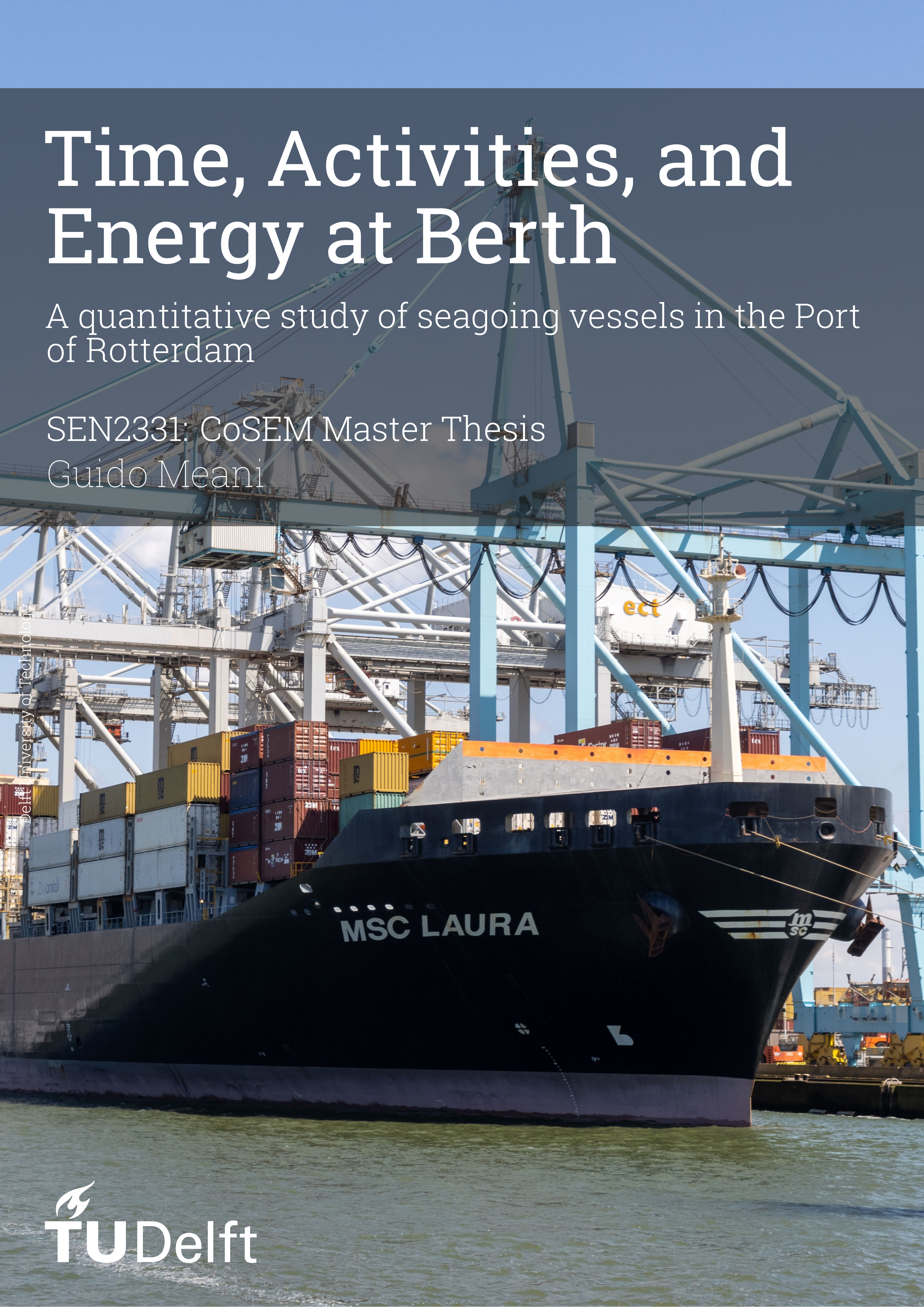

Time, Activities, and Energy at Berth

A quantitative study of seagoing vessels in the Port of Rotterdam

SEN2331: CoSEM Master Thesis

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Time, Activities, and Energy at Berth

A quantitative study of seagoing vessels in the Port of Rotterdam

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Summary

In the Netherlands, the maritime sector and ports stand as vital arteries of the nation's economy, with a legacy deeply rooted in history. Since the Dutch Golden Age, when the country emerged as a maritime powerhouse, its ports have served as gateways to the world, facilitating trade and commerce on a global scale. Over the centuries, this maritime tradition has evolved, adapting to changing times and technologies, yet retaining its fundamental importance. Today, the maritime sector and ports play a crucial role in sustaining the Netherlands' position as a major player in international trade. With world-class facilities and strategic geographic location, Dutch ports serve as key hubs for goods transhipment, connecting Europe to the rest of the world. Nonetheless, the maritime sector produces high levels of harmful pollution both for the environment and the people. Numerous research studied the effects of port-related emissions on health and the environment, linking ship exhaust emissions to a multitude of fatalities worldwide, attributed to conditions including cancer and cardiovascular diseases. The concern should be even more important in the Netherlands, considering that the Port of Rotterdam is one of Europe's highest emitter of greenhouse gases (GHGs) and air pollutants, and the two main Dutch ports alone (Rotterdam and Amsterdam) are located close to about 25 per cent of the Dutch population. Port-related emissions are partially due to berthed ships. Moored ships require a continuous supply of energy to perform essential operations such as loading and unloading cargo, maintaining ventilation and heating, and supporting the crew's needs. This energy is predominantly generated by the ships' engines, which function as power plants running on marine fuel oil or other fossil fuels. This setup leads to significant emissions in the proximity of people and limited energy efficiency, as each ship burns fuel independently, contributing to pollution and energy waste in the port environment. Nevertheless, entities like the Port of Rotterdam and research institutes could produce emission inventories to gain insight into ports' environmental impact and assist data-driven decision-making thanks to dynamic and static data provided by technical databases like the Clarskons' World Fleet Register and the Automatic Identification System (AIS) - a tracking system developed to provide identification and positioning information to both vessels and shore stations. This methodology multiplies the time each vessel spends moored by an emission factor specific to that ship's engine and fuel type. By assessing the duration of a ship's stay and applying this standardized emission factor, researchers could estimate the total emissions produced during the berthing phase.

However, this approach might not be sufficient to cope with the system's complexity. Ships frequently come and go, with some visiting a port only once, while others return sporadically, sometimes equipped with different engines or modified systems. The duration of their stay at the port can also vary widely. Moreover, the global fleet consists of thousands of seagoing vessels, each with distinct characteristics, engine types, and fuel usage patterns. This immense diversity and the constantly changing nature of ship activity make it difficult to accurately measure and track emissions, adding to the complexity of managing and mitigating their environmental impact. Although the most commonly used approach helps provide a more structured estimation of emissions, it relies on fixed factors and overlooks berthing duration and activities: they assume the same emission factors regardless of the operations performed by vessels. Thus hindering effective emission reduction strategies and infrastructure development. Moreover, the only currently available alternative to estimate emissions accurately is to collect fuel-consumption records of all ships visiting a port, which requires high transaction costs and is seldom used in literature.

Consequently, there is a need to improve current methods without excessively increasing transaction costs, but how is still unknown. This study proposes a first step towards this direction by looking at the relationship between berthing time, activities, and energy consumption of berthed vessels. This study aims not only to expose the limits of the current approach but also to show that the current emission inventories could be improved by using already-existing data.

The research employed a quantitative approach that provides a generalizable methodology while still permitting the detailed examination of specific cases. The quantitative data analysis used AIS data from the Port of Rotterdam and technical data from the Clarskons' World Fleet Register to cluster ships according to their technical and commercial characteristics and to construct temporal berthing patterns. The ship clusters have been determined based on similarities in their technical and commercial characteristics - for instance 'tankers' for all the vessels carrying liquid in bulk. The temporal patterns have been defined considering the frequency and duration of berthing events simultaneously through a modified load duration curve. The qualitative component of the study consisted of semi-structured interviews, an unstructured consultation, and a field visit to validate the results, obtain feedback, and contextualise the research.

The overall conclusion of this study is that reality is more complicated than the models we use to represent it to the extent that these models may no longer be sufficient. At the same time, there is an opportunity to improve existing systems without having to invest in new data collection systems or having to implement new legal frameworks. In detail, the quantitative data analysis showed that not all berthing events are equal but non-standard berthing events are of comparable importance to standard berthing events in terms of duration and frequency - for instance, long but rare events contribute a non-negligible share of the total time in the port due to their length. This result proved two facts: one, it suggested the inadequacy of current methods; two, it showed that it is possible to identify types of stops by looking at their length and frequency alone (thus without the need for additional data). Furthermore, the data analysis also showed that system complexity is also reflected in the absence of a shared clear relationship between vessels' size and time spent in port: assuming that the bigger the ship, the longer it will stay in port is an intuition not supported by the facts; the data show that this relationship exists only in some cases. The qualitative analysis, on the other hand, confirmed the results of the quantitative part and suggested that continuing in this direction is possible; from the interviews, it emerged that the different stops might not only be different in terms of length and frequency but also in terms of activities performed and energy consumed. Furthermore, the interviews also showed a potential inadequacy in studying ships by fleet type as the product transported can influence the technical and behavioural structures of ships. In conclusion, this study revealed the potential inadequacy of current calculation methods, suggesting that investigating their uncertainties and possible improvements is feasible and potentially relevant for the industry and to avoid policy failures.

Three principal directions for future research are suggested: continue developing the new calculation methodology, delve deeper into the relationship between time and size, and study the phenomenon of multiple berthing events per port visit. Developing the new emission calculation methodology would be the next logical continuation of the research. Identifying three distinct stop types and the qualitative differences in energy consumption associated with each initiated the discussion about the current bottom-up methodology for calculating emissions from berthed vessels. The following action is quantifying the energy consumption for these different stop types and determining the corresponding emissions. Once these are quantified, a comparison can be made between the calculated emissions and those calculated in current emission inventories or reported in databases like the Thesis MRV. This comparison could help validate or challenge existing emissions data, providing a more accurate assessment of the environmental impact of berthing activities and better-informed decision-making. Second, the relationship between vessel size and berthing times could be a promising research direction. The current study's use of size categories from different industries did not reveal clear patterns in berthing times, suggesting that these categories may not be the most effective for such analysis. Future research could focus specifically on the relationship between vessel size and berthing time, potentially through a reverse approach. Instead of applying predefined classes, future research could define size classes based on observed berthing times to develop a finer understanding of how vessel dimensions influence time spent at berth. Third, the presence of multiple berthing events during a single port visit warrants further investigation to understand its implications. Future studies could explore what these multiple stops signify regarding engine activity, operational efficiency, port congestion, and overall vessel behaviour. Analyzing these stops in greater detail could reveal patterns that might inform port management practices or suggest the need for revised pollution reduction strategies.

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Nomenclature

Abbreviations and chemical formulae

Abbreviations	Definition
AIS	Automatic Identification System
AE	Auxiliary Engine
AMP	Alternative Maritime Power
BC	Black Carbon
CH_4	Methane
CI	Cold ironing
CO	Carbon monoxide
CoSEM	Complex Systems Engineering and Management
CO_2	Carbon dioxide
DWT	Deadweight Tonnage
GHG	Greenhouse Gas
GT	Gross Tonnage
HC	Hydrocarbons
HFO	Heavy fuel oil
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MDO	Maritime diesel oil
MPP	Multi-Purpose Product vessel
ME	Main Engine
$NMVOC$	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
OPS	On-shore Power Supply
PCC	Pure Car Carrier
PM	Particulates from marine diesel engines irrespective of fuel type
PM-MDO	Particulates from marine diesel engines operated with marine diesel oil
PM-HFO	Particulates from marine diesel engines operated with heavy fuel oil
SO_2	Sulphur dioxide
VOC	Volatile Organic Compounds

Glossary

Table 2: Ship types

Term	Definition
Bulkers	Ships specially designed to transport unpackaged bulk cargo
Chemical Tankers	Ships designed to transport or store chemical products in bulk
Combos	Combinational carrier - ships intended for carriage of both oil and dry cargoes in bulk
Containerships	Vessels capable of transporting containers
Crude Tankers	Ships designed to transport or store crude oil in bulk
Cruise	Large passenger ships used mainly for vacationing
Dredgers	Vessels capable of dredging
Ferries	Watercrafts that carries passengers, and sometimes vehicles and cargo
General Cargo	Ships that can carry different types of cargo simultaneously or not.
LNG	Ships designed to transport or store LNG (liquefied natural gas) in bulk
LPG	Ships designed to transport or store LPG (liquefied petroleum gas) in bulk
MPP	Multi-Purpose Product vessel. A seagoing ship designed to carry a wide range of cargoes
Offshore	Ships serving operational purposes such as oil exploration and construction work on the high seas
Other Non Cargo	Other vessels
PCC	Pure Car Carrier. A ship designed to carry cars.
Product Tankers	Ships designed to transport or store petroleum products in bulk
Refrigerated Cargo Vessels	Refrigerated cargo ships
Ro-Ro	Roll-on/roll-off. Ships designed to carry wheeled cargo
Specialized Tankers	Ships designed to transport or store liquids or gases in bulk, specialised for a cargo type
Tugs	Vessels that manoeuvre other vessels by pushing or pulling them, with direct contact or a tow line

1

Introduction

1.1. Problem introduction

In the Netherlands, the maritime sector and ports stand as vital arteries of the nation's economy, with a legacy deeply rooted in history: in 2022, the total added value of the combined port and maritime cluster amounted to €72.4 billion (The Dutch Maritime Network, 2023). Since the Dutch Golden Age, when the country emerged as a maritime powerhouse, its ports have served as gateways to the world, facilitating trade and commerce on a global scale (NL flag, n.d.). Over the centuries, this maritime tradition has evolved, adapting to changing times and technologies, yet retaining its fundamental importance. Today, the maritime sector and ports play a crucial role in sustaining the Netherlands' position as a major player in international trade. With world-class facilities and strategic geographic location, Dutch ports serve as key hubs for the transhipment of goods, connecting Europe to the rest of the world. They handle millions of tons of cargo annually, ranging from raw materials to finished products, facilitating the flow of goods essential to industries and consumers alike.

Nonetheless, the maritime sector produces high levels of harmful pollution both for the environment and the people. Numerous research studied the effects of port-related emissions on health and the environment (such as emissions of aerosols marine diesel HFO, aerosols ship diesels MDO, carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulate matter (PM)), linking ship exhaust emissions to a multitude of fatalities worldwide, attributed to conditions including cancer and cardiovascular diseases (Xiao et al., 2018). Therefore, reducing emissions from ports is a commitment to the planet and a duty to the port workers and the citizens. Even more important in the Netherlands, considering that the Port of Rotterdam is one of Europe's highest emitter of greenhouse gases (GHGs) and air pollutants (Port of Rotterdam, 2022; Transport & Environmnent, 2022), and the two main Dutch ports alone (Rotterdam and Amsterdam) are located close to about 25 per cent of the Dutch population.

Government bodies and ports are trying to address these issues. For instance, the European Union is preparing a set of directives to guide the change in the sector. The first step was the EU MRV (Monitoring, Reporting, and Verification) Maritime Regulation (Regulation, 2015/757) which obliges some ships to report their verified emissions of CO_2, CH_4, and N_2O when visiting an European port; in 2023, the regulation was extended to a larger set of vessels (Regulation, 2023/957). These regulations pose the foundations for further intervention; for example, the FuelEU Maritime regulation (Regulation, 2023/1805). This regulation - which requires passenger and container ships to connect to onshore power supplies at major EU ports from 2030 (DNV, n.d.) - led many Dutch ports to invest in renewable energy sources such as wind and solar power to meet their energy needs sustainably and minimize harmful pollutants. One example is the Strategy for Shore Power in the Port of Rotterdam conducted in close collaboration between the Gemeente Rotterdam and the Port of Rotterdam (Port of Rotterdam, 2021). Beyond these initiatives, Dutch ports are also actively engaged in research and innovation to identify new technologies and best practices for sustainable and healthy port operations. This includes partnerships with academic institutions, industry stakeholders, and government bodies to foster collaboration and knowledge sharing. For instance, the Maritime Research Institute Netherlands (MARIN) produces every year an emission inventory from ship activity for the Dutch Emission Registry (Emissieregistratie) in collaboration with TNO (MARIN, 2022). These initiatives and regulations often result from data-driven decision-making and supported by emission inventories.

Emission inventories are essential as they allow for informed decision-making and agenda-setting; for this purpose, the European Environment Agency (EEA) publishes the guidelines to prepare national emission inventories. For the emission from vessels' activity, they distinguish three approaches, where the most precise and widely used also in scientific literature and outside Europe is a bottom-up approach. It determines pollution based on activity using two methods. The first requires knowledge of the amount of fuel consumed in each phase. The second estimate is the emission based on the activity. Knowing the precise fuel consumption requires a lot of data to be collected, interaction with many stakeholders, and a complex legal framework. For instance, ports like the Port of Rotterdam would have to interact with more than 5000 vessels and get fuel data of 30000+ port calls. As a result, the easiest way is to build emission inventories based on time spent in each activity (berth, manoeuvring, sailing) and estimate the emissions by multiplying the time times the emission factor.

Nonetheless, this method's convenience comes at a cost: this approach overlooks time, which is particularly relevant in the hotelling phase. Ships berthed at the port rely on their engines to power different operations (e.g., cargo handling, bunkering, and maintenance) (Ballini & Bozzo, 2015; Zhen et al., 2022), and these operations may not require the same amount of energy. The engines on a berthed ship would not necessarily produce a constant power output during hotelling operations. For instance, when a vessel is idling, the engines may run at a low load factor to maintain essential systems such as lighting, ventilation, and communication equipment; on the other hand, during cargo loading and unloading operations, the load factor may increase as the engine powers equipment such as cranes, conveyor belts, or pumps to transfer cargo to and from the ship. Thus, the load factor of the auxiliary engine might fluctuate based on the specific performed activities while berthed. The engine's power output would need to be adjusted accordingly to meet the varying demands of these operations while ensuring efficient and reliable performance.

From this situation, it is evident that in the dilemma between choosing an accurate estimate with high transaction costs (fuel consumption records) or an estimate with more uncertainty that relies on existing data (time as an independent variable), most researchers chose the latter. Consequently, it is necessary to explore whether and how existing methods can be improved. This study aims to perform the first step in this direction by analyzing the role of berthing time for seagoing vessels and creating a stepping stone for future research.

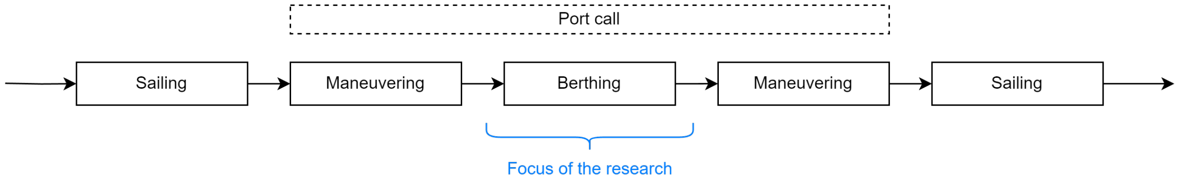
1.2. Context of the research

This section dives into the main concepts presented in the section above, outlining the research's context. These concepts emerged from the literature review extensively presented in Chapter 2. A crucial premise is that the research focuses only on the seagoing vessels that make up the socio-technical system of the port of Rotterdam. They include seagoing and international trade vessels, as well as service ships, fishing vessels and passenger ships but not Inland Waterways Ships.

The berthing phase

Vessels' in-port operations start before securing the ship at berth. Most literature and the Air Pollutant Emission Inventory Guidebook (European Environment Agency, 2023) identify three phases: sailing, manoeuvering, and berthing (Figure 1.1).

Figure 1.1: Simplified vessels' activity diagram



Sailing, in regional emission inventories, is the phase in which a vessel is still in open water and sails at high speeds - above 8 or 12 knots generally -, but it is also close enough to the port (Y. T. Chang et al., 2014; Chen et al., 2016; López-Aparicio et al., 2017; Ng et al., 2013; Tran et al., 2022; Tran & Lam, 2024; Yeo et al., 2024). Manoeuvring is the slow-speed phase where the ship approaches the dock; the literature generally applies a speed criterion to determine this phase, usually when speed is between 1 and 8 knots, (Chen et al., 2016; Ng et al., 2013; Tran et al., 2022) but some use also distance criteria (Sim, 2018). Eventually, the berthing phase, also called hotelling, is the stage where the ship is secured to land or some other fixed support inside a port and cargo is loaded and unloaded, the vessel goes through maintenance and repairs, refuelling and resupplying, et cetera. Moreover, during the berthing time, the main engines are off, while auxiliary engines and boilers are active, thus contributing the most to emissions (Chen et al., 2016). Auxiliary engines generate power for the vessels' onboard services, and boilers heat the fuel oil for auxiliary engines. In literature, to identify this stage from the status of the ship, a criterion based on speed is generally applied: if the vessel is "moving" at less than a knot, then it is docked at the port (Chen et al., 2016; Ng et al., 2013; Tran et al., 2022). Other research uses port data instead of ship data - for instance, Y. T. Chang et al. (2014) and Tran and Lam (2024) - and identifies this stage as the period between arrival and departure.

This study focuses only on the berthing phase since it is often identified as the major contributor to pollutant emissions (López-Aparicio et al., 2017; Tran et al., 2022). Additionally, according to Nguyen et al. (2022), emissions from the berthing phase are a major concern for port operators and authorities because they directly and adversely impact the health of workers and people living near port areas. (Nguyen et al., 2022).

Auxiliary Engines (AE) and Boilers

As anticipated at the end of the previous subsection, a crucial step for emission calculation is clarifying the differences between the power generators on board and their roles. Although infinite power train configurations exist in reality, many studies assume that ships have two or three types of engines: Main Engines (ME), Auxiliary Engines (AE), and Boilers (B). The Main Engines are the primary engines as they are responsible for propelling the vessel during sailing and manoeuvring (Chen et al., 2016; Tran & Lam, 2024); ships often switch them off at port (Nguyen et al., 2022). On the other hand, Auxiliary Engines are generators set for auxiliary services such as lighting, pumping, ventilation, cooling, loading and unloading of cargo, et cetera (Chen et al., 2016; Cullinane et al., 2016; Sim, 2018). Eventually, Boilers work to keep fuel and main engine cylinders warm and to meet heat demands on board (López-Aparicio et al., 2017).

On-shore Power Supply (OPS)

Although the literature review did not focus specifically on On-shore Power Supply (OPS), this technology is often identified as the most impactful solution to steeply reduce local pollution from berthed vessels. Consider, for example, the work of Nguyen et al. (2022). Thus, the results of this research could also serve to further explore the characteristics of this technology. OPS appeared in many papers in the literature with different names like Alternative Marine Power (AMP) (Sim, 2018), or Cold Ironing (CI) (Nguyen et al., 2022), all indicating the provision of electricity to ships at berth to perform hoteling activities.

Top-down and Bottom-up Approaches for emission calculations

All the studies on emissions calculation in ports from ship activity acknowledge the existence of two approaches: a top-down and an bottom-up methodology. The former estimates emissions based on the fuel sold, the latter calculates emissions based on the activities of the single ships. Furthermore, they unanimously identify the latter as more suitable for estimating in-port ship exhaust emission inventories, and so they all use it (for instance, Chen et al. (2016), Cullinane et al. (2016), López-Aparicio et al. (2017), Nguyen et al. (2022), and Tran et al. (2022)). As explained by Nguyen et al. (2022), the bottom-up approach relies on specifications of the ship, including vessel type, dimensions, main engine, auxiliary engine, fuel type, and operational details like travel distance, actual and maximum speed, port of call, and real-time activities, rendering it more precise compared to the top-down method as it assesses emissions for a specific ship at a given moment. Additionally, important institutions in the maritime sector invite parties and stakeholders to apply a bottom-up approach when calculating emissions; for instance, the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2023) or the Fourth IMO GHG Study 2020 (IMO, 2021).

1.3. Research objective

As anticipated, the main objective of this research is to investigate and elaborate on the role of berthing times in determining energy consumption. Until now, emission inventories have always used time as an independent variable, which, multiplied by an average factor, gave energy consumption and emissions as output - equation 1.1 (adapted from European Environment Agency (2023)).

$$E_{i,berth} = t_{berth} * \sum_{e} (P_e * LF_e * EF_{e,i,m})) \tag{1.1}$$

where:
E_i = emissions at berth of pollutant i (tonnes)
i = pollutant
t_{berth} = time at berth (hours)
e = engine category (Main, Auxiliary, Boiler)
P_e = engine e nominal power (kW)
LF_e = engine load factor (%) of engine e
$EF_{e,i,m}$ = emission factor of pollutant i from engine e and fuel m (kg/tonnes*kWh)

This study aims to initiate a discussion about the role of time in the current methods by exploring the ship's berthing behaviour. The research argues that multiple berthing event types exist and each has different energy requirements and air pollutant emissions, necessitating a new calculation methodology. The equation 1.2 illustrates what the enhanced calculation method should look like: each stop type should be linked to a different duration, load factor, and emission factor.

$$E_{i,berth} = \sum_{e} [P_e * \sum_{a} (LF_{e,a} * EF_{e,i,m,a} * t_{e,a})] \tag{1.2}$$

where:
E_i = emissions at berth of pollutant i (tonnes)
i = pollutant
e = engine category (Main, Auxiliary, Boiler)
a = stop type
$t_{e,a}$ = time at berth (hours) during stop type a when engine e is active and running
P_e = engine e nominal power (kW)
$LF_{e,a}$ = engine load factor (%) of engine e during the stop type a
$EF_{e,i,m,a}$ = emission factor of pollutant i from engine e and fuel m during stop type a

To initiate this discussion, the research clusters the berthing events into stop types based on their duration and investigates whether these stop types can be associated with different energy consumption - thus, air pollutant emissions. Therefore, the primary objective of this work is to identify berthing time patterns to cluster berthing events into stop types. The exploratory nature of this study calls for a real-life case to be investigated. Hence, the Port of Rotterdam will be the socio-technical system under study and the starting point for studying the existence of berthing time patterns, given its economic significance and environmental impact. The research hopes to form a stepping stone to enhance emission calculation methods for aerosols marine diesel HFO, aerosols ship diesels MDO, carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NO_x), and sulphur dioxide (SO_2).

1.4. Research questions

Collecting all the knowledge gaps from the literature review, a clear suggestion towards a study that improves the existing calculation methodologies by linking berthing times and activities performed appears, making the following research question emerge:

What is the relationship between berthing time, activities and the energy required by moored ships?

1.4.1. Sub-Research Questions

This section formulates a set of sub-questions, each forming a step towards calculating emissions from berthed ships in the Port of Rotterdam. These sub-questions aim at logically leading to the comprehensive understanding sought by the main research question:

1. *What is currently known about ship emissions, especially when near the port?*
2. *What berthing time patterns emerge by analysing the behaviour of different types of vessels inside the Port of Rotterdam?*
   It aims to identify berthing patterns within ship types. For example, ships of the same class and size could tend to stay anchored for the same time.
3. *What activities do berthing time patterns correspond to?*
   This question emerges from the previous and tries to understand why the patterns emerge.
4. *What energy consumption do berthing time patterns correspond to?*
   The intention is to quantify the emissions from the different hotelling activities.
5. *What discrepancies exist between recorded data and the feedback from maritime professionals?*
   The objective is to explore the mismatch between the quantitative data analysis and the stakeholders' feedback to understand its origin.

1.5. Relevance to the master program

This research encompasses a complex socio-technical system with multifaceted interdependencies. Firstly, maritime logistics, port operations, and environmental sustainability, each with its stakeholders, regulations, and technological requirements, converge in this topic. Furthermore, the transition towards green maritime operations implicates diverse actors, including port authorities, shipping companies, energy providers, and governmental bodies, necessitating collaboration and coordination across sectors. Moreover, this study intersects with broader societal concerns regarding public health, environmental conservation, and economic development, accentuating its significance in steering contemporary urban and industrial landscapes. Thus, the analysed system includes embedded and connected subsystems with numerous stakeholders, interdependencies and uncertainties, making it a clear complex socio-technical system.

The system complexity was not just a descriptive fact; quite the opposite: during the making of this thesis, many of the concepts addressed during the master's program emerged or proved essential to directing and understanding the research. Observer dependency and emergency, for example, were crucial to identifying time patterns: vessels belonging to the same segment follow the same set of rules, resulting in a distinguishable system behaviour visible only by a specific observer.

Therefore, this topic aligns with the Complex Systems Engineering and Management master program (CoSEM) as it entails the study of the relationships between technology, policy, and society to address pressing global challenges. By delving into the complexities of sustainable maritime transportation with interdisciplinary perspectives, the thesis can offer valuable insights into socio-technical systems, which are at the core of the CoSEM curriculum.

1.6. Thesis outline

This research is structured as follows. Chapter 2 presents a literature review on emission inventories of vessels during in-port operations. This review posed the fundamentals of this research, justified its scientific relevance by showing a knowledge gap in the literature and the common methodology, and answered the second sub-research question. Chapter 3, on the other hand, describes the methodology embraced for the research, highlighting the steps made to answer the main research question and how the use of a diverse set of approaches resolved some of their limitations. Chapter 4 presents the results from the quantitative case study in the Port of Rotterdam regarding berthing times; it presents the berthing time patterns, their influence on the total time at berth, and shows the importance of focusing on time. Chapter 5 contains the results from the qualitative analysis regarding the activities performed by ships and their energy consumption and demonstrates that the berthing time patterns found in Chapter 2 correspond to different energy requirements. Finally, Chapter 6 summarises the research, reflects on the limitations and avenues for future research, and concludes the work.

2

Literature review

This chapter presents the results of a scientific literature review on emission inventories inside ports. It introduces the methods used for article selection, presents core concepts, and outlines identified knowledge gaps used to formulate the research question.

2.1. Literature selection process

The literature review has covered the key scientific databases Scopus, Web of Science, and IEEE Xplore to find studies quantifying emissions from ship activities within ports. Furthermore, the research included two publications from authoritative institutes in the naval sector worldwide and the Netherlands specifically: MARIN (2022) and IMO (2021).

Regarding the scientific databases research, the literature review focused on container ships only to reduce the results to a manageable amount. Goods shipped in containers represented the main export and the second-largest import in the Port of Rotterdam (Port of Rotterdam, 2024); additionally, the Port of Rotterdam is the largest container port in Europe (Port of Rotterdam, 2023). Therefore, the container sector is a good starting point for understanding the existing knowledge about emissions from berthed vessels. Moreover, searching for a single shipping segment does not necessarily limit the results to it: many studies calculate emissions of all the ships visiting the port and not just container vessels. Table 2.1 and Figure 2.1 present the keywords and the databases used for the literature research. In addition, they show that two terms were excluded from the literature search to avoid results about the Berthing Allocation Problem. Similarly, some other records were excluded because they were inaccessible or out of the scope of this research. Table 2.2 presents a list of the excluded articles and the reasons for their exclusion, while table 2.3 lists the studies included and their geographical scope.

Table 2.1: Databases and search strings

Databases	**String**						
ScienceDirect *Web Of Science* *IEEE Xplore*	”emissions”	AND	”container ships” OR ”container vessels”	AND	”berth”	NOT	”allocation” OR ”scheduling”

Figure 2.1: Databases, keywords, search strings and argumentation for selection

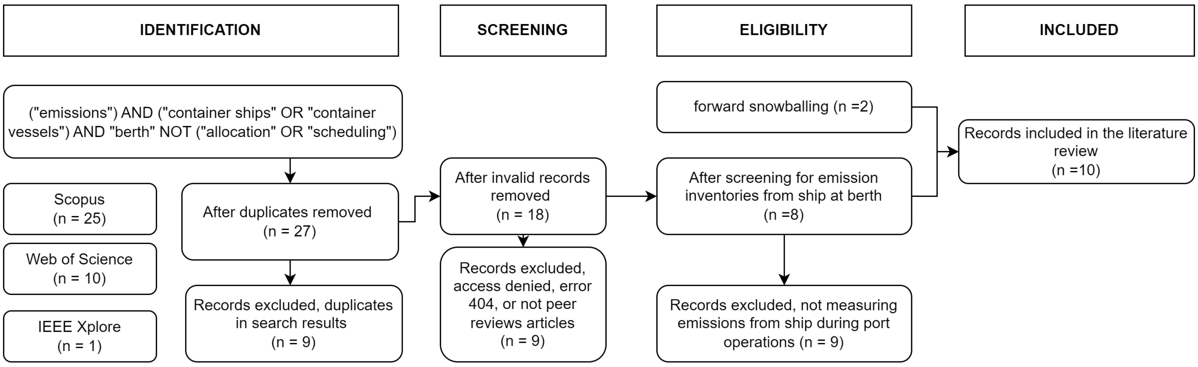


Table 2.2: Articles excluded and the reasons for their exclusion

ARTICLE	REASON FOR EXCLUSION
Liu et al. (2021)	Withdrawn by the author
He et al. (2021)	Error 404
Wang et al. (2020) Zeng and Lü (2020) Huang et al. (2017)	Access Denied
“Ironing out emissions?” (2006) “Cold-ironing aims to limit emissions in harbour” (2007) Nicholls (2008) “Port of Rotterdam and TNO study how to arrive ’just in time’: Information about berth availability can reduce sailing speed and thereby emissions” (2018)	Trade journal
C. C. Chang and Jhang (2016) Cannon et al. (2015) Yu et al. (2019) Innes and Monios (2018) Jayaram et al. (2011) McCaffery et al. (2021) Wu and Wang (2020) Okoth et al. (2022) Yiğit (2022)	Not emission inventories

Table 2.3: Reference countries

Country	**Source**	**UNFCC**
China	Ng et al. (2013) Chen et al. (2016)	yes
South Korea	Y. T. Chang et al. (2014) Sim (2018) Yeo et al. (2024)	yes
Norway	López-Aparicio et al. (2017)	yes
Singapore	Nguyen et al. (2022) Tran et al. (2022)	yes
Malaysia	Nguyen et al. (2022)	yes
Thailand	Nguyen et al. (2022)	yes
Indonesia	Nguyen et al. (2022)	yes
Viet Nam	Nguyen et al. (2022)	yes
Philippines	Nguyen et al. (2022)	yes
Netherlands	MARIN (2022)	yes
Worldwide	IMO (2021)	-
	Not aplicable	
CMA-CGM	Tran and Lam (2024)	-
Taiwan	Cullinane et al. (2016)	-

2.2. State of the art and knowledge gaps

2.2.1. Pollutants

Table 2.4 shows which pollutants are the most studied in the emission inventories of ships operating near ports. Most studies included CO_2, NO_x, PM_x, and SO_x, leaving other pollutants slightlly underepresented (CH_4, CO, N_2O, VOC, HC, and BC). These results are aligned with the expectations as these pollutants are generally addressed as the most harmful to humans, the environment, and the contributors to climate change. For instance, some of them are included in the Directive 2016/2284 (Directive, 2016/2284) or lie under the UNFCCC obligations (UNFCCC, 2014). Additionally, SO_x, NO_x, NH_3, non-methane volatile organic compounds ($NMVOC$), CO, and PM, if emitted into the atmosphere as the result of human and natural activity, are involved in acidification, eutrophication, and tropospheric ozone pollution, human and ecosystem exposure to hazardous substances, air quality degradation, and damage and soiling of buildings and other structures (European Environment Agency, 2023).

Eventually, all the works have at least a descriptive nature: they describe the pollution amounts, without regard to any causal or other hypothesis. Nevertheless, they also include hints about future developments or predictions in different scales. Within the scientific literature, Sim (2018) is the only one with a strong predictive component, focusing on emission forecasts between 2018 and 2030, while the others include policy recommendations; Yeo et al. (2024) suggests including a forecast in future work. In the Netherlands, a biennial publication provides a picture of the expected future development in national emissions of air pollutants and provides an overview of the expected range of the EU emission targets (PBL Netherlands Environmental Assessment Agency, 2023).

Table 2.4: Greenhouse gases and air pollutants studied

	Greenhouse Gases			**Air Pollutants**									
	$\mathbf{CO_2}$	$\mathbf{CH_4}$	$\mathbf{N_2O}$	$\mathbf{NO_x}$	$\mathbf{PM_x}$	PM_{10}	$PM_{2.5}$	$\mathbf{SO_x}$	$\mathbf{SO_2}$	$\mathbf{CO}$	$\mathbf{VOC}$	$\mathbf{HC}$	$\mathbf{BC}$
Yeo et al. (2024)	x	x	x	x									
Tran and Lam (2024)	x												
Tran et al. (2022)	x	x	x	x	x			x		x			
Nguyen et al. (2022)	x			x	x	x	x	x	x	x			
Sim (2018)	x												
López-Aparicio et al. (2017)	x	x	x	x	x	x		x	x			x	
Cullinane et al. (2016)	x			x	x	x	x	x	x	x		x	
Chen et al. (2016)	x			x	x	x	x	x	x	x	x		
Y. T. Chang et al. (2014)				x	x			x	x				
Ng et al. (2013)				x	x	x		x	x	x	x		
MARIN (2022)	*x*	*x*		*x*	*x*			*x*	*x*	*x*			
IMO (2021)	*x*	*x*	*x*	*x*	*x*			*x*	*x*	*x*	*x*	*x*	*x*
COUNT	**10**	**5**	**4**	**10**	**9**	5	3	**9**	8	**7**	**3**	**3**	**1**

2.2.2. Activities

Although not all studies explicitly refer to the EEA methodology, many share similar methodologies, if not compliant, with those suggested by the EEA; for instance, most studies identify three activities (sailing, manoeuvring, and berthing). These studies are Chen et al. (2016), Cullinane et al. (2016), López-Aparicio et al. (2017), Ng et al. (2013), Nguyen et al. (2022), Tran et al. (2022), and Tran and Lam (2024). Y. T. Chang et al. (2014), on the other hand, explicitly mentions the EEA guidelines, but an older version (2009) and MARIN (2022) complies with the requirements of the Netherlands Environmental Assessment Agency (PBL), which, in turn, cites the EEA.

Moreover, all these studies calculate emission as a function of time; for instance, they multiply time spent at berth times the emission factor of berthed vessels. The only study that uses a different approach is Sim (2018): it calculates the emissions as a function of the TEU loaded/unloaded. Additionally, as anticipated above, most studies focus on the three phases: sailing, manoeuvering, and berthing. There are some exceptions: Yeo et al. (2024) aggregate shipping data to a single cluster, without breaking down to the activities (EEA Tier 2), and MARIN (2022), Sim (2018), and Tran and Lam (2024) divide the study into two categories only (sailing and in port). Additionally, Cullinane et al. (2016) and Nguyen et al. (2022) focus specifically on berthing, thus forming a nice stepping stone for this thesis.

Besides the activities, studying how the works distinguished between different activities is another interesting point. All the papers that collected the AIS data combine speed and GPS data to determine a vessel's status, even though the AIS system itself provides vessel status data. The choice to derive status from the combination of these two data is a matter of reliability of the derived information: the AIS status appears to be entered manually and, thus, is often subject to error or inconsistency. Nevertheless, computing AIS data can require lots of computational resources. Therefore, studies often contacted different sources to overcome these issues; for instance, port authorities (Y. T. Chang et al., 2014; López-Aparicio et al., 2017), or other institutions. Tables 2.5 and 2.6 show the calculation methodologies, data sources, and activity division.

Table 2.5: Vessels' status and sources

Work	Sailing	Manuevering	Berthing
Yeo et al. (2024)	Division not made [EEA Tier 2]		
Tran and Lam (2024)	Liner route data	liner route data [grouped in one activity]	
Tran et al. (2022)	AIS [speed-gps]	AIS [speed-gps]	AIS [speed-gps]
Nguyen et al. (2022)	-	-	AIS
Sim (2018)	-	distance	distance
López-Aparicio et al. (2017)	Port, Authorities	Port, Authorities	Port, Authorities
Cullinane et al. (2016)	-	-	Ministry of Transport
Chen et al. (2016)	AIS [speed-gps]	AIS [speed-gps]	AIS [speed-gps]
Y. T. Chang et al. (2014)	Port's Pilot Association [speed-distance-time]	Port's Pilot Association [speed-distance-time]	Port Authority [(un)docking and departure times]
Ng et al. (2013)	AIS [speed] Marin Department [time]	AIS [speed] Marin Department [time]	AIS [speed] Marin Department [time]
MARIN (2022)	AIS [speed-gps]	AIS [speed-gps]	AIS [speed-gps]
IMO (2021)	AIS [speed-position]	AIS [speed-position]	AIS [speed-position]

Table 2.6: Emission calculation method

Work	Method
Yeo et al. (2024)	EEA Tier 2
Tran and Lam (2024)	*
Tran et al. (2022)	*
Nguyen et al. (2022)	*
Sim (2018)	ton/TEU
López-Aparicio et al. (2017)	*
Cullinane et al. (2016)	*
Chen et al. (2016)	*
Y. T. Chang et al. (2014)	EEA Tier 3 (2009)
Ng et al. (2013)	*
MARIN (2022)	PBL*
IMO (2021)	*

* These methods recall (or are indirectly drawn from) EEA Tier 3

2.2.3. Engines and generators

As mentioned in Chapter 1, a crucial step for emission calculation is clarifying the differences between the power generators on board and their roles. Table 2.7 shows which engines are involved in which activities according to the studies analysed in the literature review.

Table 2.7: Emission calculation method

	Sailing			**Manoeuvring**			**Berthing**		
	ME	AE	Boilers	ME	AE	Boilers	ME	AE	Boilers
Tran and Lam (2024)	1	1	0	*not studied*			0	1	1
Tran et al. (2022)	1	1	1	1	1	1	0	1	1
Nguyen et al. (2022)	*not studied*			*not studied*			0	1	1
Sim (2018)	*not studied*			*not mentioned*			0	1	1
López-Aparicio et al. (2017)	1	1	-	1	1	-	1	1	-
Cullinane et al. (2016)	*not studied*			*not studied*			0	1	1
Chen et al. (2016)	1	1	0	1	1	1	0	1	1
Y. T. Chang et al. (2014)	1	1	-	1	1	-	0	1	-
Ng et al. (2013)	1	1	0	1	1	1	0	1	1
IMO (2021)	1	1	*	1	1	*	0	1	*
MARIN (2022)	1	1	0	1	1	0	0	1	1
Yeo et al. (2024)	*not aplicable (EEA Tier 2)*								
TOTAL	7	7	1	6	6	3	1	10	7

1 = engine on
0 = engine off
- = engine not mentioned
* = engine activity depending on multiple factors (fleet type, size, et cetera)

There is almost full consensus regarding the use of main and auxiliary engines during different phases of navigation: main engines are used during sailing and manoeuvering but not hotelling, whereas auxiliary engines are used during all the phases and particularly during hotelling. Boilers run during hotelling and sometimes during manoeuvering, producing around twenty per cent of the total emissions according to Ng et al. (2013). However, emissions from boilers are often neglected arguing that emissions from boilers are scarce, for instance, in Cullinane et al. (2016) and Nguyen et al. (2022). Therefore, the role of boilers is not completely clear.

Nonetheless, all the studies agree that data about boilers is scarce, and this fact also contributed to ignoring boilers' emissions. Data scarcity about boilers and auxiliary engines is a common issue among the literature: Yeo et al. (2024) found that approximately 20% of the annually registered vessels did not provide main engine specifications, and data on auxiliary engines were insufficient in the domestic ship registration information. In Tran and Lam (2024), the powers of auxiliary engines and boilers and their respective load factors in the operational modes (transit at sea, berth operations in port) were often unavailable; in Tran et al. (2022), the ship registry database often did not provide the full specifications of installed power for the auxiliary engines and boilers, as well as engine usage in operational modes. As a result, the requested powers of auxiliary engines and boilers have often been drawn from other studies - for example, from the survey of the Port of Los Angeles (Ng et al., 2013; Tran et al., 2022), the study by the California Air Resources Board (Ng et al., 2013), or derived from main engine power (Cullinane et al., 2016; Nguyen et al., 2022) - bringing with them all the corresponding uncertainties.

2.2.4. Knowledge gaps and research question

As shown in the previous section, the literature often makes their limitations explicit and suggests a direction for further studies. Taking the case of auxiliary engines and boilers again, it is clear that data scarcity impacts accuracy, especially in calculating emissions during the berthing phase, where auxiliary engines and boilers are the main sources of pollution. Another interesting recurrent knowledge gap is the uncertainty of emission factors, which, for instance, are based on assumptions that may limit application under varying circumstances and do not consider differences in ship characteristics or type of activities during berthing (Chen et al., 2016; Cullinane et al., 2016; Nguyen et al., 2022).

These two aspects are enough to say that the mooring phase requires more in-depth studies; furthermore, most of the emission inventories rely on a single emission factor for all the lengths of stay at berth, implicitly saying that moored ships have the same energy requirements, regardless of the activity they are performing at berth. Consequently, a clear suggestion towards a study that improves the existing calculation methodologies of moored vessels by linking berthing times and activities performed emerges from the literature.

Concerning emission types, there is a lot of variability throughout the studies, and some papers acknowledge that they could have investigated more pollutants. Sim (2018) focuses only on CO_2 and plans to assess other air emission pollutants; similarly, Y. T. Chang et al. (2014) acknowledge their impossibility of estimating the NO_X and PM when using lower sulfur fuels in Emission Control Areas. Nevertheless, in principle, studies agree to examine mainly pollutants that have a local effect, given the ports' vicinity to population centres. Therefore, considering aerosols marine diesel HFO, aerosols ship diesels MDO, carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons combustion heavy-duty diesel engines, methane (CH_4), hydrocarbons combustion heavy diesel engines, nitrogen oxides (NO_x), and sulphur dioxide (SO_2) aligns with the existing literature.

To conclude, the following research question emerged from the identified knowledge gaps:

What is the relationship between berthing time, activities and the energy required by moored ships?

2.3. Conclusion

The literature review highlighted that the emission calculation of ships inside ports is very common, with various studies sharing remarkably similar methods and approaches. Nonetheless, all the calculation approaches do not investigate the relationship between ships at berth, their length of stay, and emission, applying a fixed emission factor regardless of these differences. Additionally, all articles agree that emission calculations strictly depend on port specificities, and transferring results from one port to another is challenging. Taking these into account and the absence of specific studies on the port of Rotterdam, the scientific validity of this research is amply justified.

3

Methodology

This chapter outlines the methodological approach employed in this research, which is summarized in Figure 3.1. The core activity is the data analysis, which starts with a general clustering and then follows three principal paths.

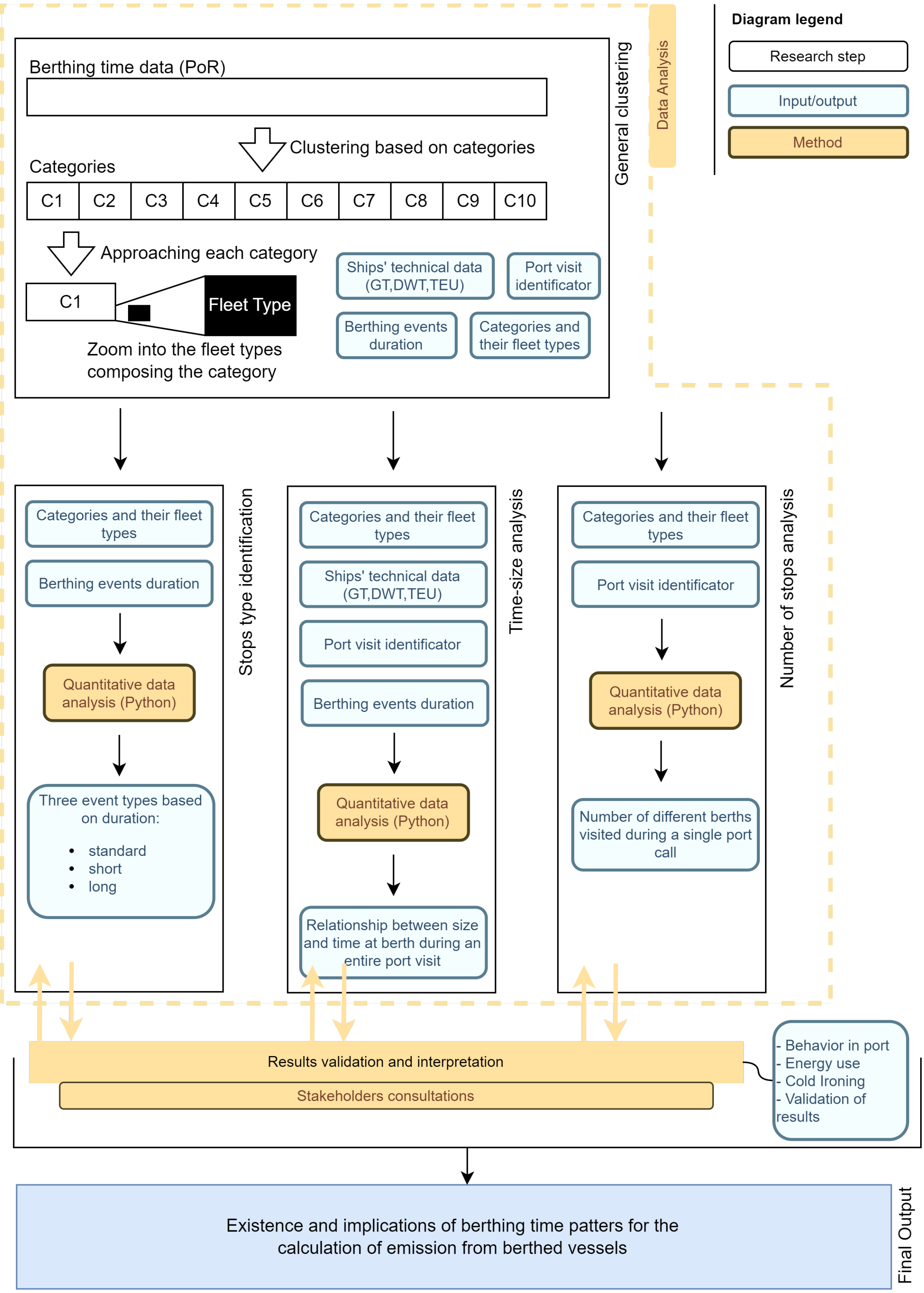
The general clustering gathers the berthing time data into categories based on the ship type; then, the elements of each category are grouped again according to their fleet type. This first subdivision is guided by similarities in product transported or fleet type and reorganizes the data logically; for example, all the berthing events registered by ships that transport liquids in bulk or liquefied gases are gathered in the ’tankers’ category. At the end of this phase, each berthing event contains the following data: duration, identifier of the port visit, and technical characteristics of the ship.

The data thus obtained are the foundation for the next steps, which are the core of the three-paths time analysis. The first path uses a method based on the duration and frequency to cluster the berthing events into three types (standard, long, short); the second path explores the relationship between the visit berthing time and three measures of size; lastly, the third path studies the number of movements ships perform while remaining inside the port.

As reported by Creswell (2009), qualitative and quantitative approaches are opposite ends of a spectrum: a study leans to be more qualitative than quantitative or vice versa. Therefore, this research will be predominantly quantitative while containing qualitative aspects. Throughout the analysis, expert consultation has been used for results validation and interpretation. Moreover, expert consultation provided insights into in-port behaviour, energy use, and cold ironing.

This mixed approach allowed the research to apply a generalizable framework without losing contextual detail. The following sections explain the research approach in more detail.

Figure 3.1: The research approach



3.1. Data Analysis

As mentioned above, this research mainly employs a quantitative approach to study berth time, behaviour, and energy consumption of vessels calling in Rotterdam. A quantitative methodology relies on objective measurements and the statistical analysis of data to determine the connection between an independent variable and a dependent variable (University of Southern California, 2024), and so does this research. By employing this approach, the study aims to offer quantifiable insights into the dynamics of ship behaviour during berthing activities, thereby informing decision-making processes regarding emission reduction strategies and infrastructure development.

The chosen research approach presents several advantages. Firstly, the quantitative analysis provides data summaries and permits objectivity and accuracy of results. Hence, it can potentially reveal patterns, trends, and correlations. Moreover, statistical data form empirical evidence to support findings and conclusions. Secondly, this research approach can avoid personal bias by inserting a 'distance' from participating subjects and using accepted computational techniques.

However, it is essential to acknowledge the limitations associated with the chosen approach. Quantitative methods may overlook contextual details, thus failing to reach the same depth of understanding as qualitative approaches. Additionally, reliance on numerical data necessitates careful consideration of measurement validity and reliability to ensure the accuracy and robustness of findings and the data scarcity presented in Chapter 2 is an example. Since quantitative approaches are solidly tied up with the baseline data they use, great care must be taken with data and assumptions.

Appendix A adds details on the data cleaning process and contains a link to the Python code.

3.1.1. Data collection

Data Collection is the process of gathering data. This research collected data from two main sources: the Port of Rotterdam and Clarkson's World Fleet Database (Clarksons, n.d.).

The Port of Rotterdam uses an automatic location-based system to monitor ships' activities inside the port. Vessels are constantly sending their position and other technical information via the AIS (Automatic Identification System), and the port uses them to assign a status to the ships. Therefore, when a vessel enters the port waters, the port assigns it a unique identifier linked to the port visit (the port_visit_id); then, when the ship reaches a berthing location, the port registers the arrival date and time and the area code linked to that location; finally, when the vessel leaves the berthing location, the port collects the date and time again. The difference between arrival date and time forms the berthing event duration. All the berthing events performed without leaving the port are registered under the same port_visit_id.

The port provided the following data regarding visits in 2023:

- port_visit_id (the unique identifier for the port visit)
- imo
- subclass
- gross_tonnage_volume_sea
- deadweight
- visit_duration_min (the duration of the berthing event)
- area_name (the identifier of the berthing area)
- berth_type (the type of berthing area; e.g. quay, jetty, etc.)

The Clarksons Research World Fleet Register (WFR) provides extensive and reliable data of up to 150,000 ships above 100 GT (TU Delft, n.d.). It was the source for the following fields:

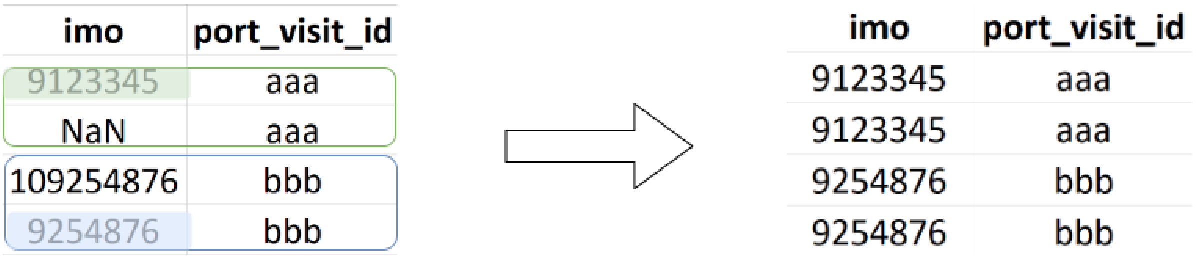
- IMO Number
- Fleet Type
- Type
- GT

3.1.2. Data cleaning

Data cleaning has been performed mostly on the data from the Port of Rotterdam, as the WFR data have been collected from data extracted from the port data: the Port of Rotterdam data provided a list of IMO Numbers used later to extract the data from the WFR.

The main data cleaning operation consisted of correcting IMO numbers. First, the analysis focused on the invalid IMO Numbers: the IMO number composed of seven digits (IMO, n.d.-a); therefore, the first step was finding the values not respecting this rule. 10.8% of port calls (port_visit_id) had invalid IMO Numbers, representing 24% of the total rows. Yet, only 53 out of 5864 unique IMO Numbers were invalid (0.90 %); therefore, a hybrid automatic-manual method was the quickest solution to improve the data. For the automatic component, the code grouped the data by port_visit_id: if different IMO Numbers existed for the same port_visit_id, the code kept the valid IMO; figure 3.2 shows this process. Other invalid IMOs have been manually corrected where possible. In the end, the number of invalid IMOs has decreased to 37 (-30%) and the sum of all the berthing events with invalid IMOs counted only for the 9.10% of the total time. Additionally, although some IMOs were impossible to correct, the berthing events still registered a subclass, thus permitting a complete analysis.

Figure 3.2: Example of the automatic IMO Number correction for different IMOs corresponding to the same port call



imo	port_visit_id
9123345	aaa
NaN	aaa
109254876	bbb
9254876	bbb

imo	port_visit_id
9123345	aaa
9123345	aaa
9254876	bbb
9254876	bbb

To conclude, the data cleaning process has shown that the data are sufficiently complete to produce quality results.

3.1.3. General clustering

The general clustering gathers the berthing time data into categories based on the ship type; then, the elements of each category are grouped again according to their fleet type. The clusters have been defined by similarities in goods transported (e.g. liquid and gas carriers under the category *Tankers*) or activity (for instance, offshore vessels and dredgers). Table 3.1 presents the clusters, the segments included, and the definitions employed.

Table 3.1: Maritime clusters and their components, with definitions

Cluster	Fleet Type	Description
Tankers	Chemical Tankers Product Tankers Crude Tankers LPG Carriers LNG Carriers Specialized Tankers Gas Tankers	Transport chemicals in bulk Transportation and distribution of crude oil derivatives Transportation and distribution of crude oil Transportation and distribution of Liquified Petroleum Gas Transportation and distribution of Liquified Natural Gas Designed with a very particular purpose in mind (e.g. edible products) Transport of unspecified gas, either LPG or LNG
Container vessels	Containerships	Transport of containers
Vehicle carriers	Ro-Ro Ships Pure Car Carriers (PCC)	Transport of wheeled cargo Transport of cars
Passenger vessels	Recreational vessels Ferries Cruise ships Passenger ships	Vessel operated primarily for pleasure (yachts, sailing ships, etc.) Transport of people, and sometimes cars or cargo Large passenger ships used mainly for vacationing Generic passenger vessels, can be any of the above
Bulk Carriers	Bulkers	Transport of dry cargo in bulk
General Cargo vessels	Multi-Purpose Product vessels (MPP) General Cargo vessels	Seagoing ship that is built for the carriage of a wide range of cargoes Transport of various types of cargo (containers, dry bulk, cars, etc.)
Refrigerated Cargo vessels	Refrigerated Cargo vessels	Transport perishable cargo, which require temperature-controlled handling
Port Operational vessels	Tugs Service ships seafaring Other non-cargo vessels	Tugboats - small watercrafts designed to tow or push other crafts Generic operational vessel, can be any of others in the cluster Patrol vessels, work/repair ships, pilot, training ships, et cetera
Offshore and dredging	Offshore vessels Dredgers	Ships that serve operational purposes offshore (e.g. construction works) Excavation of material from a water environment
Miscellaneous vessels	Other seagoing vessels Unknown ships Fishing vessels	Non-propelled barges and others Unknown ships Fishing vessels

3.1.4. Stops type identification

Identifying temporal patterns in berthing events required an approach that accounted for both the frequency and duration of these events, recognizing that the mere distribution of stops could not fully capture their significance in the context of the research objectives. The analysis was designed to go beyond just determining the most common berthing events by considering the overall impact of each event on the total berthing time.

Focusing solely on the frequency of berthing events identifies common stops but overlooks duration, which significantly influences the total berthing time. For instance, consider a scenario where vessels make ten one-hour stops and one ten-hour stop. A frequency-based analysis would suggest that the one-hour stops are the most common and the most significant. However, when considering duration, it becomes evident that the single ten-hour stop accounts for 50% of the total berthing time, highlighting its importance despite its lower frequency.

Therefore, to visualize and analyze the combined effect of frequency and duration, a modified load duration curve (LDC) was employed. This curve is traditionally used in energy studies to represent the distribution of load demands over a period of time but was adapted here to study berthing events (Figure 3.3). The curve was constructed with the following characteristics:

- **X-axis (Cumulative Share of Total Berthing Time)**: The horizontal axis represents the cumulative share of total berthing time that can be attributed to berthing events of a given duration and all longer events.
- **Y-axis (Duration)**: Each point on the vertical axis represents a specific berthing event's duration on a logarithmic scale. This scale has been chosen because while data tend to grow exponentially, observing the details at the lower and higher ends is crucial. For instance, a difference of one hour is significant when the stops are in the order of minutes or hours; on the other hand, when stops last weeks, a one-hour dissimilarity is not meaningful. A logarithmic scale allows this behaviour to be observed and is employed commonly. Thus, although it does not reflect the typically used calendar system (minutes, hours, days, weeks, etc.), the logarithmic scale represents the data most simply and effectively.

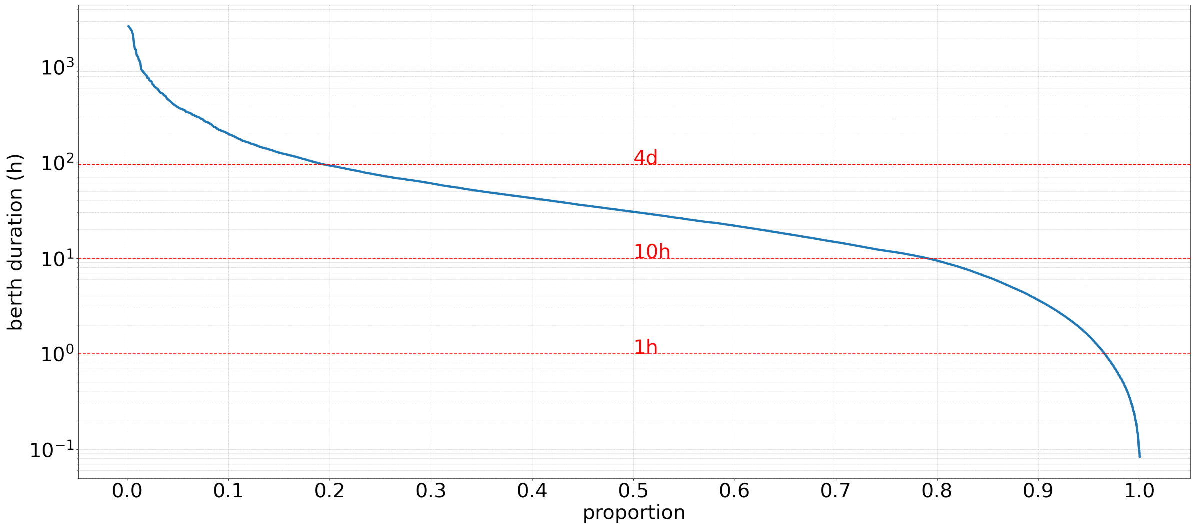
Additionally, the shape and steepness enabled the use of the elbow method to cluster the berthing events. This method involves identifying points on the curve corresponding to a noticeable change in steepness—commonly referred to as the ”elbow” point. These points are critical for distinguishing between different clusters of berthing events, such as long, standard, and short stops.

- **Long stops (zero to first elbow) - steep decrease**: berthing events in this section are characterised by being very long but also very rare.
- **Standard stops (between the two elbows) - moderate decline**: between the two elbows, the curve decreases gradually, suggesting a significant increase in the events' frequency.
- **short stops (second elbow to the end) - steep decrease**: berthing events in this section are characterised by being either short and rare or extremely short and exceptionally frequent.

By applying this method, the analysis was able to categorize berthing events into distinct clusters, each with a different impact on total berthing time. This clustering provided a clear framework for understanding the relative importance of different berthing patterns, which aligned more closely with the research objectives than a simple frequency distribution would have.

In summary, the methodological approach of combining frequency and duration through a load duration curve provided a more holistic understanding of berthing patterns. This approach allowed for the identification of not only common stops but also the identification of stops that, although less frequent, have a significant impact on total berthing time.

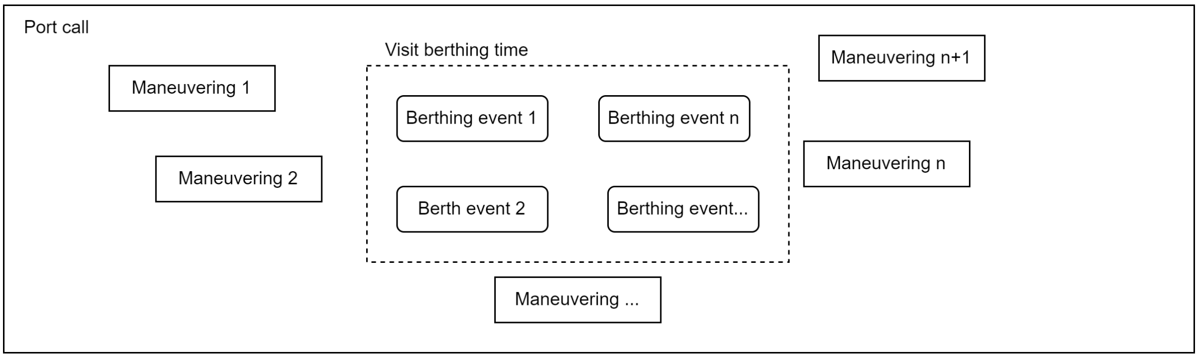
Figure 3.3: berth duration curve



3.1.5. Relationship between size and visit berthing time

In examining the relationship between ship size and time spent in port, the study shifted focus from individual berthing events to the cumulative time spent by a vessel during a port visit, referred to as the ”visit berthing time”. As illustrated in figure 3.4, a vessel enters the port and maneuvers a first time to reach a berthing location; at the berthing location, it performs a berthing event. Then, it maneuvers again to reach another berthing location and the cycle repeats until the $(n+1)$-th manoeuvring event, which guides the ship outside the port. The sum of the duration of the n berthing events gives the visit berthing time.

Figure 3.4: Visit berthing time



The analysis explored three distinct metrics for assessing the size of a vessel compared to its visit berthing time: Gross Tonnage (GT), Deadweight tonnage (DWT), and Twenty-foot Equivalent Unit (TEU).

Gross Tonnage (GT) is a function of the moulded volume of all enclosed spaces of the ship, used as a basis for manning regulations, safety rules, registration fees, and port dues (IMO, n.d.-b); additionally, the CBS used GT to define different size classes (Table 3.2). GT is universally available for all vessels, making it a comprehensive metric for size. However, as a volume-based measure, GT does not directly correlate to a ship's cargo-carrying capacity.

Table 3.2: Size classes from CBS, based on GT

	GT	
class	**min**	**max**
1	0	499
2	500	1999
3	1000	1999
4	2000	2999
5	3000	3999
6	4000	4999
7	5000	5999
8	6000	6999
9	7000	7999
10	8000	8999
11	9000	9999
12	10000	19999
13	20000	29999
14	30000	39999
15	40000	49999
16	50000	79999
17	80000	99999
18	100000	149999
19	150000	199999
20	200000	249999
21	250000	299999
22	300000	1000000

Deadweight Tonnage (DWT): This metric represents the maximum weight a ship can safely carry, encompassing not only cargo but also equipment, crew, fuel, et cetera (Britannica, n.d.). DWT is commonly used in industries such as bulk cargo and tankers, where the weight of transported goods is a critical factor (Port Economics, Management and Policy, n.d.). While DWT provides a closer approximation of a ship's cargo-carrying potential, the non-cargo elements add some uncertainty to its correlation with actual cargo transported. Table 3.3 shows the size classes for tankers and Table 3.4 presents the classes for bulkers.

Table 3.3: Tankers size classes based on DWT

		DWT	
class	**name**	**min**	**max**
0		0	9999
1	Handysize	10000	50000
2	Panamax	50001	80000
3	Aframax	80001	120000
4	Suezmax	120001	200000
5	Very Large Crude Carrier (VLCC)	200001	320000
6	Ultra Large Crude Carrier (VLCC)	320001	-

Table 3.4: Bulkers size classes based on DWT (USDA, n.d.)

		DWT	
class	**name**	**min**	**max**
0		0	9999
1	Small Handy	10000	24999
2	Mid-size Handy	25000	34999
3	Large Handy	35000	39999
4	Handymax	40000	49999
5	Traditional Supramax vessel	50000	60000
6	Ultramax	60000	69999
7	Traditional Panamax vessel	60000	78999
8	Post-Panamax vessel	79000	99999
9	Kamsarmax	79000	99999
10	Mini Capesize vessel	100000	129999
11	Standard Capesize vessel	130000	199999
12	Very large Ore Carrier (VLOC)	200000	-

Twenty-foot Equivalent Unit (TEU): TEU is a unit based on an ISO container of 20-foot length (6.10 m) (CBS, n.d.) and is a measure specific to container vessels, representing the cargo capacity in terms of standardized containers. This metric is highly relevant for container shipping, where it serves as both a measure of size and cargo capacity (Table 3.5. However, TEU's applicability is limited to container ships, making it less versatile across different vessel types.

Table 3.5: Containerships size classes based on TEU

		TEU	
class	**name**	**min**	**max**
1	Small feeder	0	1000
2	Feeder	1001	2000
3	Feedermax	2001	3000
4	Panamax	3001	5100
5	Post-Panamax	5101	10000
6	New Panamax	10001	14500
7	Ultra Large Container Vessels (ULCV)	14501	-

The analysis followed a systematic process to investigate the relationship between ship size and visit berthing time. First, the total visit berthing time for each vessel was calculated by summing all individual berthing events associated with a unique 'port_visit_id'. After that, vessels were categorized into size classes based on the three metrics (GT, DWT, and TEU) and, for each size class, the average visit berthing time was computed. Finally, the relationship between ship size and visit berthing time was visualized using scatter plots, with each ship's size plotted against its corresponding visit berthing time.

To quantify the relationship, a weighted linear regression was applied, which considered the different frequencies of size classes to ensure that the regression model accurately reflected the distribution of ship sizes.

To assess the statistical validity of the results, Yamane's formula was applied, which is commonly used to determine the appropriate sample size for a given confidence level and margin of error:

$$n = N/(1 + Ne^2) \xrightarrow{N\to\infty} 1/(e^2) \tag{3.1}$$

where:
n = sample size required to have a maximum error of e in a population of size N
e = desired error
N = population size

The analysis assumed an infinite population and considered an error margin of 5% as highly reliable and errors between 5% and 10% as acceptable. Therefore, samples of 100-399 elements were adequate and samples above 400 elements were highly reliable; this approach provided a robust basis for ensuring that the findings were statistically reliable and for identifying areas for further analysis.

3.1.6. Number of berthing events per port visit

To determine the number of berths a vessel visited during a single port visit, the study utilized a straightforward approach by grouping data according to the 'port_visit_id'. For each 'port_visit_id', the number of registered berthing events was counted, reflecting the total number of distinct berths visited by the ship during that visit.

After counting the berthing events for each 'port_visit_id', the resulting distribution of berth visits was plotted. This distribution provided an overview of the frequency with which vessels moved between different berths within the same port visit. Although the analysis of the number of berths visited is not directly related to the time spent at each berth, it offers valuable insights into the operational patterns within the port. Specifically, it helps in assessing the potential to differentiate between various stop types using location-based criteria rather than relying solely on the duration of each stop. If ships frequently visit multiple berths during a port visit, it suggests that a location-based method could be effective in categorizing different types of stops, complementing the time-based analysis. This understanding could enhance the accuracy of identifying and classifying berthing events, leading to a more nuanced analysis of port operations.

3.2. Qualitative analysis

As mentioned in the introduction, qualitative analysis was conducted to complement the quantitative analysis and address potential gaps in contextual understanding. It used three tools: semi-structured interviews with stakeholders in the maritime sector, unstructured consultation with the Port of Rotterdam, and a field visit to the port.

The principal tool was the semi-structured interview approach, which allowed for flexibility, enabling parties to elaborate on specific topics of relevance and provide insights that a purely structured approach might overlook. Out of the 26 companies contacted, only six responded positively, all Dutch (one LPG tanker, one chemical tanker, two offshore marine contractor, a reefer fleet, and a fishing company). Two of these companies declined in-person interviews but provided written insights. For the remaining four, video interviews were conducted, with each session being recorded and transcribed with the consent of the participants. Post-interview, all sensitive information was anonymized, and the interviews were summarized in technical reports. These reports were then sent back to the interviewees for verification and validation. To ensure consistency and facilitate data comparison, all reports followed the same structure. Finally, the key points from the interviews were extracted and organized into analytical tables for further analysis. Although the number of respondents was small, these interviews were valuable for shedding light on the activities conducted during berthing events (such as cargo handling, maintenance, and refuelling) and contextualising the results. Additionally, the interviews critically helped in interpreting the data accurately and assessing the validity of the patterns observed in the quantitative analysis. Furthermore, the interviews provided an understanding of the vessels' energy use within the port and their adoption of shore power. The questions used during these interviews can be found in Appendix B.

The unstructured interview with the Port of Rotterdam (data owner) was essential to interpret part of the results by understanding how the data has been collected. Specifically, this consultation clarified the limitations of the data collection system and how they may have influenced the results. Thus, this interview not only validated the results but also highlighted interesting points for future research.

Finally, the field visit, although of much less importance than the previous tools, contributed to the research as it helped to make abstract desk research real through the tangible experience of the studied complex socio-technical system. For example, it gave a taste of the system from the point of view of the agents who are part of it and contributed to acknowledging the real size of the ships, their movements and the spaces dedicated to them within the port.

However, stakeholder consultations did not only provide significant benefits but also came with certain limitations. The primary challenge was the resource-intensive nature of conducting interviews, which constrained the ability to gather a statistically significant sample within the time limits of the research. Moreover, contacting business representatives for interviews can be challenging without proper introductions. One of the main reasons is that businesses may not see an immediate benefit in sharing their information, prioritizing other commitments over an interview that does not directly align with their business goals, making them less inclined to participate. Additionally, representatives might be sceptical or cautious when approached by some stranger, especially if they are unsure of the intent or how the information will be used. This challenge is even more pronounced in maritime operations for its international nature: non-Dutch companies may have little interest in engaging with a Dutch research institute or university. Their global focus often means that local or national affiliations are not a priority, making it harder to capture their attention. Therefore, only a limited number of consultations could be performed, reducing the breadth of perspectives captured.

Despite these limitations, the consultations significantly contributed to the overall research. They provided a more reliable understanding of the operational dynamics within the port, offering insights into data quality and validity that would not have been accessible through quantitative methods alone. Additionally, the feedback from stakeholders helped to identify potential discrepancies or areas for improvement in the data analysis, ensuring that the research findings were well-grounded in real-world practices.

4

Berthing times

This chapter explores the berthing behaviour of the different vessels in the port of Rotterdam, mainly focusing on the time. This chapter answers the question *What berthing time patterns emerge by studying the behaviour of different types of vessels inside the Port of Rotterdam?* and demonstrates the need to understand the role of time in berthing activities.

To do so, this chapter begins by introducing the overall berthing situation in Rotterdam, taking the port as a whole; after that, it presents the results per category and fleet type, highlights the patterns that emerged from studying the frequency and duration of the stops simultaneously, and shows the fallacy of looking just at the frequency of the berthing event to determine crucial stops. Later on, the chapter displays the relationship between ship size and time in port to complete the analysis by linking berthing times to some physical features; the size-time analysis contributes to proving that the identified clusters are not due to different physical characteristics but for uncommon operations and strengthens the argument that reality is more complex than the models used to represent it. Finally, the chapter uses the results from the distribution of berthing events to prove that a time-based approach is the only feasible to distinguish stop types.

4.1. Port-as-a-whole analysis

The port recorded 280’402 berthing events in 2023, corresponding to 31’022 calls; the sum of all the time spent at berth amounted to almost two hundred years (190). As shown in Figure 4.1, tanker vessels are the category that spends most time at berth in Rotterdam: they stayed for almost 20’500 days, accounting for 30% of the total time all vessels spent at berth in the port during 2023. Port operational vessels and containerships follow with 14’500-15’000 and 9’500. Regarding berth locations, vessels dock mostly at quays and jetties - 32’500 days (46.8%) and 24’000 days (34.5%) (Figure 4.2).

Figure 4.1: Breakdown total time at berth per category

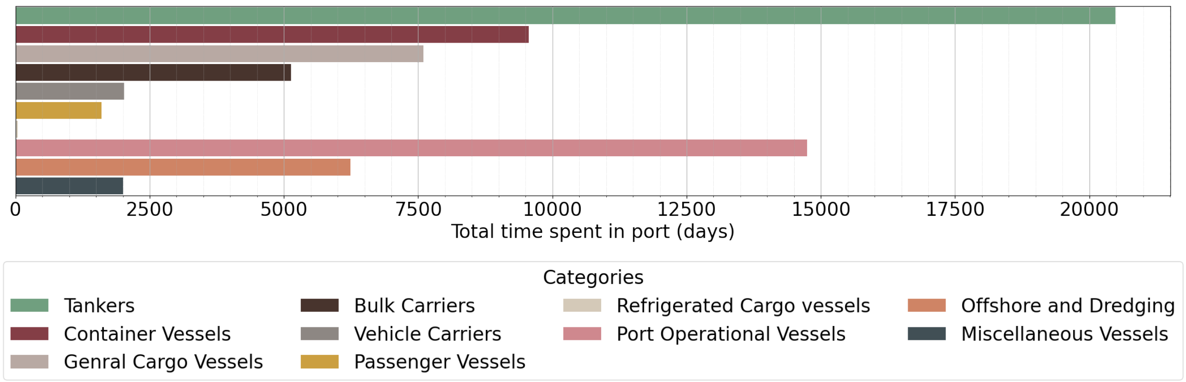
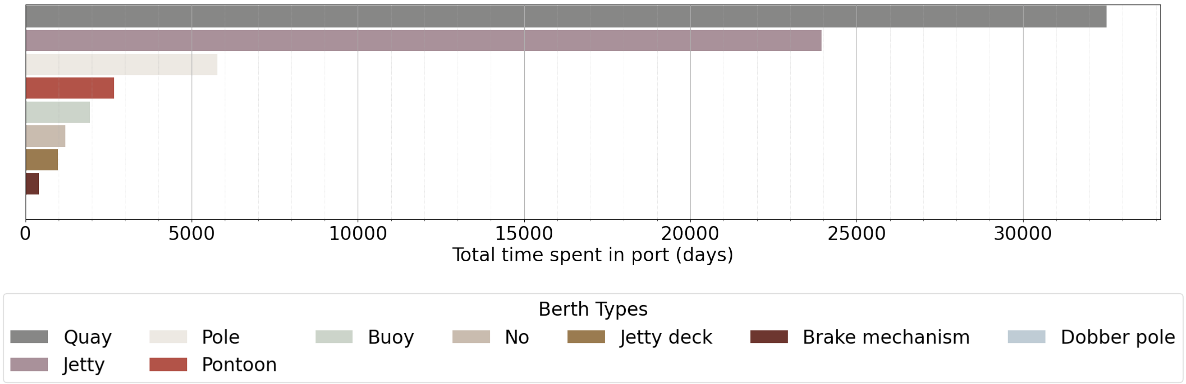


Figure 4.2: Breakdown total time at berth per berth type



By entering the details about the time, the distribution of the berthing events, reported in Figure 4.3, was a clear indicator of the registered berthing events and how often they occurred, showing a global peak of berthing events shorter than one hour and a local peak around ten hours; therefore, berthing events of less than one hours or of ten hours were the most recorded. This fact is even more evident in Figure 4.4, which indicates that almost 60% of the registered berthing events last less than one hour. However, the main objective was not to identify the most frequent stops but the main contributors to the total berthing time. When both frequency and duration are observed simultaneously, the results acquire a different shape.

The importance of the most frequent berthing events is completely diminished: although extremely frequent, their duration (<1 hour) is so short that their impact on the overall time spent in port is less than 5%. This fact is displayed in Figure 4.5: the line corresponding to one-hour berthing events intercepts the curve at a point very close to 1, which means that events lasting one hour or less have relatively low importance on the total berthing time in the year.

Figure 4.3: Distribution of berthing events based on duration (h)

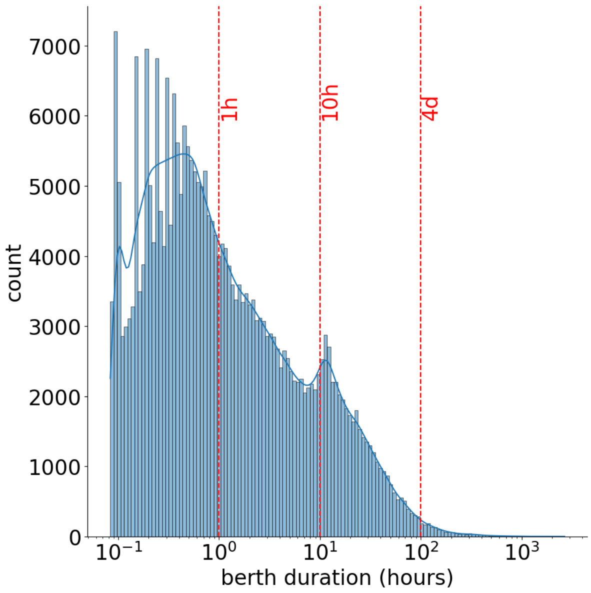


Figure 4.4: Cumulative distribution of berthing events based on duration (h)

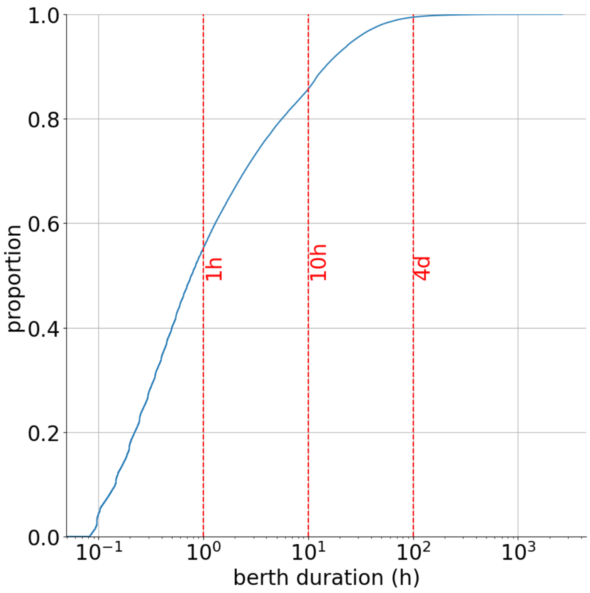
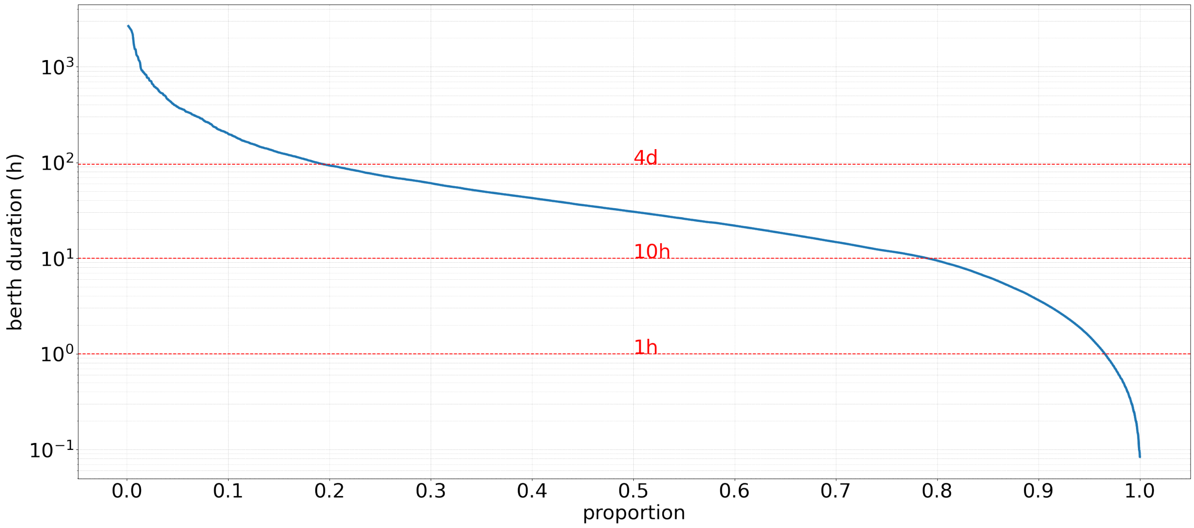


Figure 4.5: berth duration curve



By applying the elbow method to the modified load duration curve in Figure 4.5, two key durations emerge: four days and ten hours. The point corresponding to four days indicates that berthing events longer than four days contribute to 20% of the total time spent in port although they do not happen often. In fact, Figure 4.4 shows that berthing events longer than four days are extremely rare, seldom happening compared to shorter ones. Contrarily, berthing events shorter than ten hours accounted for 20% of the total berthing time in 2023 despite representing almost 90% of the total registered berthing events (Figures 4.4 and 4.5).

These results demonstrate that, when looking at the port as a whole, observing just the berthing events distribution does not identify the main contributors to the total berthing time. Additionally, the modified load duration curve exhibited three identifiable patterns with comparable contributions to the total berthing time. The first consists of events longer than four days and contributes to 20% of the total berthing time; the second collects events whose duration is between four days and ten hours and its contribution counts for 60% of the total berthing time. Finally, the third pattern gathers berthing events shorter than ten hours and accounts for the remaining 20% of the total berthing time. These three event types will be called short, standard, and long stops according to their duration. As summarised in table 4.1, this finding is crucial: if the emission inventories were built upon the standard berthing behaviour, they represent reliably 60% of the total berthing time. However, standard emission factors might not precisely describe the remaining 40%, which is a non-negligible share, thus requiring further investigation.

Table 4.1: Overall analysis berthing time patterns

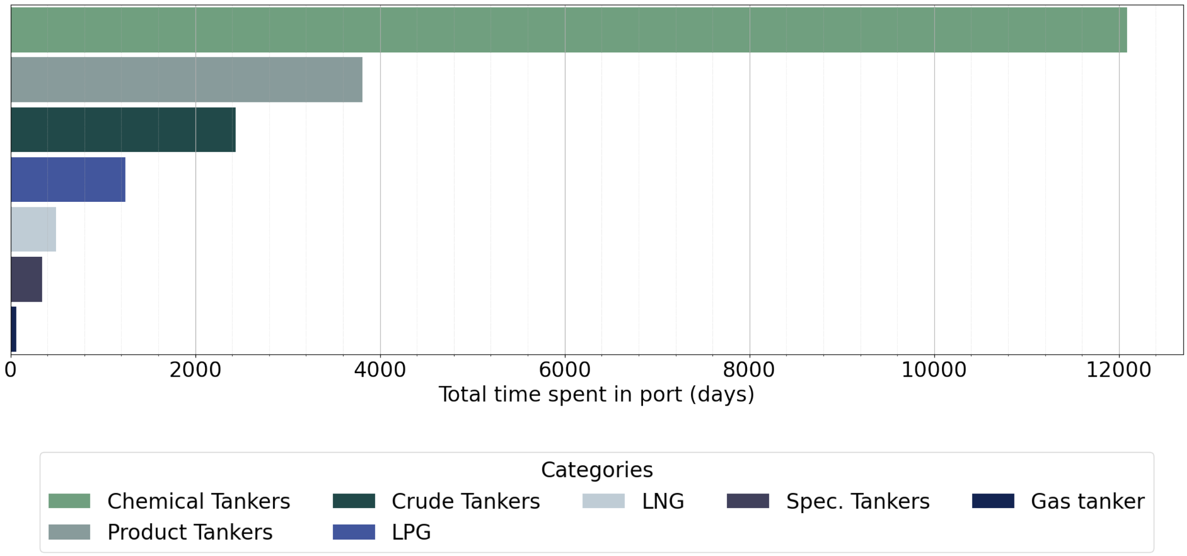
Time pattern	Duration	Share of total berthing time
Short stops	< 10h	20%
Standards stops	10h - 4d	60%
Long stops	> 4d	20%

4.2. Berthing time patterns per fleet type category

4.2.1. Tankers

Tankers are the fleet-type cluster that spent the most time at berth in Rotterdam. This category is composed of Chemical Tankers (12’000 days at berth, corresponding to 17.4% of the total time at berth), Product Tankers (2’800 days), Crude Tankers (2’200 days), LPG Carriers (600 days%), LNG Carriers (200 days%), Specialised Tankers (<200 days), and Gas Tankers - Figure 4.6. Given that Rotterdam is the largest petrochemical cluster in Europe (Port of Rotterdam, 2023), this result was aligned with expectations.

Figure 4.6: Breakdown time spent at berth of Tanker Vessels



As anticipated in the previous section, the curve displays the frequency and duration of berthing events simultaneously and permits clustering by looking at the curve’s elbows. The standard stops are contained within the linear part of the curve, whereas the loss of linearity and change in steepness mark the beginning of the short/long stops. This method identified clusters that do not always match the berthing times distribution; for example, Figure 4.10 shows that the most common berthing events last less than one hour; however, the modified load duration curve flags the events lasting between 20 and 200 hours as the most important. In fact, almost 75% of the total time spent in port by LPG carriers lies between these two boundaries.

Additionally, distribution proves to be an insufficient method even in the cases where the peak in the distribution of the events coincides with the modified load duration curve because the distribution alone does not provide information about the total berthing time. For instance, the distribution of berthing events of LNG carriers, presented in Figure 4.11, indeed shows a peak between 20 and 40 hours but cannot communicate anything about the percentage of total berthing time occupied by the peak. Consequently, the modified load duration curve proves to be a better method for identifying berthing time patterns again.

Figure 4.7: Chemical Tankers

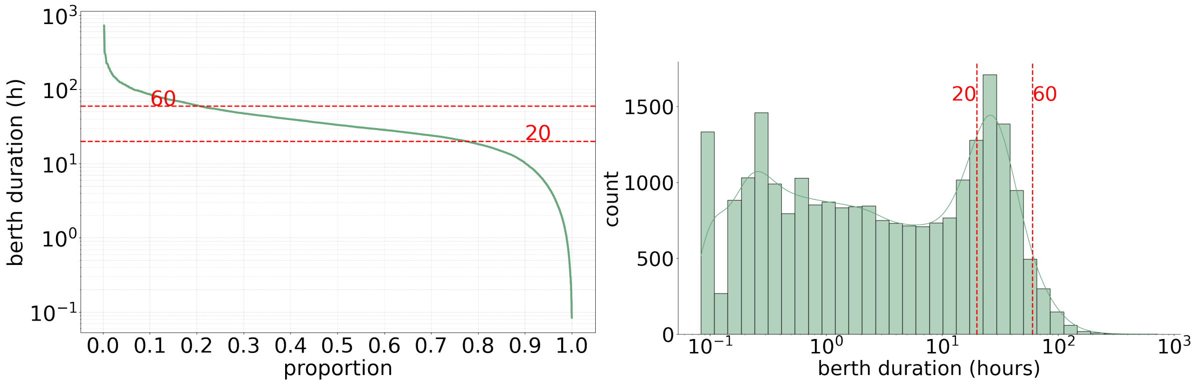


Figure 4.8: Product Tankers

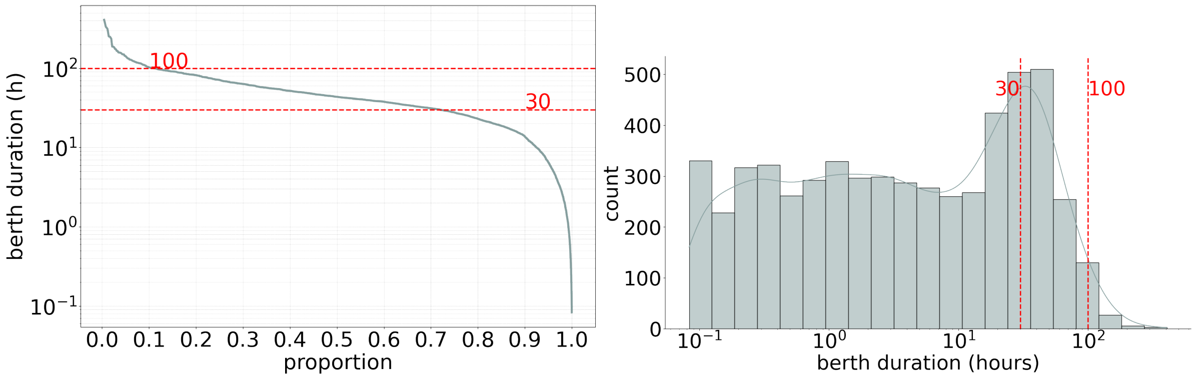


Figure 4.9: Crude Tankers

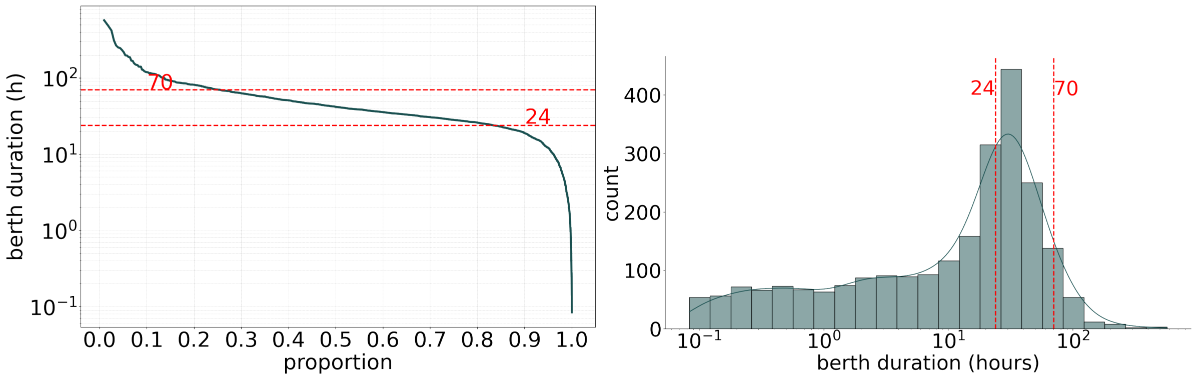


Figure 4.10: LPG

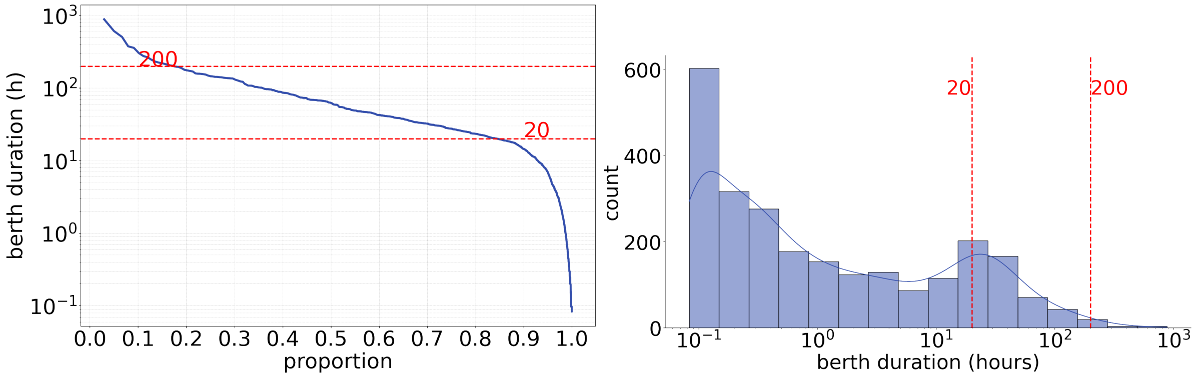


Figure 4.11: LNG

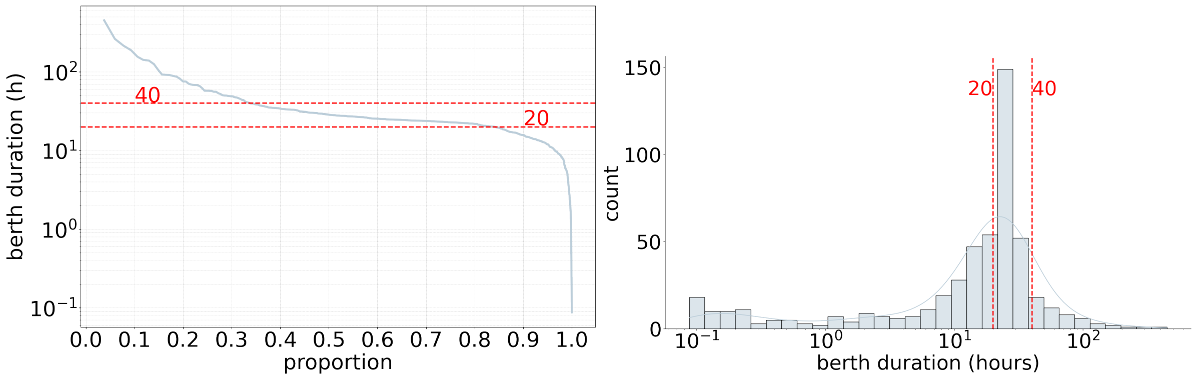


Figure 4.12: Spec. Tankers

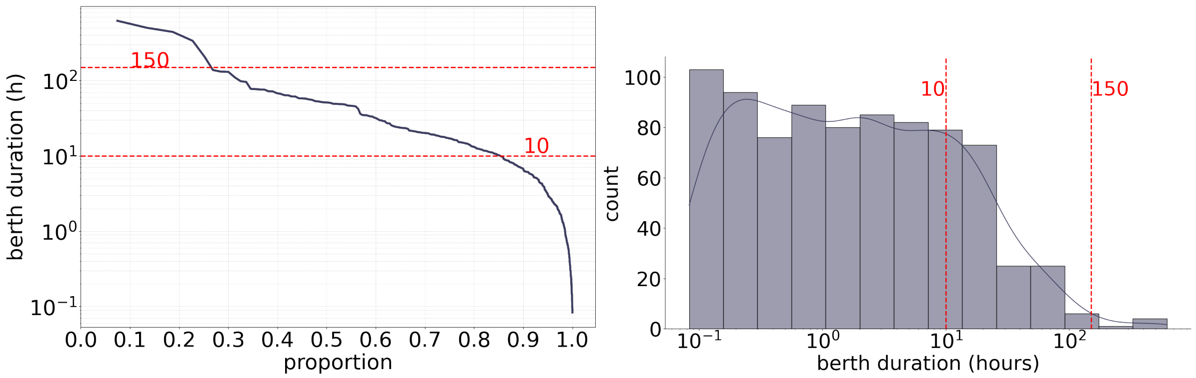


Figure 4.13: Gas tanker

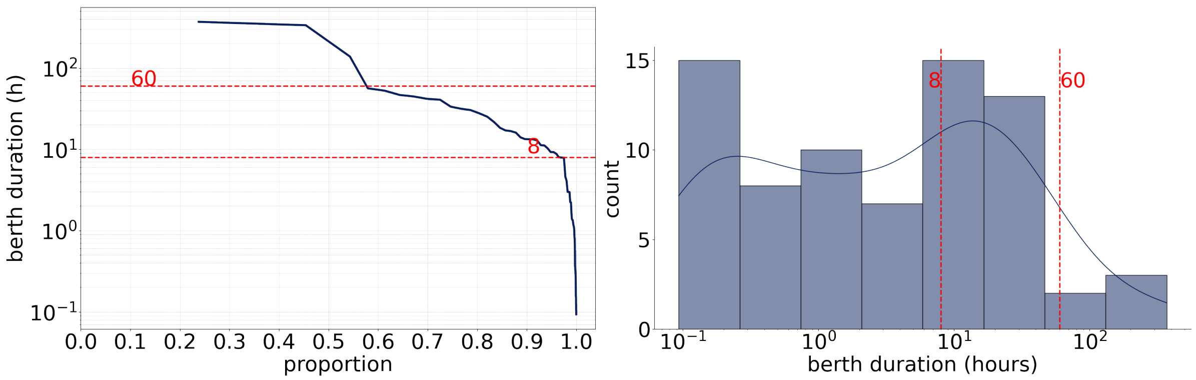


Table 4.2 collects the results of the berthing time patterns for this category. It includes the durations of the three stop types per fleet type. Moreover, it presents the share each stop type occupies in the total time spent at berth. Generally speaking for the category, the interval limiting the standard stops is usually tight, about a few days - between one and three - with some exceptions; the interval of LPG carriers is broader, with the upper limit set to approximately eight days, while for LNG is tighter - it ends at less than two days (Figures 4.11 and 4.10). Furthermore, the long stops begin between 40 and 200 hours, while the shorter stops between 10 and 30, showing that shorter berthing events last approximately the same time for every fleet type. Longer stops, instead, are longer for some vessel types (LPG carriers, Specialized Tankers, and Product Tankers). Regarding the share of the total time at berth, standard stops typically contribute to 60%, but the shares occupied by short and long stops are not distributed equally. For instance, for Chemical, Crude, and Specialized Tankers, the standard stops correspond to 60% of the total time at berth; however, for Crude and Specialized Tankers, long stops correspond to 25% and short berthing events for 15%; on the other hand, for Chemical Tankers, long and short stops are equally significant, both contributing for 20% of the total time at berth.

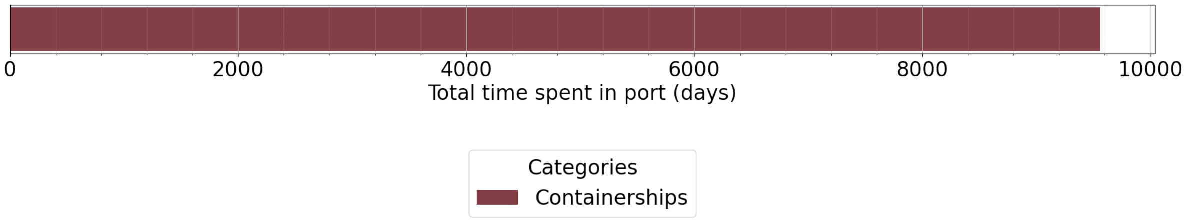
Table 4.2: Berthing time patterns for Tankers

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Chemical Tankers	<20	20	20-60	60	>60	20
Product Tankers	<30	25	30-100	65	>100	10
Crude Tankers	<24	15	24-70	60	>70	25
LPG	<20	15	20-200	70	>200	15
LNG	<20	15	20-40	50	>40	35
Spec. Tankers	<10	15	10-150	60	>150	25
Gas tanker	<8	2	8-60	43	>60	55

4.2.2. Container vessels

Containerships are the second most present fleet type in Rotterdam per time spent at berth - almost 9’500 days. Again, the result aligns with Port of Rotterdam (2023): Rotterdam is the largest container port in Europe.

Figure 4.14: Breakdown time spent at berth of Container Vessels



The left graph in Figure 4.15 identifies events between nine and eighty hours (three days and a half) as the standard stops. The events between these limits account for about 70% of the time spent at berth. However, the distribution on the right portrays a different picture: the most commonly registered events last around ten hours, and stops around eighty hours are definitely infrequent. Nevertheless, their length makes them important events concerning total time spent at berth.

Figure 4.15: Container Vessels

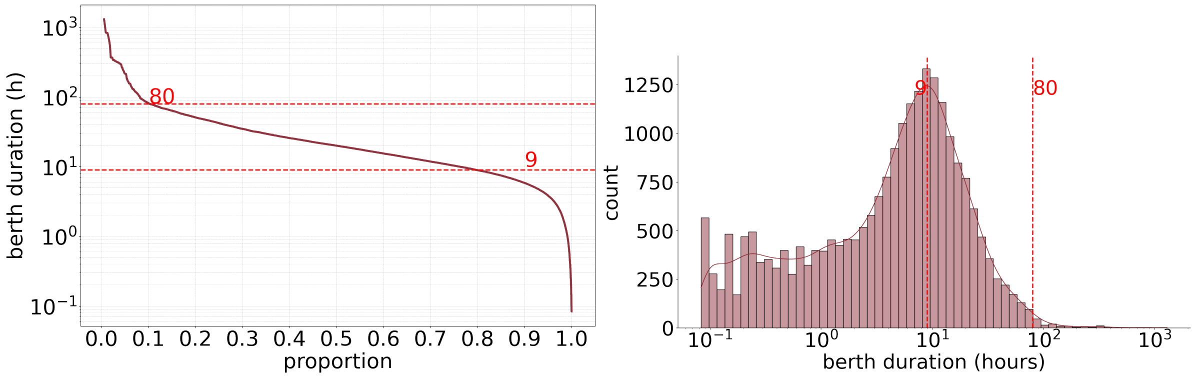


Table 4.3: Berthing time patterns containerships

Time pattern	Duration	Share of total berthing time
Short stops	< 9h	20%
Standards stops	9h - 80h ($\sim$ 3.5d)	60%
Long stops	> 80h ($\sim$ 3.5d)	20%

4.2.3. General cargo vessels

Multi-Purpose Product vessels (MPP) and General Cargo vessels are designed for flexibility and carry a large variety of cargo, simultaneously or not. The curious result about these two fleet types is that they showed similar behaviour regarding berth duration distribution and the exact same definition of short and long stops (Figures 4.18 and 4.17) - both limits are set at 20 and 100 hours accounting for 20% (long stops) and 30% (short stops) of total time at berth.

Figure 4.16: Breakdown time spent at berth of General Cargo

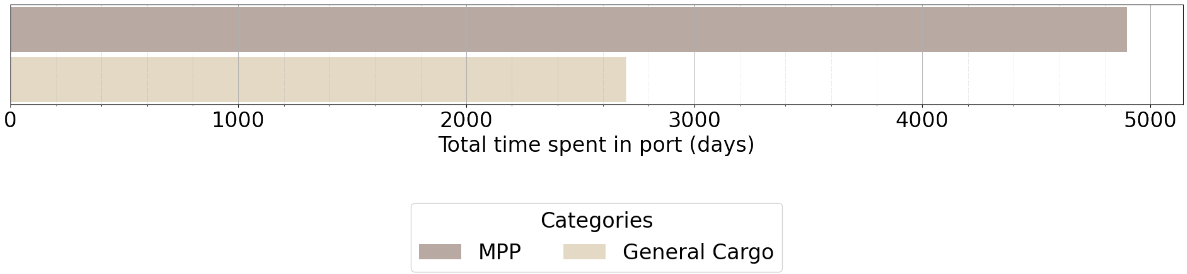


Figure 4.17: MPP

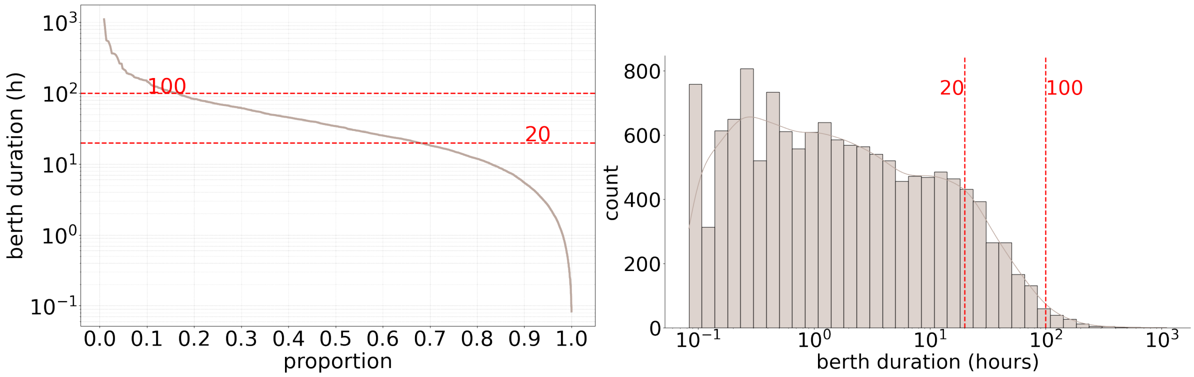


Figure 4.18: General Cargo Vessels

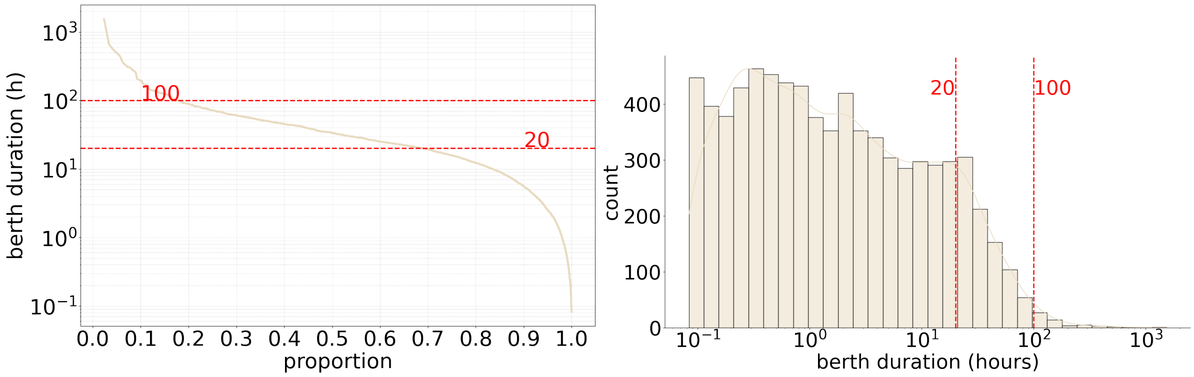


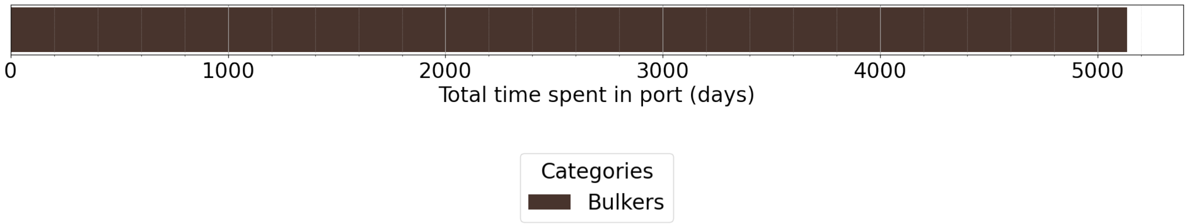
Table 4.4: Berthing time patterns for MPP and General Cargo Vessels

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
MPP	<20	30	20-100	50	>100	20
General Cargo Vessels	<20	30	20-100	50	>100	20

4.2.4. Bulk Carriers

Bulk Carriers showed intriguing behaviour from two fronts. They have no pronounced peak in the distribution and the lower boundary of short stops is quite high (Figure 4.20).

Figure 4.19: Breakdown time spent at berth of Bulkers



As anticipated, short stops end at 50 hours, and long stops begin around 200 hours (about eight days) - two of the highest limits found in the analysis. Therefore, on average, all the event types are longer compared to the other segments. Long events account for 20% of the time in port, standard for 55%, and short for 25% (Figure 4.20 and Table 4.5).

Figure 4.20: Bulkers

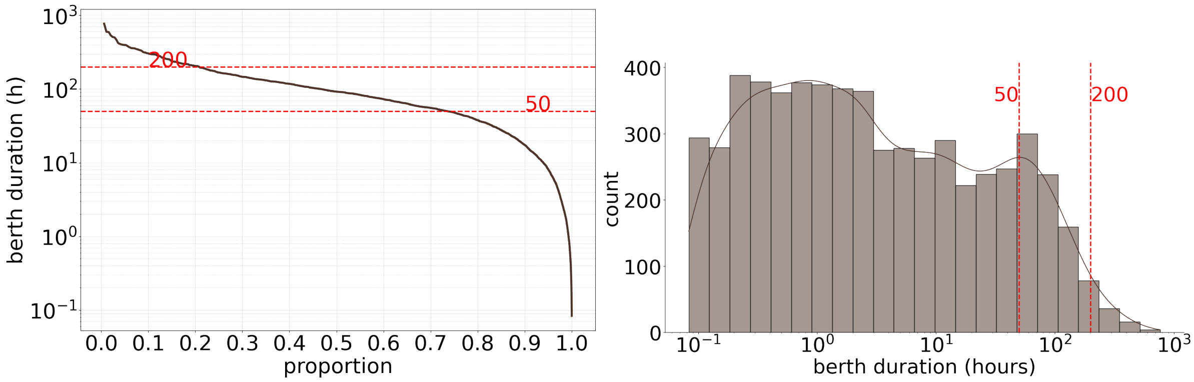


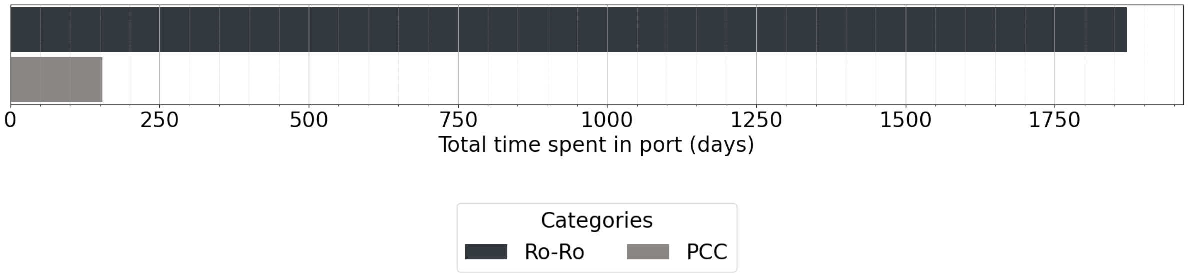
Table 4.5: Berthing time patterns Bulkers

Time pattern	Duration	Share of total berthing time
Short stops	< 50h	25%
Standards stops	50h - 200h (∼ 8.5d)	55%
Long stops	> 200h (∼ 8.5d)	20%

4.2.5. Ro-ro and PCC

Roll-on/roll-off ships (Ro-ro) and Pure Car Carriers (PCC) are designed to carry wheeled cargo loaded and unloaded via ship doors or slipways. Although they represent a tiny share of the time spent at berth, less than 3% (Figure 4.21), the port of Rotterdam is an important logistics hub for the import and export of Ro-Ro cargo.

Figure 4.21: Breakdown time spent at berth of Vehicle Carriers



Nonetheless, the distribution of Ro-Ro in Figure 4.22 shows a curious behavioural pattern with two distinct peaks: stops of 3 to 5 hours and 8 to 15 hours. Moreover, these peaks somehow coincide with the range from the graph on the left: standard events lasted between four and forty hours. For Ro-Ro vessels, long stops have a greater contribution than short stops: long stops contributed for almost 25% of the total berthing time, while short stops only for 5-10%.

Pure Car Carriers (PCC), although not presenting a similar distribution, show a closer definition of short and long stops - between 15 and 60 hours. On the other hand, they both contribute for 20-25% (Figure 4.23).

Figure 4.22: Ro-Ro

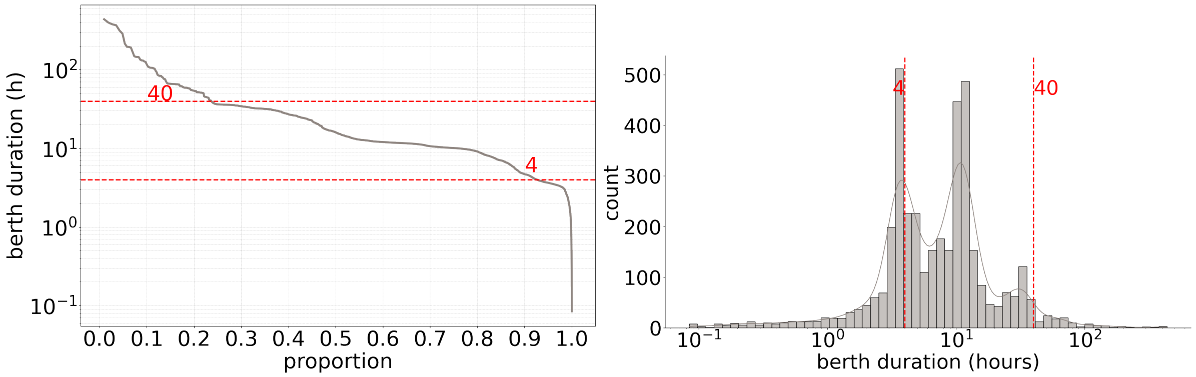


Figure 4.23: PCC

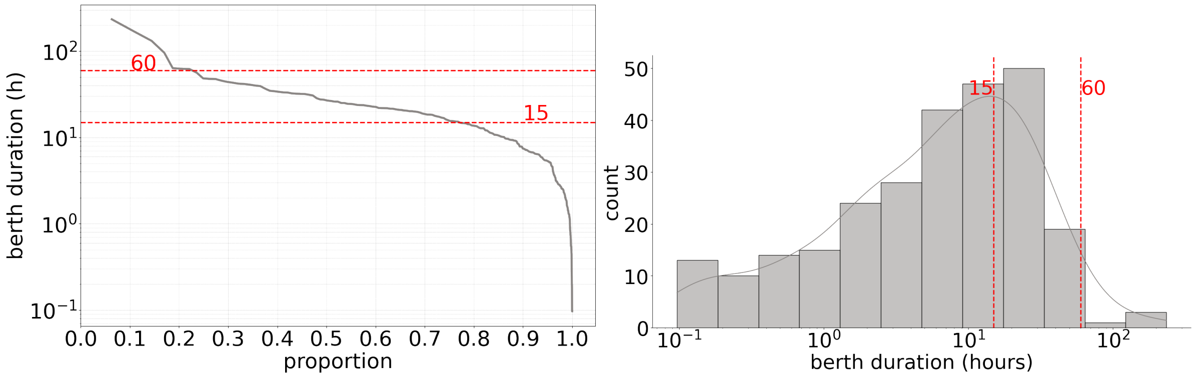


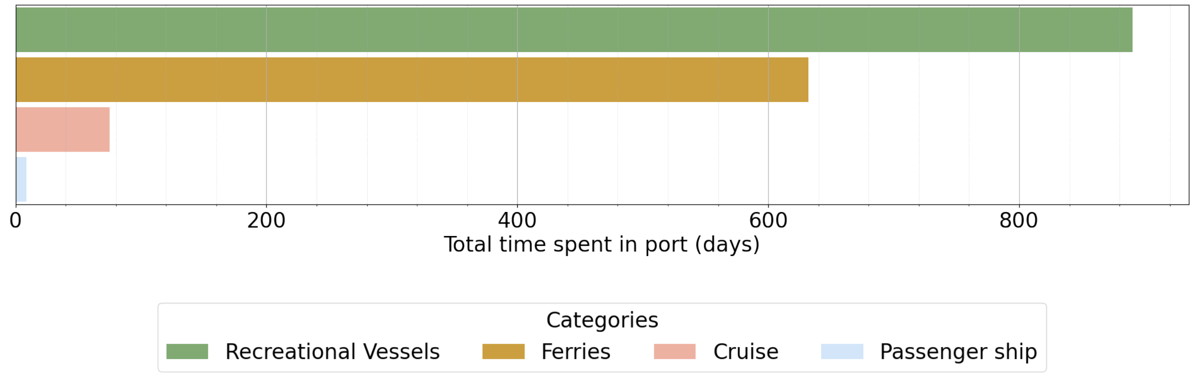
Table 4.6: Berthing time patterns for Ro-ro and PCC

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Ro-ro	<4	5	4-40	70	>40	25
PCC	<15	25	15-60	50	>60	25

4.2.6. Passenger vessels

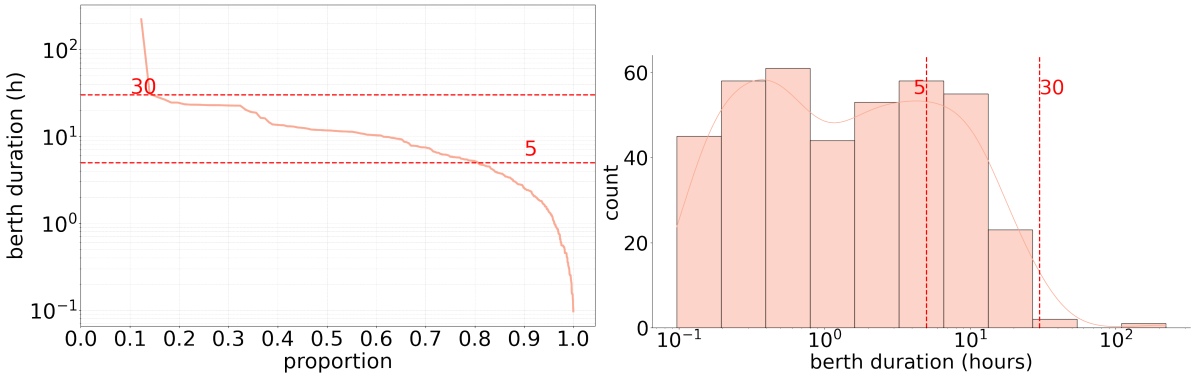
Passenger's vessels include cruises, ferries, recreational vessels (e.g. yachts or sailing ships), and undefined passenger ships. All these fleet types do not even form 2.5% of the total time at berth (Figure 4.24). Nonetheless, scientific literature focuses extensively on cruise ships (for example, Yeo et al. (2024), López-Aparicio et al. (2017), Chen et al. (2016), Y. T. Chang et al. (2014), or Ng et al. (2013)). There might be two main reasons for this: first, cruise terminals are often very close to city centres (looking at the Cruise Port Rotterdam (n.d.), the cruise terminal in Rotterdam is just before the Erasmusbrug). Secondly, cruise ships are very energy-intensive vessels, producing large amounts of pollution: in 2022, the most polluting ships visiting European ports were cruise ships (EMSA, & European Commission, 2023).

Figure 4.24: Breakdown time spent at berth of Passenger Vessels



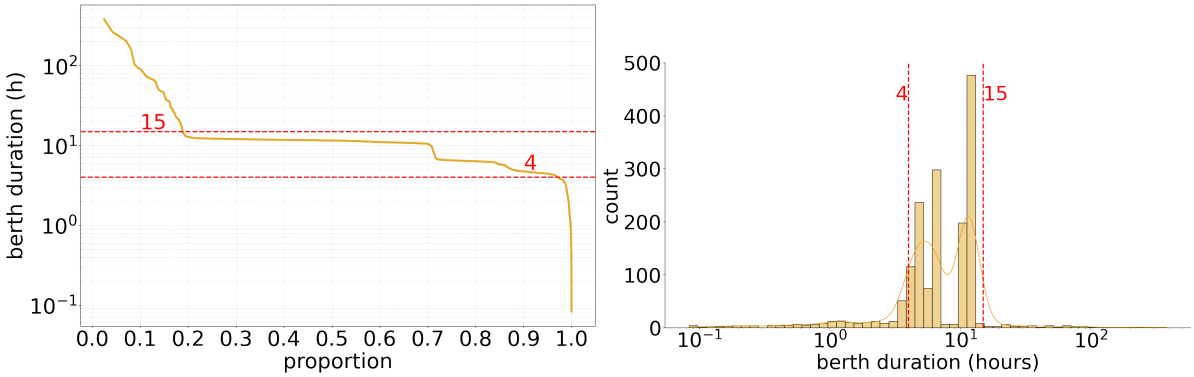
Cruise ships generally stop in Rotterdam for a maximum of slightly more than a day, and almost all time at berth is the result of stops no longer than that (Figures 4.25); stops within five and thirty hours account for cruises' 65% of the total time at berth, but long stops contribute only for 15%. Short berthing events are quick, but they still account for almost 20% of the total registered berthing time.

Figure 4.25: Cruise Ships



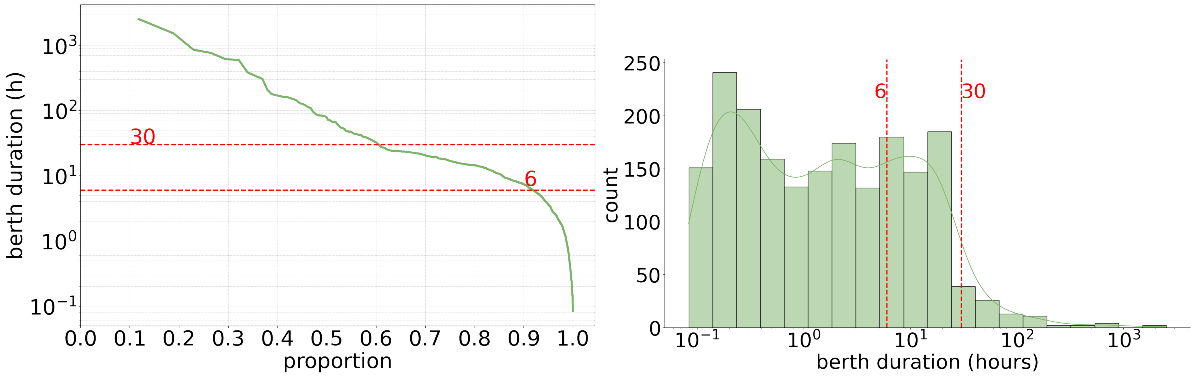
Like vehicle carriers, ferries make brief stops in Rotterdam - almost all the berthing events last within a day, Figure 4.26; in fact, ferries are often called Ro-Pax vessels to recall their resemblance with Ro-Ro ships. Compared to cruises, ferries make many more calls through the year: 1254 calls – Cruise only 400. Additionally, the interval identified in Figure 4.26 - 4 to 15 hours - coincides with the peak of the distribution, suggesting that the most frequent berthing events are also the ones contributing the most to the total mooring time. Finally, ferries have the peculiarity that the identified short berthing events are almost inexistent on the total berthing time: stops quicker than four hours account for less than 5%.

Figure 4.26: Ferries



For recreational vessels, long stops have a larger impact on the total time spent at berth: the curve changes steepness at thirty hours (Figure 4.27, leading to an interesting picture. Almost 60% of the total berthing time comes from long stops despite being very rare according to the distribution. However, these vessels are small, probably always connected to shore with the engines off, and privately owned. Therefore, skipping this last segment might not considerably impact the analysis.

Figure 4.27: Recreational Vessels



Yet, Other Passenger Vessels, do not have long stops at all. Although the curve in the left side of Figure 4.28 has a steep section between two and five hours, the segment is short and the sections before and after are almost parallel. Moreover, short stops are extremely short, lasting less than one hour though contributing to 15 % of the registered berthing time.

Figure 4.28: Other Passenger Vessels

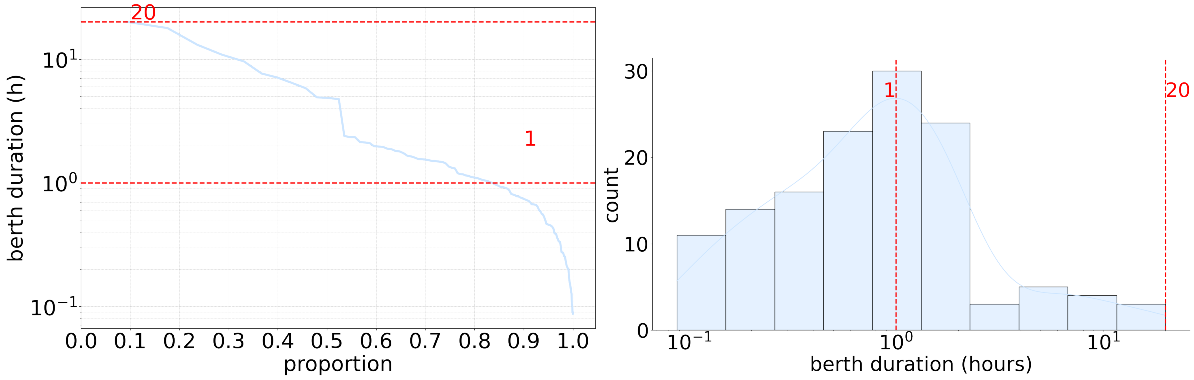


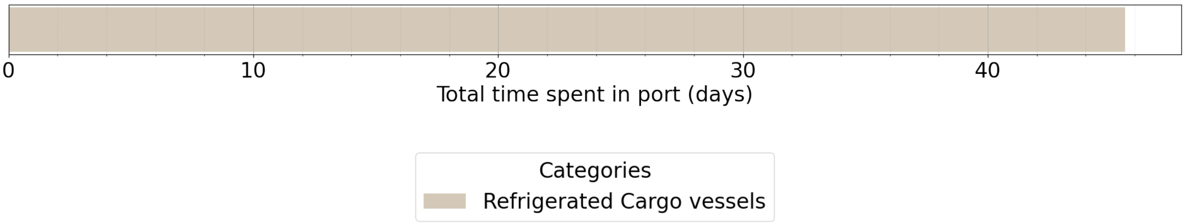
Table 4.7: Berthing time patterns for Passenger Vessels

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Cruise ships	<5	20	5-30	65	>30	15
Ferries	<4	5	4-15	75	>15	20
Recreational vessels	<6	10	6-30	30	>30	60
Other Passenger vessels	<1	15	1-20	85	>20	0

4.2.7. Refrigerated Cargo vessels

The study of Refrigerated Cargo vessels is essential despite accounting for a tiny slice compared to other segments in the Rotterdam harbour. From the emission side, temperature control is an energy-intensive action. Additionally, refrigerated and frozen food transport allows Dutch society to benefit from a range of fresh products (KVNR, n.d.).

Figure 4.29: Breakdown time spent at berth of Refrigerated Cargo vessels



The identified elbow points occur at 20 and 100 hours; however, long stops are almost non-existent. As a result, standard stops determine 70% of the total berthing time and short stops 30% (Figure 4.30 and Table 4.8).

Figure 4.30: Refrigerated Cargo Vessels

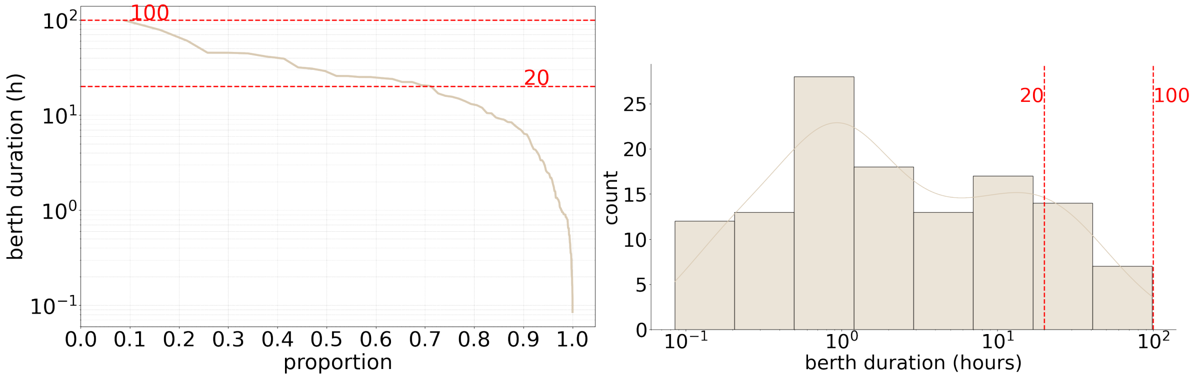


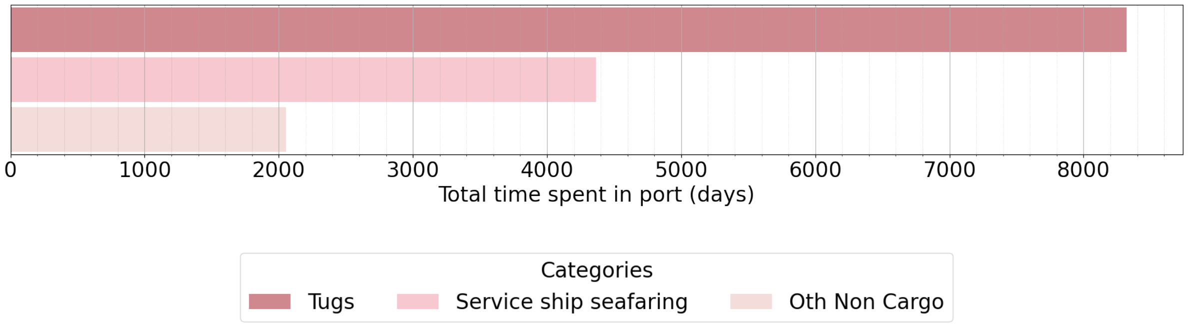
Table 4.8: Berthing time patterns Refrigerated Cargo Vessels

Time pattern	Duration	Share of total berthing time
Short stops	< 20h	30%
Standards stops	20h - 100h (∼ 4d)	70%
Long stops	> 100h (∼ 4d)	0%

4.2.8. Port Operational vessels

Port Operational vessels are those ships that do not necessarily move cargo or passengers from one port to another. They generally perform functions that are not shipping: guiding ships inside the port, bunkering, performing ship-to-ship transfers, et cetera. Additionally, they typically are smaller vessels. This category includes Tugs, Service Ship Seafaring, and Other Non-cargo Vessels. This last fleet type includes patrol vessels, research vessels, cable layers, crane vessels, bunkering vessels, et cetera. Spending most of their time in port, these vessels account for a considerable share of Rotterdam's total berthing time, with Tugs leading with 12% (Figure 4.31).

Figure 4.31: Breakdown time spent at berth of Port Operational Vessels



As shown by Figures 4.32, 4.33, and 4.34, all these fleet types perform numerous quick stops, even faster than one hour. Nevertheless, the most significant berthing events in terms of contribution to the total are the ones between 1 and 30 hours for Tugs, 1 and 300 hours (12.5 days) for service ships, and 1 and 150 hours (about six days) for Other Non-Cargo Vessels. Note how the definition of a long stop is relative: for Tugs, a 30-hour berth is considerably long, but for almost all other categories (tankers, containers, general cargo, et cetera) 30 hours is a very normal if not short time.

Figure 4.32: Tugs

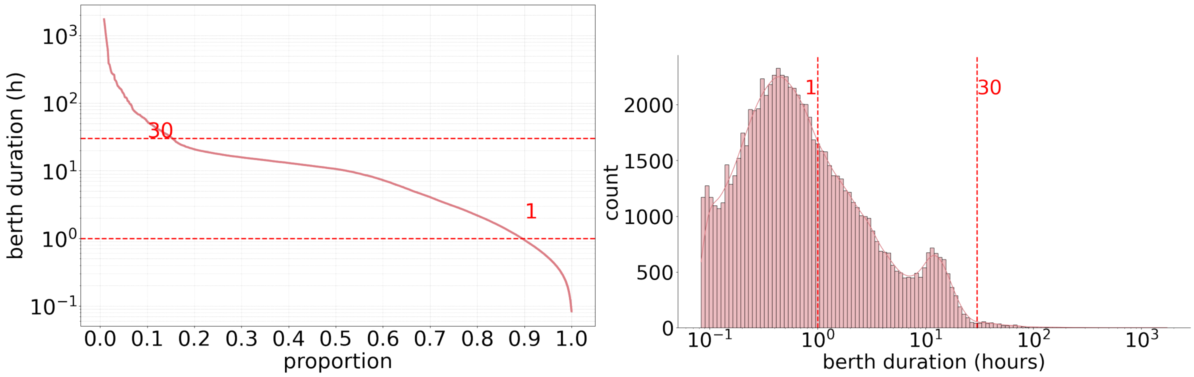


Figure 4.33: Service Ships Seafaring

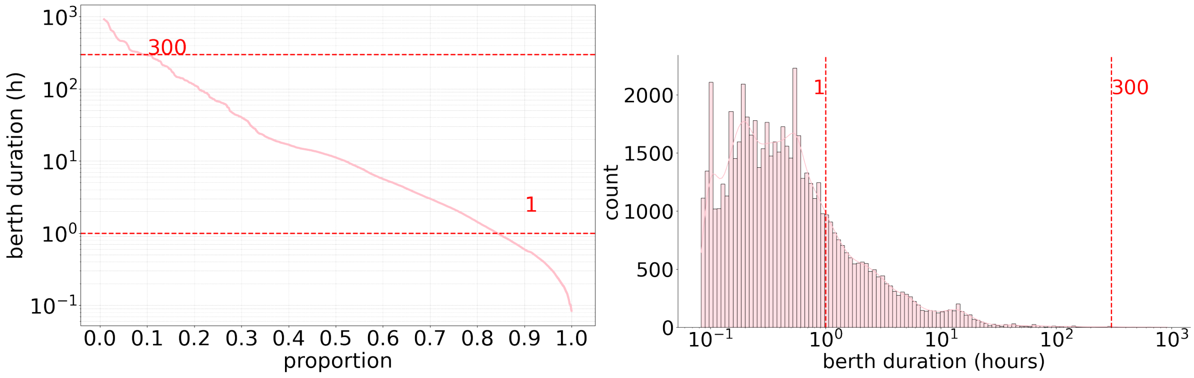
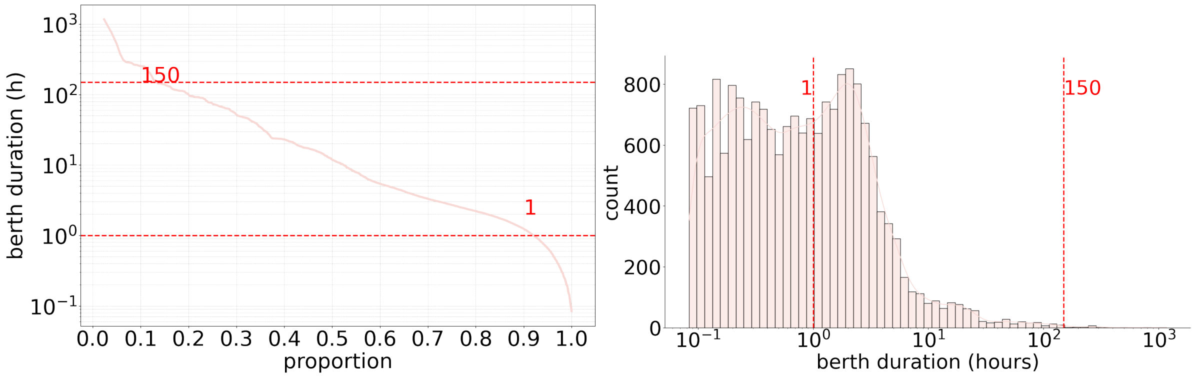


Figure 4.34: Other Non-cargo Vessels



The impact of short and long stops on the total time at berth varies based on the segment, as summarised by Table 4.9. For Tugs, longs contribute to 15% and shorts to 10%; for Service Ships, 10 and 15; for Other Non-Cargo, 15 and slightly less than 10.

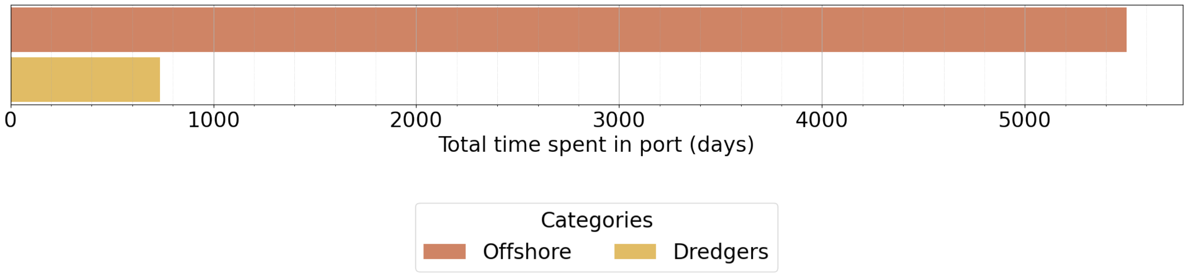
Table 4.9: Berthing time patterns for Port Operational Vessels

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Tugs	<1	10	1-30	75	>30	15
Service Ships	<1	15	1-300	75	>300	10
Other Non-Cargo vessels	<1	10	1-150	75	>150	15

4.2.9. Offshore and Dredgers

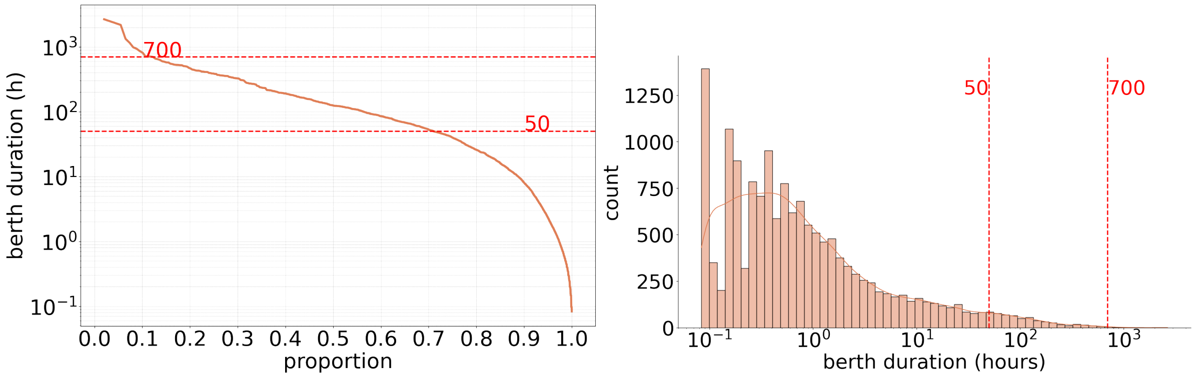
Offshore vessels are specialized ships designed to support marine operations such as oil and gas exploration or offshore wind construction; dredgers are ships used to excavate and remove sediment from the bottom of the sea to maintain navigable waterways or for land reclamation purposes. Therefore, they visit the port not to ship cargo but to prepare for their operations at sea.

Figure 4.35: Breakdown time spent at berth of Offshore and Dredging Vessels



The most common berthing events for Offshore vessels are short; nonetheless, the most significant stops for this study lie between two days (50 hours) and one month (700 hours) (Figure 4.36). Short stops occupy 30% of the total berthing time and long stops 10%.

Figure 4.36: Offshore Vessels



Dredgers show a similar result: the most frequent events last less than ten hours; however, all the stops shorter than 20 hours emerged as short and the ones above 16.5 days as long. Concerning the corresponding share, long stops account for 20% and short for 15% (Figure 4.37).

Figure 4.37: Dredgers

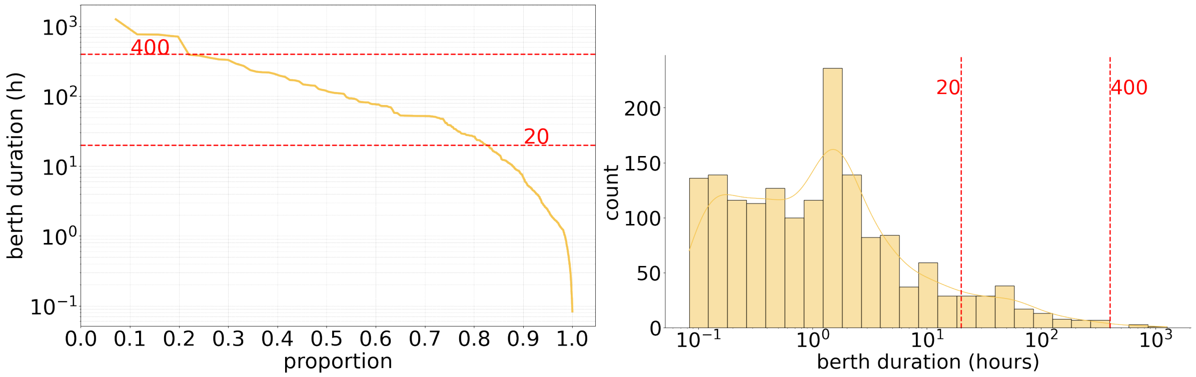


Table 4.10: Berthing time patterns for Offshore vessels and Dredgers

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Offshore	<50	30	50-700	60	>700	10
Dredgers	<20	15	20-400	65	>400	20

4.2.10. Miscellaneous Vessels

Eventually, miscellaneous vessels – unknown ships, other seagoing vessels, and fishing vessels – represent a microscopic share, less than 1%, never stopped in the port for more than two weeks, and too much information is missing. Therefore, the results are only summarized in Table 4.11.

Table 4.11: Berthing time patterns for Miscellaneous vessels

Fleet Type	**Short stops**		**Standards stops**		**Long stops**	
	Duration (h)	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**	**Duration (h)**	**% tot. berthing time**
Unknown ships	<10	25	10-100	55	>100	20
Other seagoing vessels	<22	40	22-175	58	>175	2
Fishing vessels	<3	10	3-25	55	>25	35

Figure 4.38: Breakdown time spent at berth of Miscellaneous Vessels

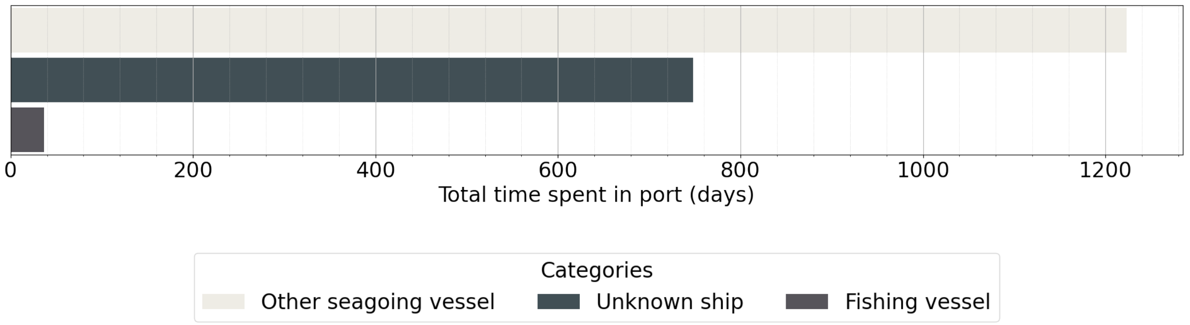


Figure 4.39: Unknown Ships

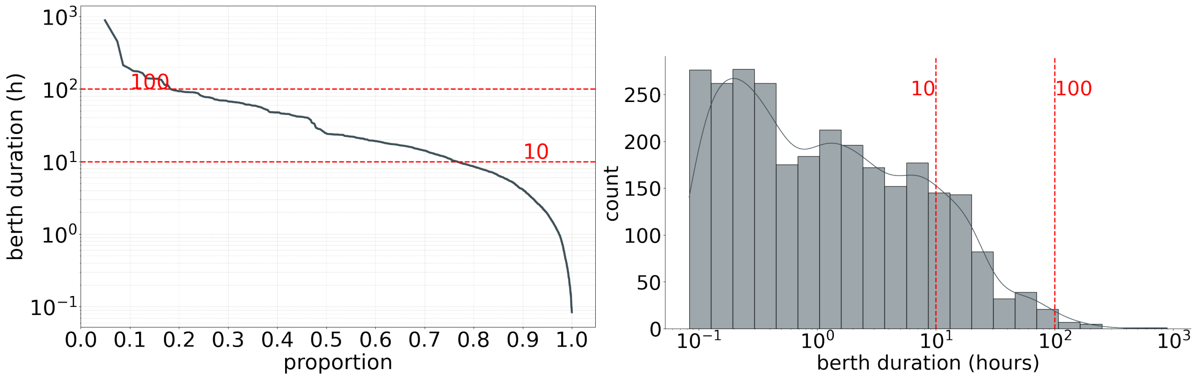


Figure 4.40: Other Seagoing Vessles

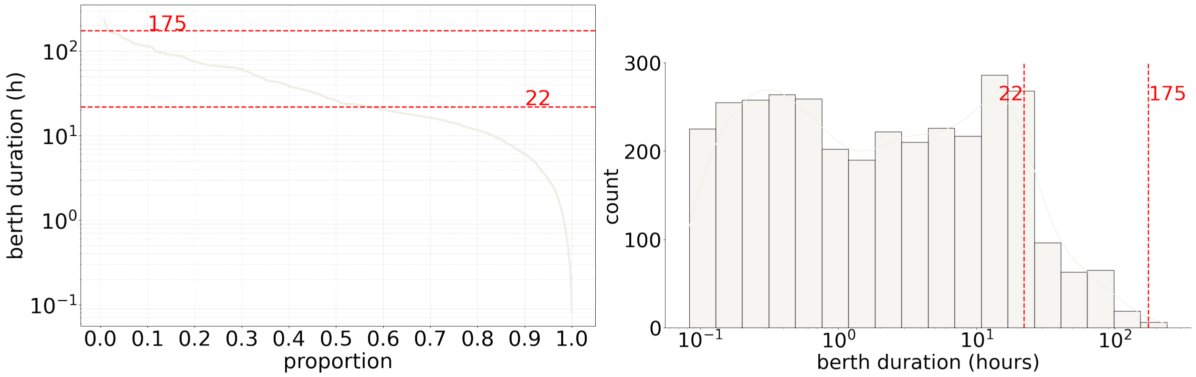
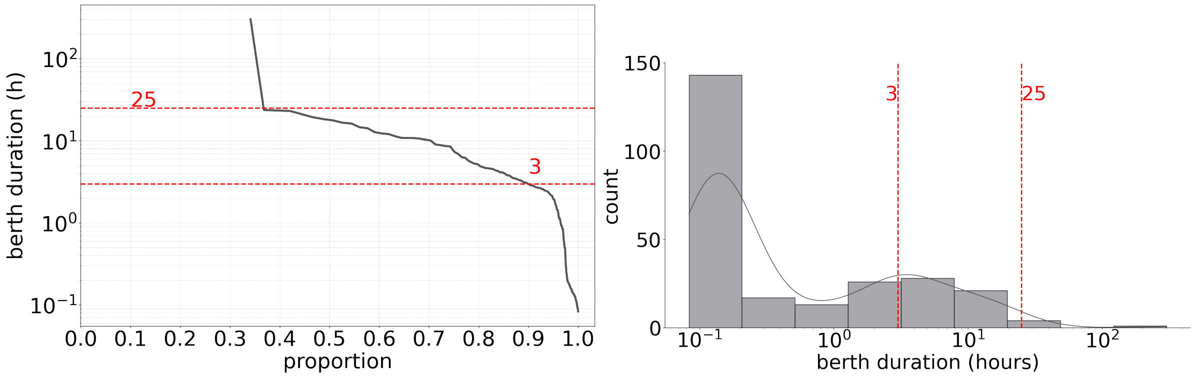


Figure 4.41: Fishing Vessels



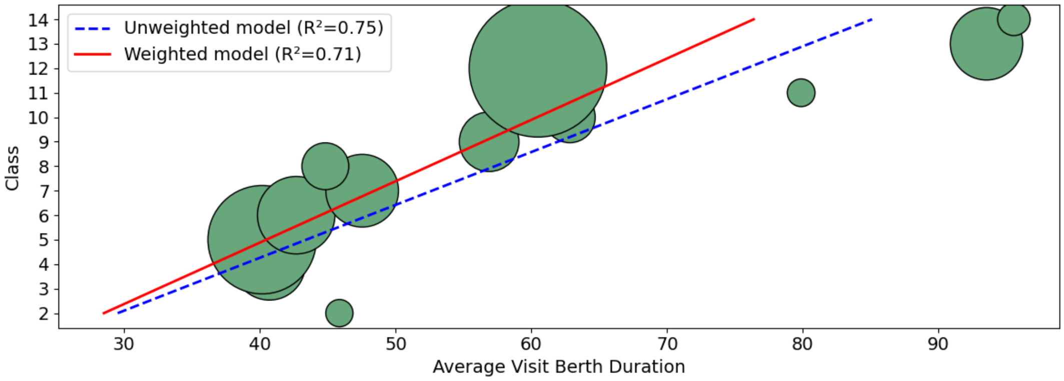
4.3. Correlation between size and visit berthing time

To provide a complete answer to the question *What berthing time patterns emerge by analysing the behaviour of different types of vessels inside the Port of Rotterdam?*, observing potential links berthing times and some physical feature other than the fleet type was necessary. Therefore, the second step in the analysis was observing whether there is a correlation between the visit berthing time and different vessel size measures (gross tonnage, deadweight tonnage, and TEU). Additionally, the size-time analysis contributes to proving that short, standard, and long stops are not due to different physical characteristics but for uncommon operations. For instance, someone could argue that the berthing time patterns presented in the previous section are not linked to uncommon operations but to the fact that ships of different sizes tend to stay in port for different times. This section responds to this claim by presenting the study of the correlation between three distinct size metrics and visits berthing time. More results from the analysis can be found in Appendix C.

4.3.1. Gross Tonnage

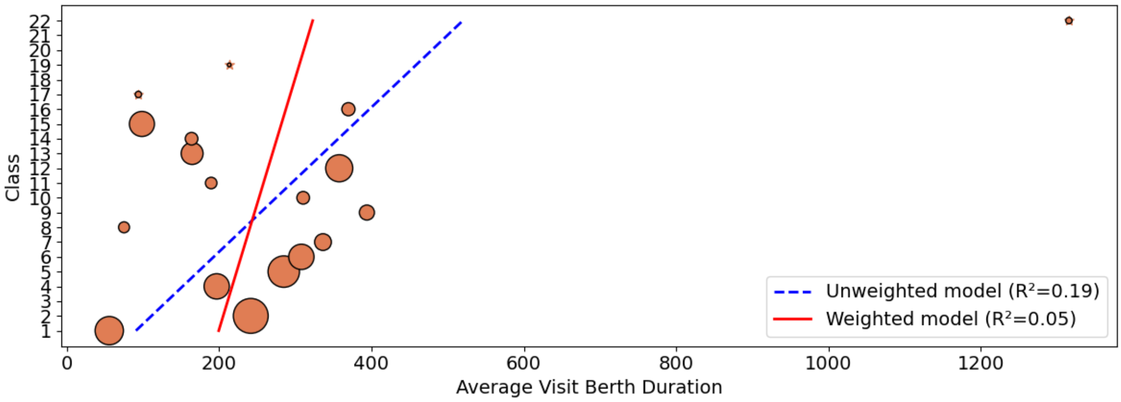
The results revealed key insights regarding the relationship between vessels' time at berth and their correlation with gross tonnage. Firstly, it was observed that not all vessels exhibit a significant correlation between GT and time at berth, indicating variability in this relationship across the dataset. Additionally, the data collected are often sparse and exhibit considerable fluctuations, with time intervals between observations ranging from hours to weeks. Finally, some size classes were underrepresented, necessitating more data for a reliable statistical analysis. Consequently, linear regression models were found to be suboptimal for this analysis; only a few vessels showed an R^2 value exceeding 0.7, and none achieved a value above 0.8. Figure 4.42, for instance, shows that chemical tankers present a fair linear relationship between the GT size classes and the visit berthing time.

Figure 4.42: Chemical Tankers, example of correlation between ship size and time in port



However, the most common result is closer to the one presented in Figure 4.43 - a regression with a low R squared value - suggesting that linear regression may not adequately capture the complexities of the relationship in this context.

Figure 4.43: Offshore



4.3.2. Deadweight Tonnage

As anticipated, the vessel DWT is commonly used in tankers and bulkers; therefore, this part of the research analysed only these categories. The size classes are based upon physical constraints, such as the Suez or Panama channels (Pruyn & Willeijns, 2022).

For tankers, the result is similar to the gross tonnage: not all vessels exhibit a significant correlation between GT and time at berth and the data collected are often sparse and display considerable fluctuations. However, LNG displayed an interesting behaviour. In the case of gross tonnage, there was no correlation between time and volume (Figure 4.44). This time, on the other hand, the correlation is present in a sufficiently linear and surprisingly inverse manner: the higher the DWT, the less time it spends at berth (Figure 4.45). Lastly, in some cases, linear regression shows significant improvements that are in fact simply due to the lower number of classes.

Figure 4.44: LNG carriers, GT

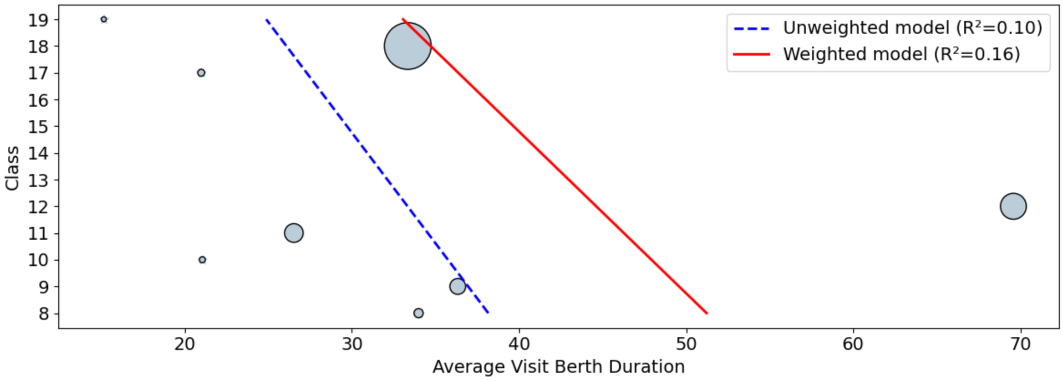
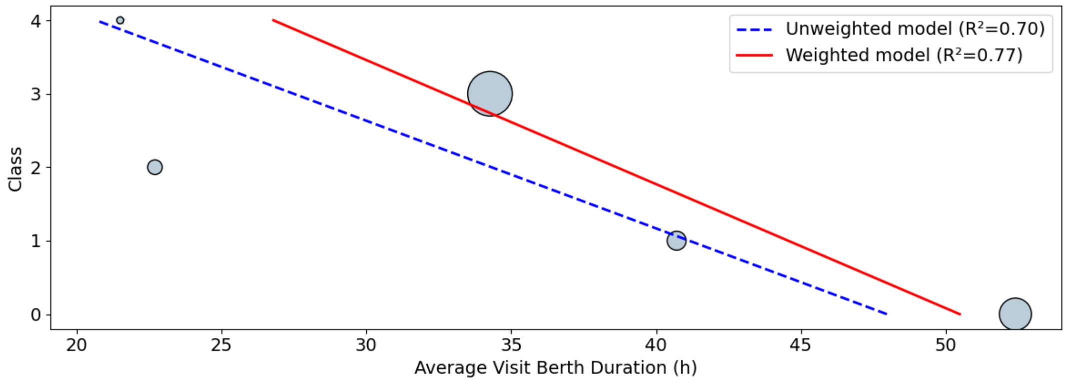


Figure 4.45: LNG carriers, DWT



As far as bulkers are concerned, they showed a convincing linear correlation regarding gross tonnage but a sparse distribution in terms of DWT (Figures 4.46 and 4.47).

Figure 4.46: Bulkers, GT

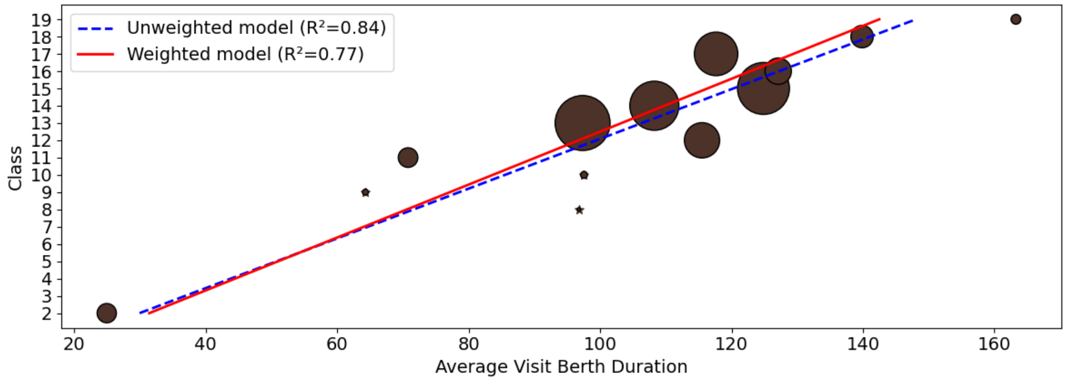
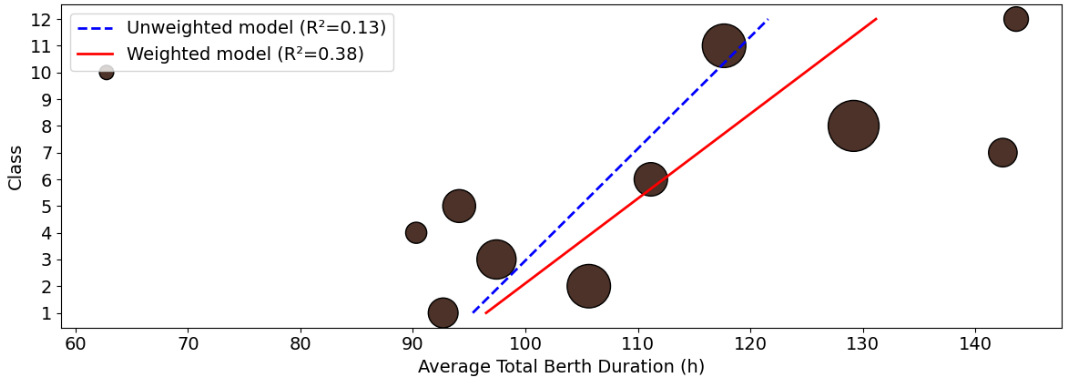


Figure 4.47: Bulkers, DWT



4.3.3. TEU

In the case of TEUs, the measure was only applied to container vessels. Although container ships are not the only vessels that can transport containers, the analysis only covered them because the capacity of the other vessels is too limited or because the sample size is too small. Somewhat surprisingly, not even TEU as a measure was able to identify a correlation with time spent docked (Figures 4.48 and

4.49). Probably, in the case of containers, multiple factors come into play to determine the time required to complete all operations. For example, loading and unloading operations may be carried out in parallel with multiple cranes and therefore the number of cranes assigned or the length of the ship could play an important role as well as the actual cargo destined for the port.

Figure 4.48: Containerships, GT

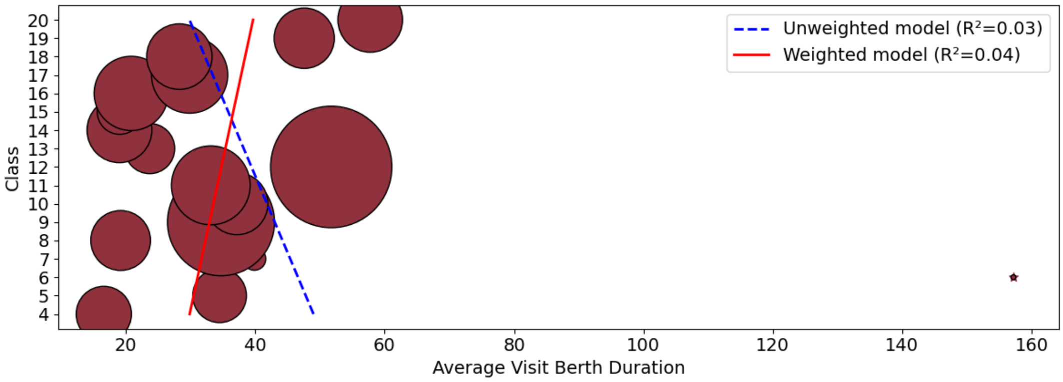
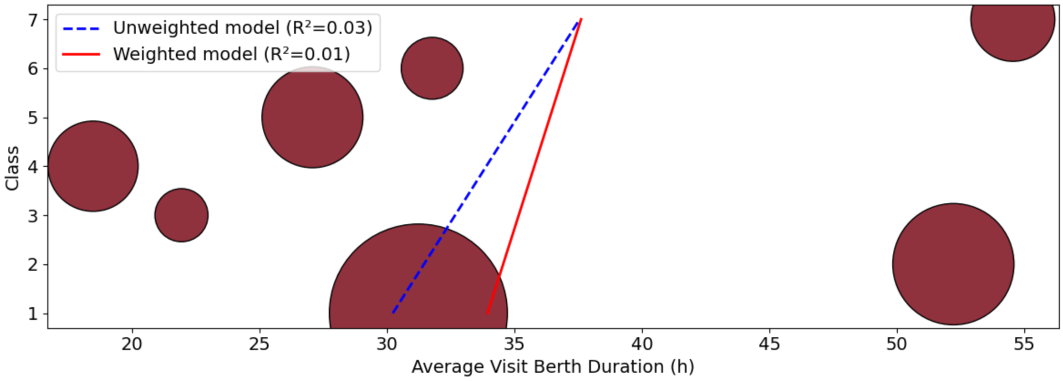


Figure 4.49: Containerships, DWT



4.3.4. Effects of the size-time relationship on the berthing time patterns

The analysis of the average visit berthing times for different size classes aligned positively with the berthing time patterns identified in the previous section. Specifically, the average visit berthing times for those size classes with sample sizes sufficient to guarantee the confidence level outlined in Chapter 3 generally fell within the limits of the standard stops. This observation reinforces the consistency of the findings and supports the narrative established earlier.

By taking the average visit berthing time as a reference point, we find that these averages are almost always included within the definition of standard stops, maintaining a coherent storyline with the conclusions drawn in the previous section. Tables 4.12, 4.13, 4.14, and 4.15 display the average values per fleet type and size class where the confidence level is 'highly reliable' (error <0.05); the cells highlighted in green indicate where the average visit berthing time falls within the standard stop limits, demonstrating that the majority of these averages—across various size metrics such as GT, DWT, and TEU—are indeed within the expected range.

While there are a few instances where this alignment is not observed, these cases are exceptions rather than the norm and, with the exception of chemical tankers, these fleet types are special and would require an ad hoc study. For completeness, a comprehensive table, including the averages for those size classes where the confidence level is not assured, is provided in Appendix C.

Table 4.12: Average visit berthing times in hours per GT size class - green values: time within the standard stop defined in the previous section

class	Chemical Tankers	Product Tankers	Crude Tankers	LPG	Spec. Tankers	Containerships	MPP	General Cargo	Bulkers
1									
2							48.75	32.63	
4	40.69			76.09			51.15	39.66	
5	40.16			44.20	58.07	34.48	46.00		
6	42.67	35.63					51.51		
7	47.53						57.34		
8	44.81					19.19	66.23		
9	56.88					34.70			
10	62.82					37.17			
11						33.12	69.23		
12	60.48					51.74	71.87		115.51
13	93.53	61.16		73.33		23.68			97.34
14	95.54	63.23				19.00			108.25
15									124.86
16		62.48	58.65			20.82			
17			53.42			29.85			117.65
18						28.26			
19			66.50						
20						57.77			
22									

class	Ro-Ro	Ferries	Recreational Vessels	Tugs	Service ship seafaring	Oth Non Cargo	Offshore	Dredgers	Other seagoing vessels
1			1268.72	183.71	33.28	143.87		252.74	186.42
2			64.63		1689.86		241.39		300.73
4						19.74	196.67		
5							284.73		822.52
6						67.33	307.84		
7							336.20		
8									
9							393.85		
10									
11									
12	15.94						357.53		
13	11.97					67.82	164.40		
14	12.66	14.08							
15									
16	16.74	7.87					369.58		
17									
18									
19							213.10		
20									
22									

Table 4.13: Tankers average visit berthing times in hours per DWT size class - green values: time within the standard stop defined in the previous section

class	Name	Chemical Tankers	Product Tankers	Crude Tankers	LPG	LNG	Spec. Tankers
0		42.11	40.19		62.30		56.18
1	Handysize	67.22	60.83		73.59		
2	Panamax		64.70				
3	Aframax		62.48	58.84			
4	Suezmax			53.56			
5	Very Large Crude Carrier (VLCC)			67.24			
6	Ultra Large Crude Carrier (VLCC)						

Table 4.14: Bulkers average visit berthing times in hours per DWT size class - green values: time within the standard stop defined in the previous section

class	name	Bulkers
0		
1	Small Handy	
2	Mid-size Handy	105.63
3	Large Handy	97.43
4	Handymax	
5	Traditional Supramax vessel	94.11
6	Ultramax	111.14
7	Traditional Panamax vessel	
8	Post-Panamax vessel	129.16
9	KamsarmaxÂ	
10	Mini Capesize vessel	
11	Standard Capesize vessel	117.65
12	Very large Ore Carrier (VLOC)	

Table 4.15: Average visit berthing times in hours per TEU size class - green values: time within the standard stop defined in the previous section

TEU class	name	Containerships
1	Small feeder	31.23
2	Feeder	52.21
3	Feedermax	21.94
4	Panamax	18.47
5	Post-Panamax	27.07
6	New Panamax	31.76
7	Ultra Large Container Vessels (ULCV)	54.54

4.4. Number of registered berthing events

The quantitative analysis also studied the number of berthing events per port visit despite not being strictly related to time. The analysis of internal port movements is interesting for understanding the ships' behaviour and has implications for the thesis objectives.

One possible objection to the time-related approach pursued by this thesis could be that in order to distinguish different berthing activities, one could look at where the ships are berthed. For example, one could argue that ships enter port, berth at point A to carry out cargo operations, move to B for maintenance, then go to C to change crew, et cetera. In this way, one would only have to look at the berthing location to recognise the activity performed. However, the results regarding the number of registered berthing events show that this is not possible in most cases: the majority of the vessels visit only one location per port call (Figure 4.50). The most common operation is entering the port, berthing somewhere to fulfil the reason for the call, and leaving the harbour. Therefore, this behaviour shows that looking at the berthing duration might be the only feasible option to distinguish one activity from the other during berthing events.

There are some exceptions, of course. Occasionally, ships visit several locations within the same call; this situation is rare for some sectors, while it is more frequent for others. For example, multiple berthing events are frequent for Tugs (Figure 4.51); however, Tugs is an isolated case and represents a very peculiar fleet type. Appendix D reports the analysis per each fleet type.

Figure 4.50: Distribution of the number of berths during a single port call for the port as a whole

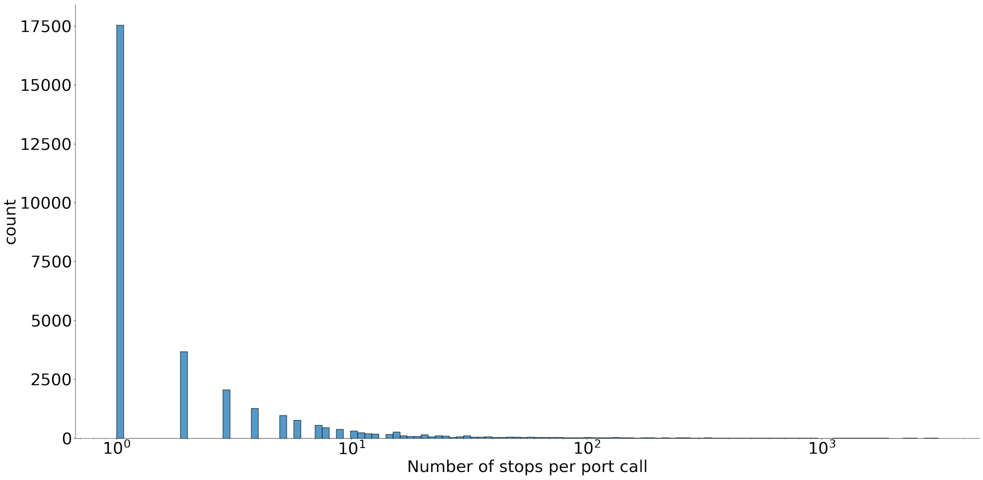
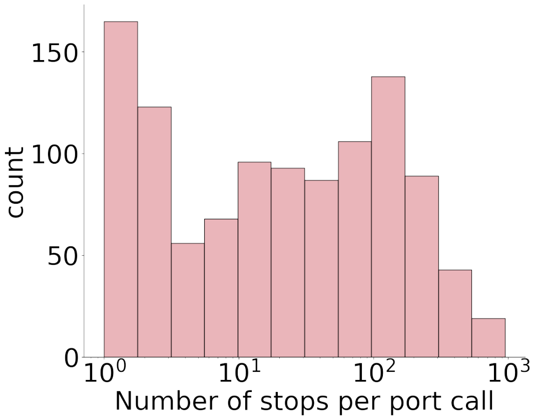


Figure 4.51: Distribution of number of berthing events per port visit - Tugs



5

Time, Activities, and Energy

This chapter continues the development of the research by answering two key sub-research questions: *What activities do berthing time patterns correspond to?*, *What are the primary determinants of energy consumption by vessels during berthing activities in the Port of Rotterdam?*, and *What discrepancies exist between recorded data and the feedback from maritime professionals?*. For the development of this chapter, the main research method was a semi-structured interview with six members of the maritime industry: one LPG tanker, one chemical tanker, two offshore marine contractor, a Refrigerated Cargo Vessels fleet, and a fishing company. The list of industry representatives is not exhaustive and does not cover all segments; however, it provides a starting point for identifying new areas to explore and issues to solve.

The chapter begins by presenting all the information gathered during the interviews. Each perspective is detailed to ensure a thorough understanding of the different viewpoints and insights that were shared. After that, the chapter collects the key points from the interviews, highlighting the most significant and recurring themes. These essential pieces of information are then inserted into the overall thesis storyline, ensuring that the data collected from stakeholders is integrated into the broader narrative and contributes to the development of the thesis argument.

5.1. LPG/Ethylene Tankers

Liquefied petroleum gas (LPG) is a fuel gas which contains a flammable mixture of hydrocarbon gases, mainly propane and butane, carried by fully pressurised, semi-pressurised, or fully refrigerated ships (RINA, 2008); however, the category *LPG Tankers* also includes ethylene carriers which are semi refrigerated ships able to transport cargoes at -104 °C (Omholt-Jensen, 2000). As propane, butane, and ethylene have different boiling temperatures at room pressure (-43, -0.5, and -104 °C), their handling requires different activities, energy usages, and procedures. Additionally, these products have distinct applications and markets: LPG is used as a fuel, while ethylene is a crucial element in the chemical industry. Therefore, notwithstanding that these product carriers are labelled under the same fleet type, it is clear that their behaviour in port is not alike. This consideration is also reinforced by the results of the interview with a commercial operator of an LPG fleet specialised in ethylene shipping.

The interviewed company is a shipping company which operates LPG tankers. Therefore, they are responsible for arranging the cargo on board and operating the vessels. The vessels are capable of refrigerating the cargo to -48 degrees Celsius; within the fleet are Ethylene carriers, which can cool the cargo up to -104.

5.1.1. Standard operations at berth

Their standard port call has the sole purpose of loading or discharging cargo; consequently, the most common port call consists of visiting a single berth and involves cargo handling. Nevertheless, ships usually arrive at the designed destination in advance but do not enter the port immediately; hence, a considerable part of their near-port activities consists of anchoring outside the port and waiting for the terminal to be ready. After that, they manoeuvre and berth to a terminal to perform their functions; at berth, there are three main operations:

1. *Pre-cargo activities*: checking all the hoses, ensuring the pipeline is connected, doing a safety meeting, et cetera. This stage can take a few hours.
2. *Cargo handling*, which is either loading or discharging. There is a significant distinction between loading and discharging cargo: the operations have distinct operational profiles and energy requirements:
   (a) *loading*: the cargo is being pumped on board by the equipment on shore; thus, it does not involve onboard equipment extensively.
   (b) *discharging* uses the vessel pumps, increasing the load of the ship and the engine loads.

   Both loading and discharging take the majority of the time, from one to three days, depending on the amount of cargo as well as any ship or shore limitations which can impact the load/discharge rate.
3. *Paperwork and decoupling*. The final phase consists of filling out all the required documents, decoupling the appliances, ensuring that the ship is properly detached from the shore pipeline, et cetera.

In addition, the ship might require to perform some cargo cooling. Although part of standard operations, this procedure differs from the others because it is performed on an as-needed basis and not during a specific phase. Moreover, cargo cooling is a key activity because it is an energy-intensive operation despite being relatively short. Finally, on average, smaller ships of their fleet stay at the berth one to maybe two days and the larger ones one day and a half to maybe two and a half or three. They have more capacity to fill, so cargo operations require more time.

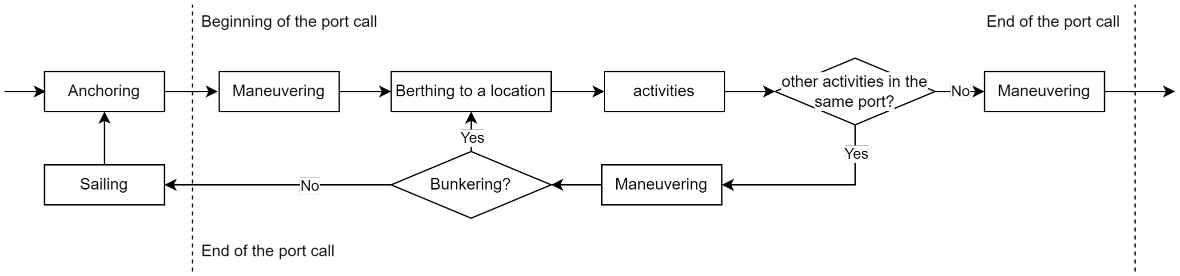
Regarding load factors and energy requirements, the hotel load requires about 15-20% of the auxiliary engine power. Cooling adds 20-35% depending on cooling severity, which, together with the hotel load, results in 45-50% total load factor. Loading adds 5-10% to the hotel load, and discharging increases by 15-20%. Moreover, common practice is to activate an extra auxiliary engine when the active engines reach 80% of their maximum load. This way, the energy system capacity can cope with sudden increases in the power output requested; nevertheless, the extra capacity implicates that engines often run outside their optimal range.

5.1.2. Uncommon operations at berth

Uncommonly long/short berth visits happen for various reasons. Short stops may happen for commercial needs or bunkering. When the short stop is due to commercial needs - for example, a client asks to load or discharge only a share of their cargo and wait for the rest -, the operational profile is closer to the standard but shorter and the berthing time depends on the share of cargo to handle; a very brief and rare port call might consist of unloading one-fifth of the cargo, thus lasting around 6-8 hours. Additionally, as shown in Figure 5.1, between cargo handling operations, vessels usually wait anchored outside the port. On the other hand, when the ship needs to bunker, it berths between four to six hours; extremely short bunkering times are no less than two hours. Nonetheless, bunkering operations generally happen as a secondary function of a port call: vessels enter the port, berth to a terminal, perform their cargo operations, and then move to a bunkering location (usually ship-to-ship transfer); generally, during cargo operation at terminals, bunkering is prohibited. Therefore, when bunkering is needed, the port call consists of two stops at two different areas inside the same port. Energy-wise, bunkering consumes slightly more than the hotel load; however, bunkering is usually rather short, rarely exceeding twelve hours.

Uncommonly long stops, on the other hand, mostly occur for cargo-related incidents. What they have seen in the past is that whenever there is an issue with the ship or the shore facilities, the ship loads or discharges at a slower rate, thus increasing the duration of their stay. For example, there might be a mismatch between the product temperature on board and the shore. In that case, the vessel and the shore have to handle the cargo slowly to meet the temperature requirements, which increases the port stay by one to three days. Concerning differences between standard and longer stops, the energy consumption in this case could be 10-20% higher than standard stops: although slower cargo handling demands less power from the ship, the total energy required is likely to be higher due to the extra cargo cooling or heating. Hence, copying with operational limits, either by shore or ship, requires more power.

Figure 5.1: LPG tankers operational scheme



5.1.3. Energy monitoring

The ships of the fleet monitor energy consumption by collecting fuel usage data. They generally report the fuel consumed daily or at each salient event (reaching or leaving a destination); the newest vessels allocate fuel consumption to specific equipment very precisely, whereas older fleet members do not possess the capabilities for accurate fuel usage allocation. The baseline daily fuel consumption generates from the hotelling load (the power required to keep the lights on, the air flowing, the heating running, etc) and, for smaller ships, is around two or three tons. Bigger ones consume between four and six tonnes a day. On top of the hotel load, fuel consumption is affected also by cargo cooling and discharging; as anticipated, cargo cooling is an energy-intensive activity: two tons are needed to reach fifty degrees below zero, and two/three tons more to get to -104. Therefore, worst-case cargo cooling can require up to eight tons of fuel.

5.1.4. Shore power

LPG carriers do not use shore power; additionally, shore power for this fleet type does not exist yet or is extremely niche because of strict safety requirements. The cargo flammability and explosivity expose the ship to a high risk of fire: there is a high chance of some gas to be present in the air which might ignite due to any (static) spark from electrical equipment. Therefore, handling high-voltage connections increases the danger.

5.2. Refrigerated Cargo vessels

Refrigerated Cargo vessels are ships intentionally built to transport perishable and frozen cargo; their cargo holds keep the cargo under constant temperature control thanks to a cooling plant. The interviewed company is a shipping company which operates different types of Refrigerated Cargo vessels: containers, fruit carriers, juice carriers, and freezer vessels. Each vessel and product transported have different temperature requirements: containers and fruit carriers keep their cargo at a temperature above zero degrees Celsius, while in juice carriers and freezer vessels, the temperature is well below zero (-10 and -20 °C, respectively). Additionally, each ship type handles its cargo differently: containerships transport containers, fruit carriers transport containers on deck and pallets in their cargo holds, juice carriers move frozen liquid, and freezer vessels carry pallets in their holds. Therefore, although they share the characteristic of transporting products in a temperature-controlled environment, there are substantial differences from segment to segment.

Table 5.1: Types of Refrigerated Cargo Vessels, with cargo and temperature

Vessel Type	Temperature [°C]	Cargo type
Juice Carrier	-10	Frozen liquid
Container	around 0	Refrigerated containers
Fruit Carrier	around 0	Pallets and reefer containers
Freezer vessels	-20	Frozen pallets

5.2.1. Standard operations at berth

Regardless of the segment, the standard port call has the principal purpose of loading or discharging cargo. Although ships also need bunkering, repairs, and maintenance, these activities usually occur in parallel with cargo operations at the same berthing location. The energy required during a port call tightly correlates to the Refrigerated Cargo Vessel type and whether the call is a discharge or load call.

Table 5.2: Refrigerated Cargo vessels - Standard berth time, duration, energy

Vessel Type	Time at berth	Energy profile
Juice Carrier	12 hours	Constant
Container	12 hours	Loading: 5 kW/TEU, increasing Discharging: 2 kW/TEU, decreasing
Fruit Carrier	24-48 hours (48 in the Netherlands)	Loading: up to 3500 kW Discharging: from 2000 kW downwards Hotel load (no ref. cargo): 200 kW
Freezer vessels	6 days to a month	1100-1200kW

Juice carriers

Juice carriers have the most simple operational profile within the fleet: independently of the nature of the call (charging or discharging), the cargo and the cargo holds are always at -10°C. Therefore, the energy requirement does not fluctuate much. The berthing time is usually around 12 hours.

Specialised Reefer vessel

The energy profile of a Specialised Reefer vessel - a containership that carries reefer containers - depends on the port call type. During *loading calls*, the energy requirement upon arrival is lower than at departure: the vessel arrives with some or without reefers on board, loads more reefers, and leaves; additionally, cargo is loaded at ambient temperature and loading occurs in South or Central America, where the ambient temperature is generally high. Therefore, not only do power requirements increase because the more the container, the higher the total cooling demand, but energy demand is also generally higher per TEU: for the first days in this high temperature ambient, containers require approximately an average of 5 kilowatts per container.

In *Discharge calls*, on the other hand, power requirements at arrival are high to keep all the cargo cooled, but as the containers on board diminish, the power requirement goes down. However, the reduction rate depends on the port container handling plan: only the reefers that are going to be discharged first can be disconnected from power. Therefore, only part of the reefers will be unplugged immediately upon arrival. Additionally, the power requirement per container is usually lower: first, the cargo is already at the right temperature; second, discharge occurs in Europe, where ambient temperatures are lower on average. Finally, container handling generally requires around 12 hours.

Fruit carriers

Fruit carriers have an operational profile closer to the reefer containers, but their configuration differs. On deck, they have space for around 150 reefer containers; above and below deck, there are about 6000 to 7000 pallets for fruit. Thus, there are separate cooling systems for the cargo.

Operation-wise, the ship first discharges the deck, then the cargo holds. As for the previous reefer type, the vessel arrives with a maximum electrical load, and the energy requirement decreases as the discharging proceeds. In fact, pallets are stored in independent compartments: when a compartment is empty, the cooling can be interrupted. Similar to containers, the absolute load in a discharge port is not as high as in the loading port due to the different ambient and product temperatures. During loading, the cargo requires approximately 3500 kilowatts, while during discharging, the load starts at 2000 and goes down to 200 - the minimum hotel load when no refrigerated cargo is on board. Lastly, cargo handling generally requires between 24 and 48 hours; during the port visit in the Netherlands, it is usually 48 hours.

Freezer vessels

Freezer vessels are smaller in capacity; therefore, the required energy is lower. Additionally, most of the time, the frozen commodities are already around minus 15°C, while the case temperature is minus 20°C; thus, the energy required to cool the cargo up to spec is relatively lower. One last difference is that they do not carry containers but only pallets with frozen cargo. Regarding the time spent at berth, freezer vessels generally stay between six days and a month, depending on the location and the cargo amount.

5.2.2. Uncommon operations at berth

Extra berth time can be needed to fix technical issues or to finish cargo operations due to bad weather, and it usually takes eight hours extra. For *juice carriers* and *containerships*, the only reason for additional time at berth is for maintenance: generally, bunkering, repairs, maintenance, et cetera happen in parallel with cargo handling; however, they sometimes require extra time. Since the maintenance finishes after the cargo handling, the extra time in European ports does not imply higher energy requirements. For *fruit carriers*, additional time can also result from bad weather: in case of heavy rain, the cargo cannot be handled efficiently; thus, operations are postponed. In these cases, the amount of energy required depends on the stage of the cargo operations: the further the interruption in discharge ports, the less energy required. Therefore, fruit carriers at berth can extend their stay for weather or maintenance; both reasons are equally likely to happen. Finally, *freezer vessels* rarely require extra time because the cargo handling operations are always long enough to allow repairs to be completed. Regarding the shortest operations at berth, the time is generally no less than eight hours.

5.2.3. Energy monitoring

The ships of the fleet monitor energy consumption in different ways. Newer vessels use an online flow metering system, while older vessels send daily reports. The daily reports send data regarding the fuel consumed daily or at each salient event (entering/leaving sea passage, arrival/departure from a port, berth); the reports allocate energy consumption to specific equipment. All the vessels have an alert system that advises the Superintendent and the crew on board to switch off the engine when not needed. However, the chief engineers usually manage the engine optimally; hence, the alert system does not turn off often.

5.2.4. Shore power

The interviewed company is getting ready for shore power, with some of their vessels already capable of connecting to cold ironing systems, including the ones that are currently being constructed. However, they signal the lack of in-port facilities: most ports they visit do not have yet a running shore power connection.

5.3. Offshore and Dredging Vessels

Offshore vessels are ships specifically serving operational purposes such as oil exploration and construction work on the high seas (Kantharia, 2023). Since the type of work requires vessels to maintain a fixed location at sea, they usually need dynamic positioning, which commonly uses a diesel-electric system. Therefore, this vessel type does not distinguish between main and auxiliary engines.

Company A is an offshore construction company operating ships from tugs (about 3-4000 GT) to crane vessels (around 150-200000 GT). Company B is a marine contractor that owns and operates its fleet.

It works in dredging, coastal protection and offshore energy; offshore energy used to be oil and gas and is now quickly transforming into renewable energy, primarily offshore winds. Given the specific needs of the work, Company B develops its vessels in-house to fit their particular needs to execute projects at sea; they own two main types of vessels:

- **Dredgers**: they dig up soil from the seabed; therefore, the cargo they are transporting is not loaded in the port but taken from the sea.
- **Offshore energy vessels**:
  - *Rock Installation Vessels*. These vessels crush rocks from quarries or load them in a port. However, the former is the most common option.
  - *Cable layers*. Cable layers load cargo from cable factories to move it to the offshore project site.
  - *Offshore wind installation vessels* load monopiles and turbines from designated locations

Given the specific work of this segment, vessels generally take supplies offshore instead of collecting them in port - as is the case with shipping companies; nevertheless, they sometimes have to visit the ports. An interesting aspect is their wide use of shore power: cold ironing is their standard when berthed.

5.3.1. Standard operations at berth

Company A generally visits the port for about three months during winter, when the weather does not allow working offshore. As the North Sea can be rough during the winter months (November to March), the vessels stay in port to prepare for the following working season; therefore, the only reason for this fleet type to enter the port is idle time, repair and maintenance, or mobilization.

- **Idle time** : there is nothing to do, which would not be good for business but could happen. In *winter time*, for instance, it can be relatively common due to rough seas; however, the shorter the idle time, the better. Sometimes, the sea is rough also during summer, but generally, summer is the offshore working period.
- **Repair and maintenance**: not being able to work, they take advantage of the winter to do maintenance. This activity takes 80-90% of the in-port time.
- **Mobilization**: mobilization is the preparation for a project. If they mobilize inshore, they prepare for the project. All the materials, equipment, et cetera needed are loaded on board, and once everything is equipped, the vessel sails offshore to execute the job. Mobilization takes around 10-20% of the time at berth.

There are two crucial points to highlight in their standard operation at berth. First, their berthing activities do not require three months but the other way around: they are forced into port for three months; thus, they need to do everything in that time. Second, idle time, repairs, and mobilization occur sequentially at the same berth; therefore, they visit only one berth during the port visits.

The activities of Company B, although similar, depend on the segment. Whenever dredges need to come into port, it is to change crew, do maintenance and repair, or lay idle - if there is no work. The Port of Rotterdam hosts many facilities for the maintenance and repair of large vessels, especially dredgers. For instance, Botlek and Schiedam accommodate multiple shipyards. Dredgers are particularly subject to wear and tear, requiring relatively more maintenance than a bulk carrier or a container vessel. Smaller ships, on the other hand, go to the company's shipyard, which is not inside the Port of Rotterdam. Generally, the company tend to repair the vessels in the Netherlands. Time-wise, these operations require three weeks to a month and stops longer than 2-3 weeks typically indicate maintenance. Lastly, dredgers and offshore vessels visit only one location during each port call. Company B did not mention seasonality in its work.

Energy consumption

ad Ships' energy requirements and engine usage are tightly linked to the ship type, the activity and the number of cranes needed. For instance, a Company A vessel has a hotel load of about 4.5 MW and a shore power system of up to 8 MW; in another, the hotel load is approximately 5.5 MW, and the shore power connection can reach 10 MW. However, the cranes can exceed the shore power connection limit: using only one crane can stay within the shore power range, while two can easily exceed 10 MW. Generally, mobilization is the activity that requires more power for its extensive use of the cranes. Therefore, the last 1-2 weeks of berthing might require up to twice the hotel load.

For Company B, energy consumption is linked tightly to the vessel's size: a large dredger would typically be more than 170 meters long with a load of around 1200 kW, including the engine room, the fuel systems, and all the heating, ventilation, and cooling (around 10-15% of the installed auxiliary power). When waiting or laying idle, the load would reduce to about 5-6 hundred kW with a full crew on board. However, the cranes are the most energy-demanding tools on these ships: to fulfil the energy requirement of a hydraulic-powered crane, the ship needs to start an extra engine. Usually, when a vessel enters a port for maintenance and repair without being in a drydock, it uses cranes discontinuously for about a couple of hours a day.

5.3.2. Uncommon operations at berth

Sometimes, in the middle of the summer season, Company A vessels go back to port. It can happen either for idle time - which would be shameful; it hardly happens but is a possibility - or to mobilize inshore for a project. Therefore, uncommonly short stops generally mean mobilization inshore, thus high energy requirements. Since getting vessels in port is expensive, they avoid staying in port for short periods; the shortest stop could be around a week.

According to Company B, dredgers never stop at berth for less than a few hours as the shortest task is crew-changing and usually requires that time. However, this situation is rare because the company always try to combine crew-changing with other operations. Worst-case scenario, crew-changing is coupled with bunkering - which requires around 10 hours - making stops shorter than 12-14 hours extremely uncommon. Offshore vessels, on the other hand, stay for even longer: loading materials on an offshore wind installation vessel requires 24 hours minimum. Energy-wise, considering bunkering and crew-changing as the shortest feasible stop for both dredgers and offshore vessels (12-14 hours), the load would be just the hotel load.

5.3.3. Energy monitoring

At Company A, monitoring is highly detailed. It receives daily progress reports stating how much fuel was used; additionally, they have numerous digital systems on board. As a result, they possess enough data to know per second the vessels' energy consumption.

At Company B, fuel consumption is measured by bunker delivery notes and converted into emissions by official documents from the factory acceptance testing; the latest vessels have all Selective Catalytic Reduction (SCR) after treatment. Additionally, newer vessels can link fuel consumption with location and activity, allowing them to measure the emissions for a specific project, which is particularly relevant for nitrogen. Additionally, investing in detailed monitoring and emission reduction aims to anticipate future regulations and plans like the Fuel EU directives. Nonetheless, older vessels cannot provide such detailed reports without a consistent investment in an integrated data collection system that is unreasonable on 20-year-old dredgers.

5.3.4. Shore power

Shore power in the dredging and offshore sectors has been installed in vessels for a long time already: all vessels can use shore power to cover at least the hotel load. As anticipated, all the vessels in Company A's fleet use shore power; connecting and disconnecting require approximately 2-4 hours each. Another interesting observation is that the seasonality of port visits is diametrically opposed to traditional electricity price trends: electricity prices used to be cheaper in summer and higher in winter (TenneT, 2016, 2019). Moreover, the electricity price trend has changed over the past few years: first, with COVID-19, then with the war in Ukraine, the traditional trend has been interrupted for two years

(TenneT, 2021). Luckily, electricity prices in winter 2023 largely improved thanks to abundant wind power production, yet still well above pre-crisis values (TenneT, 2024). Consequently, although the current period of crisis and transition could question the competitiveness of shore power, it still seems to be the most cost-effective choice for offshore vessels.

Figure 5.2: Monthly Average Day-ahead Wholesale electricity prices in the Central West Europe (CWE) region highlighting winter months and the price seasonality. Image adapted from TenneT (2019)

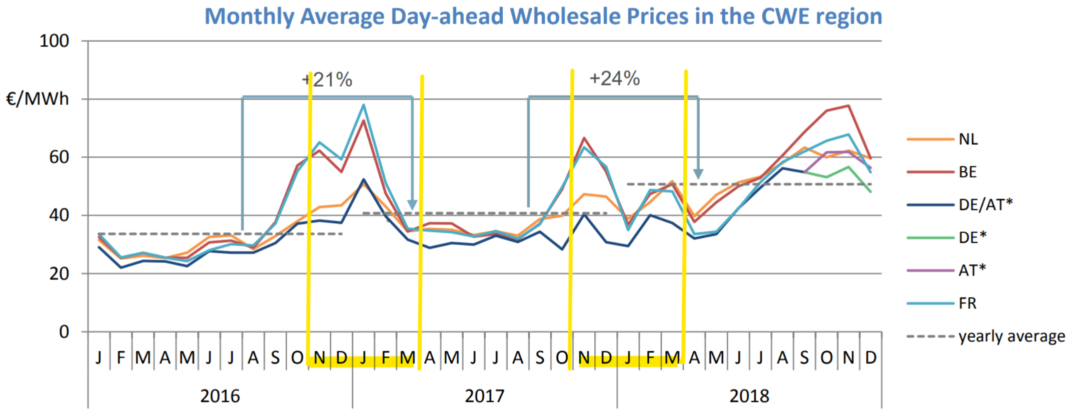
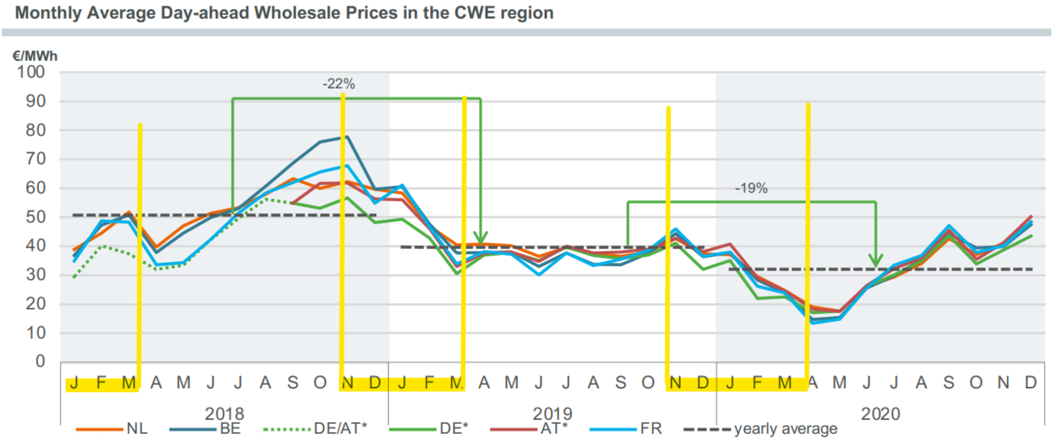
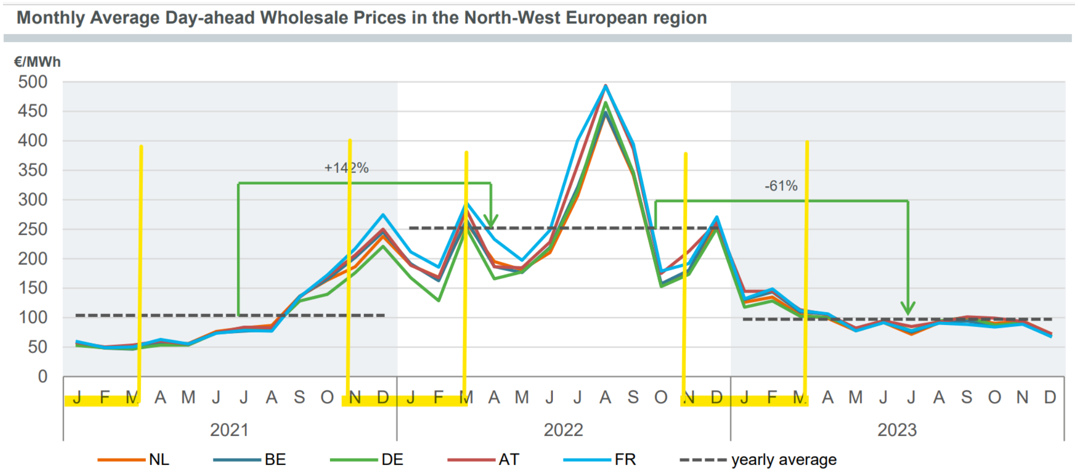


Figure 5.3: Monthly Average Day-ahead Wholesale electricity prices in the CWE region highlighting winter months and the price disruption due to COVID-19. Image adapted from TenneT (2021)



* On October 1st, 2018 the German/Austrian bidding zone split into two separate bidding zones

Figure 5.4: Monthly Average Day-ahead Wholesale electricity prices in the CWE region highlighting winter months and the price disruption due to the energy crisis. Image adapted from TenneT (2024)



At Company B, shore power has been the standard for a long time also because it helps to do maintenance in dry docks: the absence of cooling water availability makes shore supply the most feasible solution to run the accommodation and the galley. Additionally, shore power avoids noise from the engines, thus improving working conditions; moreover, cold ironing aligns with the company's net-zero ambition in 2050. Consequently, the company uses shore power whenever a port has an available cold ironing connection. Nevertheless, shore power does not always offer enough capacity to cover the cranes' demand. Therefore, cranes are typically powered by the engines onboard of the ship, except for the new vessels. For instance, those ships have a 5 MW shore connection sufficient to support a crane power demand. Regarding connection and disconnection times, they would require half an hour minimum, depending on the crew experience.

5.4. Fishing Vessels

The interviewed company is a widely integrated fishing company, from sea to shelf operating a fleet of freezer fishing trawlers ranging from 90 to 130 meters and a fleet of coastal demersal fishing vessels ranging from 24 to 45 meters.

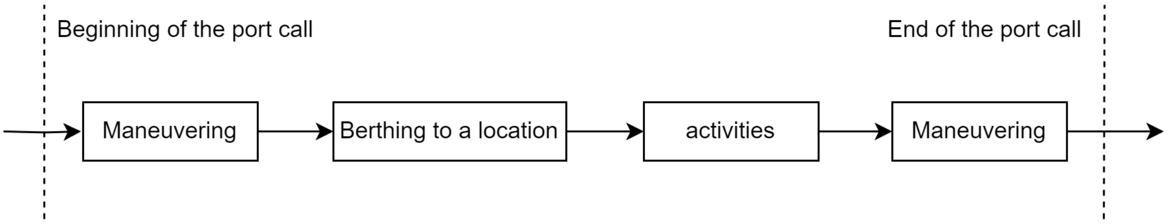
5.4.1. Standard operations at berth

The activities performed depend on the vessel size, with differences between freezer fishing trawlers and coastal demersal fishing vessels regarding time, energy, and locations. Generally speaking, large vessels discharge frozen fish, load pallets and cartons for a new trip, perform repairs and maintenance, bunker, exchange fishing nets, let the crew relief etc. The smaller ones, on the other hand, discharge the fresh fish, do repairs on the net and maintenance of the ship.

Freezer Fishing Trawlers

Usually, freezer fishing trawlers enter the port, berth to a location and remain there to perform all the required activities. This normally takes 3-8 days. For the freezer trawlers, hotel load and harbour activities require a baseline of 350-400 kWh; however, when the cooling plant has to run to keep the cargo holds cold - for instance, when discharging is not finished - an extra 400-500 kWh is added during a time frame of circa 2 to 3 hours a day.

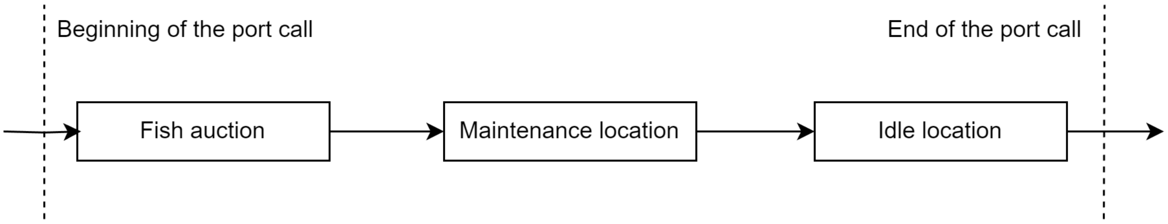
Figure 5.5: Freezer Fishing Trawlers operational scheme



Coastal Demersal Fishing Vessels

Compared to the previous ship type, coastal demersal fishing vessels stay in port for shorter periods: a normal port call lasts around 2-3 days. Additionally, they usually visit at least three locations: first discharge the fresh fish at the auction, then move to a spot for the work on the nets etc. and conclude by manoeuvring to a location where the ship can lay still for the weekend rest. Each action corresponds to distinct energy requirements: circa 200 kWh for 3-5 hours to discharge and work on the ship, and 20-30 kWh during idle time when there are no activities required.

Figure 5.6: Coastal Demersal Fishing Vessels operational scheme



5.4.2. Uncommon operations at berth

During summer, activities stop for circa 8 weeks to let the fish rest and mate, and the fleet takes the opportunity to do extensive maintenance and repairs. Sometimes the summer pause is prolonged to 3 months. Moreover, slightly longer stops happen also during winter holidays like Christmas, New Year's Eve, and the beginning of January. Finally, extraordinary port time might occur due to bad weather or other needs - e.g. unplanned extra maintenance.

Regarding energy, the requirements are lower because the cargo holds are always empty during these stops; moreover, the demand is stable during evening and night with only peaks when deck operations require winches or cranes. Lastly, no fuel is used because ships are connected to shore power.

Nevertheless, stops also happened to be shorter than usual to a minimum of 6 hours; in that case, coastal ships entered the port only to discharge fresh fish. Therefore, these port calls have a higher hourly average energy requirement (around 200 kWh).

5.4.3. Energy monitoring

Fuel is monitored via flow meters in all the freezer trawlers, while not all the coastal vessels are equipped with it: only the larger ones have these meters. Nevertheless, bunker delivery notes and meters provide adequate insights.

5.4.4. Shore power

As mentioned in the previous paragraphs, the vessels have shore power connections: freezer trawlers have a system supporting 400–600 A and coastal vessels 63 A. Regarding its usage and ease of connection, freezer trawlers need circa 30 minutes (including preparations with cables etc.) and benefit from it for 60-80% of their berthing time. Coastal vessels are quicker to connect - five minutes total - and use it 80-90% of the time at berth.

5.5. Chemical Tankers

The company runs the commercial management of a fleet of chemical tankers which transport liquids in bulk, including specialized chemicals, vegetable oils, acids, lube oils, aromatics and clean petroleum products. However, they could not answer the interview questions because the technical management is outsourced to a third party; additionally, their vessels are still pretty “analogue” and answering the questions would require collecting numerous documents, some of those hand-written. This unexpected outcome is still interesting. Although research focuses on technological innovations and solutions that require a high degree of digitisation, the current socio-technical system includes companies that are still tied to analogue data collection. After all, the vessels’ life cycle is long, capital-intensive and full digitisation is to be expected to take time. Also in interviews with other experts, e.g. LPG tankers, it emerged that the quality and quantity of data collected depends largely on the ship’s age.

5.6. Berthing patterns, activities, and energy consumption

5.6.1. Berthing time patterns

The interviews were conducted to assess the validity of the data analysis presented in Chapter 4, focusing on verifying the existence and definition of standard, short, and long stops. Overall, the interviews provided some positive feedback, though not perfectly aligned with the data analysis—understandably so, given the system’s complexity and the limited number of interviewees. Additionally, the interviews reflected general ship operations in all the ports they usually visit rather than specific to Rotterdam. Therefore, some variability was expected. Table 5.3 compares the standard berthing event from the data analysis with those from the interviews. Importantly, the results of the data analysis are broadly in line with the order of magnitude of what the interviews reported, which suggests that the findings are at least acceptable.

Table 5.3: Comparison between data from the interviews and from the data analysis

Fleet Type	Interviews		Data Analysis
	Sub-segment	**Standard berthing event**	**Standard berthing event**
LPG	LPG/Ethylene	1-3 d	20h - 8d (*)
Refrigerated Cargo vessels	Juice Carries	12 h	20h - 5d
	Container	12 h	
	Fruit Carriers	12-48 h	
	Freezer Vessels	6-30 d	
Offshore	Company A	3 m	2-30d
	Company B	3-4 w	
Dredgers		3-4 w	20h - 2.5w
Fishing Vessel	Freezer Fishing Trawlers	3-8 d	3-25h
	Coastal Demersal Fishing	2-3 d	

(*) Data concerning all the LPG Carriers, not only LPG/Ethylene carriers

For LPG tankers, the elbow method in the data analysis identified the standard berthing event duration between twenty hours and eight days, while the interviewed company reported one to three days. However, they also mentioned that LPG/Ethylene carriers of their fleet carry relatively small cargo compared to pure LPG carriers, which might stay in port longer. Therefore, the standard berthing event for LPG tankers identified from the data analysis is acceptable.

Regarding Refrigerated Cargo vessels, the discrepancy between the interviews seems higher. The standard stops of the interviewed fleet can be either 12-48 hours or 6-30 days, which contrasts largely with what emerged from the data analysis. However, this information is insufficient to determine the invalidity of the data analysis result for two reasons. Firstly, Rotterdam is not the main contact point for the interviewee company, especially concerning the Freezer Vessel, which is also the one with the standard 6-30 day stop. Therefore, just by excluding freezer vessels as a case, the comparison is reduced to 12-48h from the interview versus 20h-5d from the data analysis. Secondly, the company stated that the standard stop in Dutch ports is closer to 48 hours than 12. Therefore, by taking around 48 hours as the standard berthing event range, the interviewee’s standard berthing event is definitely more comparable to the range identified by the data analysis. In conclusion, the result of the data analysis is also confirmed by this case, at least partially and with more uncertainties. A significant result of this interview is the observation that the reality of this fleet type is much more complicated and that grouping all refrigerated cargo vessels under one fleet type is a strong assumption, as different sub-segments have very different behaviours.

As far as offshore vessels are concerned, the interval of the data analysis is not properly verified. The data analysis clustered stops between two and thirty days as standard. On the one hand, the lower limit (two days) conflicts with the company's experience, which declared that this behaviour is not very likely. On the other hand, the upper limit (thirty days) aligns with the feedback from Company B: they communicated that they generally remain in port for 3-4 weeks. As for Company A, however, the situation is worse as their standard stop last three months. However, there could be an issue related to the data collected from the port: the data from the Port of Rotterdam include the berthing events of 2023, but the three-month stops happen during the winter, approximately between November and March. Secondly, in the past, the port experienced a defect with the data collection: some ships left the port, but the system did not close their port visit because it did not receive the AIS data from the leaving vessels. As a result, the system registered longer stops than the actual real-world situation. Therefore, the port set a maximum time of 90 days for the entire port visit to overcome the issue: after 90 days, a new *port_visit_id* is assigned automatically. This threshold may have partially influenced data collection, especially for long-term stops. Consequently, the three-month berthing events might have been excluded accidentally, and the interviews could not validate the results for offshore vessels.

For Dredgers, the data analysis result is refuted. In fact, from the data analysis, the standard berthing event seemed to be between 20 hours and 2.5 weeks, but the interviewed company stated that, generally, its ships berth in Rotterdam for 3-4 weeks. However, this discrepancy does not necessarily question the elbow method used for data analysis because the data collection method of the port could play a fundamental role in this case as well. As explained in Chapter 3, the Port of Rotterdam uses a location-based method to determine vessels' status; therefore, if a dredger is performing dredging operations near the shore inside a berthing location, the data collection system registers a berthing event. Consequently, the figures regarding standard berthing events for dredgers may not be correct; however, the method is not necessarily disproved.

For fishing vessels, the data analysis result largely differs from the stakeholder's feedback. From the data, the standard berthing event should be 3-25 hours, but the interviewed company reported 2-8 days, which are completely different figures. However, the interviewed company is not located in Rotterdam, suggesting that results might not be transferable to other ports.

To recap this section, all the participants confirmed the existence of standard in-port operations. Regarding the duration of such standard stops, the figures resulting from the data analysis do not perfectly align with the stakeholders' experience. Nevertheless, the differences are understandable considering the limited number of interviewees, the system complexity, and the fact that they reported general ship operations in all the ports they usually visit rather than specific to Rotterdam. Therefore, the results are partially validated since they are at least of the same order of magnitude in many cases and do not deviate substantially from the stakeholders' experience. Furthermore, a crucial result from this section is that distinct ports and different segments show very different behaviours; therefore, finding a widely applicable clustering method for berthing time patterns is more important rather than the resulting figures.

5.6.2. Number of berthing events per port visit

Regarding the number of berths visited per port call, the interviews confirmed that most ships typically berth at a single location and rarely move inside the port. When they do move, they usually visit only one or two additional berths at most. However, this observation conflicts with the data analysis, which sometimes recorded numerous berthing events per port visit. According to some interviewed stakeholders and the Port of Rotterdam, this discrepancy may arise because a ship can dock in a place such that its position signal is on the edge of the polygon on the map. As a result, small movements can cause the status to change from berthed to manoeuvring and vice versa, leading to multiple recorded berthing events that do not correspond to actual changes in location.

5.6.3. Energy consumption and monitoring

The interviews provided critical insights into the correlation between berthing time patterns, corresponding activities, and their associated energy requirements. The data regarding energy usage has been summarized in Table 5.4, which highlights the varying nature of in-port operations across different vessel types and how these operations impact energy consumption.

Table 5.4: summary of the relationship between berthing time patterns, activity, and energy

LPG/Ethylene	**Standard**	**Short**	**Long**
Stop purpose/cause	Cargo handling	1) Partial cargo handling	Issues in cargo handling
		2) Bunkering	
Energy required (*)	-	1) Standard	Higher
		2) Standard/lower	

Refrigerated Cargo Vessels	**Standard**	**Short**	**Long**
Stop purpose/cause	Cargo handling	Crew change/bunkering	1) Issues in cargo handling
			2) Delays in maintenance
Energy required (*)	-	Lower	1) Variable
			2) Lower

Offshore Vessels	**Standard**	**Short**	**Long**
Stop purpose/cause	Seasonal in-shore time	Mobilization	-
Energy required (*)		Higher	-

Dredgers	**Standard**	**Short**	**Long**
Stop purpose/cause	Maintenance/repair	Crew change/bunkering	-
Energy required (*)		Lower	-

Fishing vessels	**Standard**	**Short**	**Long**
Stop purpose/cause	Cargo handling and preparation	Cargo handling only	Cargo handling, R&M, idle time
Energy required (*)		Higher	Lower

(*) Energy required compared to the standard stop

For LPG tankers, the interviews revealed that all in-port operations are primarily cargo-related. The standard berthing time pattern corresponds to smooth cargo operations, where everything goes as planned. However, when long stops occur, they are generally due to cargo issues, which can significantly increase energy consumption. On the other hand, short stops may happen for commercial reasons or during bunkering. In these cases, the energy consumption during short stops does not differ significantly from that of standard stops, and it may even be lower depending on the specific circumstances.

Similarly, for refrigerated cargo vessels, standard stops are also predominantly related to cargo operations. Long stops, however, can be attributed either to cargo issues or to additional maintenance requirements. If the long stop is due to cargo issues, the energy requirement may vary. If the delay is caused by maintenance, energy consumption tends to be lower because the cargo cooling plants are not operational.

In the case of offshore vessels, short stops are uncommon and generally indicate inshore mobilization activities. These activities demand high energy consumption due to the intensive operational requirements; thus, the interviews confirmed that short stops for offshore vessels are associated with significantly higher energy requirements compared to their standard berthing event. For dredgers, the energy load is slightly reduced during short stops. This is likely due to a decrease in operational activities that typically demand higher energy, such as dredging operations themselves, which are paused or slowed down during these brief stops.

Fishing vessels present an interesting contrast where short stops are associated with higher energy consumption due to unloading operations, which demand substantial energy. On the other hand, the average hourly energy demand during longer stops - which involve maintenance, repair, and idle time - is usually less.

Concerning energy and fuel monitoring, monitoring is a widely performed activity, although with differences among segments and vessels. The measurement accuracy and the methodologies used vary between segments and are linked to the ship's age, size, and function. Generally speaking, smaller vessels seem to have less detailed monitoring systems, which aligns with their relative simplicity compared to bigger ships. For example, an LPG tanker has a complex structure and multiple functions; therefore, allocating how much energy the cooling plant, the pumps, et cetera, use is in the company's interest. Lastly, regarding shore power, there is a general interest in it, with all the operational vessels already using cold ironing and moving towards a more intense use. The shipping parties, on the other hand, are slightly behind but open to it. Reefer vessels signal the lack of port facilities. LPG tankers acknowledge the potential but highlight the technical issues that need to be solved to carry on operations safely.

To recap, the interviews have demonstrated a clear connection between different berthing time patterns and the activities performed during these stops. More importantly, the findings confirm that different activities correspond to varying energy requirements. Thus, the type of stop not only serves as an indicator of the activities being conducted but also as a determinant of the vessel's energy consumption during berthing.

6

Discussion and Conclusion

This research wanted to initiate a discussion about the methodologies for calculating emissions from berthed ships by focusing on the vessels' berthing behaviour concerning duration, performed activities, and energy required. Until now, emission inventories have always used time as an independent variable, which, multiplied by an average factor, gave energy consumption and emissions as output. However, this approach overlooks the specificities of each berthing event. This study initiated the discussion about the precision of the current calculation methodologies and potential improvements by challenging the role of time and showing that different types of berthing events exist and are distinguishable without more data. This final chapter summarizes the main contributions and implications, discusses limitations, and suggests directions for future studies.

6.1. Contributions and Implications

The principal result that emerged from this work is that reality is far more complex than the most widely used models to represent it; luckily, the available data can still grasp this complexity. The latter statement is proven by the fact that all the insights from the quantitative analysis resulted from working on the same data used in emission inventories. Most of them rely on AIS data to perform the analysis, which is the same employed in this work. The statement that reality is far more complex than the most widely used models to represent it is reflected in three main facts. First, not all berthing events are equal, and the rarest ones still hold a considerable impact on the total berthing time; for instance, looking at the Port of Rotterdam as a whole, long and infrequent stops account for 20% of the total berthing time. Additionally, the differences do not exist only as a matter of frequency and duration but also imply different energy requirements, as suggested by the interviewed parties. Consequently, a model based on a standard stop only reliably captures part of the behaviour of moored ships. Continuing with the results of the port as a whole, a model based on standard stops only reflects 60% of the total berthing time. These results are transferable to each fleet type with the due differences. Second, there is no universal relationship between standard industry size classes and time spent in port. Some ship types show a positive linear behaviour (the larger the ship, the longer the visit berthing time), while others show more complex relationships. Moreover, some fleet types belong to only a few classes; therefore, no size-related difference can be observed in the behaviour of berthed vessels. These considerations apply to metrics of volume (GT), maximum transportable weight (DWT), and also cargo capacity (TEU). Consequently, the size classes commonly used in the industry - which reflect the physical limits of channels, ports, and other waterways - might be insufficient to portray the in-port behaviour of all the fleet types. Third, most ships berth at a single location during a port visit, proving that the duration of a port visit could be the only way to identify different types of berthing events. Finally, even the interviews suggested that the system is much more complex than captured by the currently used models. The division by fleet type might be an oversimplification as the product transported and the ship type considerably influence the behaviour in port and energy consumption. Ethylene carriers, although in the same Fleet Type as LPG tankers, have different technical characteristics and behaviour from other vessels in the same fleet type mainly due to the transported product. The same, but even more severe, happens with refrigerated cargo vessels, where the type of product transported changes the ship structure and behaviour completely. Some refrigerated cargo vessels carry containers, some transport pallets and others bulk liquids, which determines not only differences in structure but also in the terminals they visit.

These results contrast with the emission calculation methodologies commonly used in literature and policy documents, indicating a widespread risk of policy and investment failure because partial data and oversimplified models of reality might have driven policy and economic decisions. For instance, the overestimation of emissions and energy may have portrayed ship emissions as the primary cause of poor air quality in port areas instead of the true contributors. Thus, institutions may have enacted overly strong regulations with potentially inefficient economic, environmental, and social returns. On the other hand, underestimation might have led to the opposite result: an underinvestment in shore power facilities that could have led to better profit and higher emissions reduction. In any case, a political or economic decision based on partial data increases its risk of failure. Consequently, improving the system's knowledge is essential for informed decision-making and risk minimization. This research has shown that this objective is not only reachable but could be achievable without exponentially increasing the required data.

Finally, the thesis also has an indirect result that can directly support the modelling of maritime operations. The facts and figures that emerged along the process can be applied to other areas. For example, the figures regarding the average port visit durations per fleet type and size classes can be integrated into other models. Since the classes used for the analysis are those commonly employed in various industries, these results can serve as a key link between different data sources.

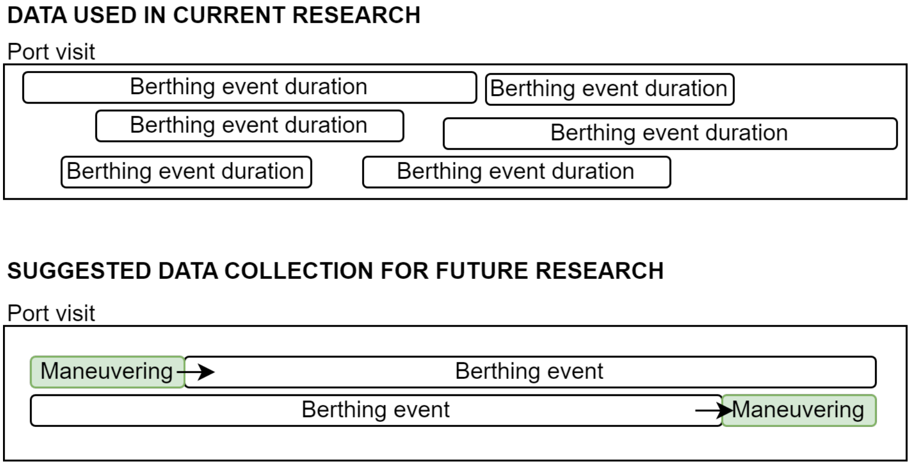
6.2. Limitations

6.2.1. Quantitative Data Analysis

The start of this study was the literature review, which provided a solid starting point and foundation with a clear research direction. However, it did not offer much guidance on data handling: previous studies typically aggregated berthing times, while this study observed single berthing events, requiring a more granular level of detail, which was relatively novel and posed unique challenges for the quantitative analysis.

The quantitative analysis was a powerful tool for statistical examination, but its effectiveness relied tightly on data quality. Despite being sourced from real-world scenarios, the data needed careful handling to avoid misrepresentations. The Port of Rotterdam uses an enhanced AIS data collection system and assigns the navigation status according to the vessel's location; a potential flaw in this system has been identified with the following situation: small movements of a ship docked near the edge of the berthing area can cause the status to change from berthed to manoeuvring and vice versa even when the vessel is not defacto moving. Moreover, the system has a time limit for the port visit duration; after a certain number of days, the data collection system assigns new port visit IDs, potentially splitting a very long port call into several shorter visits. These two criticalities might affect the accuracy regarding extreme cases and outliers. However, considering the reputation of the Port of Rotterdam and the research focus (which did not cover the most extreme cases), stating that the risks are low is possible. In any case, to further improve the quality of the collected data and future analyses, the data collection system should determine the vessels' status based not only on position but also on speed. This system would be innovative for the Port of Rotterdam, but not for the industry: IMO (2021), Tran et al. (2022), Chen et al. (2016) and MARIN (2022) already determine the status based on the speed and position of the ships. Another alternative to reduce this uncertainty - this time without changing the upstream collection system - would be to not only use the data related to berthing events but also to collect the data regarding the manoeuvring events. This way, defining berthing events more accurately would be possible. In a way, it would be like going from the top diagram in Figure 6.1 to the bottom one: in the first, the berthing events are a scattered set of durations, with no relationship between them other than that of having been recorded during the same port call. The data on the manoeuvres and the start and end date of the events would help to place events and visits in chronological order and distinguish which events have been erroneously divided into multiple instances, as shown in the bottom figure.

Figure 6.1: Differences between the current research and future research in data to shape the socio-technical system



A limitation with perhaps more effects on the research results comes from having considered only one year. As seen from the interviews, some ships spend the winter season in port; therefore, they remain berthed from the end of a year to the beginning of the following. Some important berthing events were inevitably cut by the choice of having considered one year only. This did not allow us to observe the behaviour of those ships that stopped between the end of 2022 and the beginning of 2023 and between the end of 2023 and the beginning of 2024.

Moreover, the elbow method, although being one of the most common methods for clustering, depends on the manual identification of the elbow points on the visualization curve; hence, it cannot clearly identify the clusters in a relatively smooth curve (Shi et al., 2021). Additionally, the manual identification of the elbow points has a fair degree of subjectivity and does not allow for full automation.

Finally, the relationship between time at berth and size produced an output that can be easily used for modelling purposes. In fact, a metric to predict berthing time based on a ship's physical characteristics can serve practical purposes. Moreover, the metrics used are widely available in the databases, especially GT and DWT. These features allowed the results to be significant and reusable. Nonetheless, there are two principal criticalities - one statistical and one conceptual. From the statistical side, the sample size limits the number of valid results, as certain fleet types are significantly underrepresented, particularly within the GT classification, which counts 22 categories. Conversely, DWT for tankers and TEU for containerships are often overrepresented, with only seven classes each. Reducing the number of size classes increases the sample size per class but broadens the range between minimum and maximum values, further enlarging an already notable interquartile range. A balanced approach can help mitigate underrepresentation. For instance, the DWT classification for bulkers, which divides ships into 12 classes, redistributes the samples more equally (see Table C.3 in Appendix C). Conceptually, these size classes align with industry standards and practical applications, making them straightforward to implement. However, both DWT classifications indicate maximum allowable sizes in specific areas (e.g., Panamax for the Panama Canal) and do not directly correlate with cargo transported. Therefore, they may not be the best metrics for predicting port stay durations. In fact, stakeholder interviews revealed that the primary reason for port visits is cargo handling, suggesting that metrics related to cargo handling (e.g., cargo transported, handling capacity) would more accurately reflect visit duration. Conducting a separate study to identify the most effective metric for predicting berth time would solve this uncertainty. Nonetheless, cargo metrics are less accessible and, thus, less generalizable. Therefore, redefining size classes based on actual berthing time data rather than pre-determined categories would improve predictions without needing commercial data.

6.2.2. Qualitative Result Validation and Research

Semi-structured interviews were a valuable research method that provided insights into participants' perspectives and experiences. However, some aspects limited the findings' usability, reliability, and generalizability.

The principal criticality was the small sample size. In the interviews, the focus was on depth rather than breadth, meaning that conducting semi-structured interviews was a time-intensive process which consisted of preparing interview questions, scheduling and completing the interviews, transcribing the conversations, and studying the data. Consequently, the work schedule allowed for gathering data only from a small sample, which limits the ability to derive reliable statistics or infer about the wider population. The insights gained are often specific to the individuals interviewed and may not represent the views of the broader maritime industry. This limitation is particularly significant when trying to draw conclusions about complex and diverse sectors like the maritime sector, where the experiences and opinions of stakeholders can vary widely.

To worsen the situation, reaching out to relevant stakeholders was challenging. The maritime industry is highly international, with stakeholders spread across different countries and regions, and those with no relationships with the TNO or the TU Delft or without interest in the research had no incentives to participate. Luckily, the TNO/TU Delft network made the interviews possible and enhanced the validity of the results; however, the reliance on a pre-existing network limited the diversity of perspectives obtained and might have resulted in a sampling bias - a sample that is not fully representative of the broader industry. For instance, the TNO/TU Delft network includes stakeholders that may already have a vested interest in innovation or green maritime operations. This pre-existing interest can introduce bias, as these stakeholders are likely to have more favourable views towards green initiatives than the general population in the maritime industry. As a result, the insights gained from these interviews may not accurately reflect the attitudes and behaviours of other stakeholders who are less engaged with or interested in green maritime operations. This selection bias limits the generalizability of the findings to the entire industry, as the sample may not represent the broader population. To avoid this problem, van der Gon and Hulskotte (2010) applied an effective method: the study surveyed the ships as soon as they docked in the port, making it possible both to receive a high number of responses and to include international players.

In summary, while semi-structured interviews were valuable for gaining deep insights into specific aspects of a few parties, they had significant limitations in terms of generalizability and efficiency. The small sample size, challenges in reaching diverse and international stakeholders, and the potential bias introduced by interviewing stakeholders already interested in green maritime operations all contribute to the need for caution when generalising the results. Consequently, the interviews could validate the quantitative data analysis results and provide valuable insights, but their other insights should be taken more as suggestions than as results. Additional research is necessary to apply these findings to the wider maritime industry - for example, by complementing qualitative interviews with other methods, such as surveys or quantitative data analysis, to obtain a more comprehensive understanding of the industry's perspectives on green maritime operations.

6.3. Future Research Directions

The results from this study present a foundation for future research to further our knowledge of vessel berthing behaviour. Three principal directions are suggested: continue developing the new calculation methodology, delve deeper into the relationship between time and size, and study the phenomenon of multiple berthing events per port visit.

Developing the new emission calculation methodology would be the next logical continuation of the research. Identifying three distinct stop types and the qualitative differences in energy consumption associated with each initiated the discussion about the current bottom-up methodology for calculating emissions from berthed vessels. The following action is quantifying the energy consumption for these different stop types and determining the corresponding emissions. Once these are quantified, a comparison can be made between the calculated emissions and those calculated in current emission inventories or reported in databases like the Thesis MRV. This comparison could help validate or challenge existing emissions data, providing a more accurate assessment of the environmental impact of berthing activities and better-informed decision-making.

Second, the relationship between vessel size and berthing times could be a promising research direction. The current study's use of size categories from different industries did not reveal clear patterns in berthing times, suggesting that these categories may not be the most effective for such analysis. Future research could focus specifically on the relationship between vessel size and berthing time, potentially through a reverse approach. Instead of applying predefined classes, future research could define size classes based on observed berthing times to develop a finer understanding of how vessel dimensions influence time spent at berth.

Third, the presence of multiple berthing events during a single port visit warrants further investigation to understand its implications. Future studies could explore what these multiple stops signify regarding engine activity, operational efficiency, port congestion, and overall vessel behaviour. Analyzing these stops in greater detail could reveal patterns that might inform port management practices or suggest the need for revised pollution reduction strategies.

In addition to these specific avenues, addressing the limitations outlined in the previous section is crucial for advancing the field. Improving data quality, enhancing data cleaning processes, and refining methods for determining vessel status are essential to make the findings more robust and reliable. High-quality data will not only improve the accuracy of future research but also enable more reliable comparisons and conclusions.

Moreover, employing the current approach to study the vessel manoeuvring patterns could be another promising area for future research. Just as different berthing behaviours have been identified, distinct manoeuvring patterns may exist. Investigating these could provide new insights into vessel operations, potentially leading to more efficient and safer maritime practices.

6.4. Conclusive Reflection

The principal research objective of this thesis was to form a stepping stone to enhance emission inventories for seagoing vessels by reducing uncertainties starting from the most widely used bottom-up methodologies. The study focused on the berthing phase as it appeared to be the most under-studied element, the highest source of uncertainty, the area with the highest potential due to the vicinity of cities and human establishments and the current investments into shore power. The most relevant result is having demonstrated the existence of different types of events based on duration and frequency, each with different energy consumption. Moreover, showing that each cluster contributes to an important share of the total time at berth was an essential objective and a valid result. In fact, although the quantitative and qualitative analyses showed differences in the definition of clusters, they both agreed on the existence of the clusters, the different energy consumptions, and their impact on the total time in port.

Nevertheless, the path for answering the main research question *What is the relationship between berthing time, activities and the energy required by moored ships?* has also generated meaningful insights other than reaching the primary objective. For instance, the research opened a door towards the understanding of berthing behaviour more thoroughly and has shown the limitations of conducting an analysis based solely on fleet type: the behaviour of some fleet types varies considerably depending on the product transported.

Shipping, trade, and maritime operations are the backbone of the nation's economy, providing important advantages in terms of employment opportunities, goods accessibility, and development. Nonetheless, these benefits should not sneakily backfire on maritime workers, society, and the environment through reduced air quality, exposure to toxic substances, and increased global warming. In addressing the dilemma between economic prosperity and citizens' and environmental health, political and economic decisions should be based on a sound understanding of reality. Increasing the detail of our knowledge is crucial to reducing uncertainties, precisely determining the problem source, and thinking of tailor-made and effective solutions to ensure a sustainable future and a better quality of life for society as a whole. Although complex systems are - by definition - impossible to predict and understand completely, this study hopes to form a convincing stepping stone towards increased knowledge of ships' behaviour at berth.

To conclude, the study's results suggest that studying berthing behaviour can be an effective strategy to increase knowledge of the port socio-technical system and produce significant outputs for carbon emissions reduction, port operational efficiency, and modelling purposes.

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A

Data Analysis Methodology

Snippets of the code can be found at the following link: https://gitlab.tudelft.nl/-/snippets/308

A.1. Data Collection

Data Collection is the process of gathering data. This research collected data from two main sources: the Port of Rotterdam and Clarkson's World Fleet Database (Clarksons, n.d.).
The Port of Rotterdam collected and sent data regarding port visits in 2023. Port Authority employees retrieved the data from their database following the instructions given.

The data included the following fields:

- port_visit_id
- imo
- subclass
- gross_tonnage_volume_sea
- deadweight
- visit_duration_min
- area_name
- berth_type

The Clarksons Research World Fleet Register (WFR) provides extensive and reliable data of up to 150,000 ships above 100 GT (TU Delft, n.d.). It was the source for the following fields:

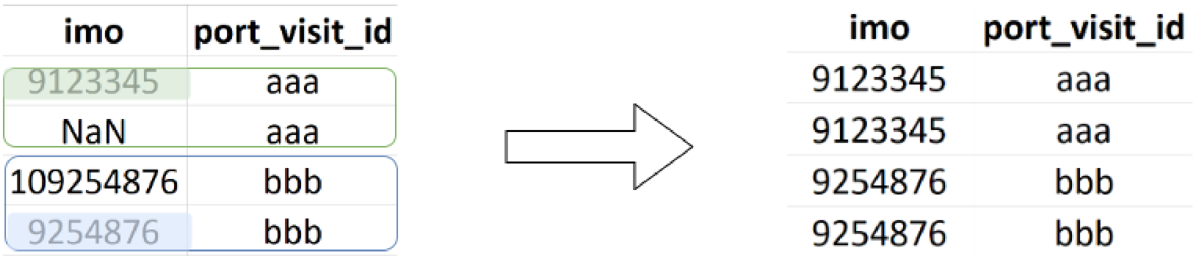
- IMO Number
- Fleet Type
- GT
- Operator
- Operator Nationality/Region

A.2. Data cleaning

Data cleaning has been performed mostly on the data from the Port of Rotterdam, as the WFR data have been collected from data extracted from the port data: the Port of Rotterdam data provided a list of IMO Numbers used later to extract the data from the WFR.

Port data cleaning consisted of the following operations: translating 'subclass' and 'berth_type' from Dutch to English, eliminating duplicates, and correcting invalid IMO Numbers. Translating the values and eliminating duplicates was an easy step. The online translation service DeepL Translator (DeepL, n.d.) translated Dutch into English, and the terms replaced the original Dutch words in the database. For the duplicates, the widely used Python function in the pandas library returned the DataFrame with duplicate rows removed (pandas, n.d.). The duplicates represented a tiny share of rows (5.3%), corresponding to 0.34% of the total time at berth.

Figure A.1: Example of the automatic IMO Number correction for different IMOs corresponding to the same port call



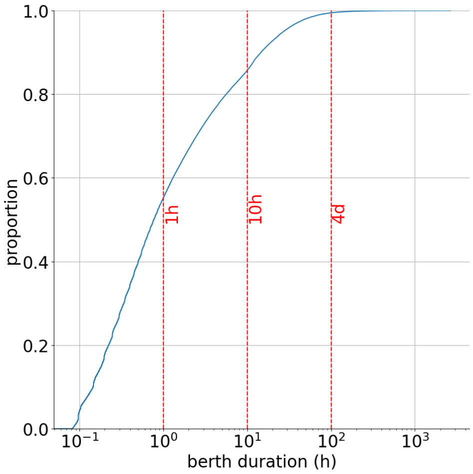
imo	port_visit_id
9123345	aaa
NaN	aaa
109254876	bbb
9254876	bbb

imo	port_visit_id
9123345	aaa
9123345	aaa
9254876	bbb
9254876	bbb

On the other hand, the IMO Number correction consisted of multiple steps. First, the analysis focused on the invalid IMO Numbers: the IMO number composed of seven digits (IMO, n.d.-a); therefore, the first step was finding the values not respecting this rule. 10.8% of port calls (port_visit_id) had invalid IMO Numbers, representing 24% of the total rows. Yet, only 53 out of 5864 unique IMO Numbers were invalid (0.90 %); therefore, a hybrid automatic-manual method was the quickest solution to improve the data. For the automatic component, the code grouped the data by port_visit_id: if different IMO Numbers existed for the same port_visit_id, the code kept the valid IMO; figure A.1 shows this process. Other invalid IMOs have been manually corrected where possible. In the end, the number of invalid IMOs has decreased to 37 (-30%). Finally, although some IMOs were impossible to correct, they still had a subclass. Since the analysis did not strictly require IMO Numbers, no data was ignored or deleted to keep the database as complete as possible.

Eventually, the field ’visit_duration_min’ might have registered some inconsistencies: as shown in Figure A.2, more than 40% of the stops lasted for less than one hour. Although this result might make sense for smaller vessels os specific segments, it is probably an error in the data collection system of the port for most ships. This suggests that dedicated studies on the AIS data collection system and status assignment should be carried out ion the future.

Figure A.2: cumulative distribution curve



To conclude, the data are sufficiently complete to produce quality results overall. As table A.1 shows, the core fields (visit duration and area name) are fully complete.

Table A.1: Completeness of Port of Rotterdam source data - share of empty values per subclass and field

subclass	Total rows	imo	GT	DWT	visit duration (min)	area name
Fishing vessel	200	0,65	0,00	0,65	0,00	0,00
Service ship seafaring	169775	0,36	0,00	0,38	0,00	0,00
Unknown ship	2827	0,28	1,00	0,90	0,00	0,00
Other seagoing vessel	13548	0,23	0,00	0,34	0,00	0,00
Dredger	1650	0,20	0,00	0,20	0,00	0,00
Passenger ship	1229	0,11	0,00	0,62	0,00	0,00
Bulk carrier	5183	0,04	0,00	0,04	0,00	0,00
Oil tanker	4274	0,03	0,00	0,03	0,00	0,00
Gas tanker	3004	0,02	0,00	0,03	0,00	0,00
Conventional general cargo ship	22106	0,00	0,00	0,01	0,00	0,00
Chemical tanker	28210	0,00	0,00	0,00	0,00	0,00
Ro-ro cargo / car carrier	5722	0,00	0,00	0,00	0,00	0,00
Container ship	23048	0,00	0,00	0,00	0,00	0,00
Other tanker	47	0,00	0,00	0,00	0,00	0,00
Refrigerated vessel	122	0,00	0,00	0,01	0,00	0,00
TOTAL	280945	0,00	0,00	0,01	0,00	0,00

Note that in the table, the values in the 'subclass' column in the table are different from those used in the next sections. This is because the *subclass* values are those in the Rotterdam port database. The data exploration and analysis uses the *Fleet Type* field from WFR, as it is more detailed. Therefore, a last cleaning process occurred after merging data from Clarkson's World Fleet Register and assigning size classes. As a result of the merge, some fleet type values indicated the same fleet type although different - for example, *Oil tanker* and *Crude Tankers* (Table A.2. The Python script smoothed out these differences.

Table A.2: redundant terms in the *Fleet Type* field and corresponding correction

Terms	Correction
Oil tanker Crude Tankers	Crude Tankers
Chemical tanker Chemical Tankers	Chemical Tankers
Container ship Containerships	Containerships
Conventional general cargo ship General Cargo	General Cargo
Dredger Dredgers	Dredgers
Bulk carrier Bulkers	Bulkers
Refrigerated vessel Reefers	Reefers
Ro-ro cargo - car carrier Ro-Ro	Ro-Ro

B

Semi-structured interview Questions

Introduction

1. What kind of organisation are you and what are your main responsibilities?
2. What kind of vessels do you operate or manage?

Standard port call

1. Which activities do you usually perform during a standard port call?
    (a) How long do they take?
    (b) How much energy do they require?
2. Do you berth to multiple berths, quays, jetties, dolphins, etc. during a standard port call?

Uncommon/exceptional port calls

1. Can sometimes port calls take longer than the usual time?
2. Why do uncommonly long stops happen?
3. What is the difference between common and uncommonly long stops in terms of…
    (a) Length?
    (b) Activities?
    (c) Fuel consumptions?
    (d) Engine load factors?
4. How long was your longest port call ever?
5. How long was your shortest port call ever?

Shore Power

1. Do you use shore power?
2. How big is the connection/average consumed power?
3. For how long do you use it? (percentage of the total port visit)
4. How long does it take you to connect/disconnect from shore power?

Fuel consumption monitoring

1. Do you register and monitor fuel consumption during port visits?
2. What kind of tools do you use?

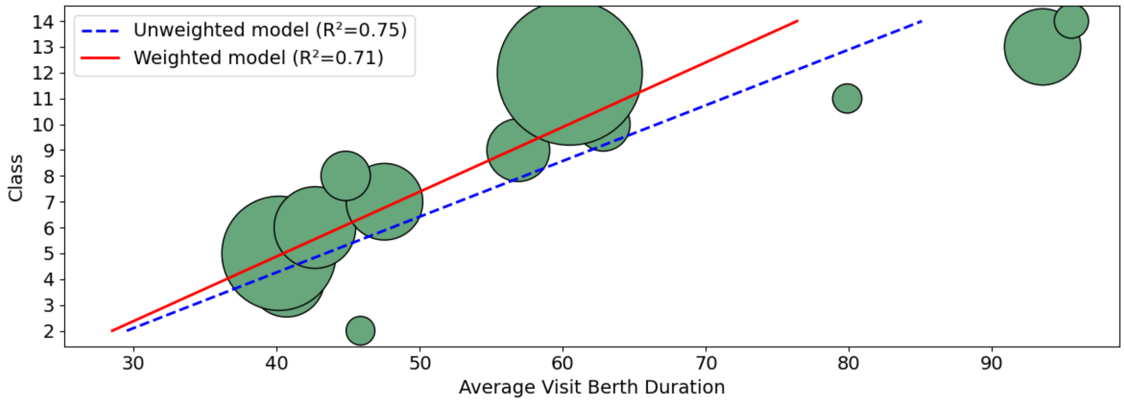
C

Correlation between size class and time spent at berth

C.1. Tankers

Figure C.1: Chemical Tankers

(a) GT



(b) DWT

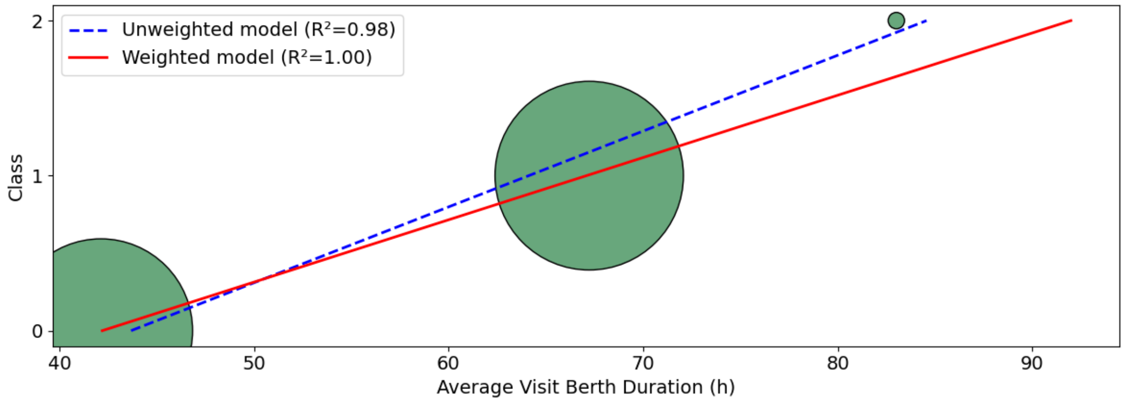
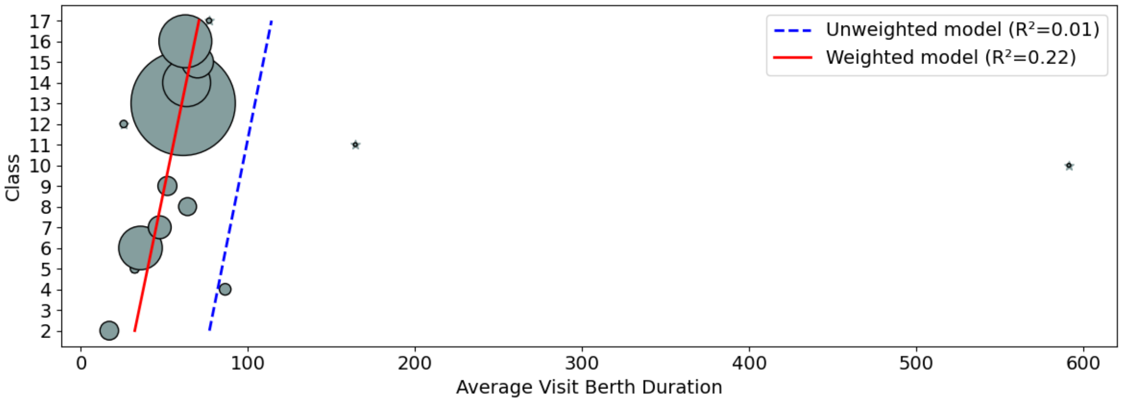


Figure C.2: Product Tankers

(a) GT



(b) DWT

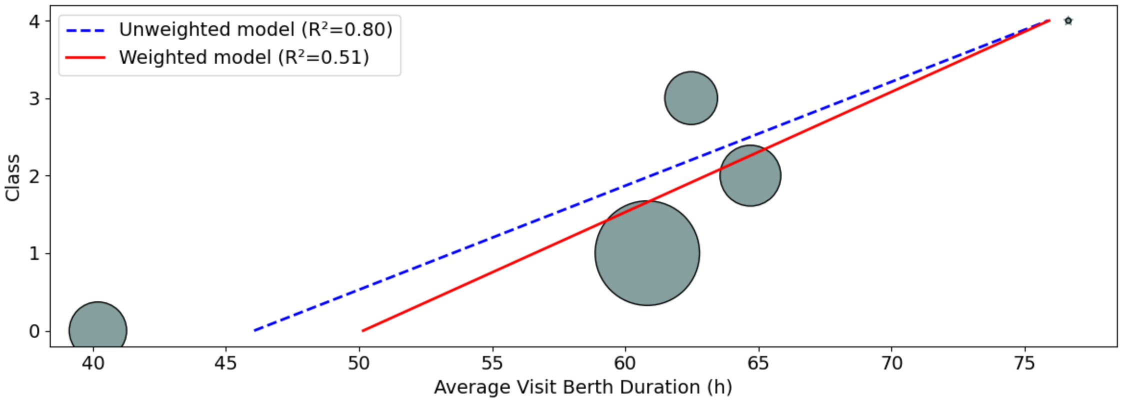
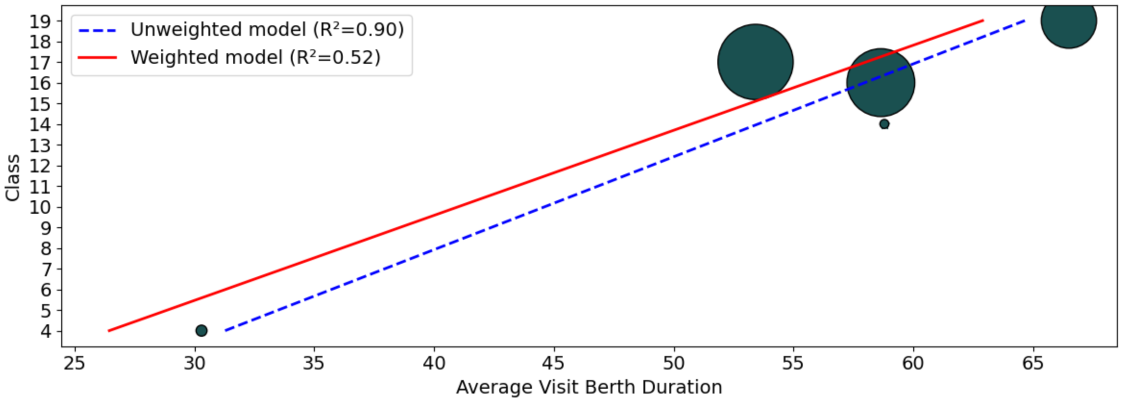


Figure C.3: Crude Tankers

(a) GT



(b) DWT

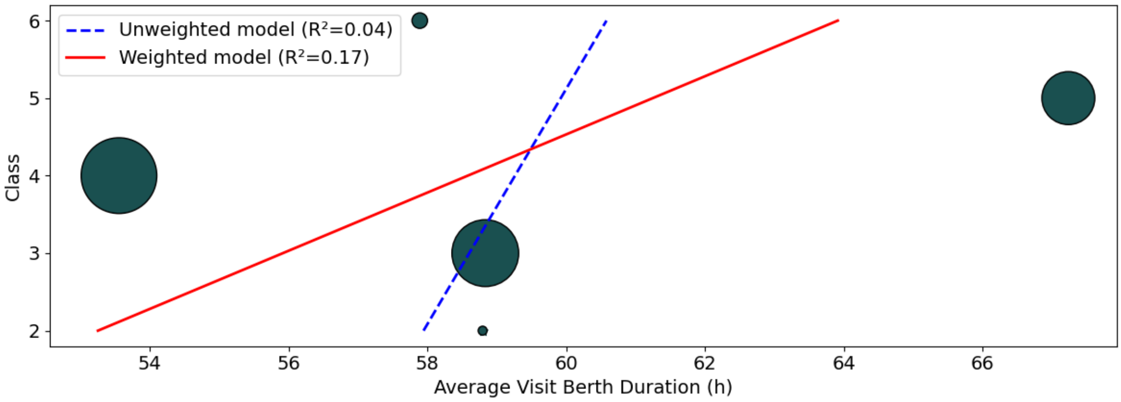
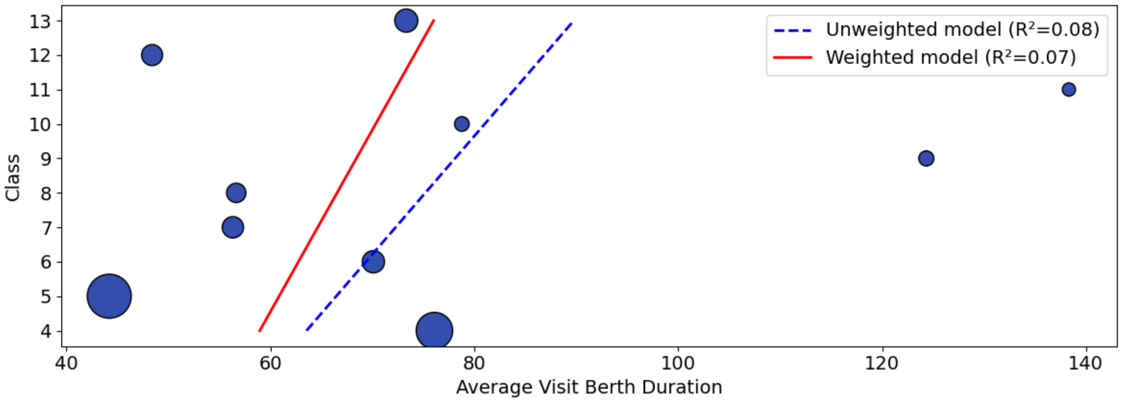


Figure C.4: LPG Tankers

(a) GT



(b) DWT

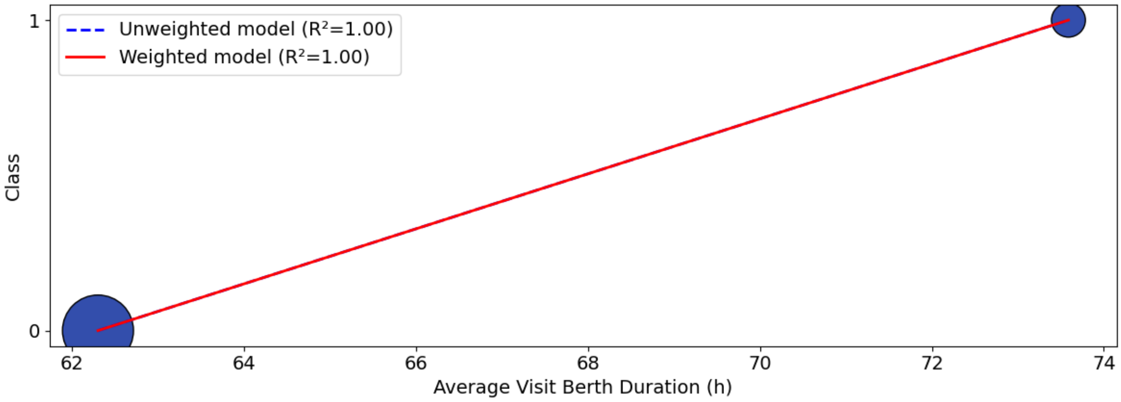
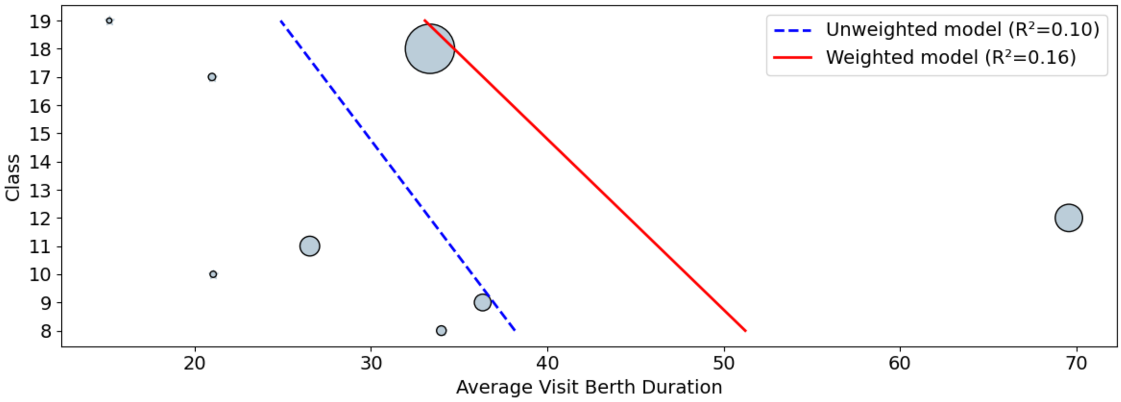


Figure C.5: LNG Tankers

(a) GT



(b) DWT

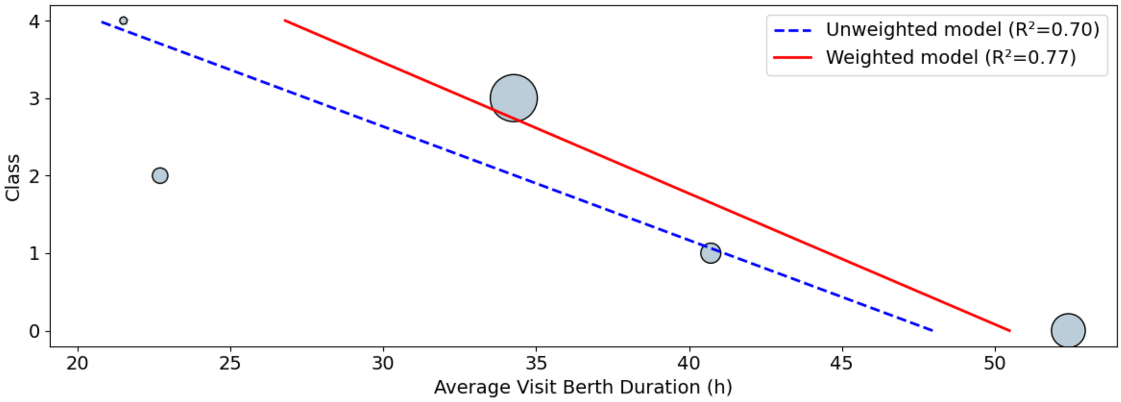
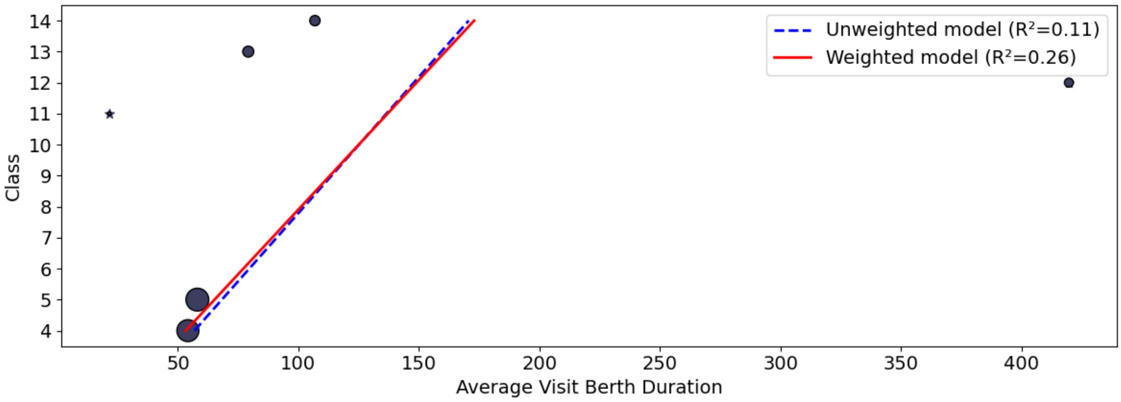


Figure C.6: Spec. Tankers

(a) GT



(b) DWT

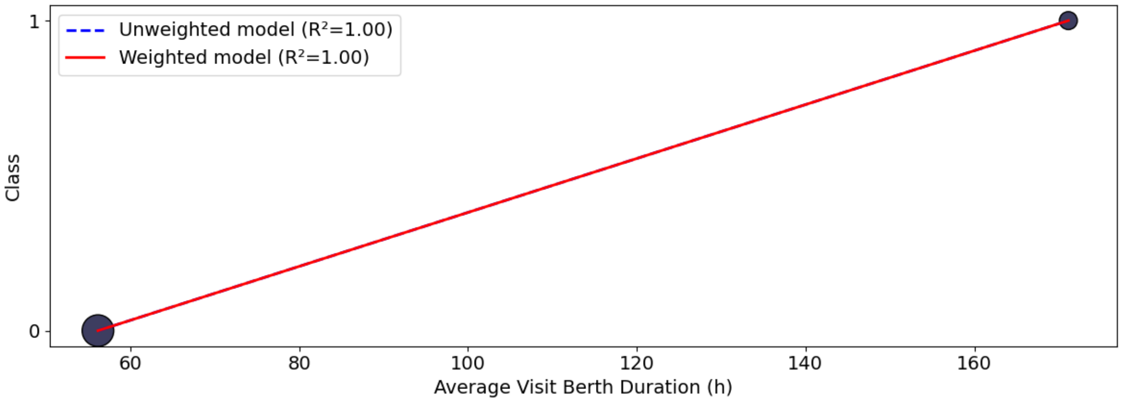


Table C.1: Average visit berthing time (h) per size class (DWT) and fleet type with expected error (%)

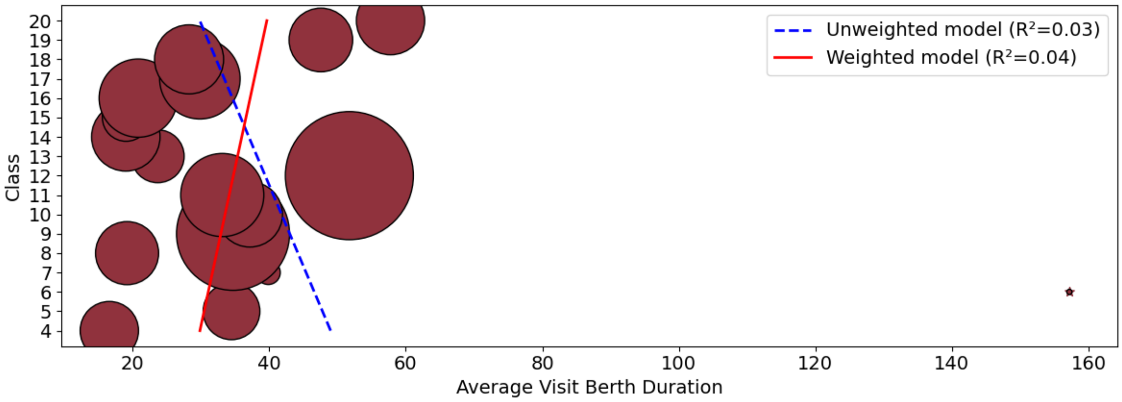
	class number	0	1	2	3	4	5	6
	class name		Handysize	Panamax	Aframax	Suezmax	VLCC(*)	ULCC(**)
Chemical Tankers	**Avg. time (h)**	42.11	67.22	83.02				
	Exp. err. (%)	0.94	0.91	8.64				
Product Tankers	**Avg. time (h)**	40.19	60.83	64.70	62.48	76.65		
	Exp. err. (%)	3.22	1.74	3.43	4.57	>15		
Crude Tankers	**Avg. time (h)**			58.80	58.84	53.56	67.24	57.89
	Exp. err. (%)			>15	3.61	3.31	4.37	>15
LPG	**Avg. time (h)**	62.30	73.59					
	Exp. err. (%)	2.64	3.09					
LNG	**Avg. time (h)**	52.41	40.71	22.69	34.27	21.49		
	Exp. err. (%)	7.04	12.91	>15	6.71	>15		
Spec. Tankers	**Avg. time (h)**	56.18	171.13					
	Exp. err. (%)	3.59	14.43					

* Very Large Crude Carrier
** Ultra Large Crude Carrier

C.2. Containerships

Figure C.7: Containerships

(a) GT



(b) TEU

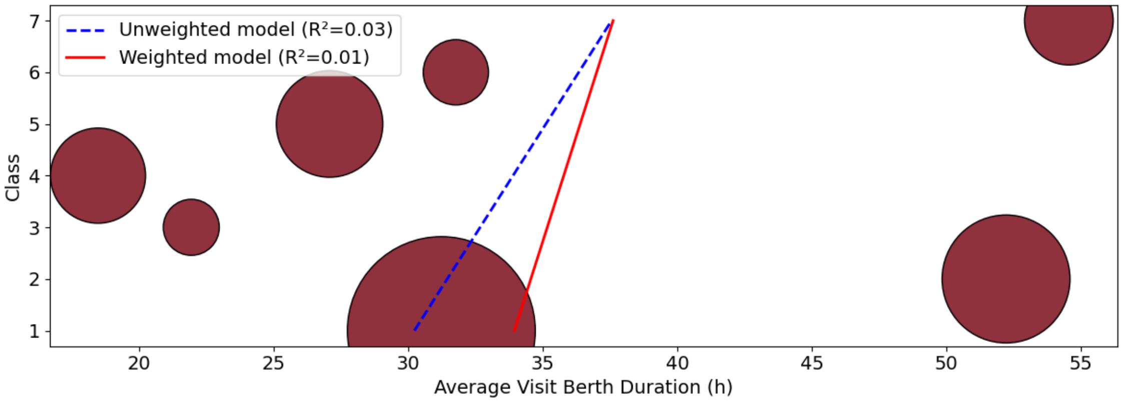


Table C.2: Average visit berthing time per size class (TEU) for Containerships with expected error

class	name	Avg. time (h)	Exp. err. (%)
1	Small feeder	31.2	0.93
2	Feeder	52.2	1.13
3	Feedermax	21.9	4.49
4	Panamax	18.5	3.00
5	Post-Panamax	27.1	2.85
6	New Panamax	31.8	4.88
7	Ultra Large Container Vessels (ULCV)	54.5	3.71

C.3. General cargo vessels

Figure C.8: MPP

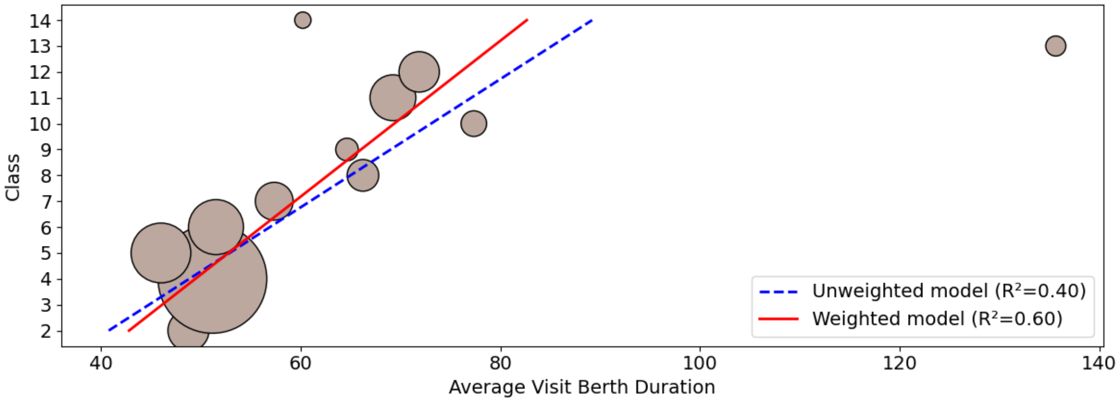
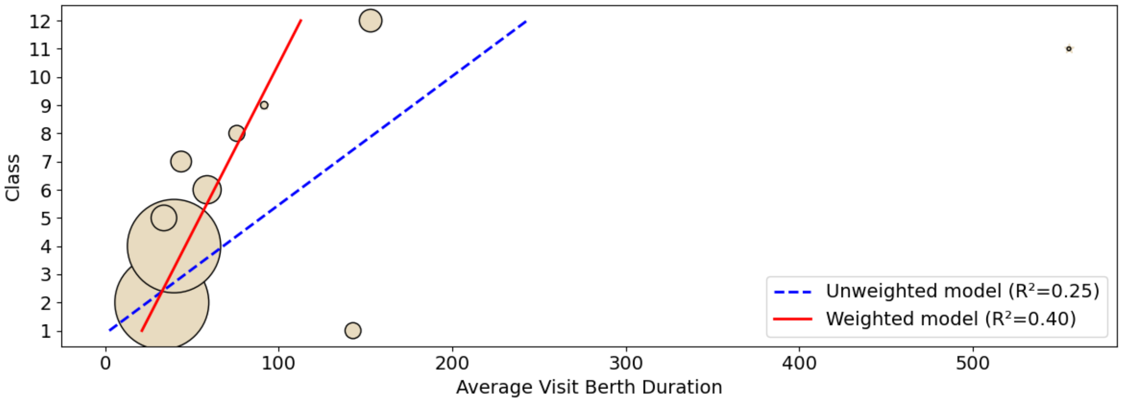


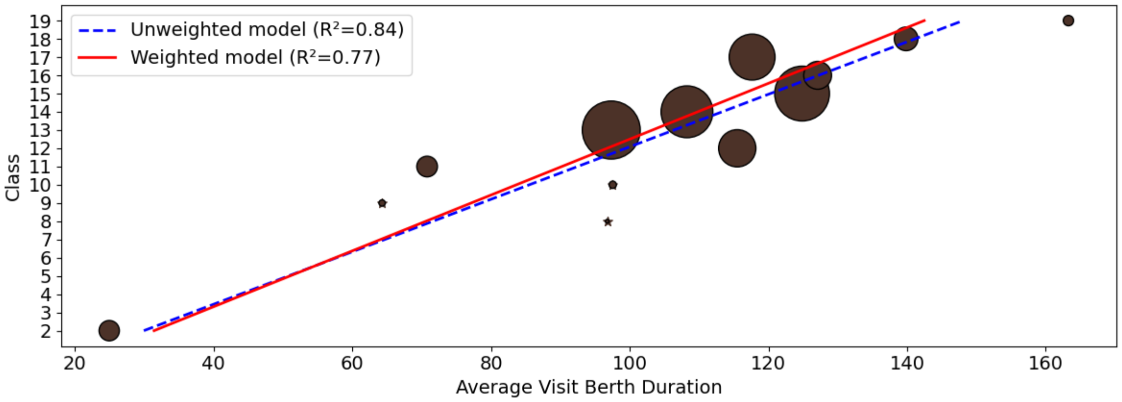
Figure C.9: General Cargo



C.4. Bulk Carriers

Figure C.10: Bulk Carriers

(a) GT



(b) DWT

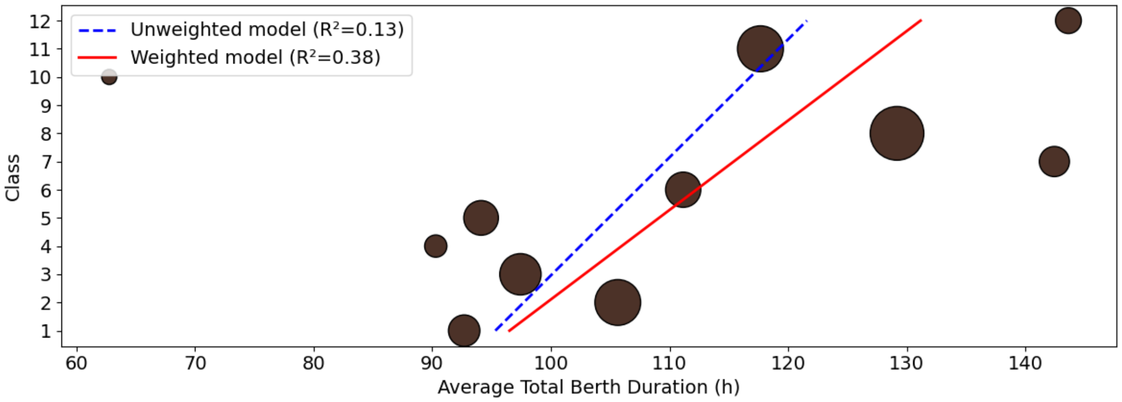


Table C.3: Average visit berthing time per size class (DWT) for Bulk Carriers with expected error

class	name	Avg. time (h)	Exp. err. (%)
0			
1	Small Handy	92.69	5.55
2	Mid-size Handy	105.63	2.96
3	Large Handy	97.43	3.25
4	Handymax	90.29	8.25
5	Traditional Supramax vessel	94.11	4.57
6	Ultramax	111.14	4.63
7	Traditional Panamax vessel	142.42	5.98
8	Post-Panamax vessel	129.16	2.95
9	Kamsarmax		
10	Mini Capesize vessel	62.78	9.41
11	Standard Capesize vessel	117.65	4.52
12	Very large Ore Carrier (VLOC)	143.60	10.6

C.5. Ro-ro and PCC

Figure C.11: Ro-Ro

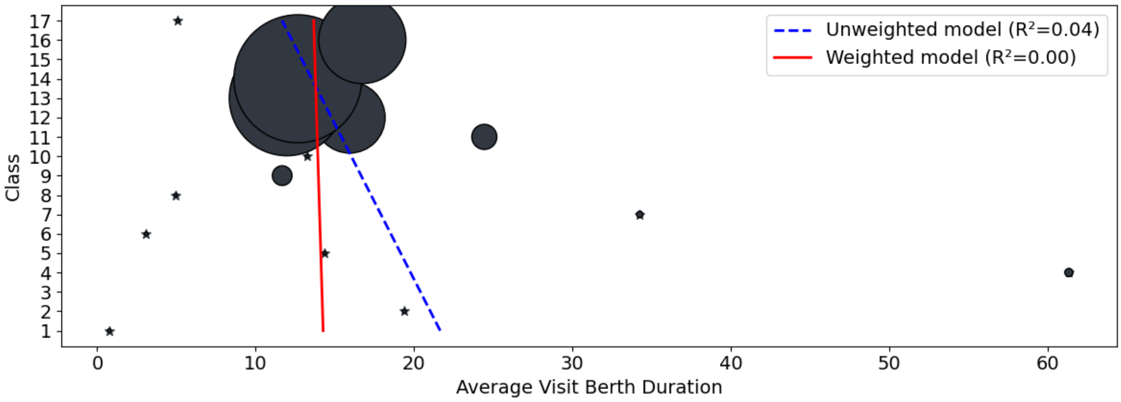
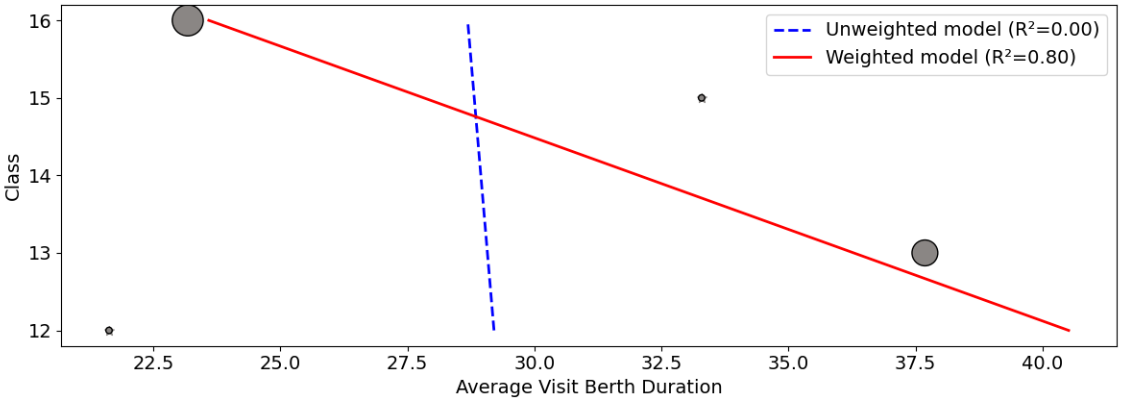


Figure C.12: PCC



C.6. Passenger vessels

Figure C.13: Ferries

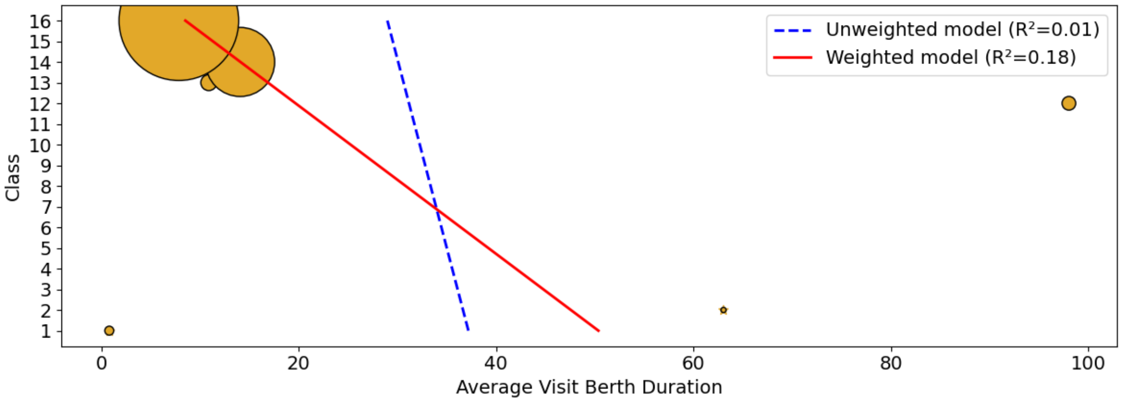


Figure C.14: Cruise

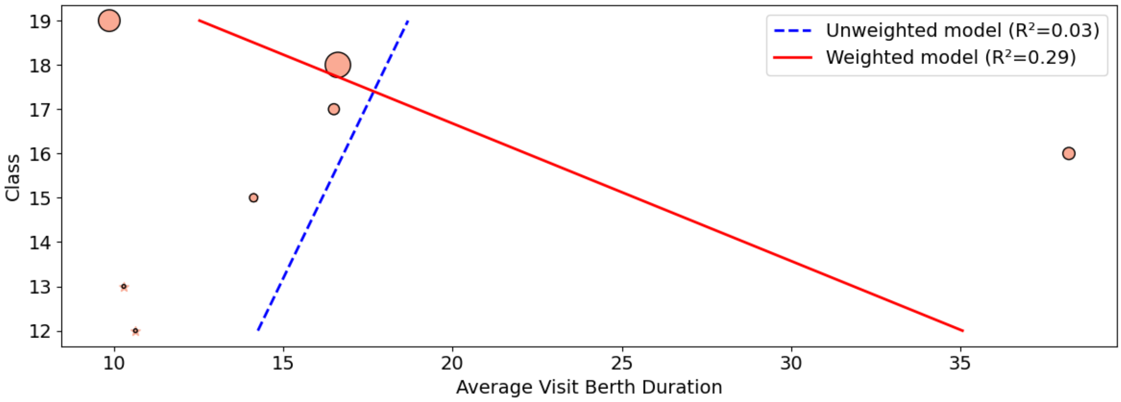
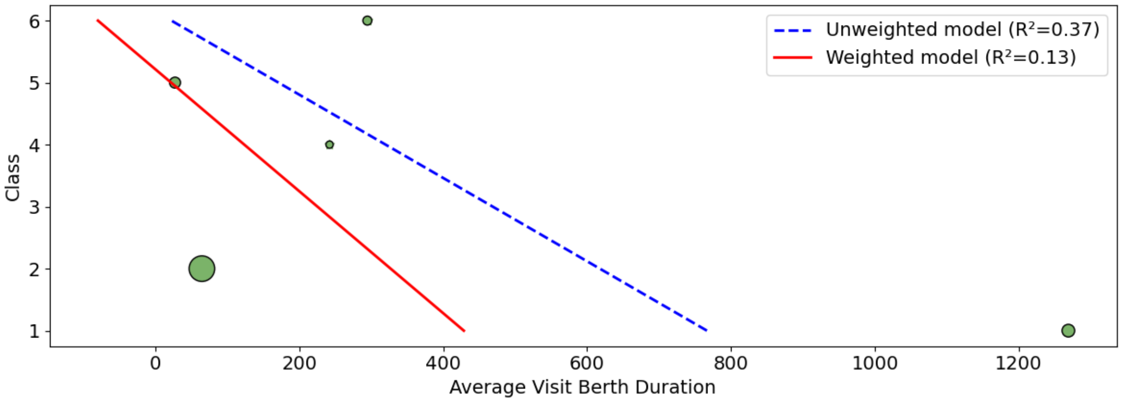
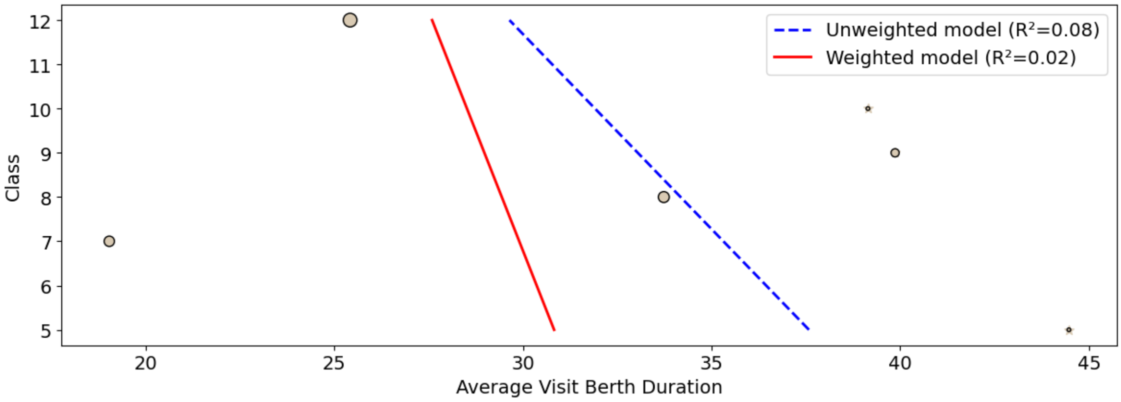


Figure C.15: Recreational Vessels



C.7. Refrigerated Cargo vessels

Figure C.16: 17



C.8. Port Operational vessels

Figure C.17: Tugs

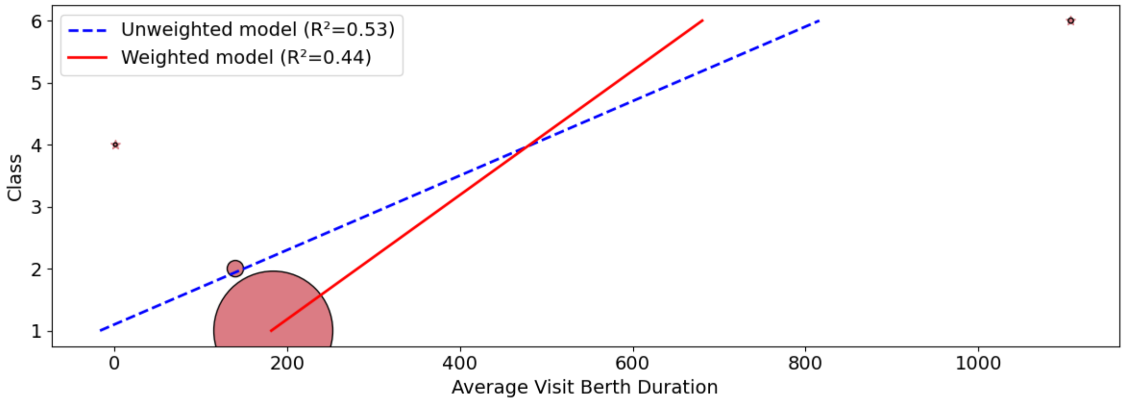
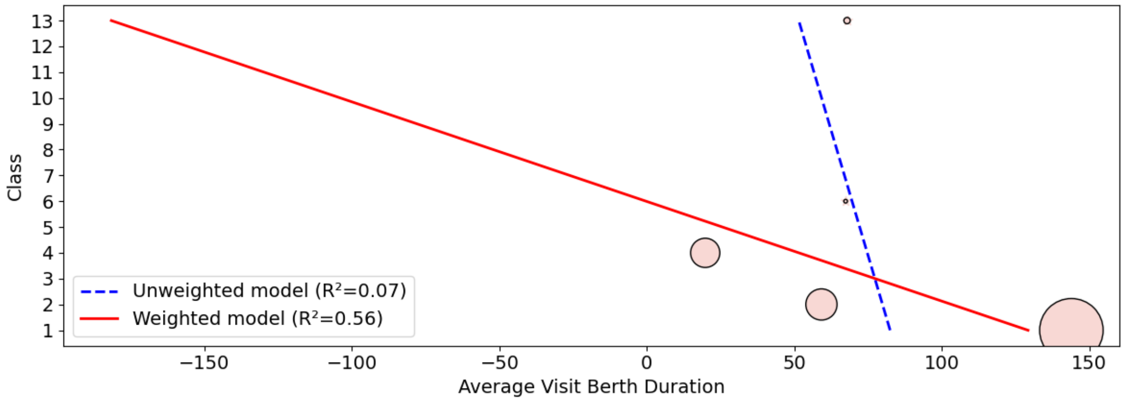


Figure C.18: Oth Non Cargo



C.9. Offshore and Dredgers

Figure C.19: Offshore

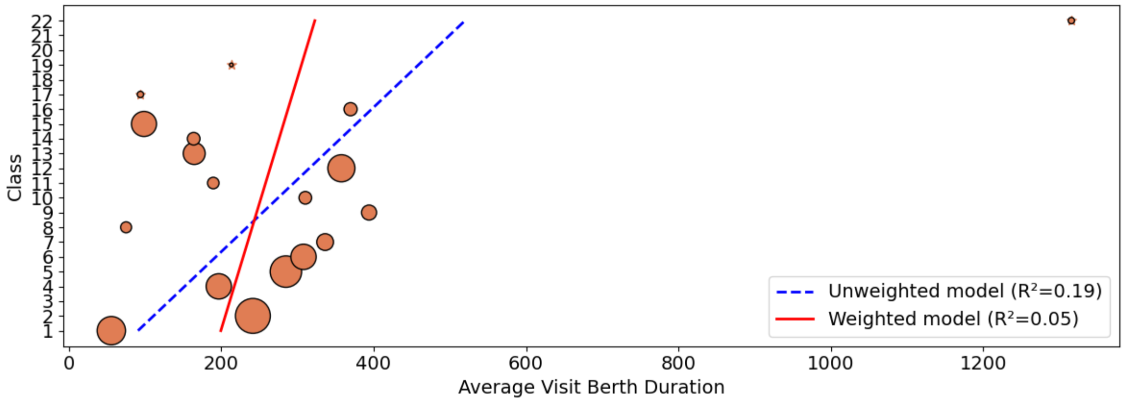
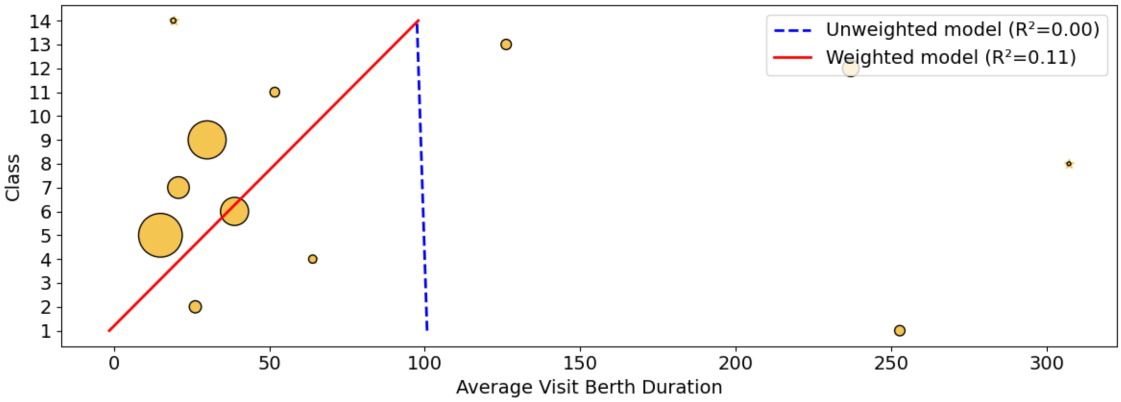


Figure C.20: Dredgers



C.10. Miscellaneous Vessels

Figure C.21: Other seagoing vessels

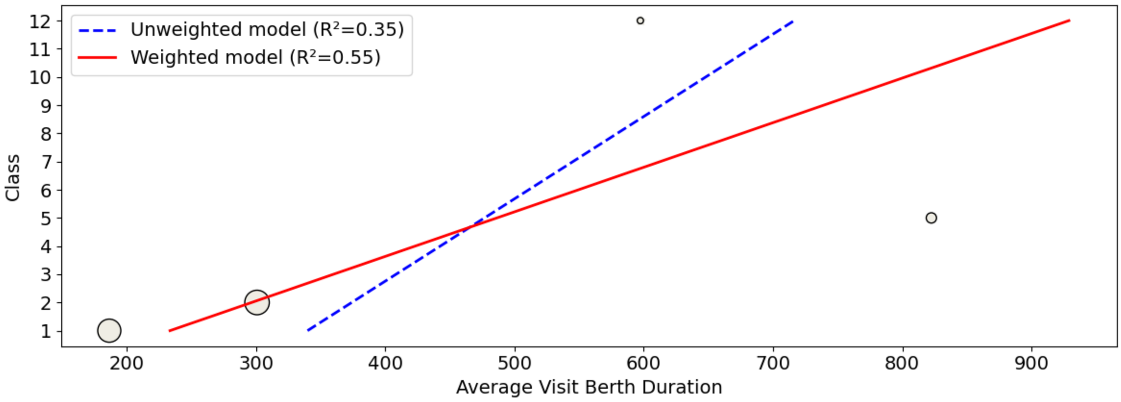
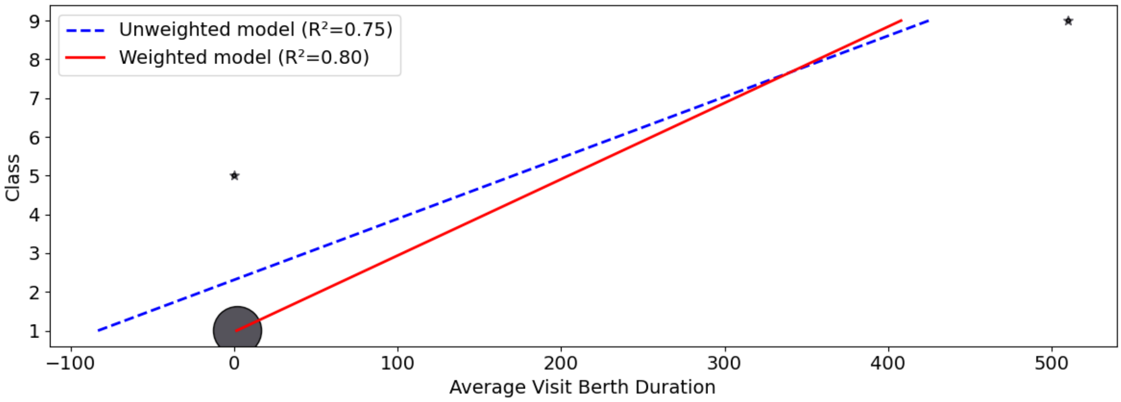


Figure C.22: Fishing vessels



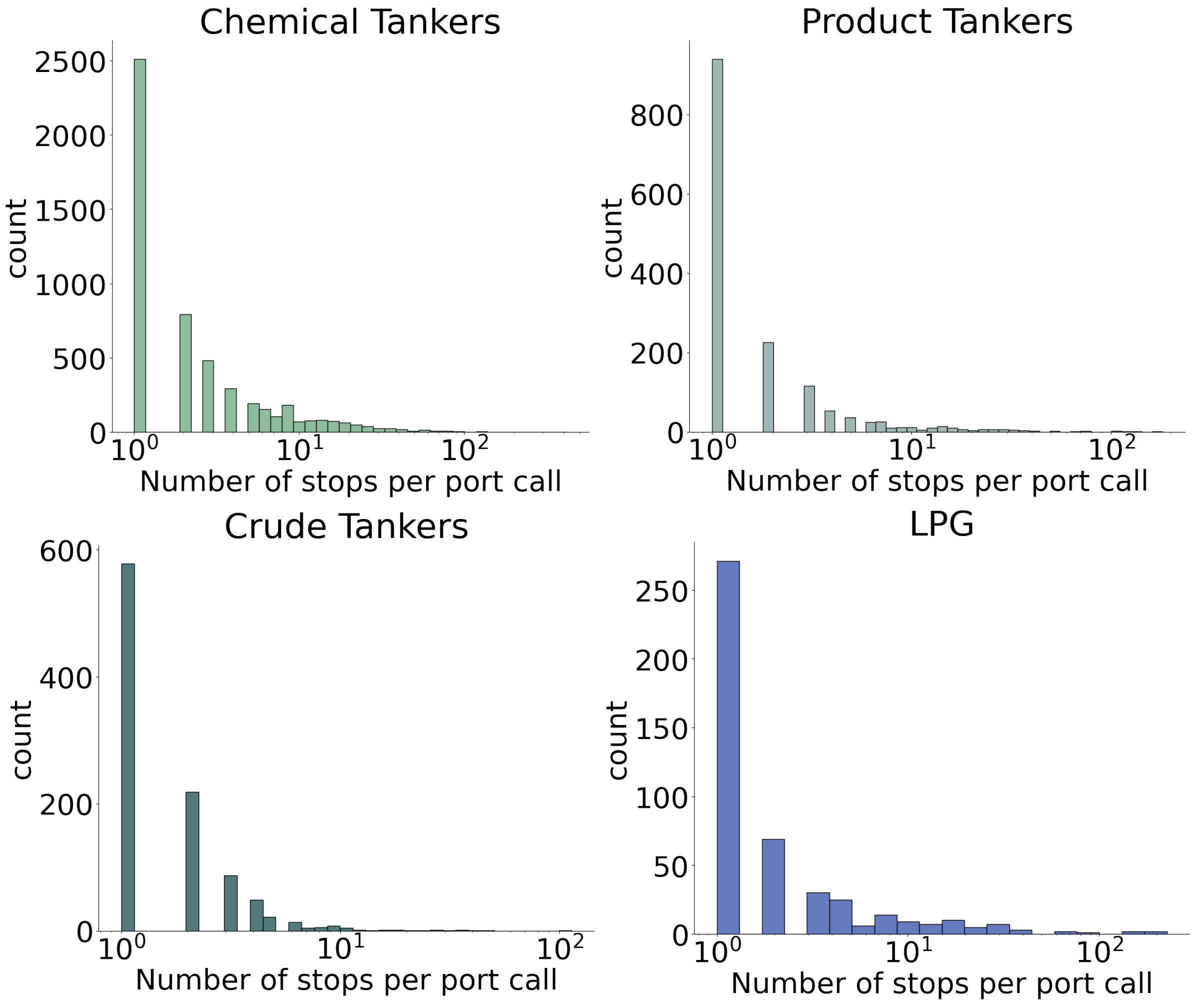
C.11. Average visit berthing time per size class (GT) and fleet type with expected error (%)

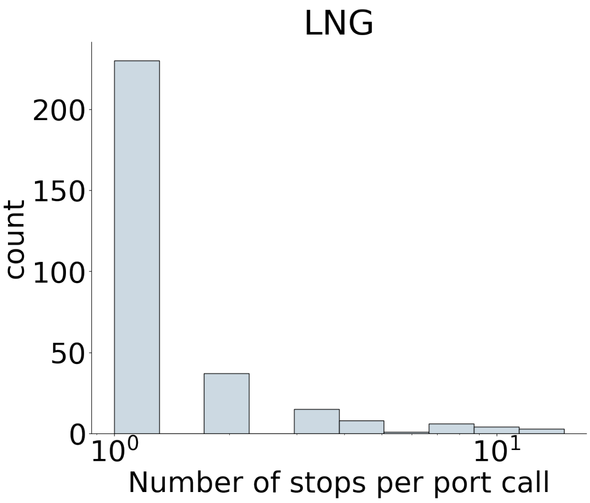
Table C.4: Average visit berthing times per size class (GT) and fleet type with expected error (%)

Class		**1**	**2**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**22**
Chemical Tankers	**Avg. time (h)**		45.85	40.69	40.16	42.67	47.53	44.81	56.88	62.82	79.87	60.48	93.53	95.54							
	Exp. err. (%)		5.58	1.89	1.51	2.31	2.43	4.17	2.91	3.26	5.18	1.25	1.88	4.58							
Product Tankers	**Avg. time (h)**		16.95	86.31	32.18	35.63	47.15	63.79	51.72	591.23	164.19	25.58	61.16	63.23	69.75	62.48	76.65				
	Exp. err. (%)		13.25	9.37	>15	4.28	7.33	>15	10.21	>15	>15	>15	1.80	4.01	5.92	4.57	>15				
Crude Tankers	**Avg. time (h)**			30.30										58.80		58.65	53.42		66.50		
	Exp. err. (%)			8.64										>15		3.55	3.34		4.24		
LPG	**Avg. time (h)**			76.09	44.20	70.11	56.32	56.65	124.34	78.78	138.33	48.40	73.33								
	Exp. err. (%)			4.33	4.62	7.62	7.76	>15	>15	>15	5.99	13.25	3.75								
LNG	**Avg. time (h)**							33.99	36.33	21.05	26.53	69.56					20.99	33.34	15.16		
	Exp. err. (%)							>15	14.74	>15	12.91	8.48					>15	6.44	>15		
Gas tanker	**Avg. time (h)**		97.08																		
	Exp. err. (%)		11.70																		
Spec. Tankers	**Avg. time (h)**			54.14	58.07						21.53	419.69	79.19	106.85							
	Exp. err. (%)			5.46	4.77						>15	>15	>15	>15							
Containerships	**Avg. time (h)**			16.59	34.48	157.19	39.87	19.19	34.70	37.17	33.12	51.74	23.68	19.00	19.04	20.82	29.85	28.26	47.57	57.77	
	Exp. err. (%)			5.23	2.92	>15	5.66	3.38	1.45	2.63	1.99	1.13	4.53	4.64	5.83	3.39	3.88	4.67	5.29	4.72	
MPP	**Avg. time (h)**		48.75	51.15	46.00	51.51	57.34	66.23	64.63	77.34	69.23	71.87	135.62	60.21							
	Exp. err. (%)		3.84	1.25	2.32	3.18	3.73	4.30	7.07	8.30	2.67	4.05	7.52	>15							
General Cargo	**Avg. time (h)**	142.82	32.63	39.66	33.83	58.75	43.77	75.87	91.64		555.43	152.97									
	Exp. err. (%)	9.21	1.77	1.79	5.74	5.74	8.48	10.66	>15		>15	5.35									
Bulkers	**Avg. time (h)**		24.94					96.76	64.29	97.55	70.78	115.51	97.34	108.25	124.86	127.10	117.65	139.86	163.27		
	Exp. err. (%)		7.04					14.43	>15	>15	8.51	3.85	2.45	3.16	2.84	6.35	4.52	11.40	>15		
Ro-Ro	**Avg. time (h)**	0.76	19.39	61.36	14.36	3.09	34.26	4.96	11.68	13.24	24.44	15.94	11.97	12.66		16.74	5.09				
	Exp. err. (%)	>15	>15	>15	>15	>15	>15	>15	>15	>15	8.57	4.38	2.92	2.76		3.92	>15				
PCC	**Avg. time (h)**											21.63	37.68		33.29	23.18					
	Exp. err. (%)											>15	8.80		>15	8.84					
Ferries	**Avg. time (h)**	0.82	63.05									98.04	10.90	14.08		7.87					
	Exp. err. (%)	>15	14.74									>15	>15	5.00		2.94					
Cruise	**Avg. time (h)**											10.63	10.29		14.12	38.20	16.50	16.61	9.86		
	Exp. err. (%)											>15	>15		>15	>15	>15	7.76	7.18		
Recreational Vessels	**Avg. time (h)**	1268.72	64.63	242.02	27.30	294.58															
	Exp. err. (%)	3.56	3.63	5.06	>15	>15															
Passenger ship	**Avg. time (h)**	4.89																			
	Exp. err. (%)	8.67																			
Refrigerated Cargo vessels	**Avg. time (h)**				44.47		19.04	33.74	39.86	39.14		25.42									
	Exp. err. (%)				>15		>15	>15	>15	>15		14.59									
Tugs	**Avg. time (h)**	183.71	139.78	0.87		1107.19															
	Exp. err. (%)	0.35	8.51	>15		>15															
Service ship seafaring	**Avg. time (h)**	33.28	1689.86																		
	Exp. err. (%)	0.41	2.18																		
Oth Non Cargo	**Avg. time (h)**	143.87	59.14	19.74		67.33							67.82								
	Exp. err. (%)	0.74	5.63	4.64		>15							>15								
Offshore	**Avg. time (h)**	55.64	241.39	196.67	284.73	307.84	336.20	75.02	393.85	310.21	189.43	357.53	164.40	163.68	98.49	369.58	93.83		213.10		1315.48
	Exp. err. (%)	5.20	1.57	4.43	2.11	1.89	2.95	6.12	3.14	>15	13.48	3.38	4.28	10.05	6.39	4.95	>15		4.81		6.59
Dredgers	**Avg. time (h)**	252.74	26.22	63.96	15.00	38.83	20.80	307.11	30.02		51.77	236.98	126.18	19.13							
	Exp. err. (%)	3.96	9.90	>15	6.47	6.54	>15	>15	7.20		>15	7.72	>15	>15							
Other seagoing vessel	**Avg. time (h)**	186.42	300.73		822.52							597.35									
	Exp. err. (%)	3.92	2.72		3.09							6.00									
Fishing vessel	**Avg. time (h)**	2.16			0.09				510.25												
	Exp. err. (%)	6.80			>15				>15												

D

Number of berthing events per port visit

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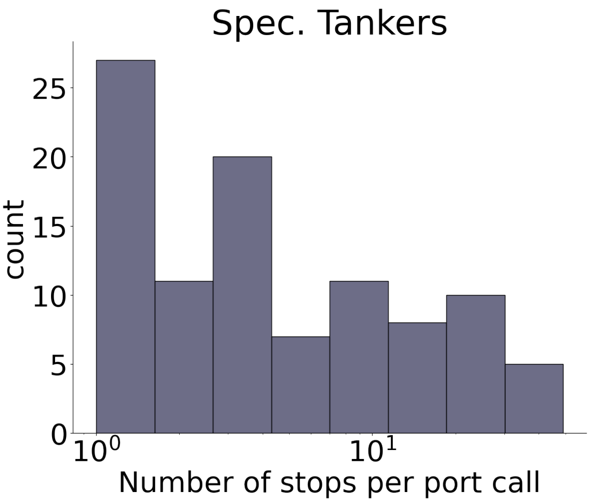
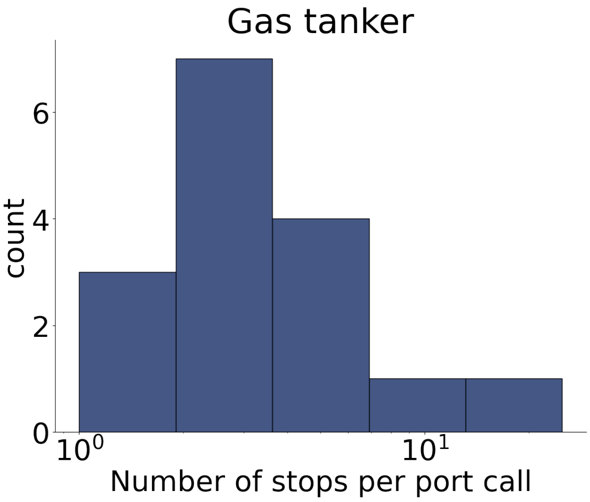

Spec. Tankers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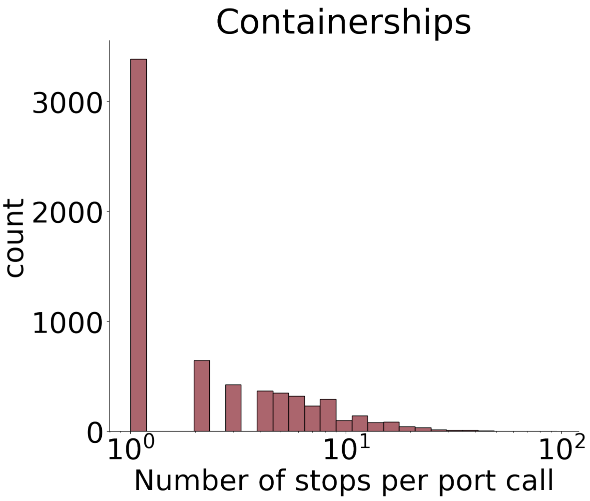
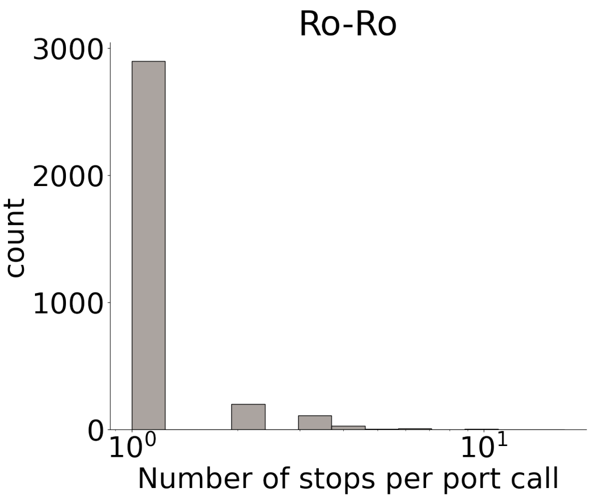
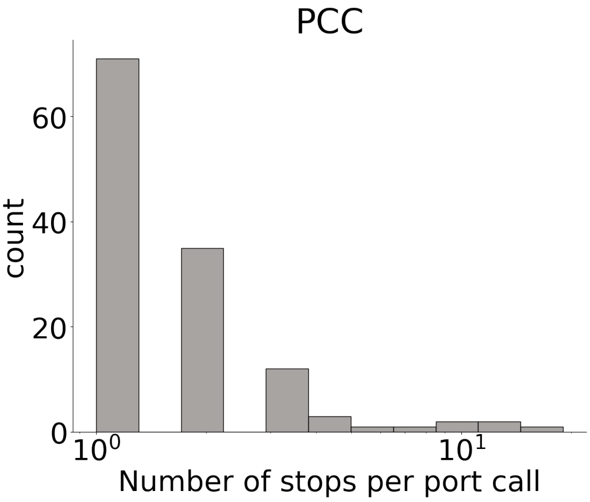
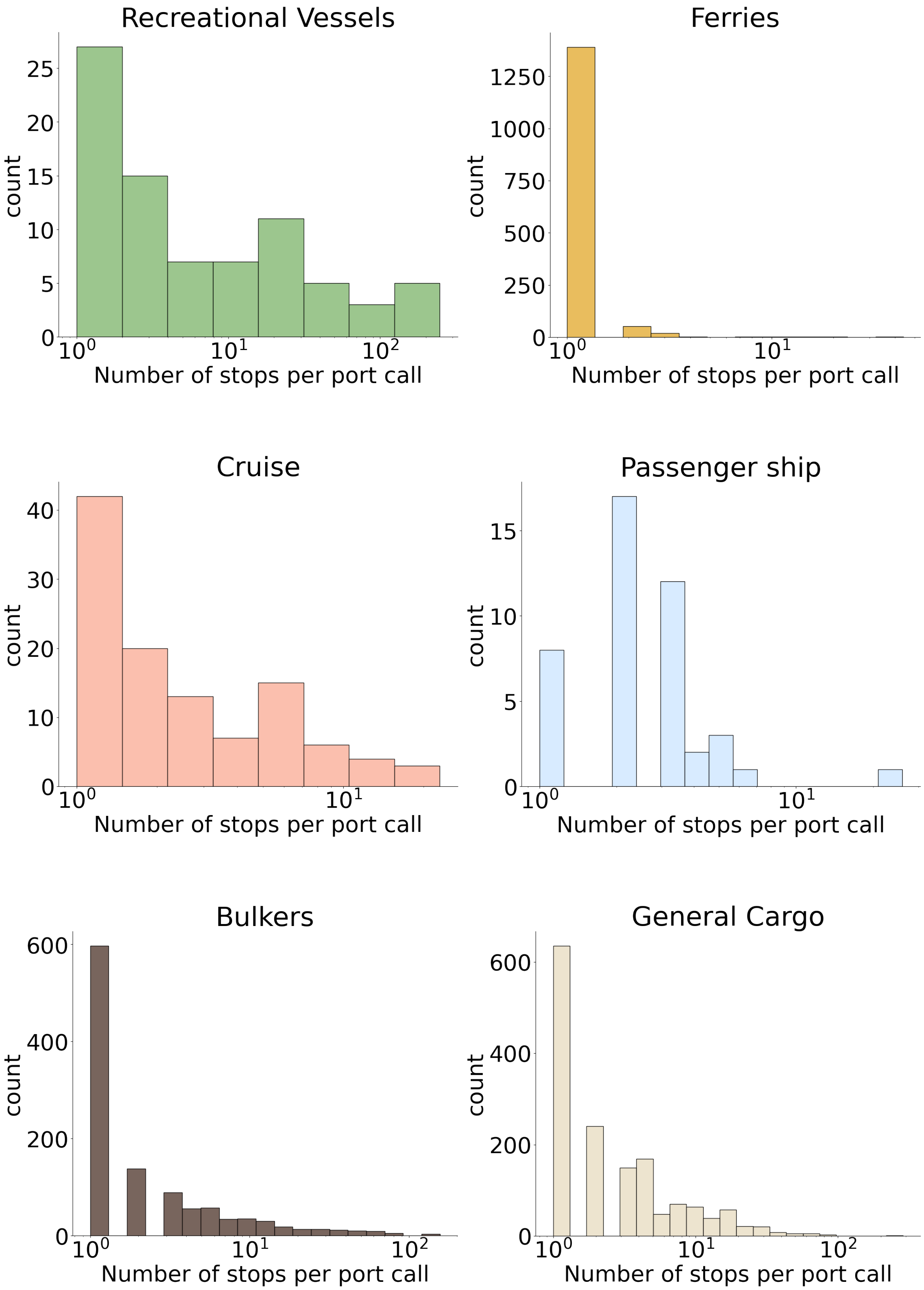

Containerships


Ro-Ro


PCC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10
15
20
25
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10^1
10^2
Number of stops per port call
Ferries
count
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250
500
750
1000
1250
10^0
10^1
Number of stops per port call
Cruise
count
0
10
20
30
40
10^0
10^1
Number of stops per port call
Passenger ship
count
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count
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200
400
600
10^0
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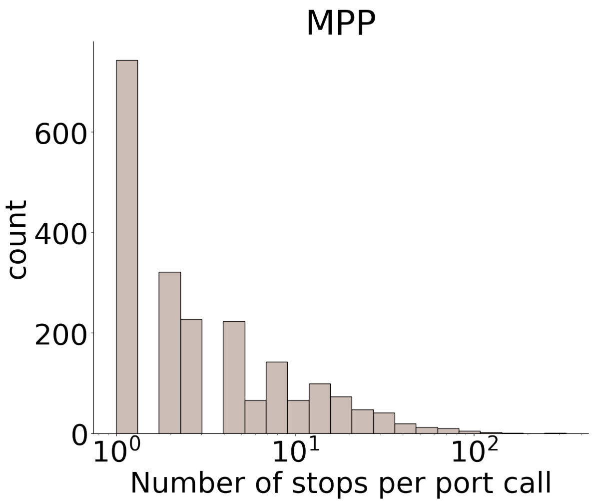
Number of stops per port call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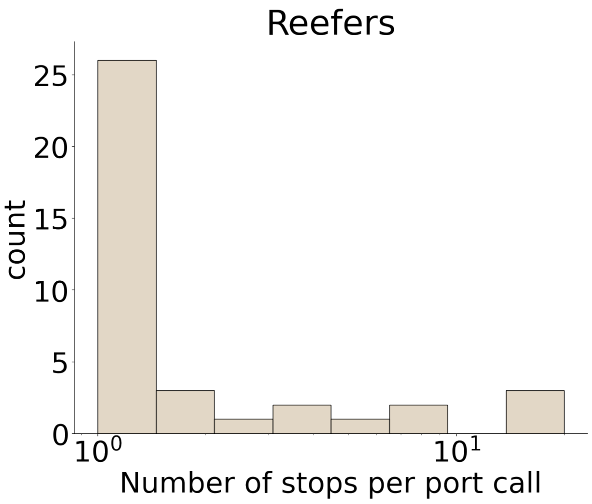
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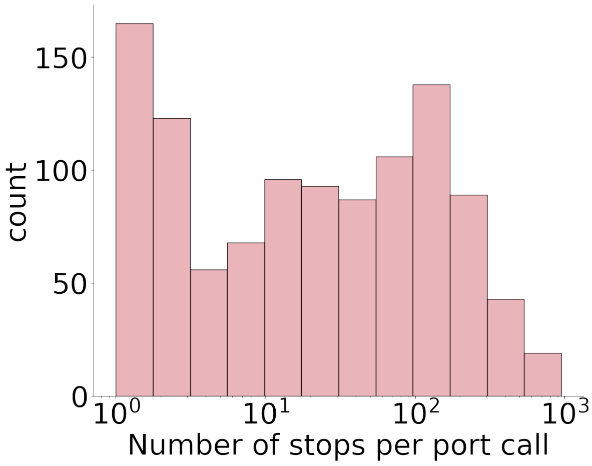
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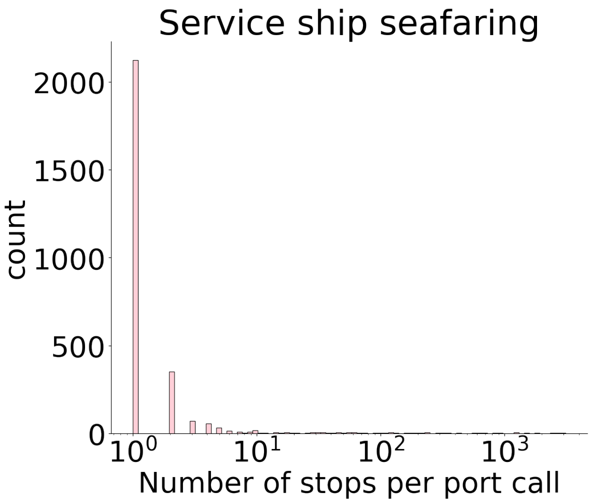
Number of stops per port call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10^1
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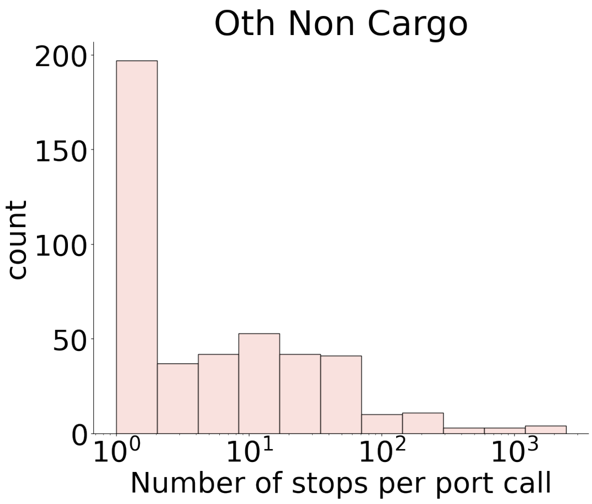
10^3
Number of stops per port call


Oth Non Cargo
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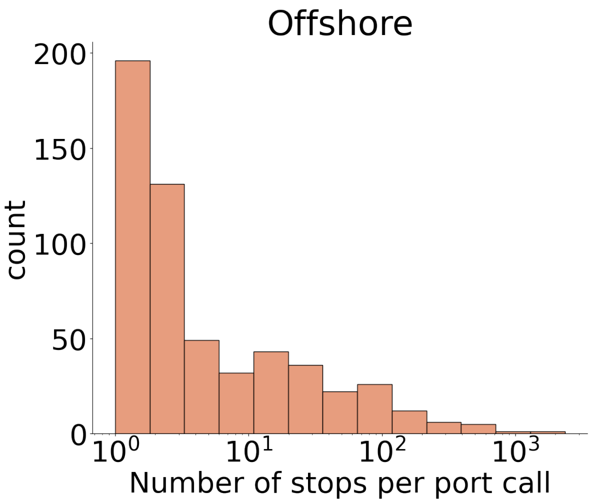
10^2
10^3
Number of stops per port call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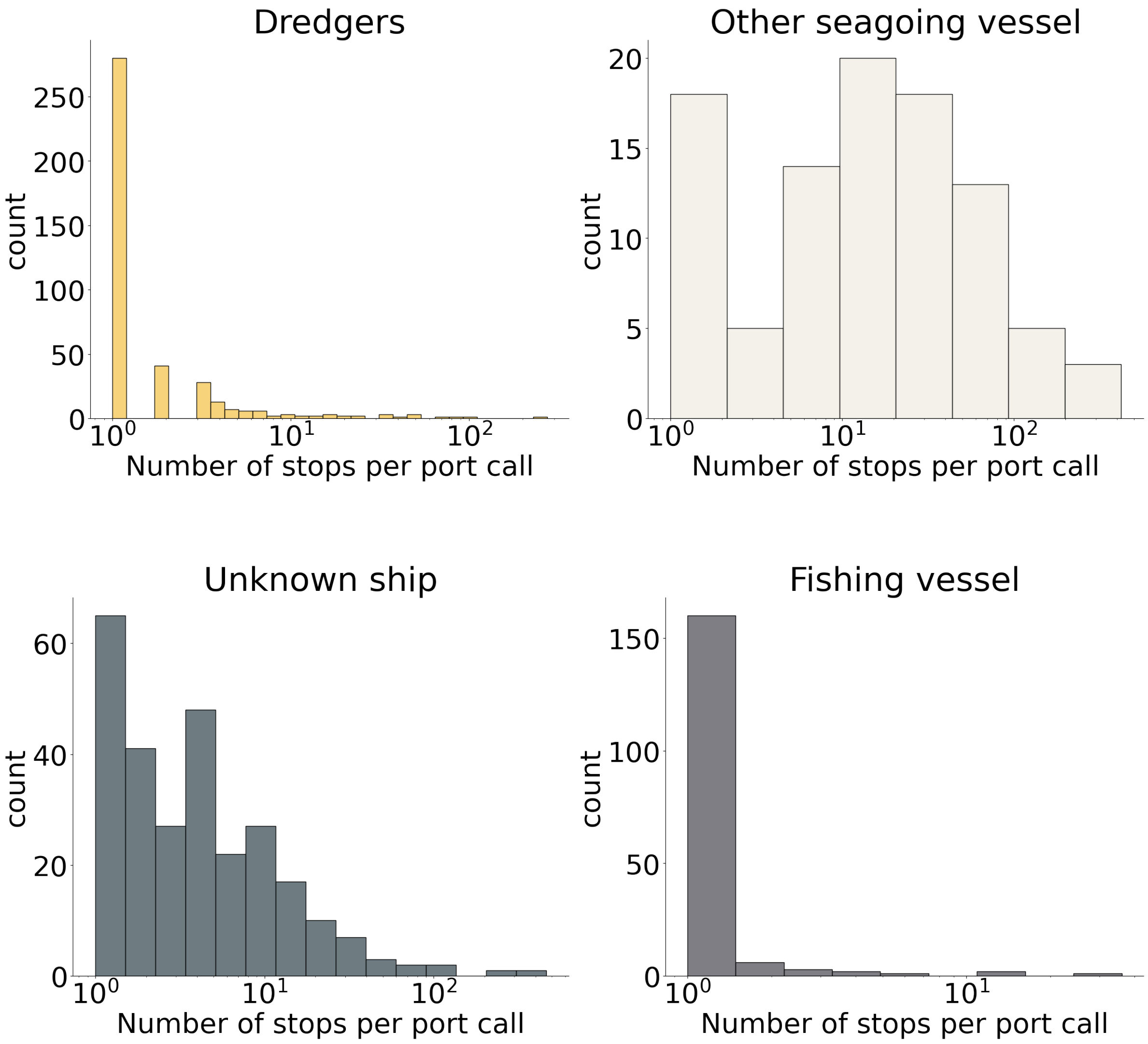
10^3
Number of stops per port call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10^2
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10
15
20
10^0
10^1
10^2
Number of stops per port call
Unknown ship
count
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20
40
60
10^0
10^1
10^2
Number of stops per port call
Fishing vessel
count
0
50
100
150
10^0
10^1
Number of stops per port call