect both vessels waiting and dwell time. Combining the resulting rise in vessel traffic, with the addition of the Liverpool2 terminals and the tidal influence on both waiting and dwell time, vessel emissions can be seen to soar in the nearest future. This will result in significant health issues for people residing in coastal areas.

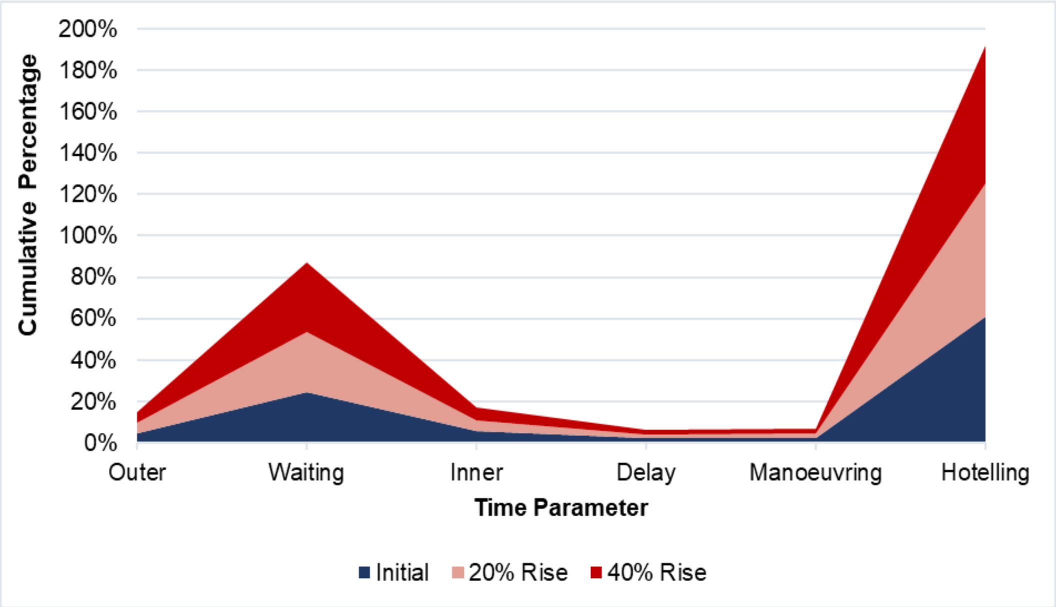


Figure 7.9: Predictive emission estimate for the port of Liverpool using model output

7.8 Summary

The coastal air quality across the port-cities including the Port of Liverpool is an emerging issue due to the indeterminate and underestimated air pollution estimations from the maritime transportation sector. The simulation method was used to estimate vessel traffic emission within the port. The result shows that compared to other modes of transport, marine emissions account for approximately 9% of the total emissions in the city of Liverpool. An increase in vessel traffic will certainly result in a rise in the total shipping emission at Liverpool. Also, the results show that a considerable quantity of air pollutants is generated especially when vessels are at the cargo terminal and waiting for a cargo terminal when they are close to land. This produces a combined environmental effect due to the superposition of SOx, NOX, PM and VOC emissions from ships, with those related to urban sources. Health effects associated with SOx, PM, and NOX at a local level such as respiratory diseases and premature death from heart and pulmonary diseases, might increase over time if nothing is done to offset this. In addition, since the vessel waiting and dwell time are influenced by external conditions like the tide, this influence increases both waiting and dwell time, which in turn will increase vessel traffic emissions within the port. The resulting environmental and social impacts could present extreme life-threatening conditions for people in the harbour area and community.

Eliminating or reducing vessel waiting times and improving cargo handling services to reduce dwell time increases the port attraction for shipping lines, freight forwarding companies and other stakeholders, thus, directly improving the economic growth of the port. However, this also reduces emission output in port as over 85% of vessel emission in the port comes mainly from these positions (see Figure 7.10). Therefore, reducing vessel waiting and dwell time establishes a balance between environmental and economic considerations.

Figure 7.10: Emission distribution within the port.

This result agrees with (Kemme, 2020) who alluded that a port that can reduce or even eliminate vessel waiting times inevitably increases its attraction for shipping lines, freight forwarding companies and other stakeholders. While this results in a strong competitive advantage for ports with reduced vessel waiting times, those ports struggling with longer waiting times face the risk of losing cargo volumes and, ultimately, revenues and welfare. Furthermore, vessels anchoring in front of the port cause unnecessary pollution of the environment. By reducing vessel waiting times, port and shipping lines contribute to the reduction of vessel emissions, which can strengthen a port’s image on the way to becoming a green port.

The outcome of this chapter is significant to understand the appropriate emission inventory methodology in a port city region because the number of marine vessel emissions calculated using top-down approaches mainly Tier 1 could be underestimated, thereby presenting a completely different perspective on the regional air emission inventory. Therefore, a more reliable estimation system and advanced calculation logic (predicting both vessel traffic and possible emission estimate) should be adopted at the local air quality management level.

Not many articles have introduced any quantitative analysis of air emissions from the marine vessels in Liverpool, thus this study would be valuable to provide certain quantitative analysis of maritime air emissions for better improvement of air quality management strategies in the port-city.

Furthermore, attaching a dispersion model to this study based on the suggestions described will help confirm the effective management and implementation made to promote a positive atmospheric environment in a coastal area. Therefore, the general outcome and implication would be useful to establish regional policy/regulation for beneficial air quality and maritime transportation management for a sustainable coastal environment in Liverpool.

Chapter 8: Conclusion and Future Work

8.1 Introduction

The previous chapter described the implementation of the port simulation model to estimating emissions including the comparisons with the emission estimates from historical data and predictive scenarios. This Chapter presents discussions of the main research themes, highlights the research limitations, suggests future activities to advance the research, and conclusions of the research activity.

8.2 Achieving research aim and objective

The study was aimed at developing a multi-method simulation model of port systems to simulate port traffic for assessing various port challenges like emission, throughputs, etc. The objectives were developed to successfully achieve the research goal, which includes:

- Review the application of a simulation model to modelling the port system to identify gaps in previous model and simulation modelling approaches.

  This objective was achieved in Chapter 2: by conducting a comprehensive literature review on three major simulation methods used for modelling port systems. The simulation methods are; Systems Dynamics, Discrete Event and Agent-Based. Reviewing these methods helps to identify gaps in previous port simulation models and helps to gain an understanding of the suitability of each method for modelling the port. The conclusion drawn from this study regarding the objective is that it provided adequate knowledge to help identify the gaps in previous port studies, which this research activity could cover.

- Identify and investigate the key systems (vessels, port processes, etc.) that make up the port and assess how they can be best modelled.

  This objective was achieved in chapters 2 and 3, 4, by conducting a review of previous port simulation models. Chapter 2 helps to understand and identify various systems within the port and gaps from previous studies in modelling each system. It also identifies the model deficiencies due to the simulation methods applied. Using the identified gaps in chapter 2, chapter 3 helps to understand how each system can be better represented and the modelling method suitable for each system. This objective helped to understand how systems in the port should best be simulated to fill gaps identified from previous studies.

- Develop a port traffic simulation model of Liverpool port using the suitable methods identified. The objective also includes data collection and analysis for the model development.

This objective was achieved in chapters 2, 3, 4, 5, and 6, by conducting state-of-the-art research in academia. After identifying gaps and issues on how entities were simulated in previous port simulation models, and the requirement for developing a port simulation model, a multi-method simulation was proposed in chapter 2. Details of how the method will be used in modelling entities were discussed in chapter 3. The system entities were modelled in chapters 4 and 5 to meet the set goal of the research and the method was validated in chapter 6. This objective helped to highlight the major influencers of the port and how they can best be represented. This objective also helped to achieve the intended aim of this research by developing a multi-method simulation model

- Assess the impact of the increase in vessel traffic on vessel emission. This includes testing of the developed port traffic model using real-world data for assessing vessel traffic emission within the study port.

This objective was achieved in Chapter 7 by conducting an experimental run using the validated port traffic simulation model in Chapter 6 in the case study. Real-world data were used as input in the validated port traffic simulation model. This objective helped to estimate emissions within the case study and provide solutions for minimization. It also serves as a means of validating the port traffic simulation model.

In summary, this research has been able to achieve its initial objectives and went beyond them to also apply the method in emission studies; it was validated by comparing the calculated simulation estimate with that of the historical estimate.

8.3 Main Findings

The findings of this research are grouped into three categories, pre-model development, at-model development, post-model development.

8.3.1 Pre-model development

This includes findings before developing the multi-method simulation from previous research and industrial literature within the context of this study. These findings include:

- Previous port simulation models major largely on port processes and did not include detailed vessel, traffic models. This is because vessel traffic cannot be easily represented using a process-based model.
- A holistic port model capable of integrating process models and agent-based traffic models is required because simulation models in the maritime sector tend to focus on either port process or vessel traffic modelling but not both.
- An agent-based vessel model is needed to simulate vessel traffic because none of the models reviewed was capable of modelling the dynamic kinetic characteristics of different vessels.

- The impact of encounter situations and external conditions needs to be implemented into individual vessel behaviour

  At-model development

  These comprise findings at the development stage of the multi-method simulation within the context of this study. These findings are as follows:

1. A port comprises of entities at different levels based on their characteristics (static, process, or interactive) and these entities are;

- Geographical area (static), which includes the waterway description, traffic network, the use of digital map and spatial data for representing the port area, (section 3.3)
- Port processes (process) such as anchorage, lock, berth, their activities, historical data analysis, modelling method, model input, model structure, assumptions and simplification and measures of assessment such as dwell time, delay time and waiting time, (section 3.5)
- Vessel traffic (interactive), includes vessel arrivals, vessel speed and course, movement and collision avoidance. The measure of assessment such as transit times, manoeuvring time, speed changes across zones and dynamic speed changes due to collision avoidance, (section 3.6)
- External conditions including tide, weather, seasonal changes and visibility, (section 3.4).

2. The developed multi-method simulation follows an object-oriented framework that combines models representing individual actors and specific processes and is characterised by the following advantages and disadvantages
   Advantages

- It allows the combination of various simulation methods and supports the modelling of various connected systems such as vessel traffic, port processes, external condition, etc.
- It captures micro-interaction within entities such as vessel movement and collision avoidance, anchorage, lock and berth processes, etc. in the port system, which can be used to assess the behaviour of the entire system.
- It overcomes deficiencies identified in other port simulation models such as majoring on one aspect of the port system like vessel traffic or port processes as observed from previous port models.
- It supports the scalability of the various port systems and can be applied at different levels of the port. Also, the method can be used globally in any port and can also be used for prediction purposes.
- It also supports the use of intelligent maps such as GIS maps for visualisation purposes
  Some disadvantages to this method are:

- Simulation complexity, as the method, includes the combination of various systems and variables.
- There is currently no specific way of validating such a model.
- The model may generate findings that may lead to distraction from the research aim.

Post-model development: This accounts for findings during the model application and implementation stage of this research. Findings from the model application stage for the study port includes;

- Vessel traffic within the port follows a specific pattern, which is, from vessel arrival to the anchorage, then to the lock, and thereafter berth, before departing. A vessel transits through three waterway areas (outer, inner, and manoeuvring) from its arrival to its departure within the study port area.
- Vessel agent speed across the various waterways differs due to the navigable room present at each waterway. Vessels were observed to move at higher speeds at the outer waterway than anywhere else.
- Speed variations were predominantly noticed for vessels within the outer waterway than any other area due to the traffic density at the outer waterway, and external conditions (visibility and weather).
- Vessel traffic within the inner (inner and manoeuvring) waterway is observed to be influenced by lock and berth availability.
- The dynamic changes in vessel speed are observed to influence the travel times of vessels regardless of type.
- Vessel duration at the anchorage, berth and lock varies across vessel types.
- Waiting time is observed to increase with an increase in vessel traffic and decrease in berth availability.
- The entire vessel handling sector of the studied port is influenced by the tidal conditions.

Findings from the model implementation stage for the study port includes;

- The percentage emission estimate from the simulation model corresponds to that from the historical data
- Emissions are mostly predominant in the berth and anchorage area
- General cargo vessels emit more emissions when compared to other vessel types. Tankers and container vessels contribute 26% and 25% respectively, while passenger's vessels are the lowest contributors
- An increase in vessel traffic will increase port emissions, especially in berth and anchorage.

8.4 Research Contributions and limitations

8.4.1 Research Contributions

The study contributed to existing knowledge focusing on developing a port model that (1) Can model the whole system at any level of detail; (2) Integrates specialist models developed for specific proposes for example by adding a model designed to assess navigation safety; (3) Can be updated using data generated from real operations. The study accomplished these in four perspectives.

Modelling Port Processes: Simulation methods used for modelling port processes and gaps from such models were identified in previous port simulation models. The study went on to develop a scalable multi-method simulation that overcomes these challenges by combining two simulation methods. The multi-method was then implemented in AnyLogic to develop various port processes, which were validated by comparing the model output with historical data (Chapters 2, 3, 4, and 6). The contributions are summarised below;

- Development of a multi-method simulation for simulating port processes, which was validated using historical data.
- Development of an independent scalable multi-method port process, which can be expanded and applied globally
- Development of an independent multi-method simulation of port process integrated with other maritime models like a vessel, or weather model and can be used for specific purposes.
- Development of port models integrated within a GIS space.
- Development of a multi-method simulation that can be applied to any related port study.

Modelling Vessel Traffic: Methods of simulating vessel traffic within the maritime industry and research gaps were identified from previous studies. The gaps were used to develop the requirements an acceptable port model should meet. These requirements were used as a framework to develop the vessel model. The agent-based simulation was used to develop the vessel model, which was integrated with the port process using AnyLogic to overcome deficiencies in previous research. The model was validated using historical AIS data of vessel traffic (Chapter 2, 3, 5, and 6). The contributions are summarised below;

- Development of a multi-method simulation for simulating both vessel traffic and port process, which was validated using historical data.
- Development of scalable agent-based vessel model comprising of vessel movement and collision avoidance model, which can be expanded by integrating the model with other specific mathematical models and applied globally.

- Development of a multi-method simulation of vessel traffic model which can be integrated with other models like emission, or weather model and can be used for specific purposes like predictions.
- Development of vessel traffic models integrated within a GIS space.
- Development of an agent-based simulation model of vessel traffic which can be applied to any related study.

  Modelling External Conditions: Research gaps identified from previous port models include issues of the non-inclusion of external conditions within the models. The gaps were part of the requirement for an acceptable port model. These requirements were used as the framework to develop an agent-based model of several external conditions. The model was developed using AnyLogic and as part of the multi-method port simulation (Chapter 2, 3, and 4). The contributions are summarised below;

- Development of scalable external condition models of weather, seasonal change, visibility and tide.
- Development of a multi-method simulation of external condition models, which can be integrated with other models like wind models for specific purposes.
- Development of agent-based simulation models of the tide, visibility, weather, seasonal changes, which can be applied in related environmental studies.

  Model Geographical environment using GIS: Research gaps from previous studies outline issues with model sustainability over time. The identified gap led to the application of the GIS system to develop the port geographical area in AnyLogic. The GIS space allows for data updates of port areas, and specific locations to maintain the sustainability of the model. The space also supports the visualisation of the simulated entity and dynamic visualisation (zooming in and out).

8.4.2 Research Limitations

The limitations of this research are presented as follow;

- The focus of the research is on port simulation majoring on the vessel handling process, so the model was developed to suit the port processes and vessel activities within the port. However, the developed multi-method simulation adopts an object-oriented approach, which allows for model scalability. Therefore, the developed model can be used to construct other aspects of the port such as the cargo handling process, port energy, etc.
- Though the validation was for both port process and vessel model, the modelling and validation data sets used were mainly AIS data of vessel traffic. For future study, data sets from the port covering the various processes are needed to effectively validate the model.

- Due to the difference in port geography globally, the traffic network must be updated when applying the model to other port areas. This can be easily accounted for by obtaining the AIS data and geographical data of the study area.
- Data analyses were done using Microsoft Excel; hence the analyses were narrowed down by the software.
- Due to the novelty of the AnyLogic tool within the port industry especially in vessel movement, the developed port model could only be validated using statistical analysis of vessels. Advanced analysis is required to achieve an in-depth study of the developed model.
- Due to the novelty of agent-based simulation in developing a multi-method simulation, there are currently no specific validation techniques; hence statistical validation techniques were used.

8.5 Future Research and Conclusion

Based on the limitations presented above, future studies could be taken in the following areas:

- Further development and application of the developed multi-method simulation model to extend the approach to the entire maritime industry.
- In applying the method to other ports globally, the traffic network would need to be updated to suit the port waterways where the method is being applied
- Advanced statistical analysis and algorithms could be used to improve the various model operations within the port system and validation techniques
- Each developed external condition model is scalable, hence, further research can be conducted to enhance the modelling capability of each model and applied in diverse research areas, like tidal study, weather changes, etc.
- The developed collision avoidance and movement models are scalable, hence, further research can be conducted to enhance the modelling capability by integrating them with mathematical models like MatLab. The method can also be applied in specific areas like vessel safety, collision investigations, etc.
- Each developed port process is scalable, hence, further research can be conducted to include terminal operations within the port. The model can also apply an in-port efficiency study, and when other relevant port aspects are added it can effectively be used in port-related studies like cost, energy efficiency, security, etc.
- The developed multi-method simulation model has predictive capabilities which can be used to forecast the impact of future events, like the impact of an increase in vessel traffic on port emission, congestion, port efficiency, etc.

In conclusion, the study was aimed at developing a multi-method simulation model of port systems to simulate port traffic for assessing various port challenges. The research activity was undertaken to fulfil the aim employed a comprehensive methodology to review existing literature and capture industry simulation methods for port models. This helped to identify the research gap which informed the framework development of a multi-method simulation model. The research output achieved the development and validation of the following;

- A multi-method simulation for simulating port process, vessel model, and external conditions within a GIS space, which was validated using historical data.
- A predictive multi-method simulation model.
- An independent and scalable multi-method model of the port process, which can be expanded and applied globally
- An independent and scalable agent-based vessel model comprising of vessel movement and collision avoidance model, which can be expanded by integrating the model with other specific mathematical models and applied globally.
- An independent multi-method simulation of vessel traffic models can be integrated with other models like emission, or weather models and can be used for specific purposes like predictions.
- Development of an agent-based simulation model of vessel traffic which can be applied to any related study.
- Scalable external condition models of weather, seasonal change, visibility and tide.
- A multi-method simulation of external condition models, which can be integrated with other models like wind models for specific purposes.
- Agent-based simulation models of the tide, visibility, weather, seasonal changes, which can be applied in related environmental studies.
- Possible predictive and forecasting abilities of the model as demonstrated in section 6.7.

This demonstrates the novel and significant contribution of the research to the port simulation model.

Appendixes

Appendix A: Vessel speed from historical AIS data

Zone 1 speed distribution

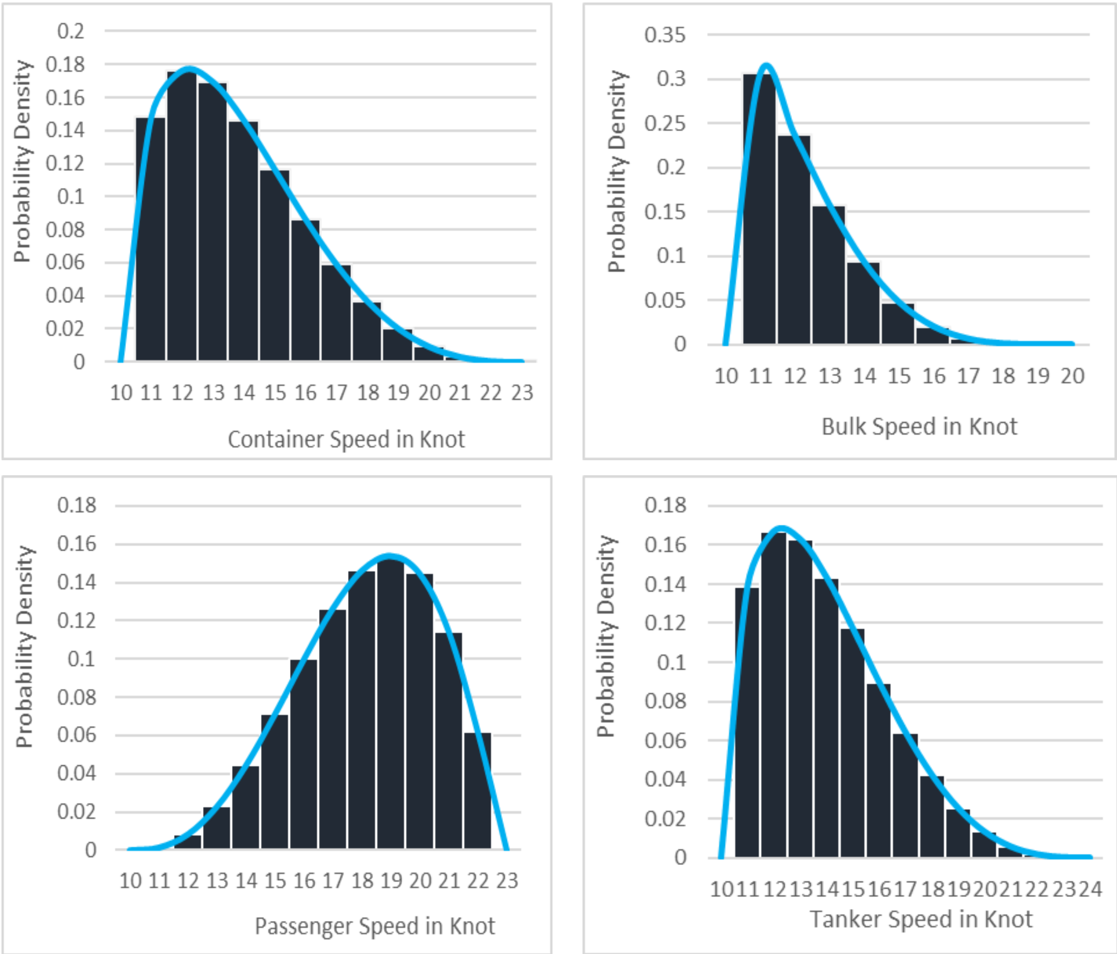


Figure 1: Appendix A: Sample Zone One speed distribution of vessels

Table 1: Appendix A: Zone One speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	13.7 knot	10	23.5	12.2 knot
Bulk	12.1 knot	10	19.6	10.7 knot
Tanker	13.9 knot	10	24.2	12.3 knot
Passengers	18.2 knot	10	23	19 knot

Zone 2 speed distribution

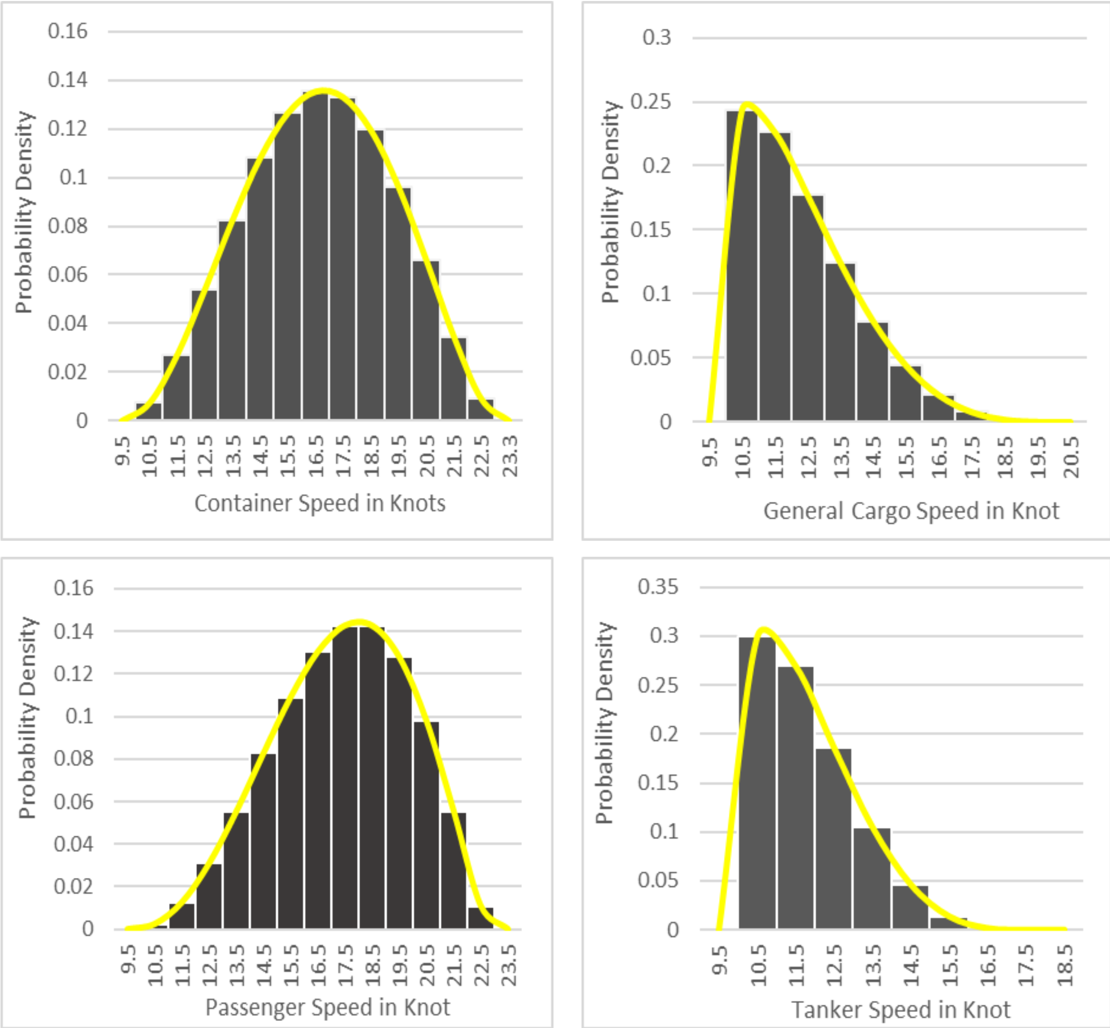


Figure 2: Appendix A: Zone Two speed distribution

Table 2: Appendix A: Zone Two speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	16.7 knot	9.5	23.3	16.8 knot
Bulk	12.1 knot	9.5	20.4	10.7 knot
Tanker	11.7 knot	9.5	17.6	10.7 knot
Passengers	17.4 knot	9.5	22.9	18 knot

Zone 3 speed distribution

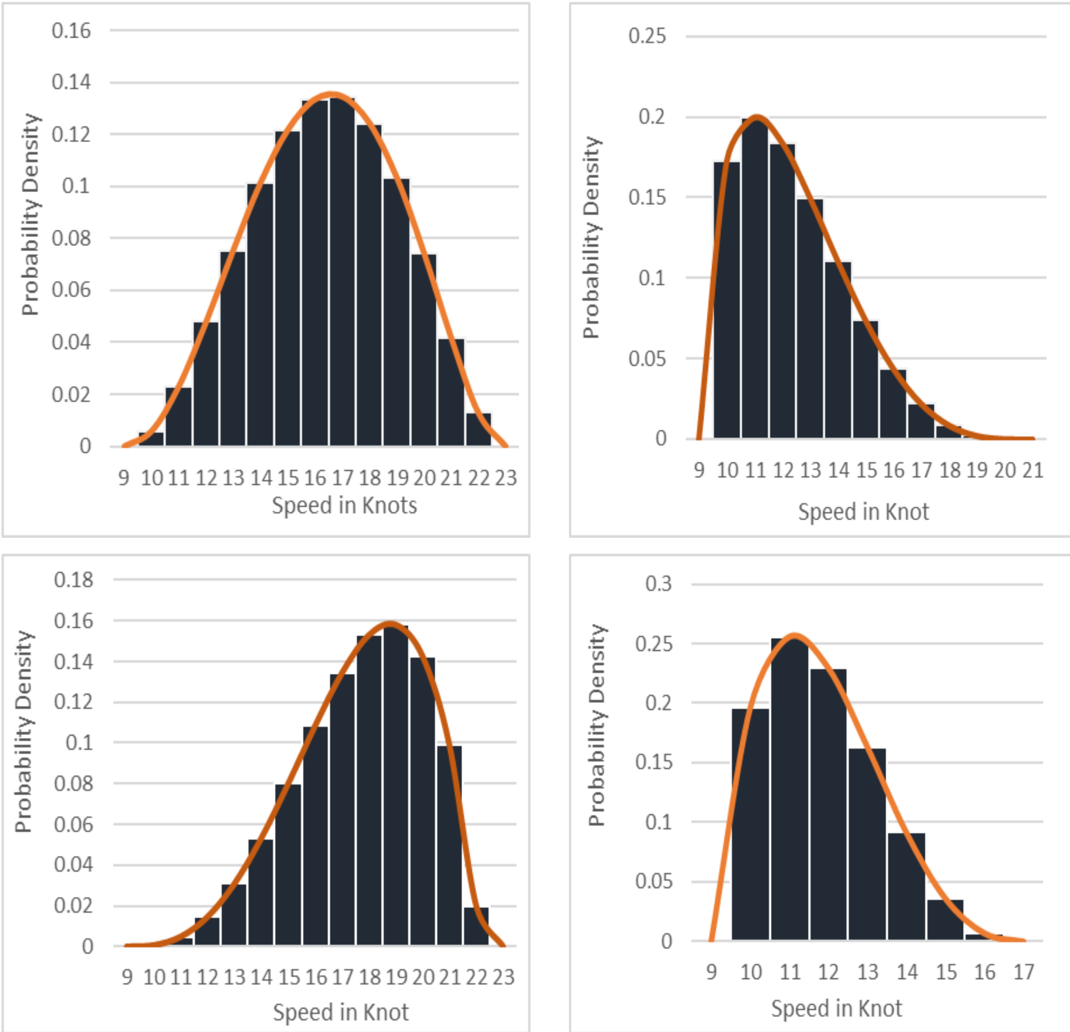


Figure 3: Appendix A: Zone Three speed distribution

Table 3: Appendix A: Zone Three speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	16.4 knot	9.0	22.9	16.6 knot
Bulk	12.3 knot	9.0	20.8	11.0 knot
Tanker	11.8 knot	9.0	17.2	11.1 knot
Passengers	17.7 knot	9.0	22.2	18.8 knot

Zone 4 speed distribution

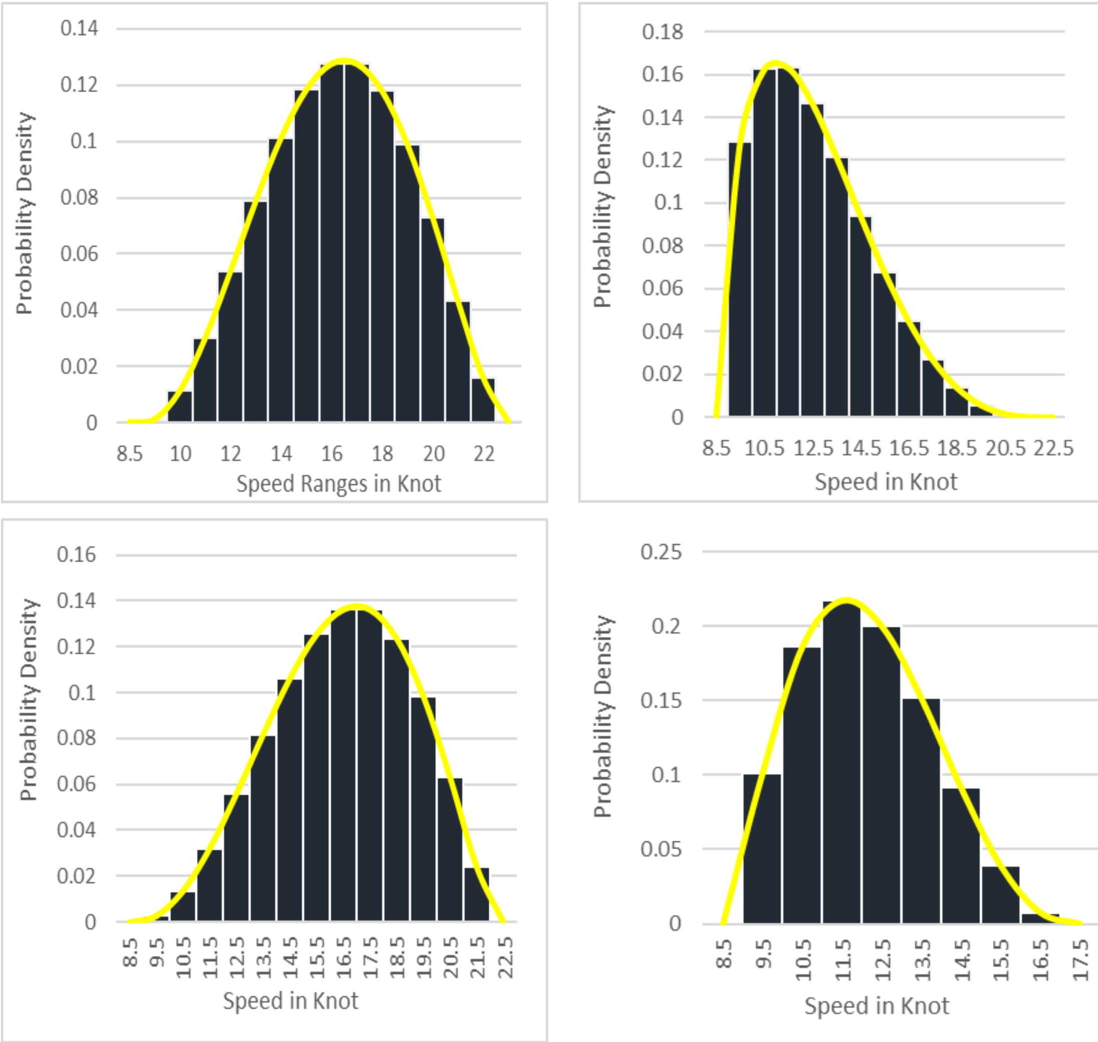


Figure 4: Appendix A: Zone Four Speed distribution

Table 4: Appendix A: Zone Four speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	16.3 knot	8.5	23.1	16.5 knot
Bulk	12.5 knot	8.5	22.5	11 knot
Tanker	12.1 knot	8.5	17.5	11.6 knot
Passengers	16.5 knot	8.5	22.4	17 knot

Zone 5 speed distribution

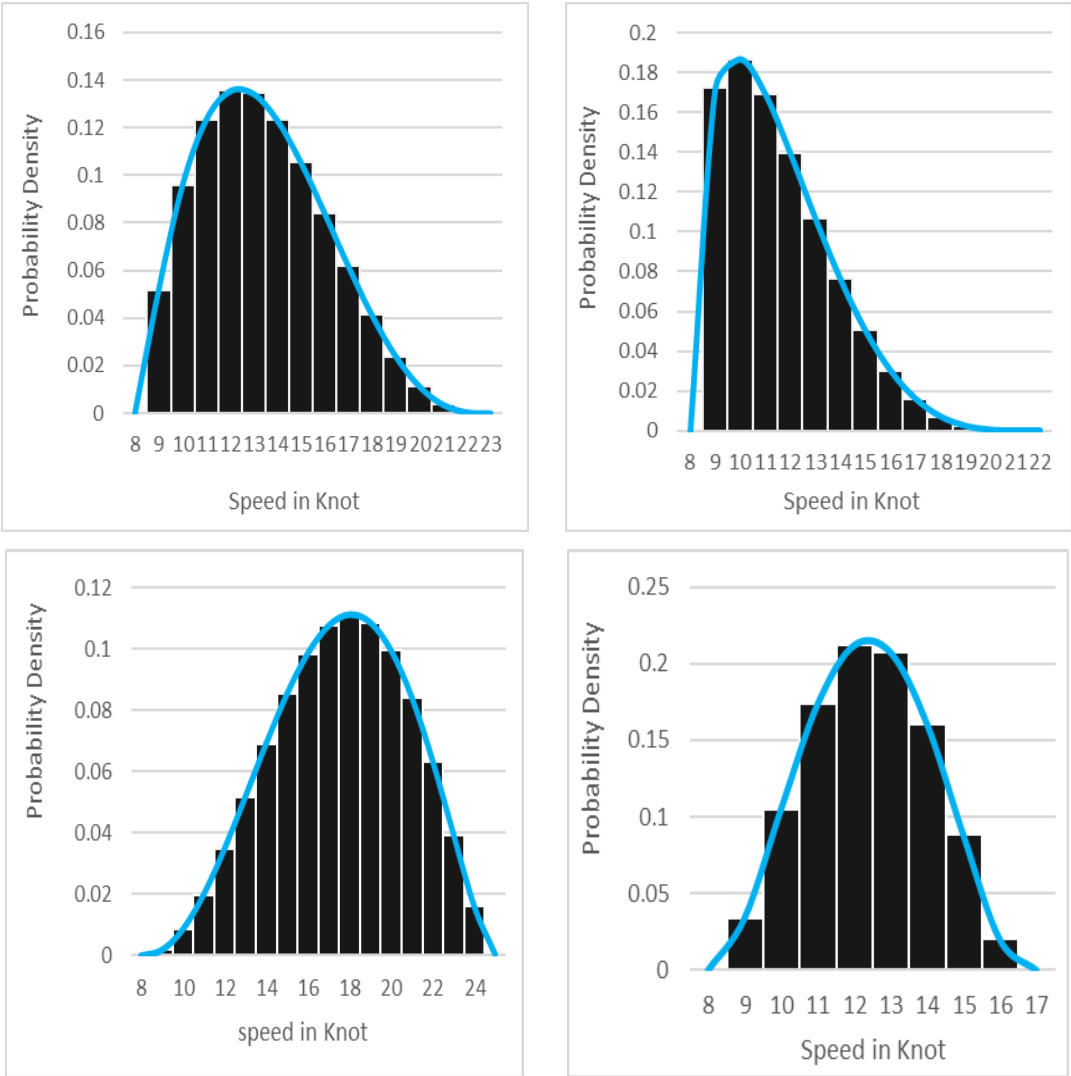


Figure 5: Appendix A: Zone Five Speed distribution

Table 5: Appendix A: Zone Five speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	13.4 knot	8	22.8	12.4 knot
Bulk	11.5 knot	8	21.5	9.8 knot
Tanker	12.4 knot	8	16.7	12.4 knot
Passengers	17.6	8	25.1	18.1 knot

Zone 6 speed distribution

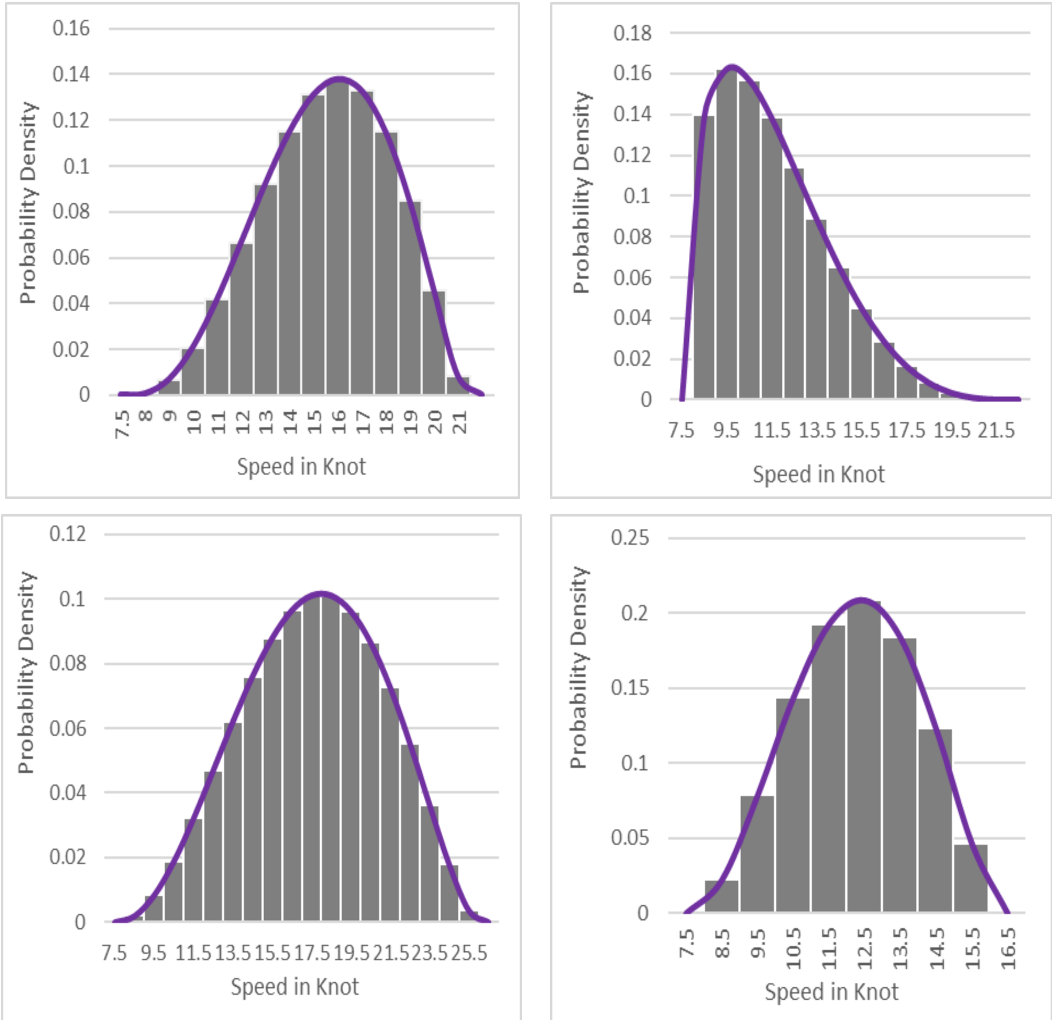


Figure 6: Appendix A: Zone Six Speed distribution

Table 6: Appendix A: Zone Six speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	15.6 knot	7.5	21.4	16.1 knot
Bulk	11.5 knot	7.5	22.6	9.7 knot
Tanker	12.3 knot	7.5	16.5	12.4 knot
Passengers	17.6	7.5	26.1	18 knot

Zone 7 speed distribution

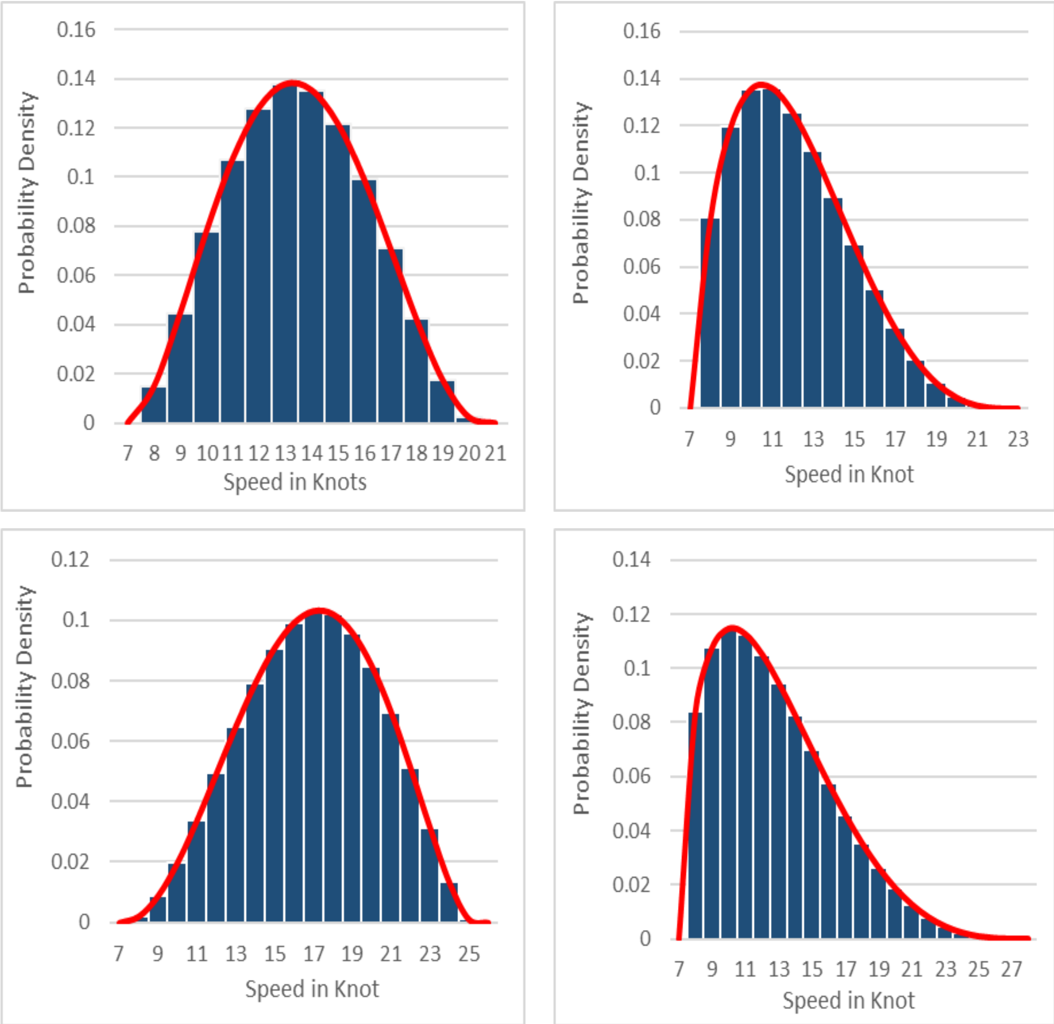


Figure 7: Appendix A: Zone Seven Speed distribution

Table 7: Appendix A: Zone Seven speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	13.5 knot	7.0	20.6	13.3 knot
Bulk	12 knot	7.0	22.9	10.5 knot
Tanker	12.7 knot	7.0	28.3	10.2 knot
Passengers	16.9	7.0	25.3	17.3 knot

Zone 8 speed distribution

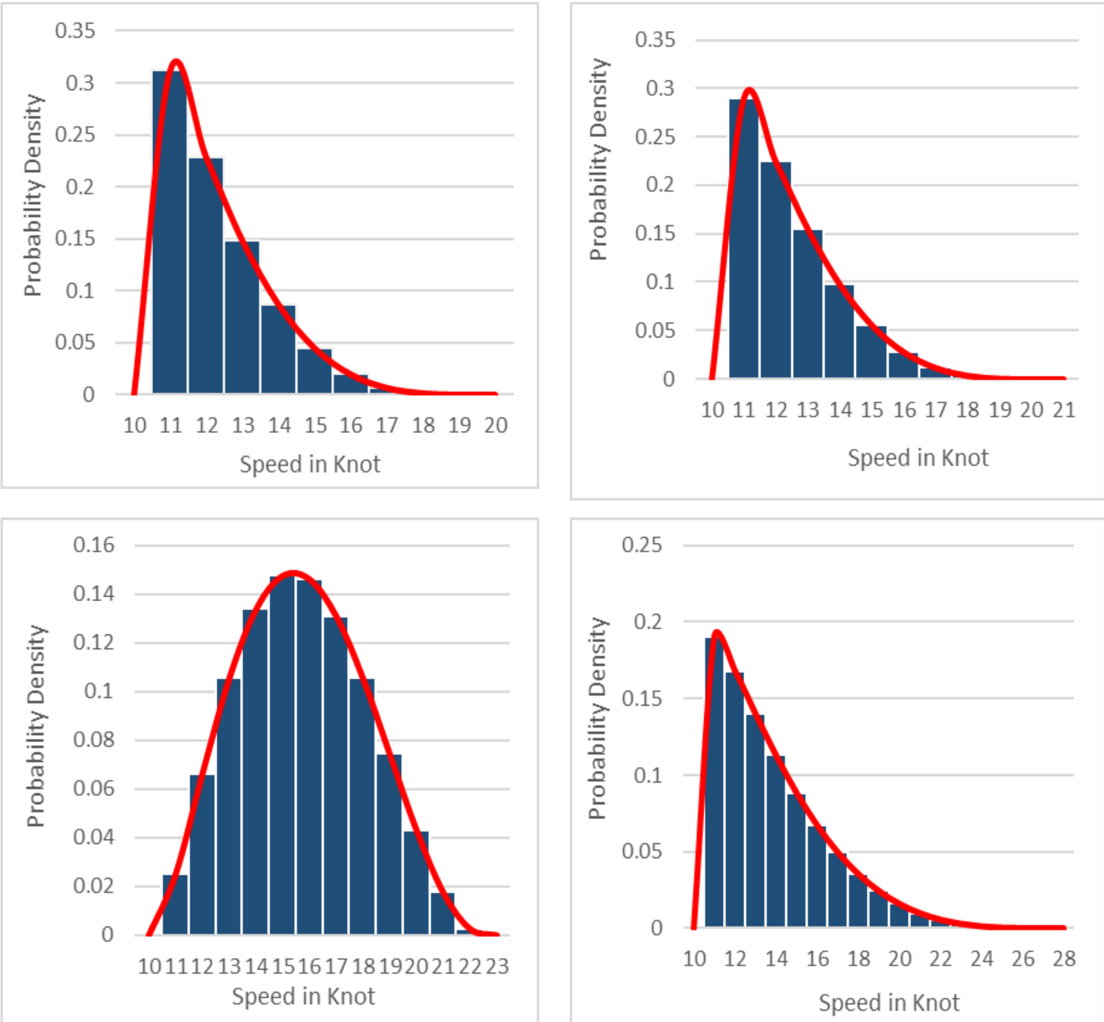


Figure 8: Appendix A: Zone Eight Speed distribution

Table 8: Appendix A: Zone Eight speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	12.0 knot	10.0	19.9	10.5 knot
Bulk	12.2 knot	10.0	20.7	10.6 knot
Tanker	13.5 knot	10.0	28.3	10.7 knot
Passengers	15.7	10.0	22.7	15.4 knot

Zone 9 speed distribution

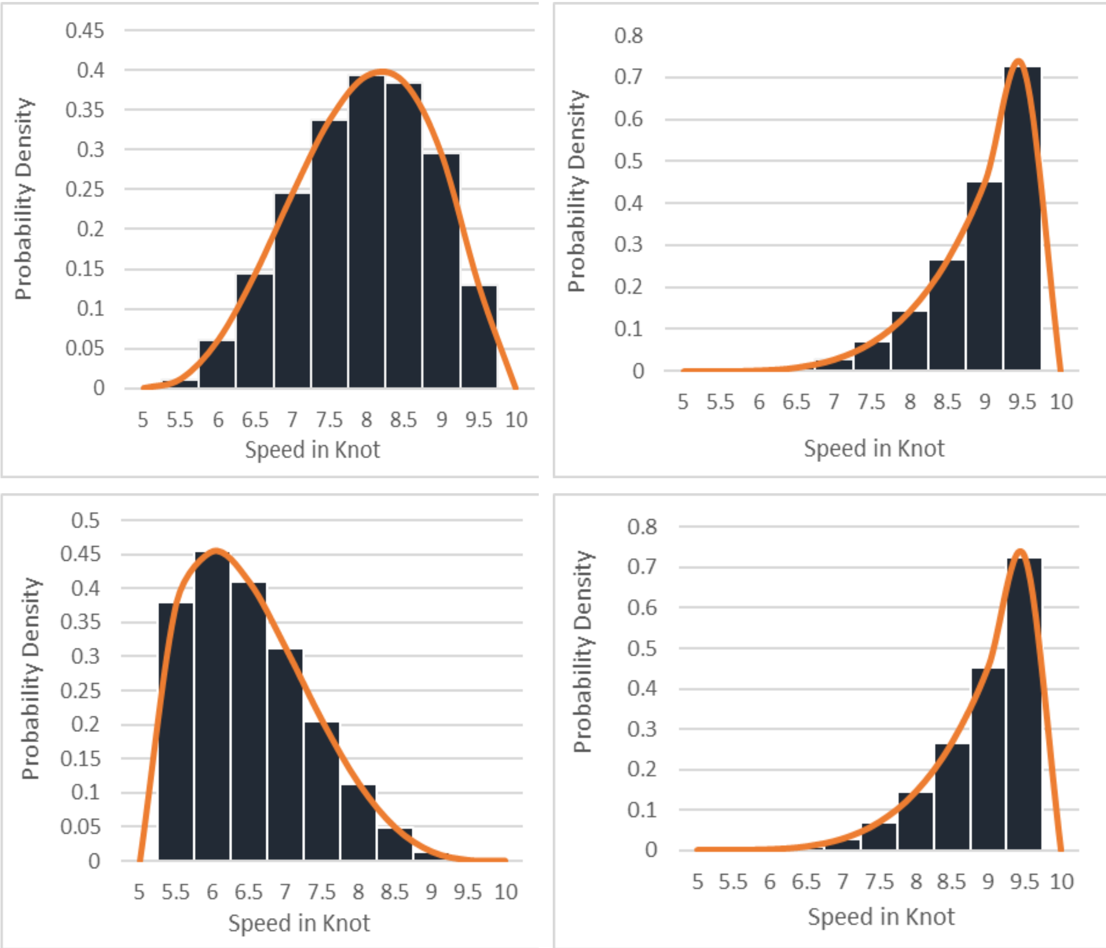


Figure 9: Appendix A: Zone Nine Speed distribution

Table 9: Appendix A: Zone Nine speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	8.0 knot	5.0	9.9	8.2 knot
Bulk	9.1 knot	5.0	9.9	9.9 knot
Tanker	9.1 knot	5.0	9.9	9.9 knot
Passengers	6.5	5.0	9.9	6.0 knot

Zone 10 speed distribution

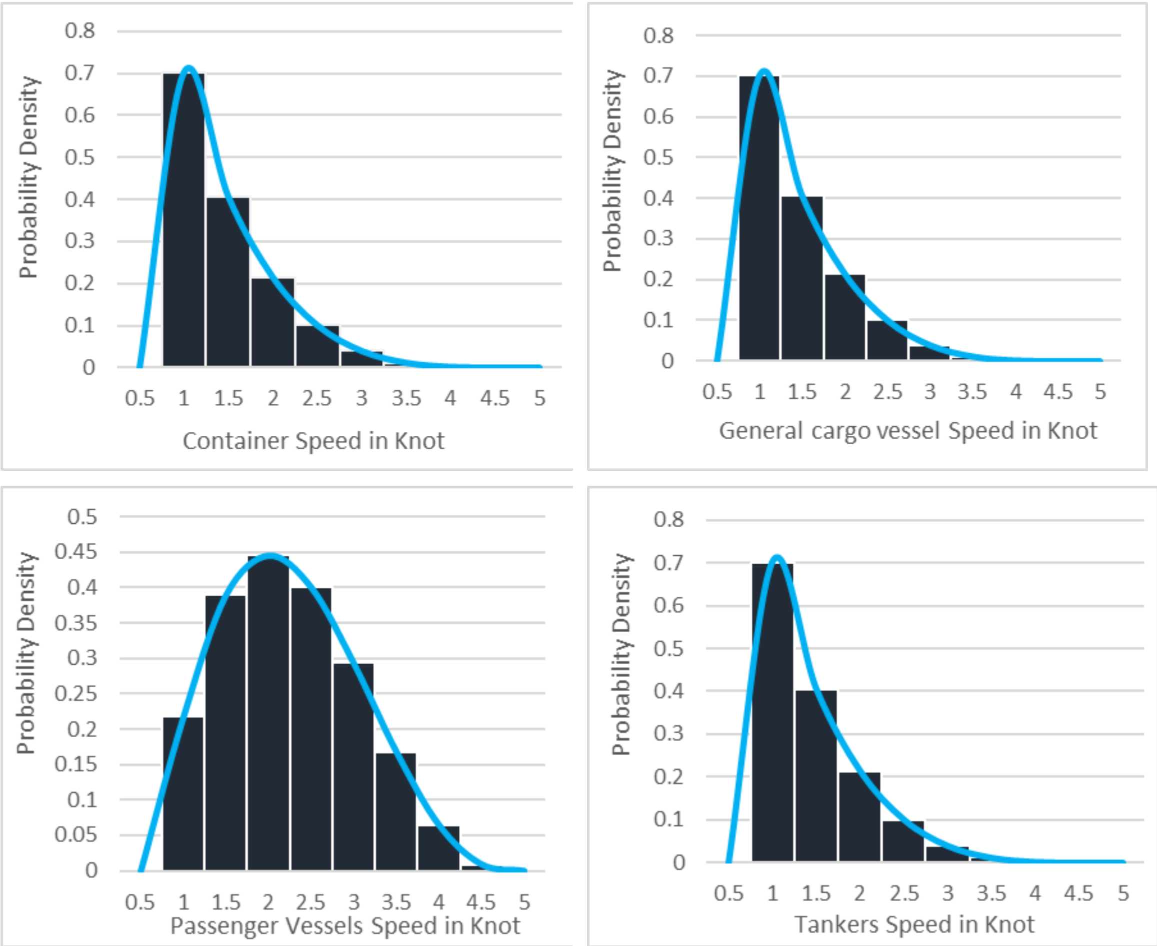


Figure 10: Appendix A: Ten Speed distribution

Table 10: Appendix A: Zone Ten speed values based on vessel types

Vessel Type	Average Speed	Minimum	Maximum	Mode
Container	1.2 knot	0.5	4.9	0.5 knot
Bulk	1.2 knot	0.5	4.9	0.5 knot
Tanker	1.2 knot	0.5	4.9	0.5 knot
Passengers	2.2 knot	0.5	4.9	2 knot

Vessel Speed when vessels stop at Cargo Terminal, Anchorage or Lock

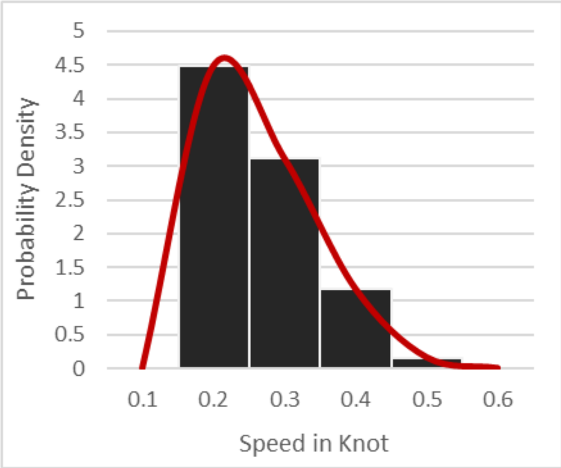


Figure 11: Appendix A: Speed distribution when vessel is stopped

Table 11: Appendix A: Zone Speed values when vessel stop regardless of vessel type

Vessel Type	Average Speed	Minimum	Maximum	Mode
All	0.3 knot	0.1	0.6	0.2 knot

Appendix B: Outer transit times distribution for the various vessel types from historical AIS data

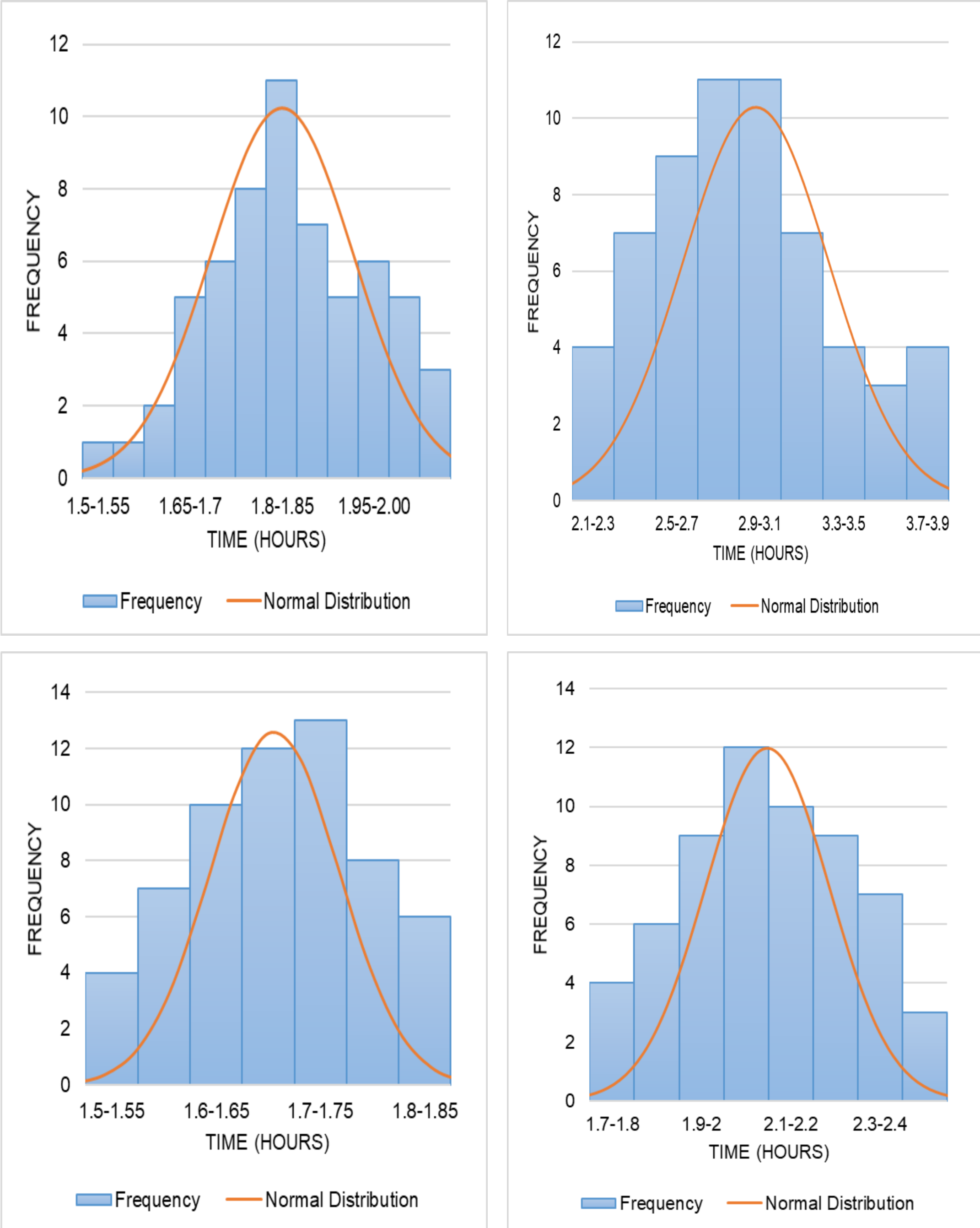


Figure 12: Appendix B: Outer Transit times distribution for the various vessel types.

Appendix C: Inner transit times distribution for the various vessel types

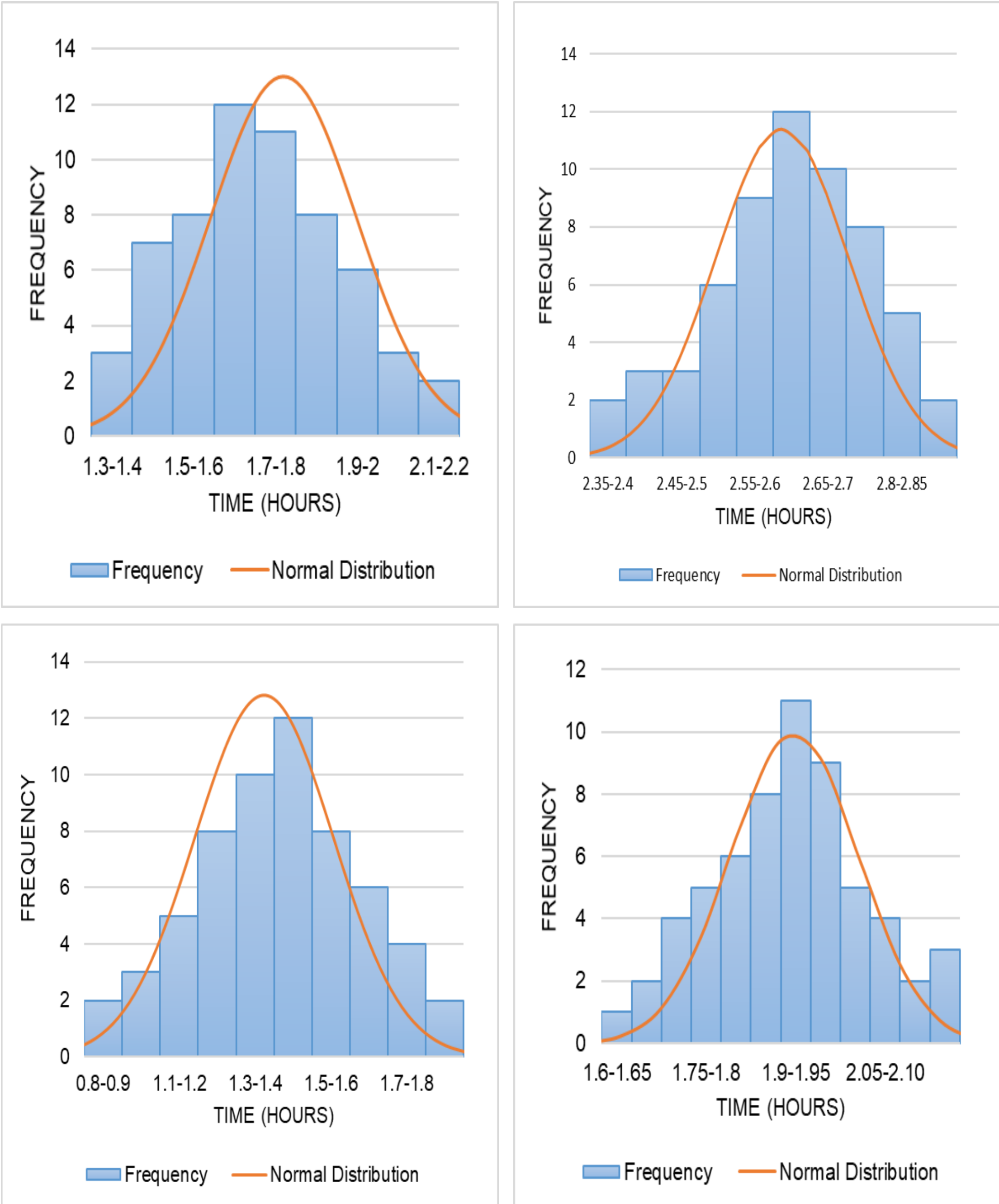


Figure 13: Appendix C: Inner Transit times distribution for the various vessel types.

Appendix D: Manoeuvring times distribution for the various vessel types

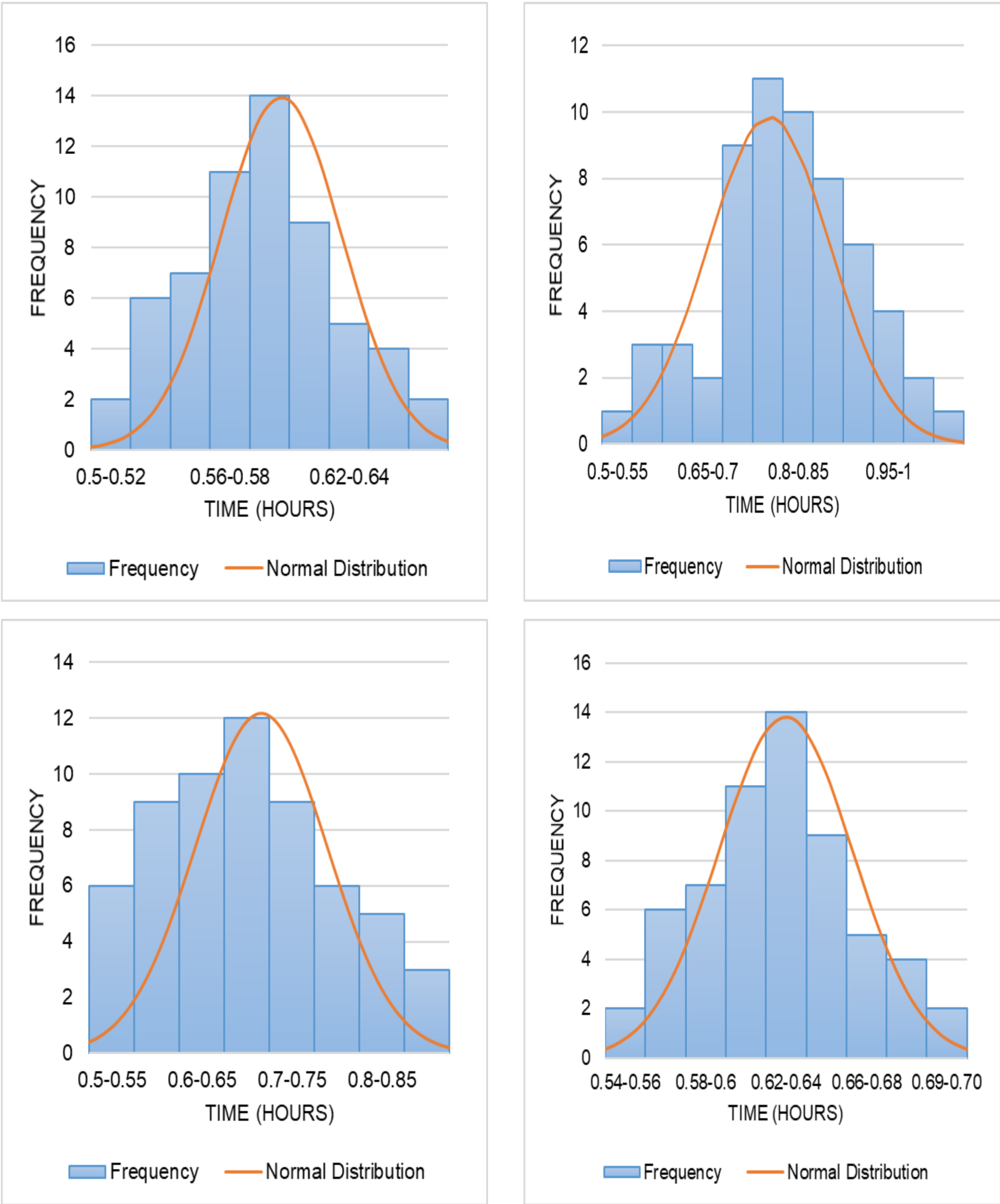
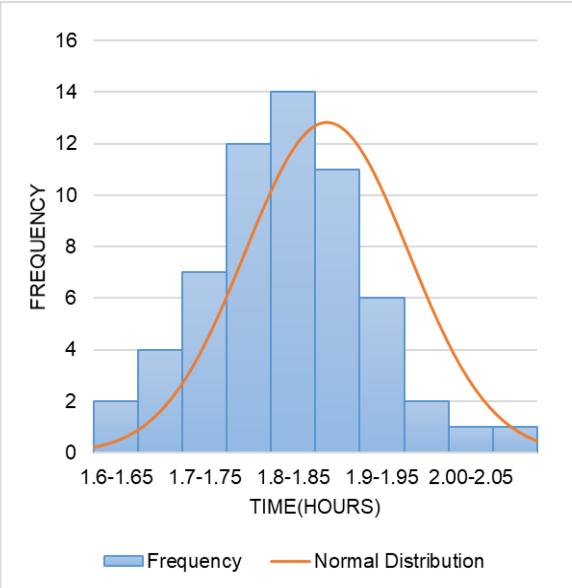
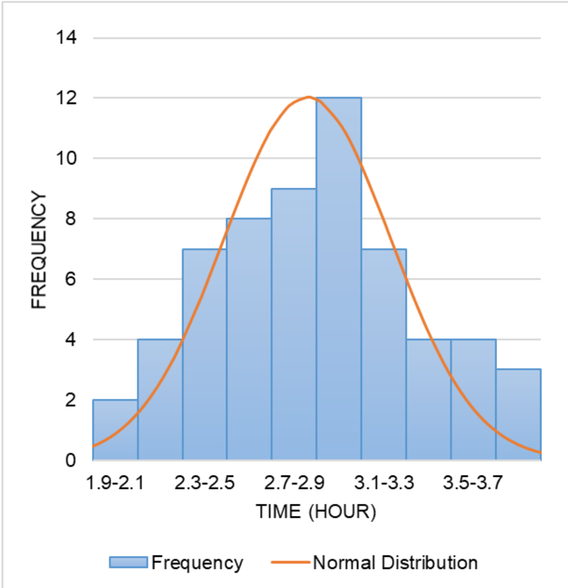


Figure 14: Appendix D: Manoeuvring time distribution for the various vessel types.

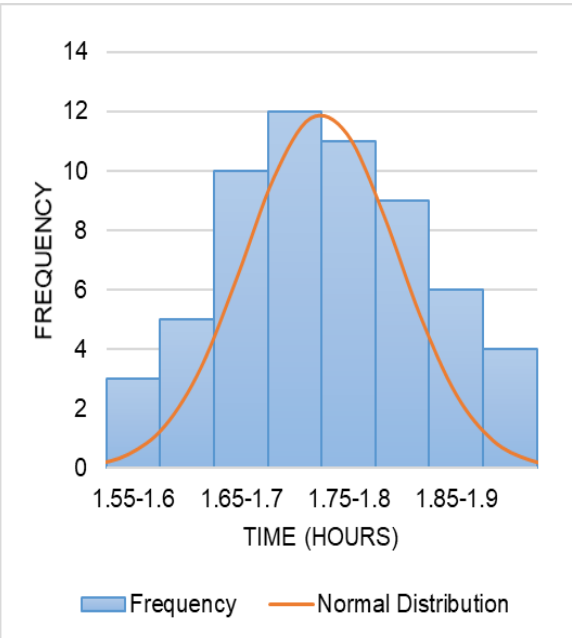
Appendix E: Outer transit times distribution for the various vessel types from simulation model output



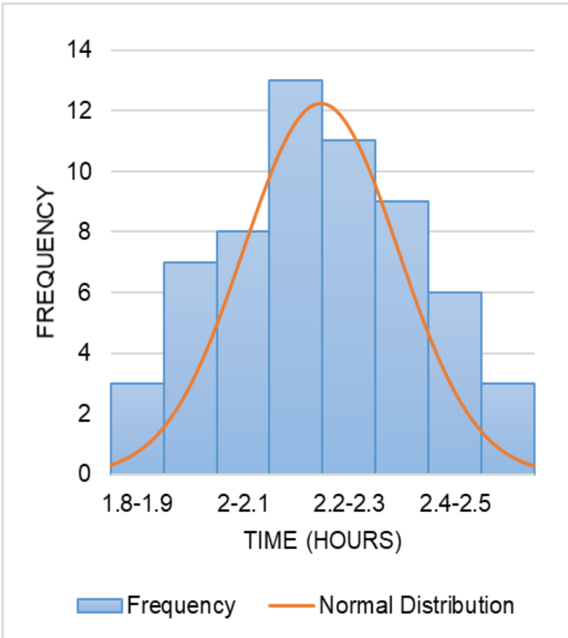
Container Vessels



General Cargo



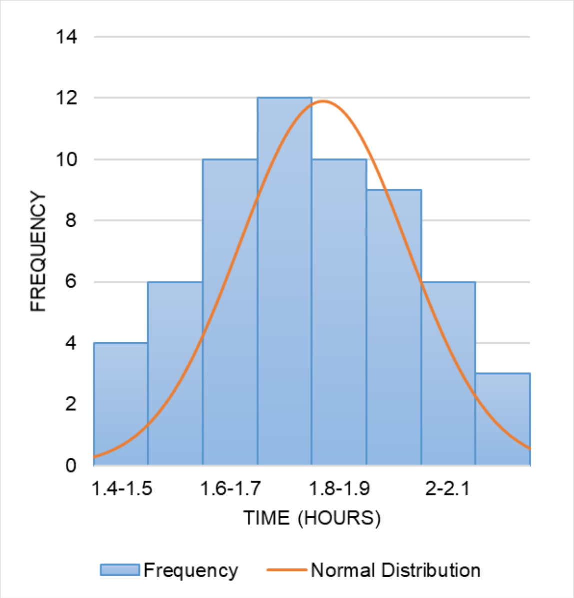
Passengers



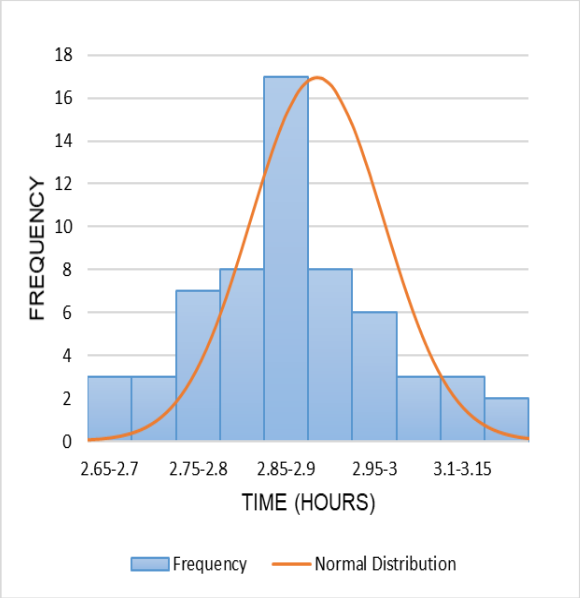
Tanker Vessel

Figure 15: Appendix E: Outer Transit time distribution from simulation model

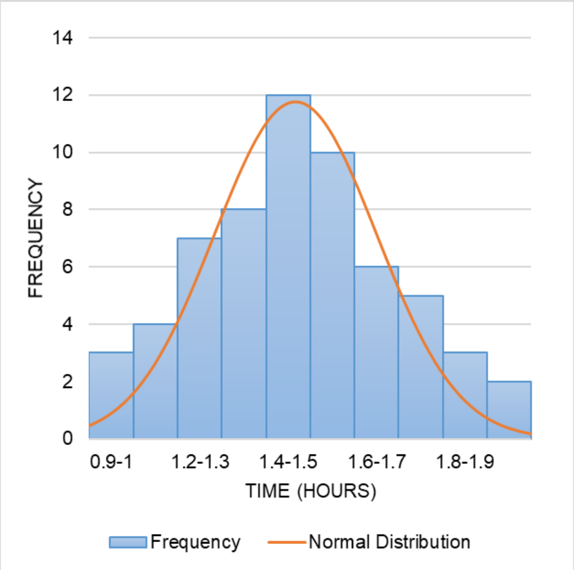
Appendix F: Inner transit times distribution for the various vessel types



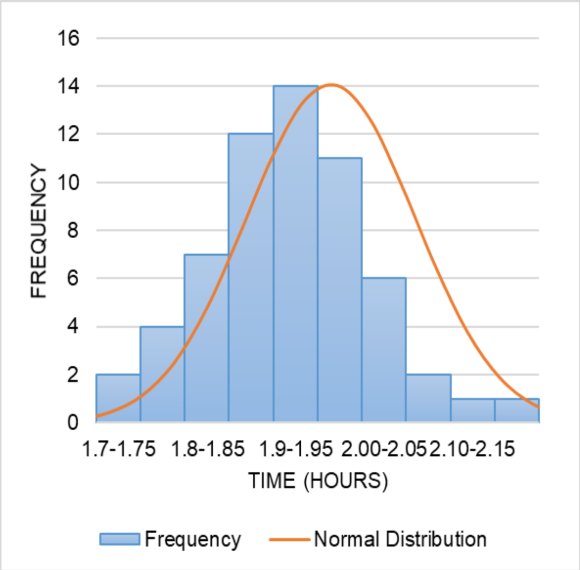
Container Vessels



General Cargo



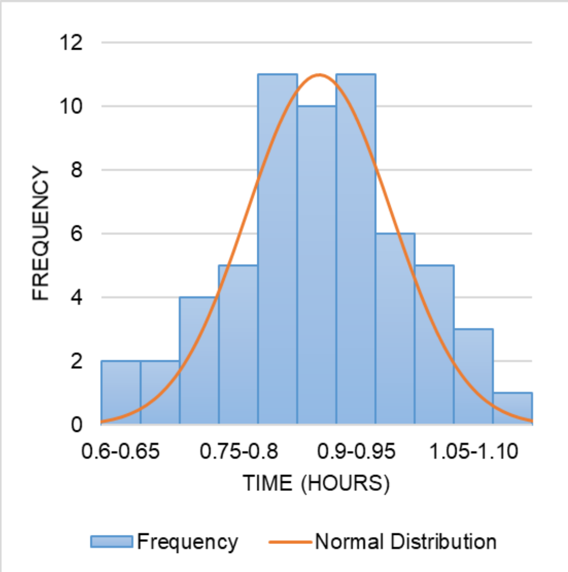
Passenger Vessel



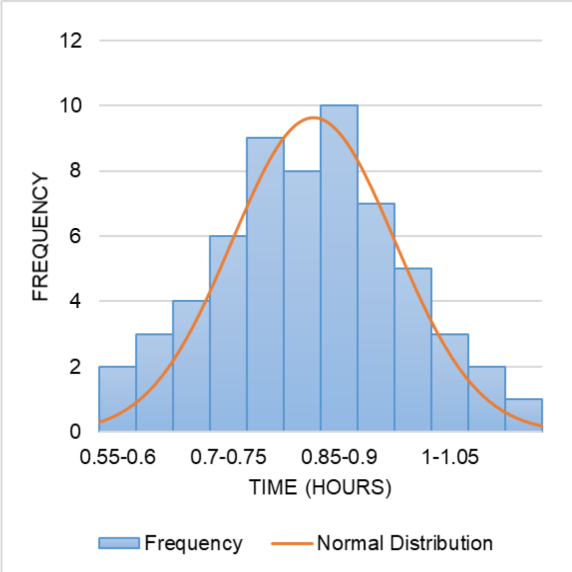
Tanker Vessel

Figure 16: Appendix F: Inner Transit time distribution from simulation model

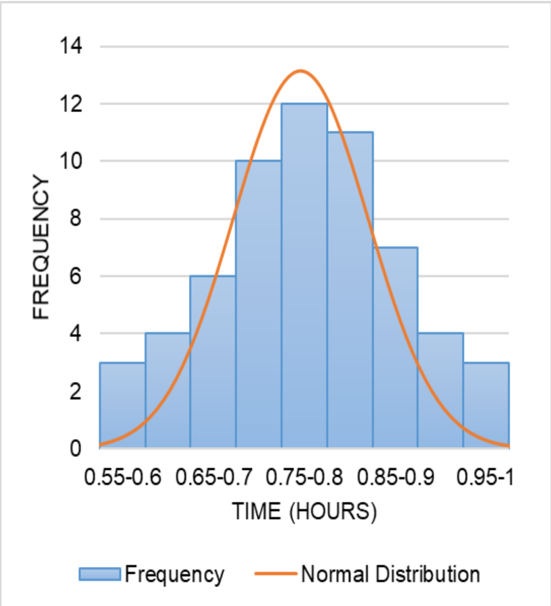
Appendix G: Manoeuvring time distribution for the various vessel types.



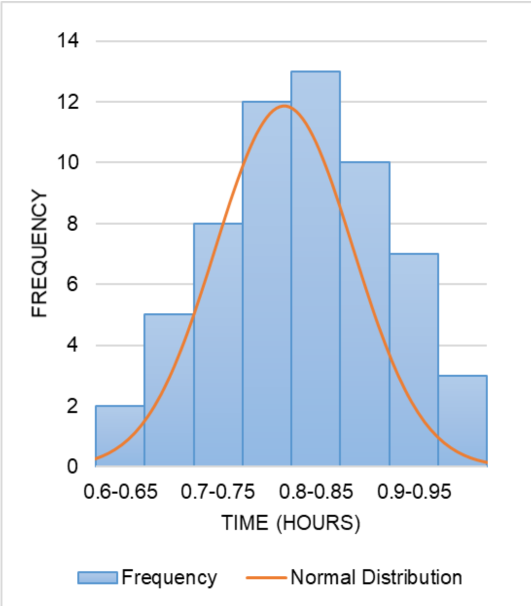
Container Vessels



General Cargo



Passenger Vessel



Tanker Vessel

Figure 17: Appendix G: Manoeuvring time distribution from simulation model

References

ABAR, S., THEODOROPOULOS, G. K., LEMARINIER, P. & O'HARE, G. M. P. 2017. Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Computer Science Review,* 24**,** 13-33.

ADAMS, M., QUINONEZ, P., PALLIS, A. & WAKEMAN, T. 2009. Environmental issues in port competitiveness. *Dalhousie University*.

ALESSANDRI, A., SACONE, S. & SIRI, S. 2007. Modelling and Optimal Receding-horizon Control of Maritime Container Terminals. *Journal of Mathematical Modelling and Algorithms,* 6**,** 109-133.

ALMAZ, O. A. & ALTIOK, T. 2012. Simulation modeling of the vessel traffic in Delaware River: Impact of deepening on port performance. *Simulation Modelling Practice and Theory,* 22**,** 146-165.

ANGELOUDIS, P. & BELL, M. G. H. 2011. A review of container terminal simulation models. *Maritime Policy & Management,* 38**,** 523-540.

ANOSIKE, A. & ZHANG, D. 2000. An Agent-Oriented Modelling Approach for Agile Manufacturing. *School of Engineering and Computer Science, University of Exeter, Exeter, United Kingdom*.

ANYLOGIC 2014. AnyLogic, 2014. [Online]. Available: http://www.anylogic.com.

BANDINI, S., MANZONI, S. & VIZZARI, G. 2009. Agent based modeling and simulation: an informatics perspective. *Journal of Artificial Societies and Social Simulation,* 12**,** 4.

BEHDANI, B. Evaluation of paradigms for modeling supply chains as complex socio-technical systems. Simulation Conference (WSC), Proceedings of the 2012 Winter, 2012. IEEE, 1-15.

BELLSOLÀ OLBA, X., DAAMEN, W., VELLINGA, T. & HOOGENDOORN, S. P. 2017. Network capacity estimation of vessel traffic: an approach for port planning. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 143**,** 04017019.

BELLSOLÀ OLBA, X., DAAMEN, W., VELLINGA, T. & HOOGENDOORN, S. P. 2018. State-of-the-art of port simulation models for risk and capacity assessment based on the vessel navigational behaviour through the nautical infrastructure. *Journal of Traffic and Transportation Engineering (English Edition),* 5**,** 335-347.

BHAMU, J. & SANGWAN, K. S. 2014. Lean manufacturing: literature review and research issues. *International Journal of Operations & Production Management,* 34**,** 876-940.

BORSHCHEV, A. Multi-method modeling. Proceedings of the 2013 Winter Simulation Conference: Simulation: Making Decisions in a Complex World, 2013. IEEE Press, 4089-4100.

BORSHCHEV, A. & FILIPPOV, A. From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. Proceedings of the 22nd international conference of the system dynamics society, 2004.

BURMEISTER, B., HADDADI, A. & MATYLIS, G. 1997. Application of multi-agent systems in traffic and transportation. *IEE Proceedings-Software,* 144**,** 51-60.

CARTENÌ, A., CANTARELLA, G. & DE LUCA, G. 2009. Simulation of a container terminal through a discrete event approach: literature review and guidelines for application. *Technical Paper, Dept. of Civil Engineering, University Of Salerno*.

CASACA, A. C. P. 2005. Simulation and the Lean Port Environment. *Maritime Economics & Logistics,* 7**,** 262-280.

CASTELLS, M., SANTAMARÍA, U. & MARTÍNEZ DE OSÉS, F. X. 2014. Manoeuvring and hotelling external costs: enough for alternative energy sources? *Maritime Policy & Management,* 41.

CHEN, L., HOPMAN, H. & NEGENBORN, R. R. 2018. Distributed model predictive control for vessel train formations of cooperative multi-vessel systems. *Transportation Research Part C: Emerging Technologies,* 92**,** 101-118.

CHEON, S. & DEAKIN, E. 2010. Supply chain coordination for port sustainability: lessons for new institutional designs. *Transportation Research Record: Journal of the Transportation Research Board***,** 10-19.

CHIU, R.-H., LIN, L.-H. & TING, S.-C. 2014. Evaluation of Green Port Factors and Performance: A Fuzzy AHP Analysis. *Mathematical Problems in Engineering,* 2014**,** 12.

CULLINANE, K. 2002. The productivity and efficiency of ports and terminals: methods and applications. In:The Grammenos C (ed) The handbook of maritime economics and business. Informa Professional, London, pp 803–831.

DARBRA, R. M., RONZA, A., STOJANOVIC, T. A., WOOLDRIDGE, C. & CASAL, J. 2005. A procedure for identifying significant environmental aspects in sea ports. *Marine Pollution Bulletin,* 50**,** 866-874.

DAVYDENKO, I. & FRANSEN, R. 2019. Conceptual agent based model simulation for the Port Nautical Services. *IFAC-PapersOnLine,* 52**,** 19-24.

DEMIRCI, E. 2003. Simulation modelling and analysis of a port investment. *Simulation,* 79**,** 94-105.

DENG, H., TAN, H., LI, F., CAI, M., CHAN, P. W., XU, H., HUANG, X. & WU, D. 2016. Impact of relative humidity on visibility degradation during a haze event: A case study. *Science of The Total Environment,* 569-570**,** 1149-1158.

DRAGOVIĆ, B., PARK, N. K., RADMILOVIĆ, Z. & MARAŠ, V. 2005. Simulation modelling of ship-berth link with priority service. *Maritime Economics & Logistics,* 7**,** 316-335.

DRAGOVIĆ, B., TZANNATOS, E. & PARK, N. K. 2017. Simulation modelling in ports and container terminals: literature overview and analysis by research field, application area and tool. *Flexible Services and Manufacturing Journal,* 29**,** 4-34.

EBERLY, D. 2001. Intersection of convex objects: The method of separating axes. *Geometric Tools, LLC http://www. geometrictools. com,(1998− 2008)*.

ENTEC 2002. Quantification of emissions from ships associated with ship movements between ports in the European Community. A report for the European Commission, July 2002.

FORRESTER, J. W. 1994. System dynamics, systems thinking, and soft OR. *System dynamics review,* 10**,** 245-256.

FRANKEL, E. G. 1987. Port Planing and Development, Wiley, New York (1987).

FRANKEL, E. G. 1989. Strategic planning applied to shipping and ports. *Maritime Policy & Management,* 16**,** 123-132.

FUSCO GIRARD, L. 2013. Toward a Smart Sustainable Development of Port Cities/Areas: The Role of the “Historic Urban Landscape” Approach. *Sustainability,* 5**,** 4329.

GALATIOTO, F., HUANG, Y., PARRY, T., BIRD, R. & BELL, M. 2015. Traffic modelling in system boundary expansion of road pavement life cycle assessment. *Transportation Research Part D: Transport and Environment,* 36**,** 65-75.

GÓMEZ, A. G., ONDIVIELA, B., PUENTE, A. & JUANES, J. A. 2015. Environmental risk assessment of water quality in harbor areas: A new methodology applied to European ports. *Journal of Environmental Management,* 155**,** 77-88.

HASSAN, S. A. 1993. Port activity simulation: an overview. *ACM SIGSIM Simulation Digest,* 23**,** 17-36.

HINDS, A. 2007. Port Sustainability Task Force grasps pressing realities. AAPA Seaports Magazine,Winter. Available at http://www.aapa-ports.org/Publications/SeaportsDetail.cfm?itemnumber=8914#seaportsarticle5. Accessed 22 February 2017.

HIRANANDANI, V. 2014. Sustainable development in seaports: a multi-case study. *WMU Journal of Maritime Affairs,* 13**,** 127-172.

HUANG, S. Y., HSU, W. J., FANG, H. & SONG, T. 2016. MTSS--A Marine Traffic Simulation System and Scenario Studies for a Major Hub Port. *ACM Transactions on Modeling and Computer Simulation (TOMACS),* 27**,** 1-26.

INCE, A. N. & TOPUZ, E. 2004. Modeling and simulation for safe and efficient navigation in narrow waterways. Journal of navigation, 57(1), 53–71, 2004.

ISLAM, S. & OLSEN, T. Factors affecting seaport capacity. 19th International Congress on Modelling and Simulation, Perth, Western Australia, 2011. 412-418.

JALKANEN, J.-P., BRINK, A., KALLI, J., PETTERSSON, H., KUKKONEN, J. & STIPA, T. 2009. A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. *Atmospheric Chemistry and Physics,* 9**,** 9209-9223.

KEMME, N. 2020. Reducing Vessel Waiting Times to Support Port Service Quality. https://www.linkedin.com/pulse/reducing-vessel-waiting-times-support-port-service-quality-nils-kemme/.

KIA, M., SHAYAN, E. & GHOTB, F. 2002. Investigation of port capacity under a new approach by computer simulation. *Computers and Industrial Engineering,* 42**,** 533-540.
KONTOVAS, C. & PSARAFTIS, H. N. 2011. Reduction of emissions along the maritime intermodal container chain: operational models and policies. *Maritime Policy & Management,* 38**,** 451-469.
KOTOWSKA, I. 2016. Policies Applied by Seaport Authorities to Create Sustainable Development in Port Cities. *Transportation Research Procedia,* 16**,** 236-243.
KUZNETSOV, A., DINWOODIE, J., GIBBS, D., SANSOM, M. & KNOWLES, H. 2015. Towards a sustainability management system for smaller ports. *Marine Policy,* 54**,** 59-68.
LAM, J. S. L. & NOTTEBOOM, T. 2014. The greening of ports: a comparison of port management tools used by leading ports in Asia and Europe. *Transport Reviews,* 34**,** 169-189.
LANSDOWNE, A. 2006. *Traffic simulation using agent-based modelling*, University of the West of England.
LEHNFELD, J. & KNUST, S. 2014. Loading, unloading and premarshalling of stacks in storage areas: Survey and classification. *European Journal of Operational Research,* 239**,** 297-312.
LI, B., TAN, K. W. & TRAN, K. T. Traffic simulation model for port planning and congestion prevention. 2016 Winter Simulation Conference (WSC), 2016. IEEE, 2382-2393.
LIN, J., GAO, B. & ZHANG, C. 2014. Simulation-based investment planning for Humen Port. *Simulation Modelling Practice and Theory,* 40**,** 161-175.
LORENZON, F., TSIMPLIS, M., PAPADAS, S. & SONG, M. 2017. International Regulations for Preventing Collisions at Sea 1972, as amended (COLREG 1972) and STM.
MACAL, C. & NORTH, M. Introductory tutorial: Agent-based modeling and simulation. Proceedings of the 2014 Winter Simulation Conference, 2014. IEEE Press, 6-20.
MCCONNELL, M. 2002. Capacity building for a sustainable shipping industry: a key ingredient in improving coastal and ocean and management. *Ocean & Coastal Management,* 45**,** 617-632.
MICHEL, F., FERBER, J. & DROGOUL, A. 2018. Multi-agent systems and simulation: A survey from the agent commu-nity's perspective. *Multi-Agent Systems.* CRC Press.
MOON, D. S.-H. & WOO, J. K. 2014. The impact of port operations on efficient ship operation from both economic and environmental perspectives. *Maritime Policy & Management,* 41**,** 444-461.
NASIRZADEH, F., KHANZADI, M. & MIR, M. 2018. A hybrid simulation framework for modelling construction projects using agent-based modelling and system dynamics: an application to model construction workers' safety behavior. *International Journal of Construction Management,* 18**,** 132-143.

OH, H. N. H., TSOURDOS, A. & SAVVARIS, A. 2014. Development of collision avoidance algorithms for the c-enduro usv. *IFAC Proceedings Volumes,* 47**,** 12174-12181.

PARASKEVADAKIS, D., BURY, A., WANG, J., REN, J., BONSALL, S. & JENKINSON, I. 2016. The impact of transport infrastructure projects on sustainable development within a major logistics gateway in North West England. *Logistics & Sustainable Transport,* 7**,** 28-40.

PARK, C. S. & NOH, Y. D. 1987. An interactive port capacity expansion simulation model. *Engineering costs and production economics,* 11**,** 109-124.

PAROLA, F. & SCIOMACHEN, A. 2005. Intermodal container flows in a port system network:: Analysis of possible growths via simulation models. *International Journal of Production Economics,* 97**,** 75-88.

PETERING, M. E. H., WU, Y., LI, W., GOH, M. & DE SOUZA, R. 2009. Development and simulation analysis of real-time yard crane control systems for seaport container transshipment terminals. *OR Spectrum,* 31**,** 801-835.

PICCOLI, C. 2014. Assessment of Port Marine Operations Performance by Means of Simulation. Case study: The Port of Jebel Dhanna/Ruwais–UAE.

R, A., DEARN 2021. The Rule of Twelfths explained. https://www.cockpitcards.co.uk/rule-of-twelfths-explained/.

RAHMANDAD, H. & STERMAN, J. 2008. Heterogeneity and network structure in the dynamics of diffusion: Comparing agent-based and differential equation models. *Management Science,* 54**,** 998-1014.

RASHIDI, H. & TSANG, E. P. K. 2013. Novel constraints satisfaction models for optimization problems in container terminals. *Applied Mathematical Modelling,* 37**,** 3601-3634.

RICCI, S., MARINACCI, C. & RIZZETTO, L. 2014. The Modelling Support to Maritime Terminals Sea Operation: The Case Study of Port of Messina. *Journal of Maritime Research,* 9**,** 39-44.

SCOTT, D., TAYLOR, D., EL-SOLH, S. & ELLIOTT, T. 2016. Port simulation modelling and economic assessment. *Journal of Marine Science and Engineering,* 4**,** 16.

SEBASTIAN 2020. Three-Point Estimating and PERT Distribution (Cost & Time Estimation). *https://project-management.info/three-point-estimating-pert/*.

SPACCAPIETRA, S., PARENT, C., DAMIANI, M. L., DE MACEDO, J. A., PORTO, F. & VANGENOT, C. 2008. A conceptual view on trajectories. *Data & knowledge engineering,* 65**,** 126-146.

SUN, Z., LEE, L. H., CHEW, E. P. & TAN, K. C. 2012. MicroPort: A general simulation platform for seaport container terminals. *Advanced Engineering Informatics,* 26**,** 80-89.

THIERS, G. F. & JANSSENS, G. K. 1998. A port simulation model as a permanent decision instrument. *Simulation,* 71**,** 117-125.

THOMPSON, M., NOWAK, V., SOUTHERN, A., DAVIES, J. & FURMEDGE, P. 2020. Re-grounding the city with Polanyi: From urban entrepreneurialism to entrepreneurial municipalism. *Environment and Planning A: Economy and Space,* 52**,** 1171-1194.

TICHAVSKA, M. & TOVAR, B. 2015. Port-city exhaust emission model: An application to cruise and ferry operations in Las Palmas Port. *Transportation Research Part A: Policy and Practice,* 78**,** 347-360.

TIME AND DATE 2020. Time and date. *https://www.timeanddate.com/*.

UĞURLU, O., YÜKSEKYıLDıZ, E. & KÖSE, E. 2014. Simulation model on determining of port capacity and queue size: a case study for BOTAS Ceyhan Marine Terminal. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation,* 8.

UNCTAD 2012. United Nations Conference on Trade and Development. Review of Maritime Transport 2012, United Nations, Geneva, Switzerland, 2012.

UNCTAD 2019. United Nation Conference on Trade and Development Review of Maritime Transport Access Date: 10.01.2020 Retrieved from https://unctad.org/en/PublicationChapters/rmt2019ch1_en.pdf.

VADLAMUDI, J. C. 2016. *How a Discrete event simulation model can relieve congestion at a RORO terminal gate system : Case study: RORO port terminal in the Port of Karlshamn.* Independent thesis Advanced level (degree of Master (Two Years)) Student thesis.

VAROL, A. E. & GUNAL, M. M. Simulation Modeling of Maritime Piracy using Discrete Event and Agent-Based Approaches. SIMULTECH, 2013. 438-445.

VAZIRGIANNIS, M. & WOLFSON, O. A spatiotemporal model and language for moving objects on road networks. International Symposium on Spatial and Temporal Databases, 2001. Springer, 20-35.

WERNER, J. 2020. Planning for Tides & the Rule of Twelfths. https://www.allatsea.net/planning-tides-rule-twelfths/.

WPS, W. P. S. 2020. Port of Liverpool. http://www.worldportsource.com/ports/review/GBR_Port_of_Liverpool_86.php.

XIANG, X., KENNEDY, R., MADEY, G. & CABANISS, S. Verification and validation of agent-based scientific simulation models. Agent-Directed Simulation Conference, 2005. 47-55.

XU, W., LIU, X. & CHU, X. Simulation models of vessel traffic flow in inland multi-bridge waterway. 2015 International Conference on Transportation Information and Safety (ICTIS), 2015. IEEE, 505-511.

YEO, G.-T., ROE, M. & SOAK, S.-M. 2007. Evaluation of the marine traffic congestion of north harbor in busan port. *Journal of waterway, port, coastal, and ocean engineering,* 133**,** 87-93.

YUN, W. Y. & CHOI, Y. S. 1999. A simulation model for container-terminal operation analysis using an object-oriented approach. *International Journal of Production Economics,* 59**,** 221-230.

ZHANG, D. Z., ANOSIKE, A. I., LIM, M. K. & AKANLE, O. M. 2006. An agent-based approach for e-manufacturing and supply chain integration. *Computers & Industrial Engineering,* 51**,** 343-360.

ZHOU, Y., DAAMEN, W., VELLINGA, T. & HOOGENDOORN, S. 2019. Review of maritime traffic models from vessel behavior modeling perspective. *Transportation Research Part C: Emerging Technologies,* 105**,** 323-345.