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Analysis on the impact of non-participating cargo vessels in a multi-lateral arrival schedule optimization model for decarbonization

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Abstract

An essential part of the decarbonization of the maritime industry is to increase operational energy efficiency. The Blue Visby Solution (BVS) aims to reduce emissions produced from international shipping by optimizing the arrival times of cargo vessels, which will allow sailing ships to reduce their speed. Speed reduction is recognized as the easiest and the most affordable way of reducing fuel consumption of the existing fleet. The analysis of a partially participating fleet is performed to evaluate the feasibility of the solution in a more realistic scenario. A simulation model used in the earlier studies, which utilizes data from the year 2019 regarding dry and wet bulk carriers, is extended in three ways: the fleet is randomly partitioned into participating and non-participating vessels, the BVS process is developed further regarding the triggers of the algorithm, and a ship-specific port transit modeling is implemented. A variety of metrics is defined to measure the benefits of being a participant, the most relevant being the waiting time change in the anchorage and the number of overtakes during a voyage. Three benefit areas are defined using these two metrics, and it is concluded that at least 80% of the fleet should participate in the BVS so that participation would generally be beneficial. However, the results differ between ports significantly. In addition, it is observed that the usage of the BVS generally reduces queues and that there exists a large group of vessels that are not affected by the BVS or the decrease in the number of participants.

Keywords Blue Visby Solution, Simulation model, Multi-lateral voyage optimization, Vessel arrival scheduling, Just-in-Time arrival, Speed optimization, Maritime shipping, Decarbonization, Energy efficiency

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Tiivistelmä

Tärkeä osa rahtilaivateollisuuden ympäristövaikutusten pienentämistä on operatiivisen energiatehokkuuden parantaminen. Blue Visby Solution tähtää päästövähennyksiin laivaliikenteessä optimoimalla rahtilaivojen saapumisaikatauluja, jotta matkat voitaisiin taittaa matalammilla vauhdeilla. Hitaampien nopeuksien käyttö on todettu helpoimmaksi ja kustannustehokkaimmaksi keinoksi vähentää nykyisen kauppalaivaston polttoaineen kulutusta. Jotta tämän ratkaisun käytettävyyttä voidaan arvioida realistisemmassa skenaariossa, tässä työssä analysoidaan systeemin käyttäytymistä, kun vain osa laivoista osallistuu BVS:n toimintaan. Aiemmissa tutkimuksissa kehitettyä simulaatiomallia, joka hyödyntää dataa vuodelta 2019, laajennetaan kolmella tavalla: laivasto jaetaan satunnaisesti osallistujiin ja muihin, BVS prosessia kehitetään algoritmin käynnistämisen suhteen ja laivojen siirtyminen ankkurista satamaan mallinnetaan yksityiskohtaisemmin. Osallistumisen hyötyjä mitataan määrittämällä joukko metriikoita, joista tärkeimmät ovat jonotusaika ankkurissa sekä matkan aikana tapahtuvien ohitusten määrä. Näiden kahden mittarin avulla muodostetaan kolme hyötyaluetta, joista voidaan vetää johtopäätös, että vähintään 80% laivastosta tulisi osallistua BVS:ään, jotta osallistuminen olisi yleisesti ottaen hyödyllistä. On kuitenkin hyvä panna merkille, että tulokset vaihtelevat merkittävästi satamien välillä. Lisäksi on huomion arvoista, että BVS:n käyttö tavallisesti aina lyhentää jonoja, ja että osaan laivoista BVS tai osallistujien määrä ei juuri vaikuta.

Avainsanat Blue Visby Solution, simulaatiomalli, matkaoptimointi, rahtialusten aikataulutus, JIT-saapuminen, nopeusoptimointi, laivakuljetus, päästövähennykset, energiatehokkuus

Preface

This is literally the last assignment of my studies at Aalto University, which started in the fall of 2016. Working on this thesis has been generally pleasant, sometimes fun, although occasionally boring. The fact that I have been able to enjoy the project and feel that I am constantly learning is a result of all the twists and turns that my time as a student has included. It is not only the courses that have prepared me for this final work but all the fun, crazy, and troublesome times. Therefore, it is in order to address my gratitude toward everyone who has been helping me.

Firstly, there is no doubt that the actual process of this thesis would have been so much harder without the amazing advisor and supervisor that I had. Thanks to Kimmo Laaksonen at NAPA for being so interested and invested in this work and to my professor Fabricio Oliveira for being the most reliable and effective supervisor.

Secondly, this has been a true trial of my project management skills, which are largely learned during my voluntary work in the Aalto community. The support and safe environment that the Aalto University Student Union provided during my work there have given me tools that make it possible to work on challenging projects all the while enjoying it. Thanks to the people that I have encountered and who have helped me to grow.

Thirdly, my studies have not always, or mostly never, felt easy. But what has in every course and every class made me work and believe in myself has been the people around me. Without my fellow students, every homework and project would have felt so much worse. Even during this thesis, having a library buddy and people to work with after a long day of skiing has meant that I have not been alone. Thanks to the ones who I have became lifelong friends with.

Finally, thanks to my family, Äiti, Iskä, Eero, and Pipari, who have always supported me. Even though it's a little funny that we all went to Otaniemi.

Otaniemi, 31 March 2023

Noora Torpo

Contents

Symbols and abbreviations

Symbols

Capital letters	
B	Constant for scaling fuel consumption
F	Fuel consumption
F^{BVS}	Fuel consumption computed using the BVS
P	Set of ports
S	Speed
T	The latest port transit time
V	Set of vessels heading to the same port
Z	Number of update points during a voyage
Lowercase letters	
d_i	Voyage distance of vessel i
e_i	The earliest arrival time of vessel i using the maximum speed
i	Index of a vessel corresponding to the notional arrival order
l_i	The latest arrival time of a vessel i using the minimum speed
n	Number of vessels heading to the same port
p	Port p
q	Queue length
r_i	Recommended ETA for vessel i
s_i	Service speed of a vessel i
s_z	Speed between update points z and $z + 1$
t_i	Scheduled arrival time (Blue ETA) of a vessel i
t_z	Time between update points z and $z + 1$
v_i	Vessel i
z	Index of an update point on a voyage
Greek letters	
α	Speed reduction factor
β	Responsiveness
ρ	Target inter-arrival time
Other	
P_{BVS}	Optimization problem

Abbreviations

AIS	Shipborne Automatic Identification System
BVS	Blue Visby Solution
CCI	Operational Carbon Intensity Indicator
DCS	Data Collection System
dwt	death weight ton
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EEXI	Energy Efficiency Existing Ship Index
ETA	Estimated time of arrival
FCFS	First-Come-First-Served
FL-%	Freeloader percentage
GHG	greenhouse gas
IMO	International Maritime Organization
JIT	Just-in-Time
kn	knot
LNG	Liquefied natural gas
LSFO	Low Sulphur Fuel Oil
MARPOL	International Convention for the prevention of pollution from ship
MGO	Marine Gas Oil
nm	nautical mile
POC1	the first Proof of Concept study (Sung, Zografakis, and Nielsen, 2022)
POC2	the second Proof-of-Concept study by Blue Visby Consortium
SEEMP	Ship Energy Efficiency Management Plan
UNCTAD	United Nations Conference on Trade and Development

1 Introduction

The shipping industry produces close to 3% of all the emissions in the world, and furthermore, the amount of emissions from the maritime industry has been growing (IMO, 2021a). Most of the shipping is carried through sea passage as it is currently the most economically and environmentally sensible option (IMO, 2018a). Therefore, it is clear that the industry needs to be able to aim higher and meet global emission reduction goals. This has been recognized internationally, and shipping companies are facing new regulations and demands. Obviously, the key interest lies in new energy sources and alternative fuels to decarbonize the maritime industry. However, energy efficiency needs to be increased both from technical and operational perspectives.

The most effective measure of operational energy efficiency has been recognized to be the speed optimization of ships. Speed has a great impact on fuel consumption for which usage of slow steaming is a great example (IMO, 2018a). In addition, it is common for vessels to spend idle time in anchorage waiting for a berth; queueing times can be even weeks (GloMEEP Project Coordination Unit, 2020). Therefore, there exists a potential for reducing speed and arriving later to the port area without the total shipping capacity diminishing. This would result in fuel savings that directly impact the emissions. In many ways, this approach seems like a win-win situation that should be implemented across the industry.

However, the industry suffers from an energy efficiency gap. There are multiple barriers that prevent taking advantage of this potential. Many initiatives have, of course, been considered. Just-in-Time arrival has been researched widely, and the virtual arrival clause has been implemented as an answer to the contractual structure of the industry. The practitioners have not used these methods on a large scale, even if slow steaming is occasionally used when it economically makes sense. From the perspective of a port, berth allocation and optimization of the port operations have been researched but widely applicable solutions are still to be found. In addition, the research regarding more systematic approaches is only from a perspective of a single shipping company, which does not answer to the competitive landscape.

Given the above, multi-lateral optimization of arrival schedules for multiple vessels and multiple ports has not been presented earlier. Blue Visby Solution (BVS) aims to answer this exact need. The concept has first been introduced by Sung, Zografakis, and Nielsen (2022), and it has been further developed by the Blue Visby Consortium, which Napa Ltd is coordinating. The BVS is currently evolving into a real-time platform combined with a contractual structure that allows a fair share of benefits. The idea behind the BVS is to synchronize the arrival times of vessels to match the service rate of a port. For each port, the queue at the anchorage and the upcoming vessels are observed. Ongoing voyages receive ETA recommendations computed using the target inter-arrival time, current queue length, and the number of ongoing voyages according to the BVS algorithm. This allows vessels to reduce their speed and arrive closer to their port call. The key idea is to keep the arrival order intact so that participation is always beneficial and the ports do not need to be involved in the process.

In earlier studies, it has been assumed that all of the ships participate in the BVS. However, this is not a realistic scenario since some vessels will most likely remain to use their normal service speeds. This means that the arrival order can change, which is against the basic principle of the BVS. Therefore, it is essential to study the behavior of the system under a partially participating fleet. This will reveal if there are major weaknesses that will affect the feasibility of the platform. The underlying assumption that the ports do not need to be incorporated into the system might have to be changed or new development requirements may arise. The research question addressed in this study is exactly this: What proportion of the fleet needs to participate in the BVS so that the participation is still beneficial? In addition, the sensitivity of the system under different selections of participants is examined, and the reasons behind differently impacted voyages are discussed.

The study is performed by means of a simulation model using historical data comprising worldwide voyages of dry and wet bulk carriers from the year 2019. The system has been researched earlier in a form of a Proof-of-Concept by Napa Ltd, and in this work, the simulation model is extended further. The main developments to the existing model are implementing the partially participating fleet, developing the algorithm so that the non-participating vessels are observed, and creating a ship-specific port transit modeling to allow the measurements of the waiting time changes in anchorage. The results are analyzed using a variety of metrics, such as speed, fuel consumption, potential savings, waiting time, and arrival order changes.

The benefits are evaluated using several different aspects, but exact monetary calculations are not performed. This is decided to be out of the scope of the study as the benefits-sharing mechanism of the BVS should be taken into account in detail. Hence, this study includes an analysis of the algorithmic behavior of the system when the environment, where it is applied, is changed. Furthermore, the participants are randomly picked from the dataset, which means that further analysis is required to evaluate how realistic this selection is, and possible market analysis on the matter should be completed in the future.

The thesis begins by presenting the background of the study in section 2. Decarbonization in the maritime industry is discussed, and different methods and research are introduced. Section 3 includes a detailed presentation and explanation of the Blue Visby Solution. In section 4, the extensions to the simulation model are explained and motivated. The simulation process is described, and the experimental setting is presented in detail. In addition, the determination of the warm-up and cool-down periods as well as the sensitivity analysis is performed in this section. Results are presented and analyzed in section 5. Finally, section 6 concludes the study by summarizing the content and the main results. The limitations and recommended developments are discussed at the end of this thesis.

2 Background

2.1 Decarbonization in maritime shipping

2.1.1 GHG emissions in maritime shipping

International shipping produced 2.89% of the total human-generated emissions worldwide in 2018 according to a report on greenhouse gas (GHG) emissions published by the International Maritime Organization (IMO) (IMO, 2021a). In the report, it is stated that the amount of GHG emissions has grown by 9.6% from 2012 to 2018 within the shipping industry containing both international and domestic shipping as well as fishing. Maritime shipping is currently the most economically and environmentally sensible way of transporting cargo and carries altogether 80% of global trade (IMO, 2018a). Furthermore, a report by United Nations Conference on Trade and Development (UNCTAD, 2021b) declares that the shipping industry will grow by 2.4% between 2022 and 2026. Major trends that currently are recognized to shape the shipping industry are discussed in the report including globalization, energy transition, digitalization, and new consumer behavior due to the increasing amount of e-commerce.

Hereafter, it is clear that the shipping industry cannot be separated from global sustainability targets and needs to be developed at the same ambition level. The total number of vessels in the global fleet has been growing over the past decade, but, on a positive note, the growth of emissions has been slower (UNCTAD, 2021b). In the same review, it is also concluded that this relative improvement will not be enough to meet global emission reduction targets and reasons behind the slower growth can be found from economic drivers, rather than sustainable ones, which are not guaranteed to prevail. In the report by IMO (2021a), the future development of GHG emissions is projected using several plausible scenarios. The results show that when compared to the peak year of emissions, 2008, the amount of emissions will grow from 90% to 90%-130% between 2018 and 2050.

The majority of emissions in the shipping industry are produced from fuel consumption, which depends on the used fuel type. Currently, the most common one is heavy fuel oil, covering 79% of total consumption in 2018 (IMO, 2021a). Over the recent years, the use of other fuels, such as marine diesel oil, liquid nitrogen gas, and methanol, has grown. Overall, the mix of different fuels used in the industry is broad, and even a single vessel may use multiple fuels by utilizing dual-fuel engines (IMO, 2021a; UNCTAD, 2021b). The study by IMO (2021a) states that three types of ships produce clearly the largest amount of emissions: container ships, dry bulk carriers, and oil tankers. Other typical types of vessels are chemical tankers, general cargo ships, and liquefied gas tankers. Together with the above-mentioned types, these ships produced 86.5% of total international shipping emissions between 2012 and 2018.

International shipping has been operating for centuries, but its environmental impacts have been considered only lately. According to Barreiro, Zaragoza, and Diaz-Casas (2022), the most relevant international institution in the field, International Maritime Organization (IMO) operating within United Nations, was founded in 1948.

Regarding emission regulations within the field, setting goals, and developing measures to increase energy efficiency in shipping, IMO is the most significant organization. In the early years, the center of attention was mostly on preventing pollution and reducing environmental risk, especially in oil shipping. For this purpose, the International Convention for the prevention of pollution from ships (MARPOL) was created in 1973. Later on, MARPOL was modified to include regulations to reduce GHG emissions as well. The first mention of the energy efficiency of ships has been noted in 2009, and the interest in GHG emissions has been increasing ever since. Simultaneously, the interest in academia has been expanding, and the amount of articles published on the energy efficiency of ships has grown throughout the last decade as presented by Jimenez, Kim, and Munim (2022). The authors even conclude that the growth has been exponential since 2016.

IMO published a GHG strategy in 2018 to guide the green transition in the industry (IMO, 2018a). The aim of the strategy is to reduce CO_2 emissions per transport work by 40% by 2030 and by 70% by 2050 compared to 2008 levels, and the total annual GHG emissions by at least 50% by 2050. The strategy presents short-term and long-term measures to make the carbon intensity of ships and international shipping decline, and GHG emissions of the shipping industry first peak and then decrease. In the following, the proposed measures and currently used methods of decarbonization are presented and divided into regulatory measures (section 2.1.2), ship energy efficiency (section 2.1.3), and operational measures (section 2.1.4).

2.1.2 Regulatory measures

As mentioned in section 2.1.1, IMO is the main institution regulating the shipping industry globally. According to Barreiro, Zaragoza, and Diaz-Casas (2022), other significant international parties and conventions are European Union, Hong Kong Convention, Poseidon Principles, Sea Cargo Charter, and earlier mentioned MARPOL. Energy efficiency is monitored and regulated by several indexes, some of which have already been used for over a decade, but new metrics are introduced as a result of the GHG strategy (IMO, 2018a).

In the following sections, the main focus will be on energy efficiency, but it should be noted that other regulations exist to protect the maritime environment and biodiversity. For example, IMO established new sulfur limits in 2020 to restrict the type of fuels used in addition to Emission Control Areas (ECA) that have further regulations regarding allowed fuel. Other environmental risks involve untreated ballast water, biofouling on the underwater surface of the ship, and oil spills (UNCTAD, 2021b).

Since 2013, existing vessels are required to have Ship Energy Efficiency Management Plan (SEEMP), which records the measures done to increase operational and technical efficiency. The plan should include, for example, improved speed and voyage planning, cleaning of the underwater parts and propellers, and more advanced technical solutions such as new parts or technologies adapted to the vessel (IMO, 2018a). The realization of SEEMP is monitored using Energy Efficiency Operational Index (EEOI) which measures CO_2 emission in grams per ton nautical miles (Barreiro, Zaragoza, and Diaz-Casas, 2022; IMO, 2009). In addition, large-scale ships have been required to systematically collect data on fuel consumption through Data Collection System (DCS) from 2016 onward (IMO, 2018a).

IMO is adopting new regulations for the existing fleet by creating two metrics to measure both technical and operational efficiency as described in the report by UNCTAD (2021b). Technical aspects are measured using Energy Efficiency Existing Ship Index (EEXI) (g CO_2/t/nm), and operational measures are indicated using Operational Carbon Intensity Indicator (CII). CII is tightly connected to the SEEMP as it measures the total emitted CO_2 per transportation work for a given year. Requirements for certificates of EEXI and CII will come into force in 2023 (UNCTAD, 2021b; IMO, 2021b; IMO, 2021c). According to Barreiro, Zaragoza, and Diaz-Casas (2022), from 2023 onward, ships will be rated on a scale from A to E based on their operational carbon intensity, and this rating should be improved annually.

The technical energy efficiency of newly built ships is measured using Energy Efficiency Design Index (EEDI) (g CO_2/t/nm) which has been established by IMO (IMO, 2018b). The usage of the EEDI has become mandatory for all new vessels in 2011 (Barreiro, Zaragoza, and Diaz-Casas, 2022). IMO has adopted a scheme to incrementally reduce the index of the new ships compared to the baseline values from the year 2013 during the following years according to IMO (2018a). For example, the phase 3 reduction rate for the largest container ships is 50% compared to 2022. For smaller vessels, the rate is decreased gradually and over the years the requirements will be strengthened even more.

Article by Barreiro, Zaragoza, and Diaz-Casas (2022) surveys the literature on ship energy efficiency, and it shows that many studies have been made using EEDI as a metric. It is mentioned that EEDI works well for comparing different results and, as it is calculated using different parameters for different kinds of ships, it takes into account different constraints and functionalities. However, the authors state that EEDI is not currently working as desired as a large proportion of new ships already fulfill the demands for EEDI levels for the year 2025. Many studies use different metrics and calculations for fuel consumption leading to varying results for the amount of emissions. In IMO (2021a), various metrics are used including EEOI (g CO_2/t/nm), Annual Efficiency Ratio (g CO_2/dwt/nm), and measures based on traveled distance and spent time.

The usage of the above-mentioned indexes and regulations is part of IMO's GHG strategy, and they are recognized as important tools for improving energy efficiency already in the near future (IMO, 2018a). In 2021, an assessment on the impacts of IMO short-term regulatory measures was published by UNCTAD (2021a). The study shows that the adaption of EEXI and CII will cause negative impacts on maritime logistic costs followed by effects on trade flows and GDP, especially for small island states and least-developed countries. However, the study concludes that the increase in energy efficiency and the usage of renewable energy will generate economic benefits in the long term. Therefore, it is essential to research and develop new methods to increase the energy efficiency of international shipping so that the green transition can be accomplished more equally in an international frame.

2.1.3 Technical measures

Technical improvement of the existing fleet, as well as newly built ships, is an important part of overall development when reducing GHG emissions in international shipping. New technologies and designs can be used when new ships are built, but the main development goals in the long term are zero-carbon and fossil-free fuels as stated by IMO (2018a). As motivated by Barreiro, Zaragoza, and Diaz-Casas (2022), the most common source of GHG emissions comes from combustion engines and their fuel consumption in the maritime industry. Technical solutions need to include more than new energy sources but energy efficiency needs to be increased in general. The authors conclude that this development would give both ecological and economic benefits.

There are multiple areas of ship design that can increase energy efficiency and are currently researched as studied by Barreiro, Zaragoza, and Diaz-Casas (2022). One field of interest is hull design where the goal is to reduce the resistance by optimizing the dimensions of the hull. The same goes for the propulsion system and engine optimization for which incorporating alternative fuels and energy sources is a key interest.

According to UNCTAD (2021b), lower emission fuels are already being used, such as liquefied natural gas (LNG) and biofuels, but not always with success. For example, LNG has been criticized for producing methane emissions in a production state. As future alternative fuels, Barreiro, Zaragoza, and Diaz-Casas (2022) mention using hydrogen as a promising way of creating zero-carbon fuel. According to them, new technologies are implemented in hybrid propulsion systems where different energy sources are combined and electrical energy storage is used. Alternative fuel sources include fully electric propulsion systems where wind and solar power are utilized. Optimizing the overall energy usage of the auxiliary operations on board can be used to create a fully working energy system where the consumption, storage, and even production are balanced.

The average time that a ship is used varies in different categories, roughly from 10 to 30 years. The average ship age in the world fleet in 2021 was 21.6 (UNCTAD, 2021b). Therefore, it is important to be able to affect the energy efficiency of the existing fleet, especially in the short term. Some of the fuels can be used in existing ships if the machinery is updated accordingly, but, as concluded by Barreiro, Zaragoza, and Diaz-Casas (2022), deploying new technologies to existing ships can be too expensive and too exhaustive operation.

2.1.4 Operational measures

IMO's GHG strategy includes many operational measures that can make a difference already in the short term. Often developing operational energy efficiency is the easiest and the cheapest way of cutting emissions. It is not only important when developing the energy efficiency of the existing fleet but in the long term as well. Future fuels can be expected to be far less energy intensive and, on top of that, more expensive meaning that operational measures will remain important factors to consider economically (IMO, 2018a).

The review by Barreiro, Zaragoza, and Diaz-Casas (2022) highlights slow steaming, route, and trim optimization as operational measures to increase energy efficiency. In slow steaming, fuel consumption is minimized by varying the speed of the vessel (section 2.2.3). Route optimization incorporates environmental factors such as weather, wind, and depth to route and speed optimization (section 2.2.4). Trim optimization aims to load the ship in an optimal way in varying conditions. In a review by Jimenez, Kim, and Munim (2022), different clusters of research areas within energy efficiency are studied. Alongside alternative fuels and regulations, speed management is found to be one of the main clusters. This means that within the operational measures speed management alone has attracted a great deal of attention.

In the GHG strategy by IMO (2018a), speed optimization and reduction as well as logistic optimization of ports are seen as important short-term measures. It has been recognized that cooperation between ships and ports allows the usage of Just-in-Time arrival (JIT, section 2.3.1) and virtual arrival (section 2.3.2) as well as makes it possible to optimize arrival scheduling (section 2.3.3) and berth allocation (section 2.3.4). Using speed reduction as a means to reduce emissions is the key motivation for the study presented in this thesis, and different methods that utilize this are further presented in the following sections of this chapter.

2.2 Speed reduction and optimization

2.2.1 Relationship between speed and fuel consumption

Speed reduction and optimization have been listed as short-term measures in the IMO's GHG strategy, and they are often referred to as the easiest and cheapest ways to reduce emissions in the shipping industry (Adland, Cariou, and Wolff, 2020; UNCTAD, 2021b). Before diving into measures and research where speed reduction is used as a decarbonization method, this section introduces the basic theory of fuel consumption and recent research on the relationship between speed and consumed fuel.

Speed is hardly the only factor that affects the fuel consumption of a vessel. A review by Yu et al. (2021) explains that it is demanding to express all the elements that play a role in fuel consumption as a mathematical formulation. Roughly, the factors can be divided into ship operation and environmental factors. The first group includes aspects such as speed, trim, draft, hull roughness, and engine power. Environmental factors contain waves, wind, sea currents, and other weather conditions. Therefore, it is no surprise that the literature includes differing formulations for determining fuel consumption. Yu et al. (2021) even note that sometimes they lead to controversial views.

As presented by Adland, Cariou, and Wolff (2020), the relationship between speed and daily fuel consumption (F) is often modeled using relationship $F \sim S^{\beta}$ where S is the speed and the parameter β describes the responsiveness. Generally, the value three ($\beta = 3$) is used in which case the formula is referred to as a cubic law.

Besides the cubic law, there exist many different values for the parameter β in the literature. Values may vary for different types of ships between 1.5 and 5 (Adland, Cariou, and Wolff, 2020). According to an empirical study completed by Adland, Cariou, and Wolff (2020), the cubic law is only reliable when the ship is moving at its design speed. When speed reduction is considered, it is relevant to know how the relationship changes. The authors find out that the value of the parameter β decreases rapidly when the speed is decreased. Therefore, using the cubic law when estimating emission reduction, as is the common practice, might be problematic.

Thus far, only outside factors have been considered, but, essentially, the speed is originated from the power of the engine. Adland, Cariou, and Wolff (2020) explain that the fundamental theory of fuel consumption is based on resistance modeling. Zis, Psaraftis, and Ding (2020) present different environmental factors that affect the resistance of the ship, including calm water resistance and added resistance from waves, wind, and currents. The required power can then be calculated from the resistance and the aimed speed over water. It is good to note that fuel is typically needed for the main engines, which are producing most of the power for the voyage, for auxiliary engines, which are for on-board activities such as electricity and ventilation, and, finally, for the boilers that maintain required temperatures when the main engines are not used.

The range of speed that can be used is limited by technical and safety reasons. If the speed is reduced significantly the maneuverability suffers as discussed by Faber et al. (2012). As mentioned, the ships have a specific design speed where their engine works at the highest efficiency, and it is not usually relevant to consider a higher velocity than this in the context of shipping. In fact, Adland, Cariou, and Wolff (2020) consider the design speed as the maximum speed. Weather conditions affect the required power to sail at the desired speed and have an impact on safety which may dictate the overall schedule that the ship can follow.

2.2.2 Estimation of GHG emissions

Now that the relationship between speed and fuel consumption has been established, it is noteworthy to continue to the relationship between fuel consumption and GHG emissions. Adland, Cariou, and Wolff (2020) describe this relationship as one-to-one, and often simple scaling is used. There are different ways to calculate the total amount of emissions, but they are based on the fact that produced emissions are proportional to the used fuel.

As described by Jia et al. (2017), the proportionality is modeled using the so-called "emission coefficient" for each gas. The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from which carbon dioxide is the largest pollutant. In addition, vessels produce other pollutants, such as sulfur dioxide, that are not greenhouse gases but may have other ecological impacts. According to Jia et al. (2017), emission coefficients are not constant as they vary based on fuel quality and engine conditions. In their study, they used values established by IMO's third GHG study (IMO, 2014).

According to Smith, Parker, and Rehmatulla (2011), the emission can be divided into embodied energy emissions, which are related to the construction of the ship, and operating energy emissions. The authors create a comprehensive carbon dioxide calculation for the total lifetime of the ship and conclude that reducing speed has an important role in the big picture. Consequently, there is significant potential in optimizing speed to reduce the total emission that the shipping industry produces.

2.2.3 Slow steaming and regulated speed reduction

The practice of using slower than the design speed is called slow steaming, and it is generally used to reduce fuel consumption when the market situation requires that as defined by Psaraftis (2019). After the year 2008, slow steaming was adopted increasingly as an economic measure in the recessed market situation (Armstrong, 2013). The effects can be seen in emitted GHG emissions; IMO (2014) studied fuel consumption between the years 2007-2012 and concluded that slow steaming greatly suppressed the increase in emissions. However, this trend is due to the market, and when the world's economical environment changes, it is possible that used speed will increase back to a higher level.

According to IMO (2021a), a similar trend of slower operating speeds and reduced days at sea can be still seen during the years 2012-2018 even if ships nowadays tend to be larger and have higher installed power. Design speed and, hence, also operating speed vary between different categories and sizes of ships as well as depending on whether the ship is in ballast or in laden condition. IMO (2021a) reports the average operating speeds for the three most emitting categories from 2012-2018, and they range for bulk carriers roughly between 9-13 knots, for container ships between 13-17 knots, and for oil tankers between 8-13 knots.

Yin et al. (2014) examine slow steaming for container ships and describe the often discussed trade-off related to it. There is a potential for reducing fuel consumption and emission by reducing operating speed. However, the downside is a lengthened overall voyage time that leads to higher operating costs. Barreiro, Zaragoza, and Diaz-Casas (2022) highlight safety risks regarding slow steaming, such as decreased stability and longer time spent at sea. Furthermore, the total capacity of shipping decreases when voyages take longer time, which would eventually lead to a larger required fleet. Therefore, slow steaming does not per se reduce potential idle time. Moreover, even if time spent in anchorage could be reduced, many standard charter party contracts require the vessel to sail at "utmost despatch" regardless of destination port conditions, hence directly preventing usage of slow steaming.

As mentioned above, slow steaming is widely used as a method to reduce fuel consumption when it makes sense economically. It is a more recent idea to use slow steaming as an environmental solution. As a decarbonization method, it is currently used as a voluntary measure, according to Psaraftis (2019). Different methods for calculating potential savings are presented in the literature; some are more concentrated on speed optimization and others on straightforward speed reduction. For example, Barreiro, Zaragoza, and Diaz-Casas (2022) report that reducing speed by 5% can produce fuel savings between 16-19%. In general, the speed reduction is listed as a short-term measure in IMO's GHG strategy (IMO, 2018a).

As a solution for speed reduction, regulated slow steaming has been suggested. Faber et al. (2012) examine the feasibility and possible costs and benefits of regulated slow steaming that could be implemented as global or regional speed control or speed controlled by the flag state of the ship. They identify similar benefits as mentioned previously related to slow steaming and assume that speed limits would produce higher building and operating costs as the shipping industry would need more ships to operate. Finally, they conclude that regulated slow steaming would be legally feasible. However, Psaraftis (2019) presents very differing opinions and results, stating that using speed limits, even if they would depend on the size of the ship, are not a lasting solution. Instead, the author proposes a bunker levy that would guide ships to use a lower speed as it is often observed that when freight rates are higher, ships naturally decrease speed and thus reduce emissions.

2.2.4 Voyage optimization

More intelligent ways of reducing speed lead to speed optimization or more widely called voyage optimization. As explained by Yu et al. (2021), a vessel's voyage optimization includes setting the trajectory to the destination port as well as determining needed engine power based on weather conditions and desired speed. The term "speed optimization" has been used by IMO in the GHG strategy alongside "speed reduction" (IMO, 2018a). Psaraftis (2019) clarifies this by noting that in SEEMP optimum speed is defined as the speed at which the fuel consumption per ton mile is at minimum. The author discusses that this is not practically useful as it mathematically leads to the smallest possible speed. An alternative definition for speed optimization is presented as selecting an appropriate speed profile to optimize a specific objective function whilst meeting constraints. S. Wang, Meng, and Liu (2013) consider minimizing fuel consumption and determine three categories in literature: minimizing operating costs by optimizing speed, incorporating the amount of emissions to the optimization model, and incorporating fuel consumption to port operations optimization. The last one is also connected to berth allocation, which is discussed in section 2.3.4. The usage of such methods can make operations more competitive and sustainable as well as increase safety.

Different mathematical formulations and solution methods for the speed optimization problem have been presented in the literature. Relatively straightforward methods can be used when the cost model for the voyage is developed. Yin et al. (2014) formulate an equation for the costs including, for example, bunker cost, operational cost, and carbon trade. They arrive at a convex optimization problem with speed being the decision variable and solve it by simple derivation. A study by S. Wang, Meng, and Liu (2013) reviews and extends optimization methods for minimizing fuel consumption or related costs. Smith, Parker, and Rehmatulla (2011) build a model that directly optimizes carbon dioxide emissions and conclude that speed has an impact on both revenue and costs. Zhang, Teo, and X. Wang (2015) examine optimality properties of an optimization problem where the objective is to minimize fuel costs on a voyage where there is a time window constraining the arrival time.

Zis, Psaraftis, and Ding (2020) discuss weather routing that they define as finding the optimum route with respect to destinations, expected time of arrival, speed, power, and weather conditions. The process includes multiple environmental factors such as waves, currents, water depth, and wind direction and force. Increased availability of computing power and higher quality of data have increased interest in weather routing and made it possible to use it for reducing emissions. The authors underline the difference between weather routing and ship routing problem which is a tactical-level optimization problem for planning voyages and scheduling a vessel or a fleet. These kinds of systematic approaches are discussed in section 2.3.3.

2.3 Vessel arrival scheduling

2.3.1 Just-in-Time arrival

Thus far, it has been established that slowing down the speed of vessels can have a significant effect on GHG emissions, and different approaches for deploying that in practice have been discussed. For slow steaming as well as speed limits, one of the major downsides is the prolonged travel time and the possible need for a larger fleet. As defined by GloMEEP Project Coordination Unit (2020), Just-in-Time arrival (JIT arrival) is a method for optimizing the voyage so that the idle time in the anchorage is minimized or skipped altogether. As a consequence, the total time used does not increase whilst fuel consumption is reduced.

The port call process includes the vessel to start approach the berth so that loading or unloading tasks can be completed. As described by GloMEEP Project Coordination Unit (2020), the process is not generally optimized, which results in many ships anchoring or maneuvering near the port area for hours or even weeks. The report states that depending on the ship type the time used in anchorage can be up to 9% of the total time. Normally, ports use the so-called First-Come-First-Served (FCFS) principle meaning that the vessels are served in the order of arrival. This, alongside the existing contractual structure, promotes Rush-to-Wait practice instead of JIT arrival (Sung, Zografakis, and Nielsen, 2022). It is common that vessels voyage to the destination at service speed regardless of the availability of berth or the length of the queue in the port.

Therefore, it is clear that there is potential in optimizing the arrival times by using JIT arrival. GloMEEP Project Coordination Unit (2020) studies a container ship traveling between Bremerhaven and Rotterdam and concludes that by JIT arrival fuel would be consumed 23% less than by standard policies. It is noteworthy that decreasing the time at anchorage has its benefits on its own. Even in anchorage, auxiliary engines and boilers are running, and hence, JIT arrival can reduce the produced emissions near the port area. The document also states that ships may often choose to avoid dropping an anchor and instead circle at a slow speed or drift. In addition, less traffic increases safety as the risk of collisions is reduced.

2.3.2 Virtual arrival

JIT arrival is difficult to implement perfectly for several reasons, one being the contractual structure used in the industry. The main concept to define is the relationship between the charterer and the shipowner, but note that other stakeholders exist as well. As defined by Ahokas (2019), a charterer organizes the carriage of the cargo, and the compensation can be agreed on multiple ways, for example by fixed monthly price or based on the amount of cargo. The shipowner is the entity that owns or hires the ship. Agreements between the stakeholders include multiple clauses some of which are related to demurrage and dispatch. Demurrage is compensation paid to the shipowner when there is a delay in the port operations, and, on the contrary, dispatch is paid to the charterer when these operations are completed faster than planned.

As an answer to an existing contractual structure, the so-called virtual arrival practice has been implemented to make the JIT arrival reality. OCIMF, INTERTANKO (2011) define virtual arrival as a process for revising the vessel arrival time by reducing the speed when there is a known delay in the destination port. This involves agreeing to the procedure in the Carter Party clause so that the revised arrival time does not change possible dispatch or demurrage. Therefore, virtual arrival is a contractual tool that charters can use to reduce fuel consumption. The idea is that the vessel virtually arrives as it would have using the original service speed so that it is already "queuing" for berth but will actually arrive later, closer to the port call.

Virtual arrival has been researched and the potential fuel savings and emission reductions have been evaluated. Jia et al. (2017) examine different scenarios for utilizing it and conclude that only by reducing 25% of the idle time in anchorage the fuel savings can range from 7.26% to 19%. When all of the waiting time is eliminated, which results in JIT arrival, the reduction is even more significant even if harder to achieve in practice. Andersson and Ivehammar (2017) examine possible fuel and emission costs by considering different speed reductions that the vessel can make when it receives information of a delay from the destination port in the Baltic Sea. The authors examine the impacts of vessels getting notification from the port 1h, 4h, 12h, and 24h before arriving. They conclude that a total of 27 million euros could be saved annually if vessels would receive 12h prior information to reduce speed by 25%.

Poulsen and Sampson (2019) discuss the problems related to virtual arrival and begin by concluding that as the approach has not been widely used in the industry, regardless of the apparent fuel-saving opportunities, there might exist reasons not to use it. They perform a qualitative analysis and find multiple reasons why practitioners do not wish to use virtual arrival even if the option is on the table. Ships may wish to have more buffer time for unexpected events as the cost of arriving late is often higher than the benefit of the virtual arrival. In addition, contractual structures may incur that, once in a while, the demurrage paid for the shipowner is higher than the benefits of fuel savings. Especially, these reasons are highlighted when the value of the cargo is high as then the financial benefits often exceed fuel costs. Apart from purely economic reasons, Poulsen and Sampson (2019) discuss the lack of trust between the shipper and the port regarding the exchanged information and the realization of virtual arrival. In addition, the current practice is that the fatigue of the crew during the voyage is compensated during the idle time, which makes virtual arrival a less attractive option.

2.3.3 Tactical level scheduling

JIT arrival and virtual arrival concern the cooperation of a single ship and its destination port, but more systematic approaches have not widely been implemented. Fruitful ground for systematic optimization of ships can be found in liner shipping. As explained by Maxim A Dulebenets (2021), shipping operations can generally be divided into three categories: liner, tramp, and industrial shipping. In liner shipping, the operating companies have fixed routes and lines that the ships operate on and the transportation can be reserved accordingly. The container shipping industry often operates in this way. In tramp shipping, the shipment is not organized in any fixed schedule, and hence, it can be used on short notice and flexibly. Industrial shipping occurs when the cargo owner is responsible for shipment as well.

According to Maxim A Dulebenets (2021), the liner shipping company faces different questions from the size of the fleet to cargo bookings. On a tactical level, the company plans the schedules and needed sailing speeds amongst other things. Due to the company orchestrating the routes and timetables, more systematic optimization is possible and beneficial in liner shipping. Therefore, it is not surprising that various research initiatives exist on the matter.

Maxim A Dulebenets (2021) reviews such studies and recognizes five types of problem formulation found in the literature. The general vessel scheduling problem aims for determining basic schedules given liner shipping routes and related costs so that the revenue is maximized. Additionally, uncertainties related to sailing, waiting, and port handling times can be incorporated into the model. Thirdly, the model may concentrate on collaborative agreements between shipping companies and ports. These agreements can be observed to significantly increase efficiency, and, as discussed in a study by Maxim A. Dulebenets (2022), they play an important role in reducing emissions in liner shipping. In the study, a multi-objective mathematical model is created to highlight the possibilities of collaborative agreements, which may involve more flexible arrival times and routes for vessels. As continued in the review, there are models where the aim is to recover optimal schedules after a disruption has occurred, and, lastly, the category of green liner shipping is mentioned where emissions are explicitly modeled.

Research regarding systematic optimization of arrival schedules, where the ports are not actively involved, is far less common. Some examples are found regarding tramp shipping. Norstad, Fagerholt, and Laporte (2011) present a routing and scheduling problem from the perspective of a tramp shipping company that needs to allocate cargo to vessels and determine optimal routes and schedules. Notably, speeds on different legs of the journey are used as decision variables in the optimization of costs. Systematic optimization in both tramp and liner shipping is related to allocating resources and tasks as well as deciding trajectories. Generally speaking, methods traditionally employed for the vehicle routing problem class can be utilized when the decisions are made by a single shipping company (Zis, Psaraftis, and Ding, 2020).

2.3.4 Berth allocation

Optimizing the operations in ports is an important factor in the decarbonization of the shipping industry, and this has also been recognized by IMO (2018a). This brings us to the concept of the berth allocation problem, or, as referred by Golias et al. (2009), the berth scheduling problem, which is defined from the perspective of the port. The task is to optimize the berthing of arriving vessels and, in the best case, inform the vessel of their time of port call so that the speed can be adjusted accordingly.

There are multiple references in the literature considering different objective functions, models, and decision variables. Not all proposed models in the literature allow vessels to adjust their speed or even consider that as a factor. As an example, Golias et al. (2009) create a berth scheduling policy for container vessels. Vessel arrival times are optimized so that the waiting time in port, emissions, and fuel consumption in idle mode as well as the number of delayed departures are minimized. Du et al. (2011) note that shipping companies are interested in reducing fuel consumption during the journey whereas the ports are concerned with the emissions in the anchorage. Therefore, a berth allocation problem is extended to consider fuel consumption and the produced emissions so that the arrival times of the vessels are considered as decision variables. The authors conclude that this strategy results in both less emission from sailing as well as from waiting while, at the same time, maintaining the service rate of the port.

Alvarez, Longva, and Engebrethsen (2010) compare different berthing policies including currently widely used FCFS, standardized estimated arrival time, and global optimization of speed berth and equipment allocation. The results were compared in relation to total fuel consumption, service times as well as idle times, cancellations, and economical results. It is concluded that FCFS is clearly the worst of the proposed policies. However, it is admitted that each individual vessel most likely would not benefit from a systematic berth allocation strategy. The authors conclude that additional contractual mechanisms need to be developed and a competitive environment considered.

2.4 Barriers to closing the energy efficiency gap

As highlighted by Sung, Zografakis, and Nielsen (2022), the shipping industry is highly fragmented in terms of different vessel categories as well as a high number of different entities as stakeholders. According to Ahokas (2019), the two key stakeholders are determined as a charterer and a shipowner. In addition, there might be involved various other stakeholders such as traders, brokers, and cargo owners. On top of this, Sung, Zografakis, and Nielsen (2022) point out that the diversity of ports increases the complexity of the industry.

This is one of the major reasons why the implementation of technical and operational measures is not straightforward. Barreiro, Zaragoza, and Diaz-Casas (2022) discuss the so-called "energy efficiency gap" and note that in many ways progress is stopped by the conflict of interest of stakeholders. They describe this by an example: installing new and more energy-efficient technologies to ship is an economical investment for the shipowner, whereas the charter can be the one paying for fuel and, hence, would be the one benefiting from the reduced consumption.

GloMEEP Project Coordination Unit (2020) discusses the barriers to implementing JIT arrival in practice and recognizes both contractual and operational barriers as discussed regarding virtual arrival. Successful implementation requires collaboration between several stakeholders, such as port authorities, terminals, and shipping companies. Contractually, the current modes do not support the sharing of benefits that JIT would produce, and other strategies can be financially more beneficial for deciding stakeholders. In operational barriers, the major subject is high-quality data that can be shared between parties so that JIT arrival times can be reliably computed and new contractual structures can be based on.

Similarly to the whole shipping industry, ports are also very fragmented. A large number of operators within one port can make it difficult to optimize port operations, not to mention berth allocation, so that measures such as virtual arrival could be implemented. Furthermore, Sung, Zografakis, and Nielsen (2022) note that even though recent developments in communication and weather routing have made it possible to optimize single vessels, no systematic approach to the shipping industry has been taken. As discussed regarding liner shipping, other shipping forms do not support systematic approaches due to the competitive environment and widely used FCFS principles in ports.

3 Blue Visby Solution

As discussed in section 2, no systematic approach has been taken to optimize vessels' arrival times apart from the container shipping industry and the berth allocation from a perspective of a single port. There exists a potential for increasing energy efficiency worldwide by arriving close to the port transit time instead of using the Rush-to-Wait policy. Sung, Zografakis, and Nielsen (2022) point out that there exists a significant gap in the literature regarding JIT and virtual arrival. Most of the studies only evaluate different speed reduction scenarios and use them to draw conclusions on possible savings. The means to achieve these scenarios are left wide open. To answer these challenges, Sung, Zografakis, and Nielsen (2022) propose the Blue Visby Solution (BVS).

Blue Visby Solution is a system that consists of two parts: a technical platform to systematically optimize arrival times and a contractual framework that allows a fair share of benefits (Zografakis et al., 2022). Blue Visby Solution has been first introduced by Sung, Zografakis, and Nielsen (2022) in the first Proof-of-Concept study (POC1), and further developed and analyzed in the second Proof-of-Concept study (POC2) by Blue Visby Consortium, which Napa Ltd is coordinating. Currently, the BVS is being developed into a real-time platform that can be used by shippers all around the world. This thesis presents a further analysis of the technical system of the Blue Visby Solution.

Sung, Zografakis, and Nielsen (2022) introduced an idea to optimize approaching vessels' inter-arrival times to reduce queue lengths rather than trying to optimize port operations or a voyage of a single vessel. In fact, port transit times are handled as a last-mile problem and are not considered in the optimization formulation. Hence, arrival times of approaching vessels are synchronized so that they arrive at steady intervals, which correspond to the service rate of the port. Therefore, the approach is to see the shipping industry as a supply chain with the aim of balancing the supply and the demand in ports. Furthermore, to keep the competitive landscape intact the vessels' arrival order is kept the same as it would be without the usage of the BVS. As a result, ships may use slower speeds when it is known that there is a queue in the destination port; all of this without explicit cooperation from the port. The process works dynamically so that when a new voyage starts the suggested arrival times are updated.

Sung, Zografakis, and Nielsen (2022) found out that fuel consumption can be reduced by 9% per voyage when analyzing 100 large-scale ports. As a reference, Jia et al. (2017) concluded that by using JIT arrival it is possible to save 19.3% in fuel consumption. This means that considerable savings can be gained with the BVS compared to the so-called optimal potential. In the POC2, the simulation model was developed further, especially concerning fuel calculations, fuel types, weather conditions, and routes. With these modifications, the results are even more promising as the typical CO_2 reduction per voyage is 16% (Blue Visby Services Ltd., 2022). CO_2 emission can be computed from the fuel consumption using the emission coefficient, hence the relative emission reduction is close to the resulting fuel reduction values. This means that with more accurate simulation, the results indicate even higher promise. However, it should be noted that the type of fuel impacts the emissions, which means that the CO_2 emission calculation can only be considered as an estimate, and the values are not directly comparable to fuel savings computed by Sung, Zografakis, and Nielsen (2022) and Jia et al. (2017).

3.1 BVS algorithm

Sung, Zografakis, and Nielsen (2022) defined the optimization problem as follows. The BVS always concerns all ships heading to the same destination port. Let n be the number of those vessels. Each ongoing voyage is assigned a queue number, $i \in [1, n]$. It is an important factor competitively to keep the arrival order of the ships intact, or as intact as possible. Therefore, the queue numbers are assigned using the vessels' notional arrival time. This is computed using the normal service speed and the distance to the destination. Consequently, notional arrival times should correspond to the historical arrival times.

The speed range of a vessel needs to be restricted so that the speeds stay at realistic levels. The range for vessel i is denoted as $[\alpha s_i, s_i]$ where s_i is the service speed, and α is a factor to determine how much speed can be lowered. The allowed time window for the arrival of vessel i is determined using the voyage distance d_i as

$$[e_i, l_i] = \frac{d_i}{[s_i, \alpha s_i]}. \tag{1}$$

The earliest possible time for arrival is then e_i and the latest l_i based on the allowed speed range. As mentioned above, the transit to the port is left out of the problem formulation, meaning that the voyage distance and the arrival time are to the anchorage area.

For each port, a target inter-arrival time is needed to synchronize the arrival times. This is denoted by ρ and should be estimated using the service rate of the port. The actual decision variables in the optimization problem are the arrival times for each vessel i as t_i. The problem is formulated as

$$(P_{BVS}) \qquad \min_{t_i, 1 \leq i \leq n} \sum_{i=1}^{n-1} (t_{i+1} - t_i - \rho)^2 \tag{2}$$

$$t_i \leq t_{i+1} \qquad \forall 1 \leq i \leq n-1 \tag{3}$$

$$e_i \leq t_i \leq l_i \qquad \forall 1 \leq i \leq n. \tag{4}$$

As a result, inter-arrival times of vessels are synchronized with the service rate of the port (2), the notional arrival order is preserved (3), and all vessels arrive in their allowed time window keeping the speeds realistic (4). Consequently, the speeds are not directly optimized but rather the Blue ETAs allow speed reductions.

Problem P_{BVS} is initiated every time a new vessel starts its journey. This means that a single vessel may receive multiple updates during the voyage because it is possible that a vessel departing later will still have an earlier notional arrival time.

Note that the notional arrival time is always computed using the original sailing speed and starting position. The BVS process is defined by Sung, Zografakis, and Nielsen (2022) and is presented in algorithm 1.

Algorithm 1 BVS process by Sung, Zografakis, and Nielsen, 2022

$P \leftarrow$ a set of ports
Trigger procedure: A new voyage to a port $p \in P$ starts.
$V \leftarrow$ a set of vessels with destination p
$n \leftarrow |V|$
Require: $n \geq 2$
Compute notional arrival times for V.
Sort V by notional arrival time.
Solve P_{BVS}.
Assign resulting Blue ETAs to vessels in V.

The BVS algorithm was further developed in the POC2 in 2021 with the aim of testing the feasibility of the system under realistic circumstances. The main difference from the algorithmic perspective is that the optimization problem P_{BVS} was replaced with a heuristic approach. It is clear that when the constraints are loose enough the optimal result is always to have ships arriving with a steady interval that corresponds to the target inter-arrival time ρ. This result can be obtained without solving P_{BVS} by simply using the inter-arrival time and the notional arrival order. The revised BVS process can be seen in algorithm 2.

Algorithm 2 Revised BVS process

$P \leftarrow$ a set of ports
Trigger procedure: A new voyage to a port $p \in P$ starts or a vessel in a port $p \in P$ transits to berth.
$V \leftarrow$ a set of vessels with destination p
$n \leftarrow |V|$
Compute notional arrival order $i \in [1, n]$ for V.
Sort V by notional arrival order.
$q \leftarrow$ the queue length
$T \leftarrow$ the latest port transit time
$r_1 \leftarrow T + \rho \times q$ ▷ the first ETA recommendation
for $\forall v_i \in V$ **do**
    $[e_i, l_i] \leftarrow$ the earliest and latest arrival times based on the speed range
    $t_i \leftarrow \max(\min(l_i, r_i), e_i)$
    $r_{i+1} \leftarrow t_i + \rho$
end for
Assign resulting Blue ETAs and corresponding speeds to vessels in V.

Different results can be seen between the two approaches when the constraints limit the produced so-called Blue ETAs given by t_i. In P_{BVS}, when the time constraints are met, the arrival times are computed to minimize the value of the objective function. In this case, there may be multiple equally good results as the first vessel can arrive at any time within its time window. However, finding a feasible solution may be difficult and the stability of the problem becomes an issue. Instead, with the heuristics approach, it is decided that the Blue ETA will be either at the limits of the speed range or the recommended ETA computed using the inter-arrival time. The next ETA recommendation is calculated using the earlier Blue ETA and the target inter-arrival time. This means that the same constraints are fulfilled as the order is preserved and the vessels arrive in the possible time window but the computations are simplified.

The algorithm by Sung, Zografakis, and Nielsen (2022) optimizes inter-arrival times, and the hope is that fuel consumption is reduced as a side effect. In reality, minimizing fuel consumption might occasionally be more important than maintaining steady arrivals. Consider a case where the target inter-arrival time cannot be maintained. Suppose the recommended ETA is before the earliest possible arrival time, and there is a queue at the port. In that case, it is more beneficial to use slow steaming and save fuel than optimize all the arrivals so that the inter-arrivals are as close to the target as possible. Therefore, the heuristics approach supports practical behavior.

The other development point concerns the fact that there possibly is a queue at the anchorage. This is a reality in many ports, and even with synchronized arrivals, it is possible that sometimes the queue will grow due to disruptions. Furthermore, some ports may prefer that there is a buffer of vessels waiting for loading and unloading rather than keeping the queue empty. This is an aspect that the problem formulation by Sung, Zografakis, and Nielsen (2022) does not take into account. The first ETA will be assigned based on the following arrivals regardless of the circumstances in the port. To solve this problem, the current queue length is taken into account when computing the first ETA recommendation. This leads to a situation where the queue is observed, and BVS updates should naturally be made based on the current information. Therefore, the BVS process is additionally triggered when a ship starts its transit to port meaning that the queue is shortened. In practice, this means that the queue is monitored more closely, and it is possible that the algorithm delays or rushes arrival times.

3.2 Experimentation in the first Proof-of-Concept study

In the POC1, Sung, Zografakis, and Nielsen (2022) performed an experimental analysis on the model using a dataset from 2018 originating from the Shipborne Automatic Identification System (AIS). AIS is used for transferring identification and tracking information, and the usage is mandatory for all large-scale ships (Ahokas, 2019). The dataset included over 14 000 voyages to 975 destination ports. The analysis was performed as a simulation model so that the voyages were generated using historical data. The voyages were modified so that the used speeds correspond to ETAs produced by the BVS algorithm that used historical travel distance, service speed, and port transit time. The BVS update was triggered when a new voyage starts as defined in algorithm 1.

In the study by Sung, Zografakis, and Nielsen (2022), some assumptions were made to simplify the calculations. The path of the voyage was assumed to be a straight line along the Earth's surface. For fuel computations, all vessels were assumed to use the same fuel consumption profile, and weather conditions were not taken into account. Additionally, fuel consumption in the anchorage or in the port was not calculated. The overall fuel consumption of a vessel was then computed using the cubic law as

$$F^{BVS} = \sum_{z=1}^{Z} B s_z^3 t_z, \tag{5}$$

where z presents the BVS update with a total of Z different speeds, s_z. B is a constant and t_z is the time between two update points. The reference values for fuel consumption were computed from the historical data in the same manner.

The service rate of a port has a significant effect on the results, and the success of the BVS is heavily dependent on the accuracy of these values. However, they need to be estimated and, in their experimentation, Sung, Zografakis, and Nielsen (2022) used a median of weekly discharge rates computed from the dataset. The other estimated values are the service speeds and the speed ranges. As a service speed, Sung, Zografakis, and Nielsen (2022) used the historical speed, and the speed conservation factor α was set to 0.9.

Sung, Zografakis, and Nielsen (2022) examined how large fuel savings can be achieved per voyage and concluded that 8.75% savings can be obtained for the 100 busiest ports. On the other hand, when all the ports in the dataset were included, the mean fuel saving is 7.47%, and the median is only 3.03%. The authors admitted that the savings are relatively small but pointed out that for ports with fewer voyages, the BVS is not very useful in general. In fact, the algorithm is only defined for more than only one ongoing voyage. In the simulation, the results were also computed for JIT arrival times as a reference. The mean fuel consumption with no waiting times is 33.6%, and Sung, Zografakis, and Nielsen (2022) concluded that the BVS produces significant savings considering that it does not involve berth management or port cooperation, which are requirements for implementation of JIT arrival.

Sung, Zografakis, and Nielsen (2022) noted that due to speed range limitations, constraints (3) and (4) might be impossible to satisfy. The exact processing of infeasible solutions is not explained in detail. Nonetheless, the authors examined whether the arrival order can be maintained using the BVS and concluded that only 2.5% of voyages experienced a queue number increase larger than one. In addition to the fuel savings, Sung, Zografakis, and Nielsen (2022) examined the supply-demand balance that the optimization aims to improve. It was found that, in almost all the ports, the inter-arrival time approaches the service rate of the port. Furthermore, the authors remarked that prolonged travel time may bring negative consequences and increase costs. For this reason, the voyage time prolongation was investigated, and it was concluded that the changes are relatively moderate. The travel time grows only by 6% on average.

3.3 Experimentation in the second Proof-Of-Concept study

In the POC2, the revised algorithm 2 was used, and the system was studied under more realistic circumstances. The developments addressed especially the assumptions made by Sung, Zografakis, and Nielsen (2022) in the POC1. The simulation proceeds similarly to the earlier study using historical data. The model developed in the POC2 is extended in this study, and most of the components are used directly. Therefore, the used dataset and the calculation methods are presented in this section. On the other hand, the simulation process has been considerably developed, and thus it is presented more closely in section 4.

3.3.1 Data

The dataset used originated from AIS and included voyages from the year 2019 including 14 000 ships consisting of dry and wet bulk carriers. AIS data consists of the voyage tracks, which can be used to determine the used routes, and some static information about the voyages, such as draft and IMO number, which is an identification number established by IMO. After pre-processing the data, the set contained 150 278 voyages.

In the pre-processing phase, the key points of the voyage were determined. Every voyage needs to have information about the departure time and the destination port, the arrival time to anchorage, and the arrival to port or more specifically to the berth. These can be derived from the AIS track using the known location of ports and waiting areas. The arrival time to the anchorage is defined as the sea passage end time, which means that the ship either anchors, drifts, or transits to the port directly. Port transit time is defined as the time that the ship starts its journey from the anchorage to the berth. This identification was completed so that the speeds are categorized into three groups: stopped, maneuvering, and steaming. In addition, the start points of steaming periods were matched with port, terminal, and anchorage information so that stops during the voyages were not counted. Combining these two facts, the voyage time, the anchoring time, and the arrival to the berth were recognized for each ship.

An important part of the POC2 was to examine the system behavior under realistic scenarios that included weather conditions. Therefore, information about the weather and water depth was acquired from global ocean weather providers in addition to the AIS data.

3.3.2 Technical developments

As mentioned earlier, the revised BVS algorithm 2 was used in the POC2. This is a significant modification to the POC1 completed by Sung, Zografakis, and Nielsen (2022). In addition, the following technical upgrades were implemented so that the system can be tested under realistic circumstances.

1. **Port service rate:** The service rate for each port was estimated using the weekly averages of historical inter-arrival times so that the 20^{th} percentile was used as the final target inter-arrival time. This is a more conservative approach than in the POC1.

2. **Voyage distance:** The traveled distance for each voyage was computed using the historical track points from the AIS data. Therefore, the distance corresponds to

the actual traveled distance.

3. **Service speed:** The service speed for each ship was computed the same way as before from the historical data but using the actual traveled distance and the voyage duration.

4. **Minimum speed:** To take into account the efficiency of the engine, ship maneuverability, and optimal fuel consumption, the minimum speed of each ship was determined by applying 15% engine load using ship-specific performance models. This typically resulted in minimum speeds between 6kn to 10kn.

5. **Weather and bathymetry interpolation:** Weather, water depth, and sea current data were used to interpolate the environmental factors of the historical location to the simulated time. This means that the historical track is used but, since the speed is modified, the environmental parameters are interpolated to reflect the changed time frame.

6. **Fuel consumption calculation:** Fuel consumption was calculated using the location and the weather conditions but also using a ship-specific performance model. This model includes ship hull, propulsion system, and engine modeling. Using detailed resistance modeling, fuel consumption can be calculated more accurately.

7. **Fuel types:** Two types of fuel were used depending on the location of the ship. The assumption was that Low Sulphur Fuel Oil (LSFO) is always used with an exception of Emission Control Areas where Marine Gas Oil (MGO) is used. These fuels have a different energy density, price, and CO_2 coefficient which was taken into account when computing the final results.

8. **Earliest allowed arrival:** It is possible that the historical average speed is actually slower than the computed minimum speed. The reason for this may be that the speed limit is incorrectly computed or that the data includes errors. To be able to handle this conflict, an additional step was implemented for the determination of the Blue ETA. The earliest allowed arrival time was defined as the historical sea passage end time. If the arrival with the minimum speed would be placed before this time, the Blue ETA is automatically assigned as the earliest allowed arrival.

3.3.3 Conclusions of the second Proof-of-Concept study

In the POC2, results were computed for a historical case, where no optimization is used, for a scenario where the BVS is used for all voyages, and for JIT arrival times. Speed reduction, voyage duration, fuel consumption, and savings potential were computed as defined above. The results were analyzed for different ship categories, such as Panamax, Capesize, and Gas tanker, as well as with respect to the destination port. In addition, the differences between laden and ballast voyages were examined. Whether the voyage is laden or ballast was determined based on the draft.

It was observed that laden voyages have a smaller savings potential than ballast journeys for almost all of the size categories. This implies that fuel consumption can be reduced more significantly for ballast voyages that do not carry cargo. When the savings potential of the laden and ballast journeys was examined with respect to the destination port, considerable variation was observed, especially regarding the ballast voyages. In addition, dry bulk carriers and tankers were examined in more detail. It seems that, in general, higher savings potential lies in laden tanker voyages. For bulk carriers, the typical savings potential is 11-13% while the same for tankers is 9-18%. For all of the vessels, a typical savings potential is 16%.

The distributions of possible savings per ship were examined, and it was observed that the results were remarkably close to values gained by JIT arrival, which supports the similar observation made by Sung, Zografakis, and Nielsen (2022) in the POC1. Furthermore, the result validates the usefulness of the BVS as the simulation was modified to take into account more realistic factors, such as voyage tracks and weather conditions. Finally, it was concluded that the overall CO_2 reduction is 13% but the potential varies between destination ports. For the analyzed vessel segment, the most significant emission reductions could be gained in Port Hedland and Ponta da Madeira.

4 Simulation model

4.1 Research question: What proportion of the fleet should be part of the BVS to produce benefits to all participants?

Currently, the BVS is evolving into a real-time platform and requires further analysis on multiple fronts. To mention some, estimating port service rates and modeling queues in detail are central questions for the accuracy and usability of the system. In the previous studies, it has been assumed that all the ships are part of the BVS, and they follow the given arrival schedule.

However, we can fairly say this is not the case in practice. Therefore, it is necessary to analyze the system's behavior when only a part of the fleet is participating in the BVS. This question directly affects the platform's feasibility, and how attractive the usage of the system is for vessels. The fact that ports do not need to actively participate in the BVS for the system to produce benefits for the participating vessels is considered to be an advantage. Whether this assumption can hold in the future depends strongly on the same question. The BVS has been designed to take into account the competitive landscape but it needs to be verified whether the system can be taken advantage of. It is possible that participating vessels do not benefit from the system due to the usage of the First-Come-First-Served (FCFS) principle, or due to many freeloaders overtaking them during the voyage.

A development need that is addressed in this thesis is exactly this: the behavior of the system when not all vessels participate in the BVS. Therefore, the research question is to determine the proportion of non-participating vessels that the BVS can bear so that participating vessels still earn benefits. Benefits are quantified using multiple metrics, defined later in the following section. The aim is to measure how average speed, fuel consumption, and idle time in anchorage change when the proportion of the participating vessels is varied. It should be noted that the contractual structure affects economical profits, and the exact monetary calculations are out of the scope of this study.

In the analysis, two secondary research questions are addressed. Single voyages are examined with respect to the proportion of non-participating vessels so that the reasons behind different tolerance or sensitivity can be understood. It is possible that there are vessels that lose benefits with fewer freeloaders, which would mean that they have a higher tendency to become freeloaders and take advantage of the system. Therefore, the bivariate dependencies between the resulting metrics and features of voyages are examined briefly. Secondly, the system's robustness with respect to the chosen set of freeloaders is analyzed. The non-participating vessels are chosen from the historical voyages randomly, and hence, the robustness of the system should be addressed.

The research is performed by expanding the simulation model and using the dataset presented in section 3.3. The simulation uses the same structure, and all the technical developments mentioned in section 3.3.2 are included. The primary distinction is that experimental scenarios are performed with different proportions of non-participating vessels. From now on, they are also referred to as freeloaders as they are seen to take advantage of the system without participating in it. Freeloaders are always assumed to use their historical speed, voyage track, and arrival time. Incorporating freeloaders into the simulation model requires some developments as historical port transit times are not realized when a freeloader overtakes a participant. The conceptual modeling of the extension is presented in section 4.2.

4.2 Conceptual modeling

4.2.1 Assumptions

The model used includes assumptions about the behavior of vessels and ports. In the POC2, most of the simplifying assumptions that were made by Sung, Zografakis, and Nielsen (2022) have been replaced by detailed calculations. The following assumptions are held in this study:

1. Waiting time in the anchorage and time passed in a berth are not included in the fuel calculation. In addition, everything that happens after the port transit is excluded from the model.

2. Participating vessels use historical voyage track but follow BVS updates to adjust speed to arrive at Blue ETA.

3. Freeloaders use historical voyage track and speed. Therefore, freeloaders are assumed not to proactively exploit the BVS by adjusting their speed to overtake more vessels.

4. Freeloaders are observed when their sea passage ends and they enter the queue. This means that the arrival is the first point when a freeloader affects the simulation and the BVS process.

5. Ports serve ships only at historical berthing slots. It follows that ships can transit to ports only at historical port transit times. An exception is made in the rare case where there are no vessels in the anchorage and the next arriving ship is late from its original port transit time.

6. Ports serve ships in the historical order but freeloaders' overtakes and participants' late arrivals affect the order. Ports serving order follows often the FCFS principle but not always. This assumption is dealt with in more detail in section 4.2.4.

4.2.2 Freeloader selection

The first question that needs to be addressed when extending the model with freeloaders is how these vessels are chosen from the dataset. The data includes the voyages from 2019 and for simulation purposes, some of these are assigned to be freeloaders and the remains are assigned as participants. Using the assumptions mentioned above, the simulation can then be carried out by simulating participants' voyages using historical departure times and AIS tracks, while the freeloaders sail as described in the data.

Different approaches for freeloader assignments were considered. The first is a simple random choice, which is the method used in this study. It is important to understand the behavior of the system under a partially participating fleet, and a random choice acts as a baseline for more advanced methods. Secondly, it would be possible to use knowledge about the field and the market to assign vessels as participants or freeloaders depending on possible scenarios. For example, some companies could be considered unlikely or more likely to participate in the BVS. As this approach would require an analysis of the market situation and evaluation of possible freeloaders and participants, this method was not chosen for this study. Thirdly, the freeloaders could be chosen from vessels that benefit more from being a freeloader than participating. This would more faithfully reflect the competitive landscape but requires an analysis of the freeloader tendencies. For example, it might be that short voyages benefit less from the BVS than voyages with long duration. Therefore, this approach is left for future research.

The freeloaders are chosen from historical voyages uniformly at random. This is an essential baseline for further analysis and already gives the needed understanding of the system. The BVS update is always run for all voyages heading to the same port. This means that voyages sailing to different destinations are separated, and, in practice, the simulation is carried out for ports one by one. Therefore, the freeloaders are sampled uniformly at random from all the voyages heading to the same port before the simulation starts.

The behavior of the system needs to be examined by running the same simulation with different amounts of freeloaders. For this purpose, the term freeloader percentage or proportion (FL-%) is introduced. The system is tested with different values of FL-%, which means that, for example, 10% of voyages are assigned as freeloaders. The random component is implemented in a way that each voyage has a probability FL-% of being a freeloader and 100% − Fl-% probability of being a participant. The simulations are run multiple times with different freeloader proportions.

Due to the randomness, different runs of the simulation will produce different results. Therefore, the simulation needs to be run several times for the same FL-%. In addition, the robustness of the system needs to be addressed by performing sensitivity analysis, and understanding the system from this perspective is decided to be one of the research questions in this study.

4.2.3 Triggers of the BVS algorithm

As it has been discussed in section 3, the BVS update is triggered slightly differently in algorithms 1 and 2. In the simulation model that this study extends, the algorithm 2 is used, and hence, the update round is triggered when a new voyage starts and when a vessel transits to a berth. It should be noted that the arrival of a participant does not trigger a BVS update. This means that the BVS update is triggered when there are additions to the virtual queue of ongoing voyages or when the queue in the anchorage is shortened. The voyages arriving using Blue ETA are not considered to change anything at the queue as it is planned behavior.

This leads to the question of how freeloaders should be considered. In the scenario, where only a part of the fleet is participating, there are two new events: a freeloader arrives at the anchorage, and a freeloader transits to the port. It is natural that all the port transits are handled the same way as the vessels in the queue do not differ from each other. Hence, a freeloader port transit triggers a BVS update.

It would seem natural that the arrival of a freeloader would trigger a BVS update as this presents an unexpected increase in the queue. In general, this is desired behavior because one of the benefits of the BVS is that the voyages can slow down if there is traffic in the port area. This is also most likely possible to implement for the real-time platform. In fact, it is an interesting question whether freeloaders could be observed earlier so that the BVS could foresee the queue increase. As this clearly would need more investigation and research on how freeloaders could be identified, it is decided that the first observation of a freeloader is obtained when they arrive at the anchorage. On the other hand, it is possible that the participants will slow down due to the arrivals of freeloaders resulting in that even more vessels will overtake them during the voyage. Nevertheless, the arrival of a freeloader is defined to trigger a BVS update.

Therefore, the algorithm 2 is further revised so that the BVS update is triggered when three events occur:

1. A new participating voyage starts.
2. Any ship in the anchorage transits to the port.
3. A freeloader arrives at the anchorage.

This means that the BVS algorithm reacts to unplanned changes in the queue in the anchorage and the virtual queue of the ongoing voyages. The port is treated as a black box, which leads to the fact that the port transit times are unknown and are not incorporated into the optimization. In a more general way, the freeloader arrival could be replaced by an increase in the queue as one of the goals of the BVS is that when it is observed that the queue increases, the ships that are still sailing could react to that. In addition, environmental factors, problems in supply chains, or even strikes in harbors might have an unplanned effect on the queue.

4.2.4 Ship-specific port transit modeling

The simulation model in the POC2 used the historical port transit times meaning that the arrival times are simulated but the transit to the berth occurs at the time defined in the dataset. However, the results show that some of the simulated arrivals take place after the historical port transit time, which is defined as the time the vessel starts approaching the berth. This behavior is explained by the fact that the BVS slows down the vessels when there is a queue in the port. From the algorithmic perspective, the port transit times are not known beforehand, which makes it possible for a vessel to arrive late. When the FCFS principle is assumed, the port transit times should be in the same order as the historical arrivals, which the BVS aims to preserve. However, this is not always the case, which may cause the ETA of a vessel to be delayed due to traffic even though the vessel historically had an earlier port transit time compared to the order produced by the FCFS principle. In the analysis of the POC2, it was concluded that this is not a problem as a berth slot is always used, and it is not relevant to the behavior of the BVS which ship actually transits as the queue length is still known.

When evaluating the benefits of being a participant or, on the other hand, a freeloader, it is an interesting question to understand how the waiting times in the anchorage change. It can be assumed that when a freeloader overtakes a participant, it benefits from an earlier arrival and possibly earlier port transit time. How large an effect the overtake has is not straightforward, which makes it necessary to model the port transit time on a ship-specific level. This means that for each port transit time, it is known which ship left for the berth.

It should be noted that modeling berthing slots is difficult as the behavior of a port is not known. Some ports may use the FCFS principle whereas some operate on fixed schedules. In addition, some specific companies may have separate agreements with ports, or a port may include several terminals and stakeholders with different principles. This means that the results of the port transit modeling should be critically observed, and other more reliable metrics should be used as well.

When a ship arrives normally at the anchorage according to the historical arrival order, it is assigned the port transit time that historically occurred. This is done in order to model the behavior of the port as realistically as possible. As a result, if a port uses the FCFS principle the arrival order is the same as the port transit order but, nevertheless, the historical transit order is preserved.

The first exception addressed in the port transit order is a freeloader overtake. This means that a freeloader arrives at the anchorage earlier than a participant or participants that originally arrived before. For the purpose of the simulation, each ship is first assigned the historical port transit time and the realizing time is tracked. When an overtake occurs the port transit times of the freeloader and the participant are swapped if this makes the freeloader's port transit time better. An earlier port transit time is considered to be more beneficial. If a freeloader overtakes several participating vessels, the events are handled in the order of occurrence so that the overtaken participant with the latest notional arrival time is considered first.

As mentioned above, it is possible that a participant arrives later than their historical port transit time. In this case, the participant loses their original berthing slot. The port is not assumed to wait for a ship to arrive, with the exception that there are no ships in the anchorage queuing. Normally, this leads to a later port transit time. However, the aim is to modify the historical port transit times as little as possible so that the use of the FCFS principle would not result in a strong bias to the results. For this purpose, when a participant is not present when its assigned port transit time occurs, a random ship from the queue is chosen instead. In addition, it is required that the chosen queuing ship has a port transit time later than or equal to the current ETA of the late ship. This means that the port transit times of the late ship and the randomly chosen one are swapped. If there are no potential ships to swap transit times, the port transit of the late ship is delayed to the arrival time. However, this is a rare case and corresponds to a situation where there is no queue.

4.3 Progress of the simulation

The flowchart of the simulation can be seen in figure 1. The simulation is run for each port and FL-% separately using the dataset of 2019 AIS tracks. In the beginning, the data is retrieved and preprocessed in the same way as in the POC2. After this phase, the progress of the simulation follows a very similar pattern as described by Sung, Zografakis, and Nielsen (2022) with few alternations, and the BVS update follows algorithm 2 with the additional trigger explained in section 4.2.3. Other extensions to the POC2 are the implementation of the ship-specific port transit modeling and, of course, the existence of freeloaders as described in sections 4.2.4 and 4.2.2.

It should be noted that ongoing voyages include only participants, and the freeloaders are first observed when they arrive at the anchorage. Therefore, the simulation is implemented by detecting the following events from the data: a start of a participating voyage, a port transit, and an arrival of a freeloader. These correspond to the triggers of the BVS process, which means that when an event takes place, the Blue ETAs of ongoing voyages are updated based on the current queue length and the target inter-arrival time. Overtakes are processed when the freeloader in question arrives at the anchorage. The overtaken participants are still sailing at this point so their future berthing slots are tracked. Late arrivals are detected only when the vessel in question arrives. Therefore, it is possible to update the port transit times retrospectively but, as all the berthing slots are assumed to be used, this does not change any outcomes.

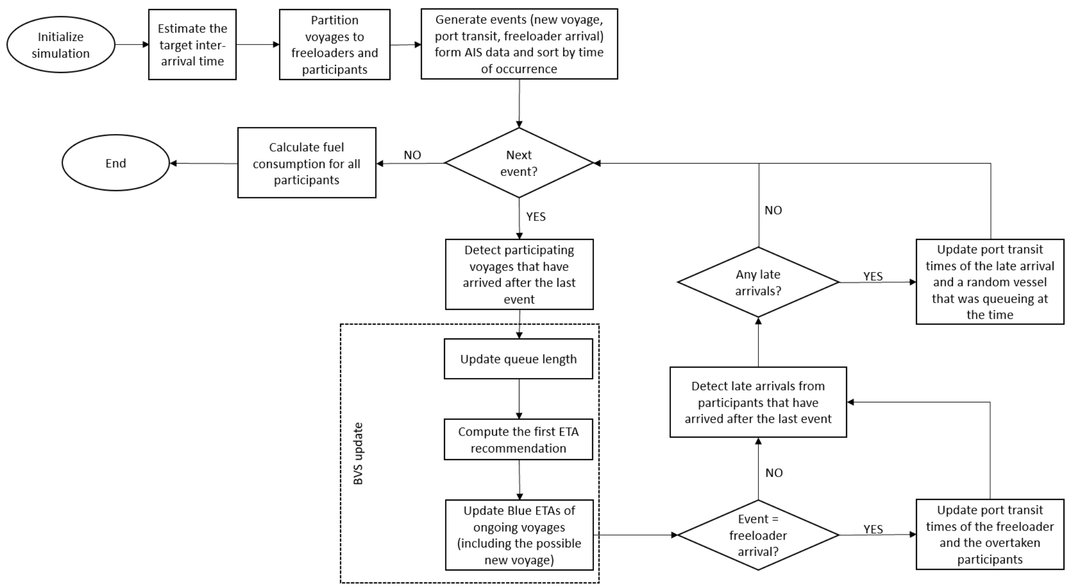
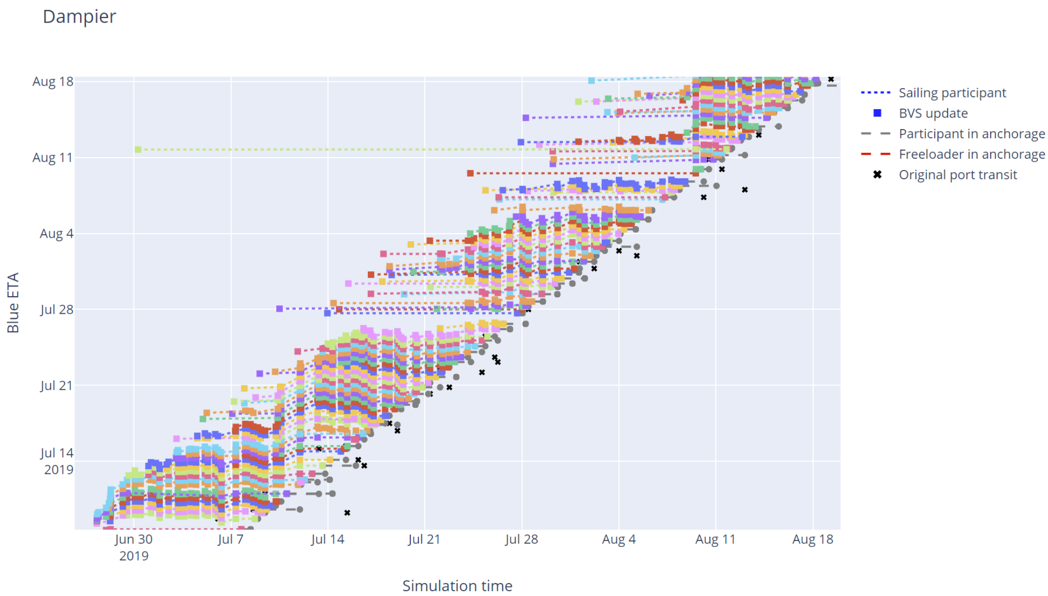
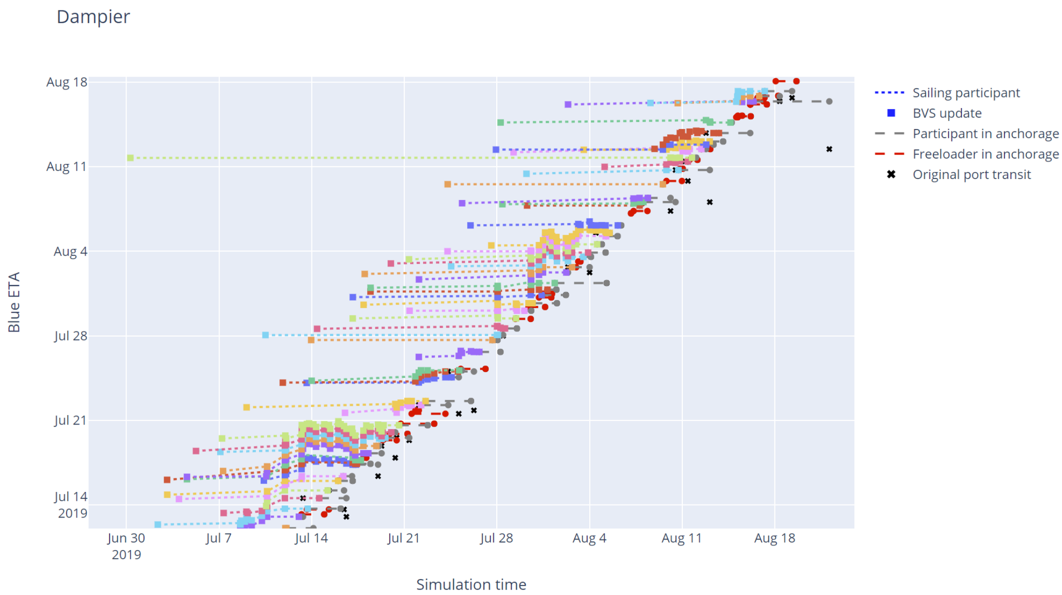


Figure 1: Flowchart of the simulation for a certain port with a certain FL-%.

A single simulation run can be visualized using a chart with simulation time on the x-axis and the Blue ETA on the y-axis. In this way, the voyage can be plotted, and the development of the recommended ETA can be seen. Figure 2a presents a snapshot of the simulation for port Dampier when all vessels are participating in the BVS. Dotted lines present the vessels still on the sea passage, and the dashed lines the waiting time in the anchorage. In addition, the original port transit time is marked with a cross so that late arrivals and their impact can be detected.



(a) FL-% = 0%



(b) FL-% = 50%

Figure 2: Snapshots of simulations for Dampier so that there are no freeloaders in the top figure and half of the fleet is participating in the bottom figure.

It can be observed that when the whole fleet is participating, waiting times are rather short even if there are multiple ongoing voyages. The Blue ETAs tend to grow during the voyage but occasionally they may shrink as well. During rush times, there is a large number of update points. Late arrivals can be seen when the original port transit time occurs earlier than the simulated arrival. In these cases, other vessels may obtain significantly better port transit times. The reason for the relatively large number of late arrivals is built into the simulation principle and relates to the fact that the ports do not always follow the FCFS principle. This is an interesting question and will be further discussed in section 6.

Figure 2b presents a simulation for port Dampier when only half of the fleet participates in the BVS. As freeloaders are only observed when they arrive at the anchorage, they are not plotted during the voyage. The red dashed line presents the freeloader's arrival and waiting time. It can be seen that the participant waiting times seem to be longer while freeloaders wait relatively short times. To understand the systematic behavior of the process, further analysis is needed.

4.4 Experimentation

4.4.1 Experimental scenarios

The simulation model is used to compare results for different proportions of freeloaders. For this purpose, the simulation model is run for several different experimental scenarios using the same data sources as in the POC2. As this study requires multiple scenarios of freeloaders, as well as multiple replications of the same run, only a subset of the voyages is used, including 23 relevant ports. Some ports include multiple terminals, and they are grouped together the same way as in the POC2.

In figure 3, a pairwise scatter plot of four features is presented so that the ports are plotted as different colored dots. The total number of voyages arriving at a port varies from 1000 to 6000, but there seem to be three different size categories. The average queue length at a port has values between 0 and almost 40, meaning that there is considerable variation. Most of the ports having a small number of voyages also have low queues but there is no clear dependence as there are exceptions. The average distance presents the mean of the voyage distances arriving at a port. Average inter-arrival time means the time between two arriving vessels. This value and the total number of voyages are clearly correlated, as expected. It also seems that, in general, longer queues occur in ports that are busy in the sense that the inter-arrival time is small.

Inter-arrival times are relevant to examine in more detail, as the target inter-arrival times used in the BVS algorithm are computed from this data directly. Recall that the service rate of the port is estimated as the 20$^{\text{th}}$ percentile of the weekly inter-arrival times. Hence, these values affect the results of the simulation. The inter-arrival times are presented as histograms in figure 4. It can be observed that the histograms are similarly distributed but some have higher peaks and the skewness is even more highlighted.

Compared to the POC2, this simulation is much more computationally demanding. Therefore, the amount of different freeloader proportions needs to be limited. To acquire enough understanding of the system, the simulation is run for FL-% values 0%, 10%, 20%, 30%, 40%, and 50%. Additionally, the simulation is run without the fuel calculation for FL-% values 60%, 70%, 80%, and 90%. Note that the case

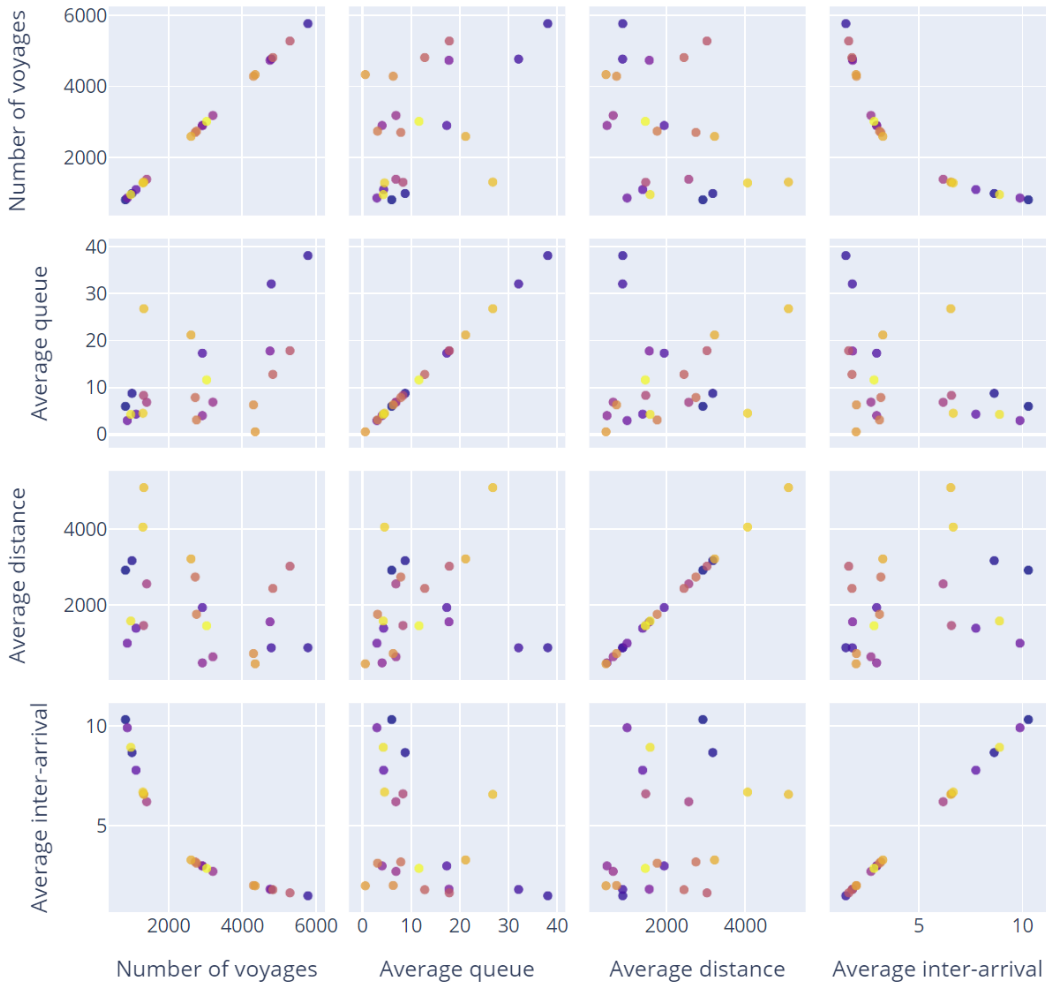


Figure 3: Basic features of 23 relevant ports that were included in the analysis.

where FL-% = 100% is identical to the historical behavior. Multiple replications are needed so that the influence of randomness of the freeloader choice can be controlled. Therefore, each experimental scenario is run 5 times. The choice is further justified in section 4.4.4 where a sensitivity analysis is presented. An exception is made for FL-% = 0% with no randomness, which is run for one time only.

4.4.2 Metrics

The goal is to understand the system's behavior under different proportions of freeloaders and, especially, understand how the benefits that participants receive change. For this purpose, some metrics need to be defined to evaluate how the proportion of freeloaders affects the results for each port. As has been observed in the POC2 and discussed in section 3.3, differences between ports are significant, and, for this reason, the results are examined for ports separately. For each FL-% and port, the following metrics are introduced.

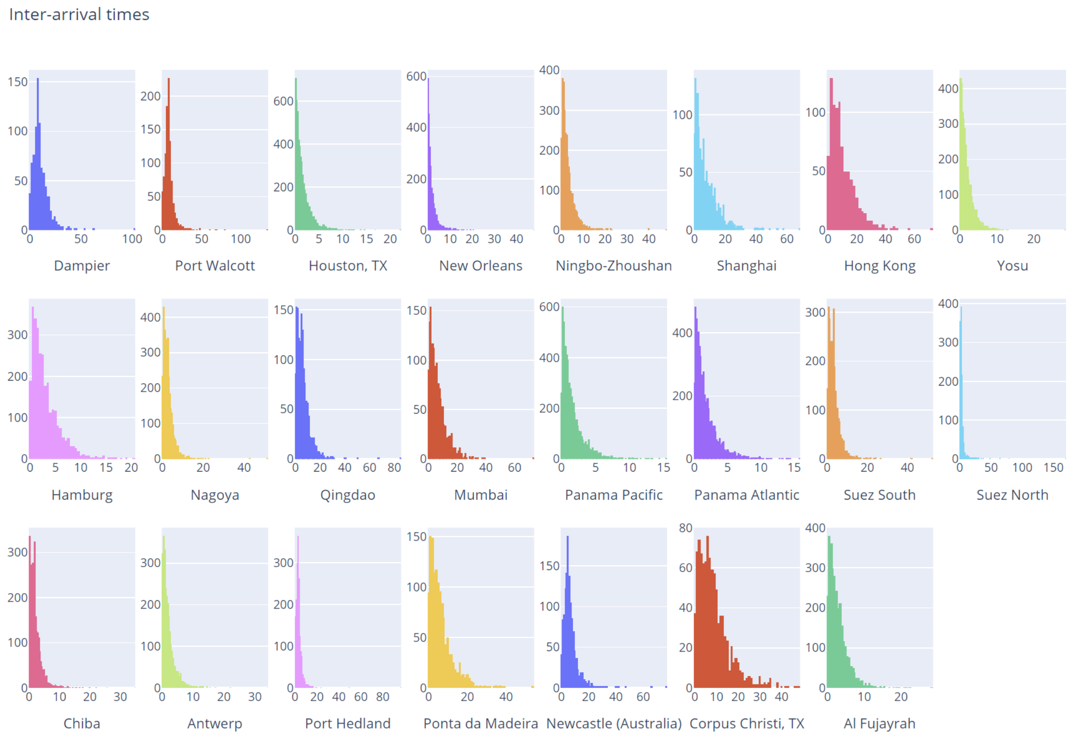


Figure 4: Histograms of inter-arrival times for all 23 ports. Inter-arrival times are used for estimating the service rate of the port and have a great impact on the results of the simulation.

1. **Number of overtakes:** An overtake is defined so that a freeloader arrives earlier than a participant that historically arrived before. When an overtake occurs, the freeloader receives a better port transit time while the participant is left with the later berthing slot. In fact, the overtakes mean additional overtakes in relation to the original arrival order that the BVS aims to preserve. This means that the number of overtakes is an important metric to evaluate how participants' benefits change. The metric is computed for each simulation and can be presented per freeloader or per participant depending on the perspective that needs to be highlighted. In addition, the number of overtakes can be presented as per nautical mile so that the length of the voyage is taken into account.

2. **Number of late arrivals:** As discussed earlier, the BVS produces late arrivals that are defined so that the simulated arrival time occurs later than the original port transit time. The number can be computed from the progress of the simulation, and the metric is presented per participant.

3. **Arrival lateness (h):** To extend the understanding of late arrivals, the magnitude of lateness is recorded. For each late arrival, the time difference between the simulated arrival and the original port transit time is computed in hours.

4. **BVS speed (kn/%):** Participants often use multiple speeds during a voyage to adjust to the Blue ETAs. The average speed of a voyage is recorded as a

BVS speed. The metric is presented as knots or as a percentage of the original average speed.

5. **BVS delay (h):** The voyage duration of a participant grows when the speed is lowered. The lengthened travel time is recorded in hours and referred to as a BVS delay.

6. **LSFO fuel consumption (t/%):** Fuel consumption is computed the same way as in the POC2 and is divided into two fuel types. The first one is Low Sulphur Fuel Oil (LSFO), and the consumption is given in tons or as a percentage of the fuel consumption computed using the historical AIS track and speed.

7. **MGO fuel consumption (t/%):** The second fuel type is Marine Gas Oil (MGO) and the metric is measured similarly to LSFO. The fuel consumption of MGO can be zero as some voyages may only sail outside of ECAs where MGO is used.

8. **Savings potential in $ (%):** The economical savings potential in US dollars is computed from the used fuel and the prices of each fuel type. The fuel prices used are 500 $/mt for LSFO and 650 $/mt for MGO. The metric presents how large percentage of the fuel costs could be saved.

9. **CO_2 reduction (t):** CO_2 reduction is given as tons and is computed from the fuel consumption in the same way as in the POC2.

10. **Participant waiting time change (h):** Waiting time in anchorage is computed for each participant from the simulated arrival time and the simulated port transit time. The difference to the original waiting time is calculated so that a negative value means that the queueing time is shortened.

11. **Freeloader waiting time change (h):** A similar metric is computed also for freeloaders using the historical arrival time and the simulated port transit time.

12. **Queue length:** The queue development is followed in the simulation as it has a great impact on the behavior of the BVS. The queue length is measured as the daily average as well as the proportion of the simulated average value over the historical average queue length.

In addition, some static information, which is not influenced by the freeloader proportion, about a port is known, such as the total number of voyages. Some of the ports are canals in reality but the behavior is considered to be similar to a port. The number of freeloaders and participants differs slightly between replications as the partition is done using the probability FL-%.

4.4.3 Warm-up and cool-down periods

Before the final results can be computed and analyzed, possible warm-up and cool-down periods of the simulation should be recognized. The simulation includes data from 2019 so that only voyages that have departed and arrived during this year are included. As a result, at the beginning of the simulation horizon, there is no queue and at the end, new voyages are not departing anymore.

The question is examined by plotting the daily average values of the number of ongoing voyages, the number of queuing vessels, and the original voyage duration of ongoing voyages. For this analysis, the results of all 23 ports are grouped together including a total of 64 500 voyages. The resulting graphs can be seen in figure 5 where the metrics are plotted for the entire simulation time.

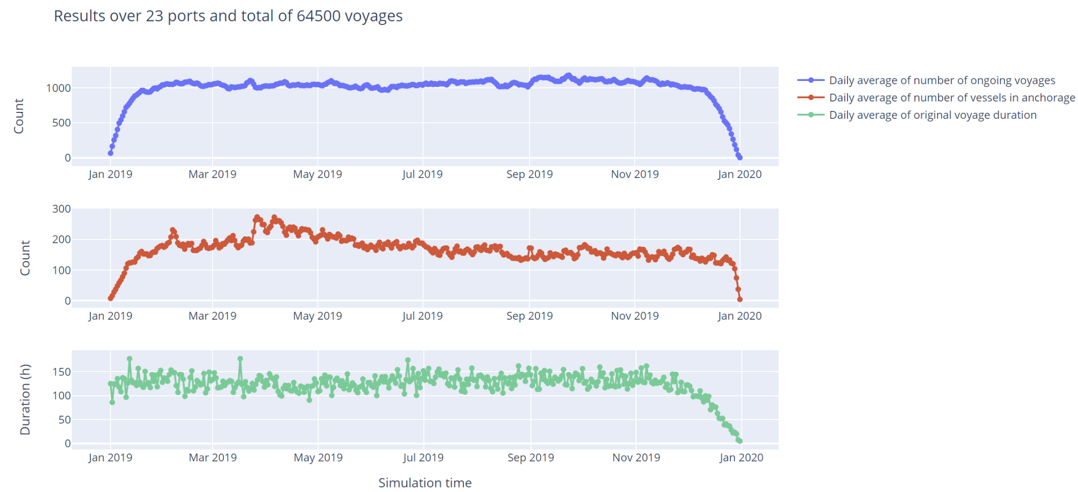


Figure 5: The average values of ongoing voyages, number of queuing vessels, and original voyage duration are plotted for determining warm-up and cool-down periods.

It can be observed clearly that there exist warm-up and cool-down periods. The number of ongoing voyages decreases and increases symmetrically at the beginning and at the end of the simulation. In the average queue length, the change is not as obvious but the queue clearly increases at the beginning and drops when the simulation approaches its end. The duration of ongoing voyages is steady until, at the end of the simulation, it decreases. Therefore, we decided that both warm-up and cool-down periods are three weeks, and these time periods are removed from the final results.

Consequently, the metrics are computed for voyages that have the start and the end within the evaluation period except for queue lengths. This means that all information about participating vessels is computed for voyages that have the departure time and the simulated port transit time within the time period for which the warm-up and cool-down periods are cut. These metrics are the number of overtakes per participant, the number of late arrivals per participant, the arrival lateness, the BVS speed, the BVS delay, both fuel consumptions, the savings potential, the CO_2 reduction, and the waiting time change. Metrics for freeloaders are computed for voyages for which the arrival time and the simulated port transit time are within the evaluation period. These metrics are the number of overtakes per freeloader and the waiting time change. For queue developments, only values that take place within the evaluation period are included.

4.4.4 Sensitivity analysis

The aim of the sensitivity analysis is to understand the robustness of the system under random freeloader selection and determine the number of replications that are needed to obtain accurate enough results. In addition, the manner in which the metrics are computed from multiple replications of a single run must be defined. For the sensitivity analysis, the simulation is run for the 23 ports and for FL-% values 25%, 50%, and 75%. All combinations are run 5 times. Several aspects of the behavior of the system are examined, including the number of overtakes, the number of late arrivals, the BVS speed and delay, the waiting time changes, and queue developments.

The number of overtakes as well as the number of late arrivals are presented per participant. There is one value for a single simulation and a mean over the five replications is computed. Consequently, the variation is examined by computing 95% confidence intervals. These results can be seen in figures 6 and 7. The heatmap indicates the width of the interval, and the actual range is given as a label. It can be seen that the intervals are generally narrow. For the number of overtakes per participant, most port and FL-% combinations have interval widths less than 0.3. Some wider intervals exist, for example for Ponta da Madeira and Port Hedland, but a 95% confidence interval is always less than one overtake per participant. The maximum interval width for the number of late arrivals per participant is 0.08 meaning that there is an 8% difference in the number of late arrivals between most replications.

For each participating voyage, the average speed is computed as the BVS speed. The values of each replication are plotted as histograms side-by-side in figure 8 so that different freeloader proportions are presented in separate figures. Note that all ports are combined in the sensitivity analysis, and the distribution is bimodal as a result. It can be seen that the histograms of each replication correspond to each other very closely, even if a small variation can be seen. In addition, there is no large difference between the different freeloader proportions.

A similar analysis is made for the BVS delay and the waiting time changes. The distributions have a very high peak, and hence, boxplots are used. In figure 9, BVS delay values are presented for each replication, and the skewed distributions are always very similar to each other. The tail has some variation but as these are single cases, the system behavior still seems robust. Similar observations can be made from the participant waiting time change in figure 10, and the freeloader waiting time change in figure 11. In addition, for most voyages, the waiting time changes are very small or non-existent. For these metrics, it is important to note the shape of the distribution when computing descriptive statistics.

A similar heatmap, as for the number of overtakes and late arrival, is computed for the average queue length. This is presented in figure 13. It can be seen that the confidence interval is at most 0.7, and the widest intervals can be seen for the ports that have generally longer queues. Most of the intervals are narrow as only three entries exceed width 0.4. In addition, the queue developments for each port are examined in detail. For example, Port Hedland is presented in figure 12a and Hong Kong in figure 12b. Firstly, there is a large difference between ports. It can be observed that for Hong Kong all simulated queues are very similar, whereas for Port Hedland there is a much

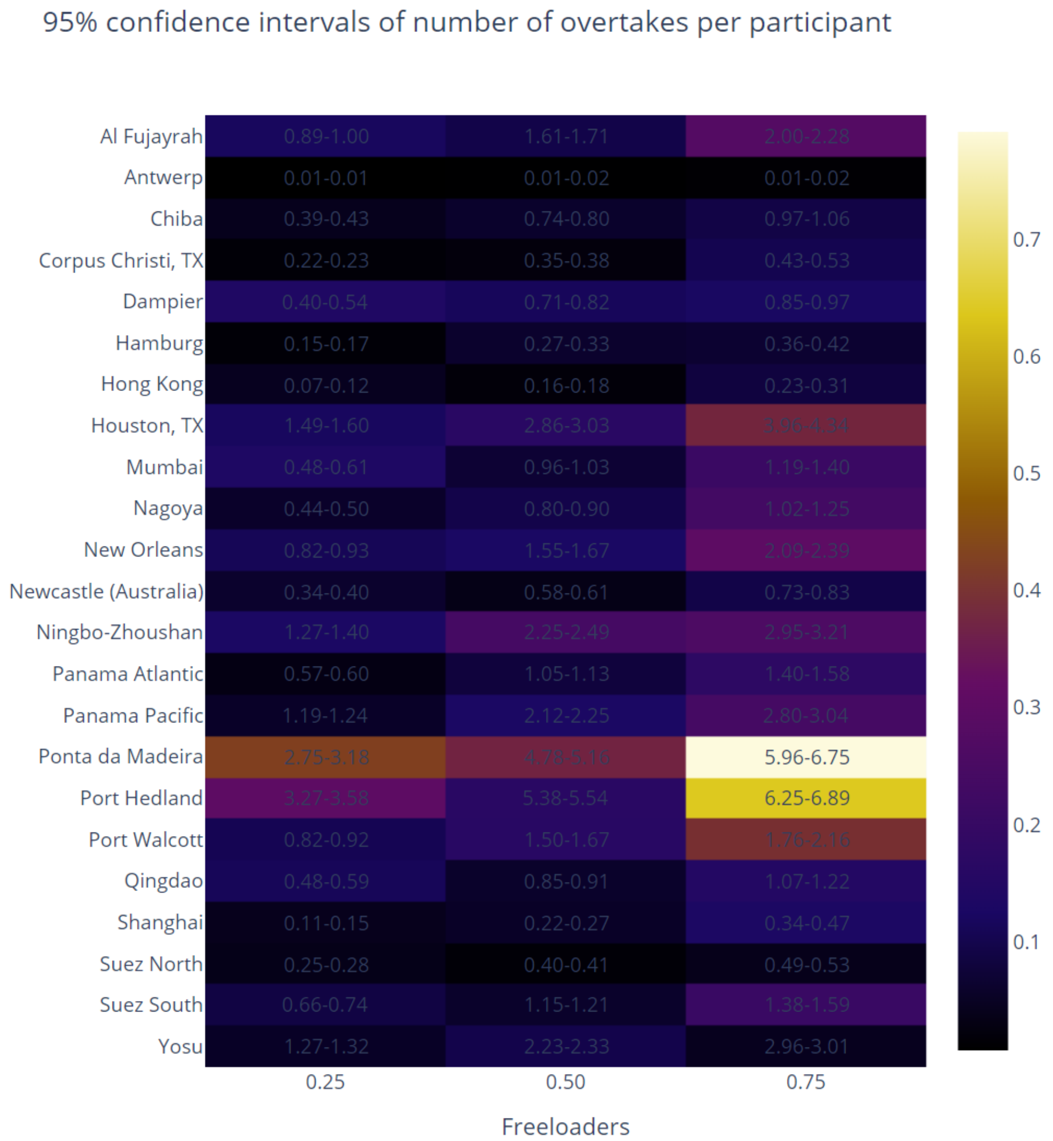


Figure 6: The width of 95% confidence intervals of the number of overtakes per participant for each port are presented as a heatmap with the interval range labeled in the map.

stronger impact from the number of freeloaders. Even if there is variation between different simulation replications, the behavior of the queue is very similar and follows the same trend.

It is concluded that the results do not differ significantly between different replications of the same simulation. Therefore, it can be said that the behavior of the system is fairly robust with respect to the freeloader choice. The results for a single ship may, of course, differ considerably as the same vessel may sometimes act as a freeloader or a participant. However, from the system perspective, the results are not varying significantly. The chosen number of replications, 5, is deemed sufficient as

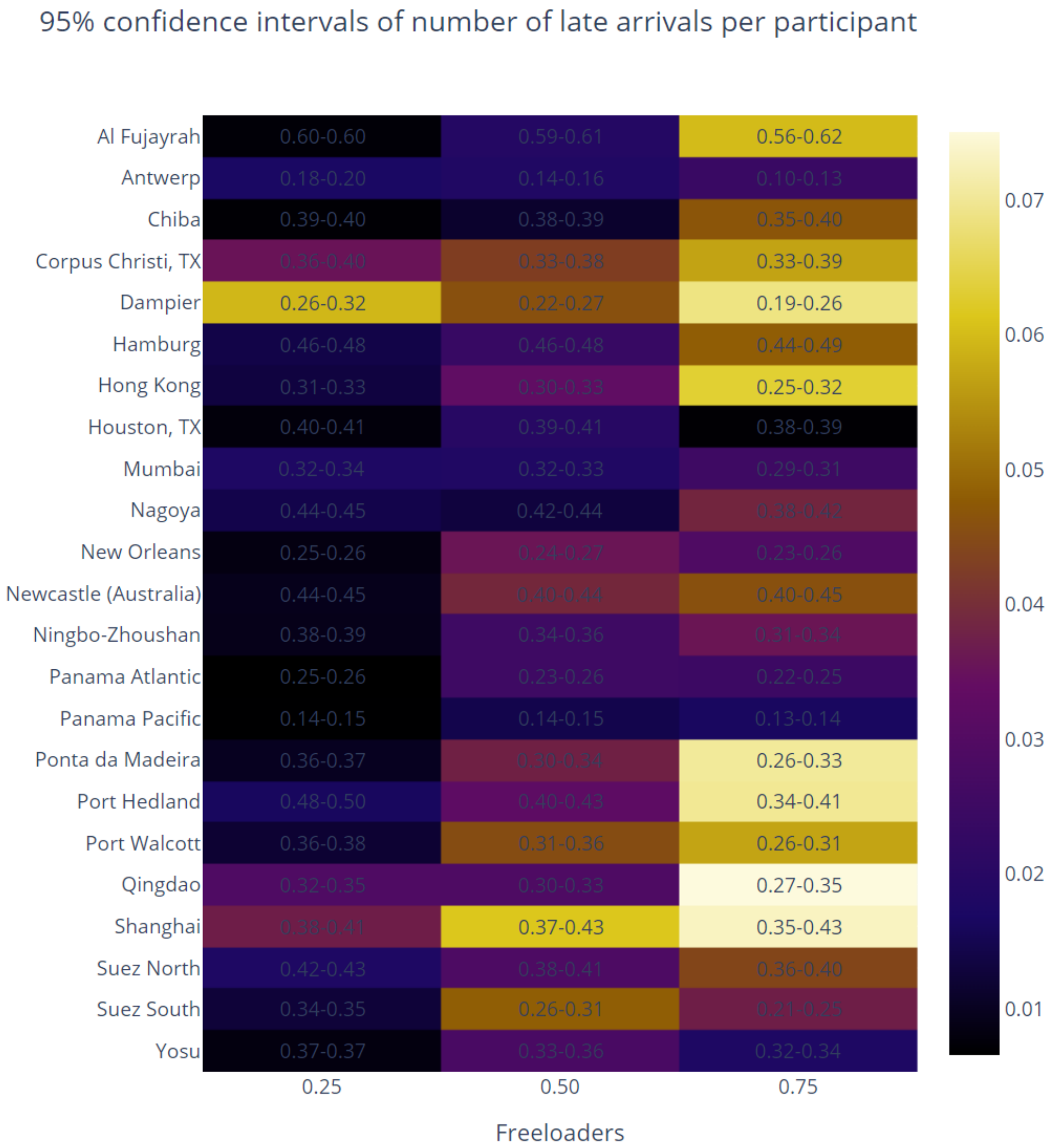


Figure 7: The width of 95% confidence intervals of the number of late arrivals per participant for each port are presented as a heatmap with the interval range labeled in the map.

the 95% confidence intervals for the metrics are narrow enough, and considerably more knowledge would not be gained for running such heavy computations longer. In addition, it is noted that the metrics should be computed so that the results over replications are pooled. For the metrics with very skewed distributions both mean and median values should be examined when drawing final conclusions.

Figure 8: The average BVS speeds computed for all voyages, and five simulation replications are visualized as histograms side by side.

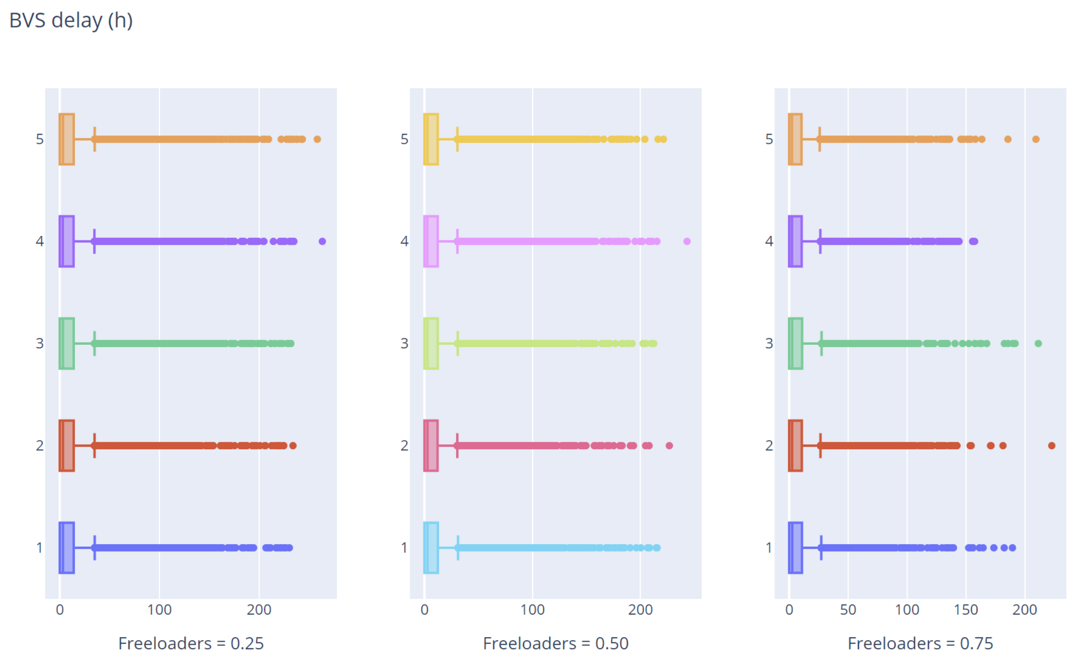


Figure 9: The BVS delays (the lengthened sailing time) of all voyages are visualized using boxplots for each simulation replication.

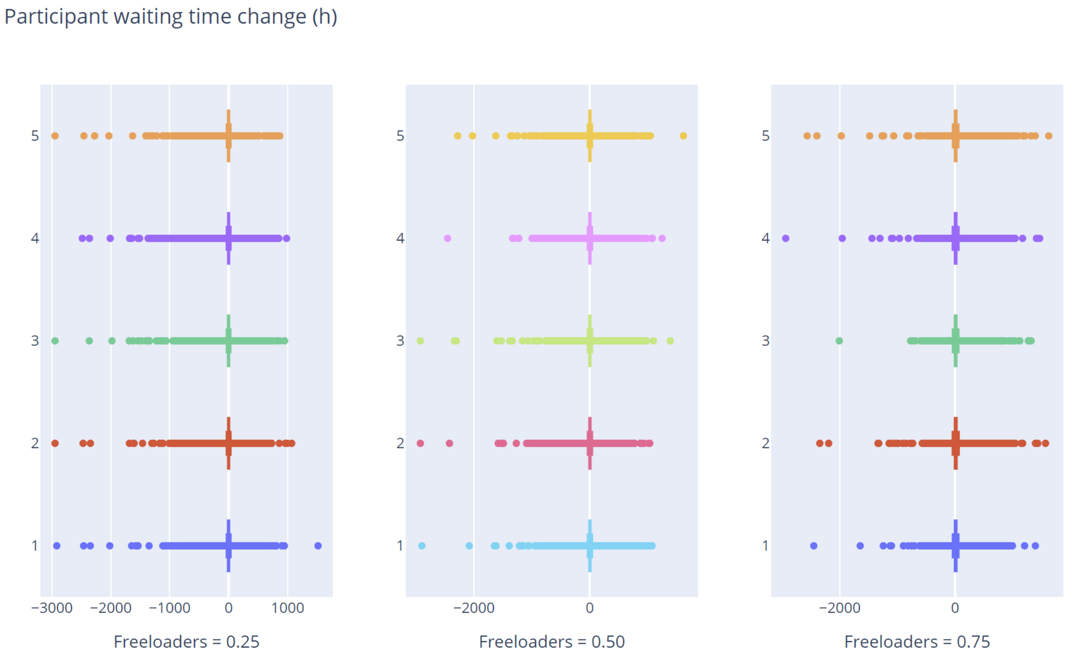


Figure 10: The waiting time changes of participants are visualized using boxplots for each simulation replication.

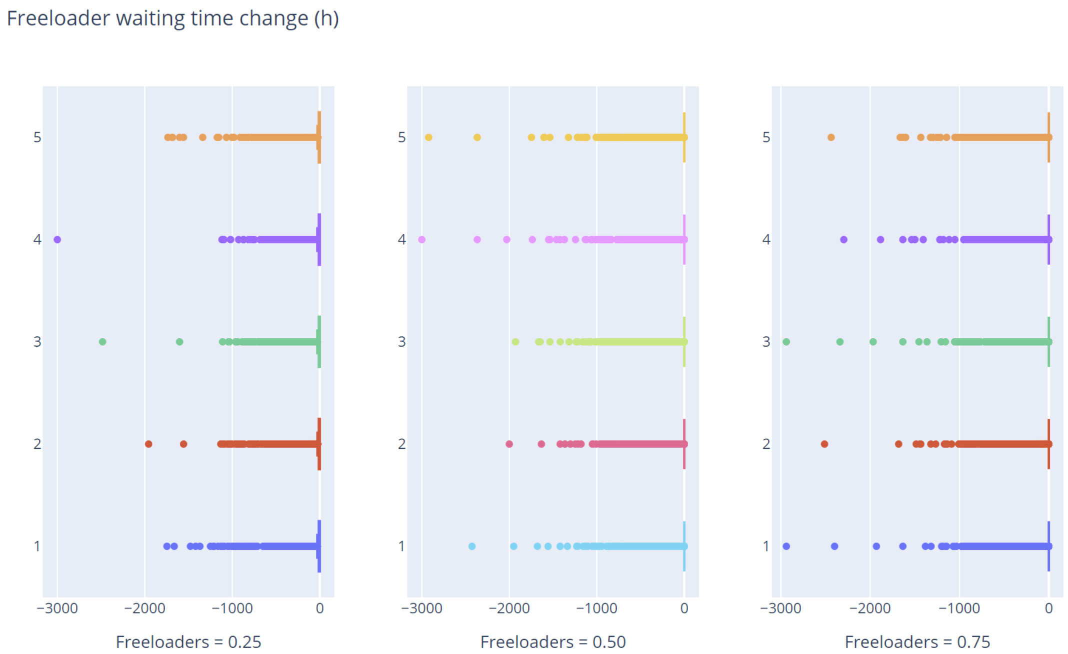
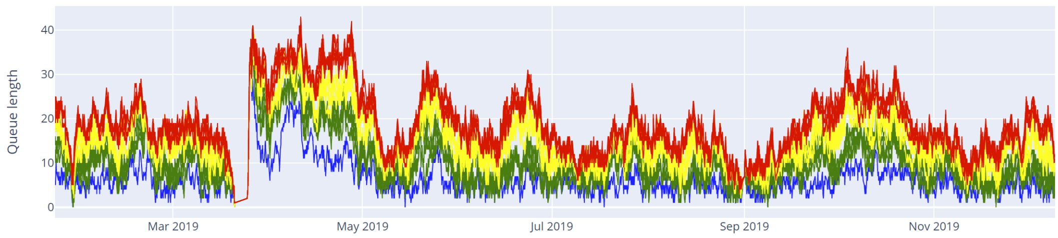
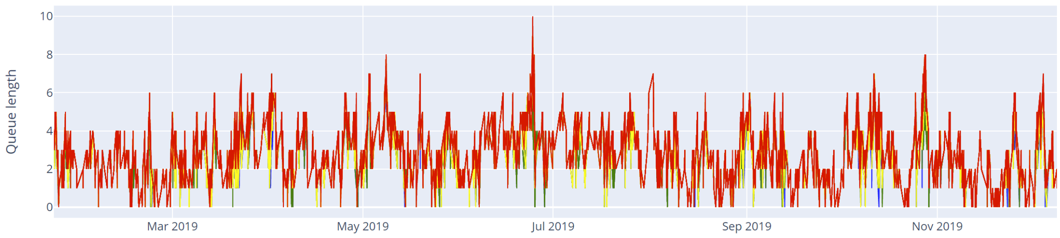


Figure 11: The waiting time changes of freeloaders are visualized using boxplots for each simulation replication.



(a) Port Hedland



(b) Hong Kong

Figure 12: The queue developments for Port Hedland and Hong Kong for each simulation replication so that the blue line presents the case with no freeloaders and other colors, green, yellow, and red, FL-% values 25%, 50%, and 75% respectively.

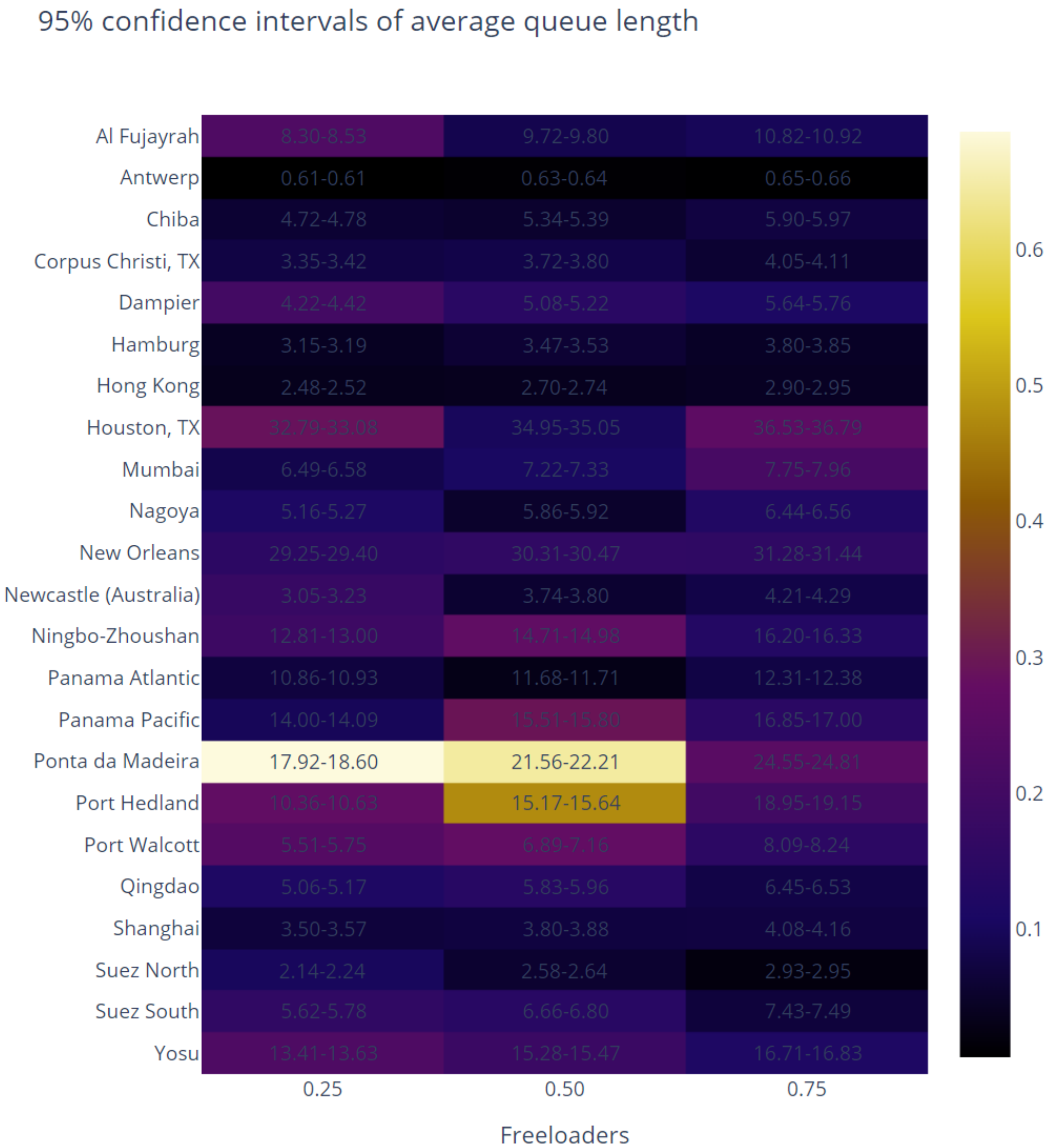


Figure 13: The width of 95% confidence intervals of the average queue length for each port are presented as a heatmap with the interval range labeled in the map.

5 Results

5.1 Impact of non-participating vessels

As described in section 4.4.1, the experimental scenarios of different proportions of non-participating vessels (freeloaders) are run 5 times each. The freeloader proportions used are from 10% to 90% with 10% step size with the exception that the fuel consumptions are computed only until 50%. The simulation results comprise data gathered about the simulated voyages, their fuel consumption, waiting times at anchorage, and so forth. The results are analyzed in this section so that freeloaders' impact can be understood systematically. It should be noted that a single vessel may act as a freeloader and as a participant in different simulation runs.

The dataset is preprocessed as described in section 3.3.1. Nevertheless, some erroneous data remains undetected, which results in irregularities in the results. Therefore, the voyages that are included in the analysis are filtered based on the original average speed of the voyage as well as the traveled distance. We decided that voyages less than 30nm and above 15 000nm are filtered out following the principle of the POC2. This means that very short trips for which the BVS is not designed are excluded. On the other hand, voyages with longer distances than the maximum value are most likely erroneous as they are longer than the longest sailing distance occurring in practice. In these cases, a port visit is most likely missed from the original dataset.

The speeds that the BVS can assign are restricted so that unrealistic results do not occur. However, the dataset includes voyages that have average speeds outside of this range. In these cases, it is possible that the simulated speeds are higher or lower than what they theoretically should be. This may be correct if the differences are not significant but, when examining the results, it can be observed that there exist voyages with an average speed of one knot. These are not realistic, and hence, the results are filtered so that only voyages with the original average speed between 5kn and 30kn are included. The range is based on the analysis completed in the POC2. In addition, only the voyages that are within the evaluation period, which is determined in section 4.4.3, are considered.

The results are evaluated using the metrics defined in section 4.4.2. The metrics are computed so that the results of replications over the same experimental scenario are pooled and descriptive statics are computed. These are the mean, the median, the standard deviation, the first and the third quartiles as well as the 95% confidence interval for the mean.

5.1.1 BVS behavior

The BVS aims to lower average speed when possible and, in that way, reduce fuel consumption. This systematic behavior is tracked by the metrics defined in section 4.4.2 for each port and FL-% and presented in figure 14. The BVS speed is defined as the proportion of the average speed over the original average speed. The BVS delay means how much longer the sea passage is with the simulated speed. The number of late arrivals per participant and the arrival lateness are tracked as they give more insight into the behavior of the system. The fuel consumption is measured with respect to two fuels, LSFO and MGO, and they are given as a proportion of the original consumption. In addition, potential savings and CO_2 reduction are computed.

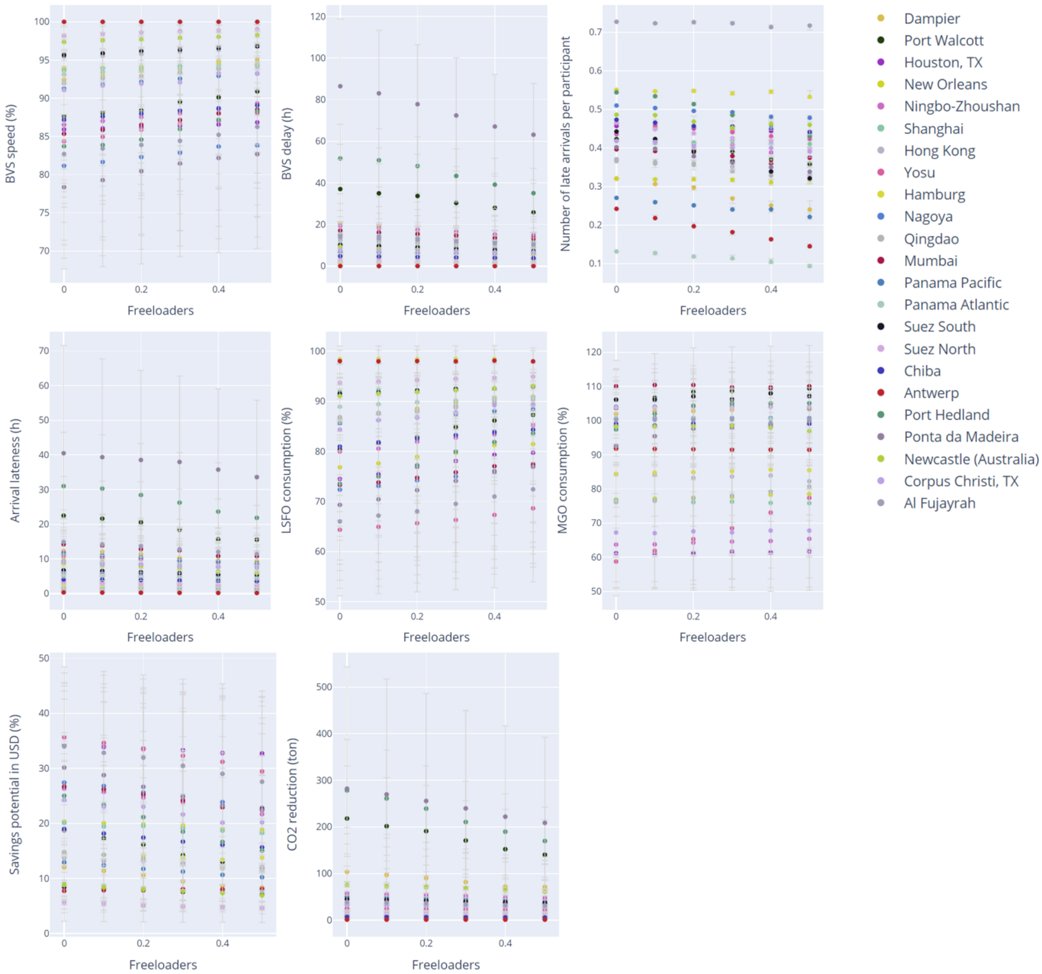


Figure 14: Medians and quartiles of the BVS speed (proportion of the original average speed), the BVS delay (the travel time change), the number of late arrivals per participant, and the lateness of those arrivals, the LSFO and MGO fuel consumption (proportion of the original consumption), the savings potential in \$, and the CO_2 reduction plotted for each port.

The medians and quartiles are plotted for each port in figure 14. It can be observed that the results are widely distributed for most of the ports but the general trend can still be seen when the number of freeloaders grows. The only metric that does not have wide quartiles is the number of late arrivals per participant, which is understandable as this is the only metric of the group that has a single value per simulation whereas the other metrics have much larger sample sizes.

When there are no freeloaders, the median BVS speed can be as low as 78% of the historical speed (Ponta da Madeira). For some ports, such as Antwerp, there is no significant speed reduction, and hence, the impact of the BVS does not show. When the freeloader proportion is increased to 50%, BVS speed increases or remains at 100% for all ports. In conclusion, one impact of freeloaders is that the used speeds grow towards the normal service speeds. From the system point of view, this means that the effect of the BVS decreases, but it is noteworthy that even with only half of the fleet participating in the BVS, there is still clear speed reduction potential.

The reason for the increasing speed trend can be addressed by looking at the BVS updates. Recall that the BVS update is triggered when a new voyage starts, a freeloader arrives, or a vessel transits to port. As a result, the total number of update points remains constant. However, the ability to predict the queue length is weakened. The queue is observed the same way, but the only prediction that can be made is based on the ongoing voyages. This number is reduced when the number of freeloaders is increased as they are only observed when they arrive at the anchorage. Consequently, when a new voyage starts, it seems that there will be less traffic, and for this reason, the suggested speed is higher.

Many of the other metrics presented in figure 14 are consequences of the BVS speed. BVS delay means the shortened travel time that is obviously decreased when the speed increases. The same applies to LSFO fuel consumption, even if the relationship is not as straightforward. LSFO consumption increases but the median values remain below 100%, which is expected as the speeds remain lower than the normal service speeds.

However, some of the upper quartile values for LSFO consumption exceed 100%. The reason behind this phenomenon can be found in the weather condition simulation. Weather routing decisions are not considered in the simulation, meaning that the historical route is used as it is and the weather conditions are projected to a new time window. Therefore, the vessel may end up sailing in worst conditions than it historically did. This effect is even more amplified in MGO consumption, which for multiple ports is above 100%. MGO is only used in the ECAs that generally are located near the coast. Therefore, the usage of MGO is located at the beginning or at the end of the journey. Firstly, this means that the amount of the consumed MGO is less significant than LSFO as the time spent at ECAs is much shorter. Secondly, the end of the journey may take place much later than it used to as the time difference cumulates. Consequently, MGO consumption is much more sensitive to weather conditions changes than LSFO consumption.

Even if the MGO consumption can increase in the simulation, the total fuel consumption decreases, resulting in potential economical savings. Figure 14 presents the potential savings computed from the fuel used. From this perspective, there are potential savings for all of the ports even when FL-% is 50%. They are, of course, decreased from the optimal scenario but they are significant nevertheless. Possible CO_2 reductions also decrease while the number of freeloaders is increased. For Ponta da Madeira, Port Hedland, and Port Walcott, the reductions remain high but for the ports that do not have a large impact from using the BVS, the reduction is even lower.

In addition to these metrics, the number of late arrivals per participating voyage is computed. It is noteworthy that the simulation results in a significantly high number of late arrivals, meaning that a vessel arrives later than it originally left the anchorage. This is a result of the fact that the port's principle of processing the queue is not known.

What is known is that the arrival order of the vessels does not always correspond to the handling order of the port. However, this is the principle that the BVS operates with, and so when there is traffic in the port, the arrivals of new vessels are delayed. Theoretically, this is the correct behavior, but it may result in some of the vessels arriving late. For some ports, an extreme case is Al Fujayrah, the number of late arrivals per participant may be greater than 0.5, meaning that most of the voyages arrive late. In these cases, the problem may be related to inaccurately estimated target inter-arrival values. However, when the number of freeloaders increases, the number of late arrivals and also the amplitude of lateness is decreased. This is a side effect of increased speeds.

5.1.2 Benefits of being a participant and a freeloader

To be able to evaluate the benefits of participating in the BVS or, on the other hand, being a freeloader, it is important to look at what happens after the sea passage has ended. Clearly, lower speeds often result in lower fuel consumption followed by better potential savings. However, it should be understood that prolonged travel time has its costs as well. In addition, the voyage needs to be examined until the port transit so that the waiting time in the anchorage can be taken into account. The BVS aims for shortened anchoring times, but, as the impact of freeloaders is added, it is possible that the order of service in the port changes. Therefore, two metrics are used to evaluate the benefit of the BVS to participants: the waiting time change in the anchorage and the number of overtakes per participant.

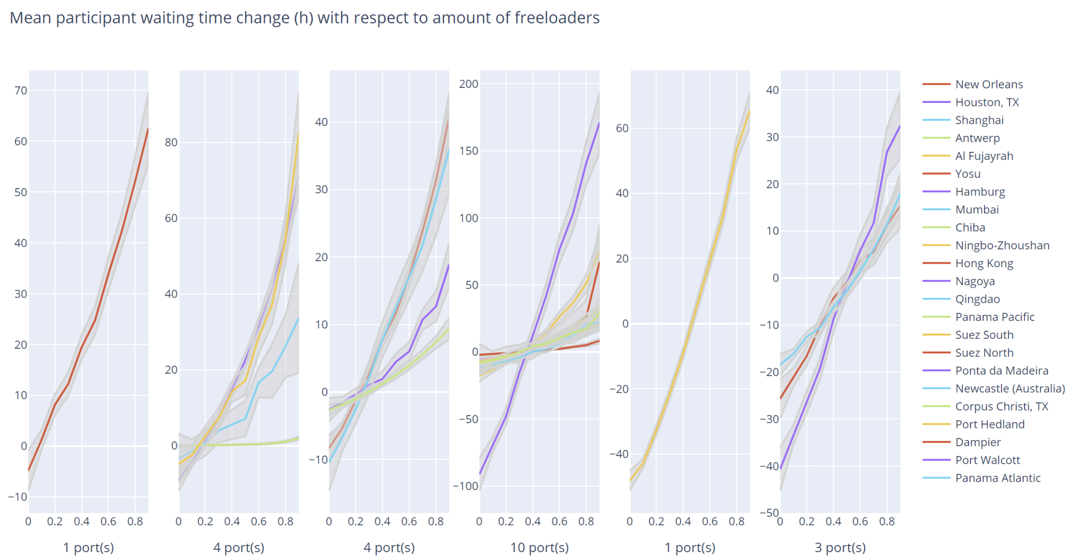


Figure 15: The participant waiting time change in hours plotted for each port so that the line presents the mean value and the grey area 95% confidence interval. The ports are divided into multiple figures based on the FL-% where the values exceed zero.

Figure 15 presents the mean value and 95% confidence intervals of the waiting time change for participating vessels. Ports are divided into figures based on when the values exceed zero, meaning that the waiting time in the anchorage is actually longer than it historically was. We can see that there is significant variation between ports. For example, in New Orleans, the waiting time change is positive already with 10% of freeloaders. In some ports, such as Dampier, Port Walcott, and Panama Atlantic, the resilience towards freeloaders seems to be much higher as the waiting time changes exceed zero after 50%. The majority of ports are located in the middle ground so the waiting times change becomes positive between 30% and 40% of freeloaders. On the other hand, most of these ports have moderate waiting time changes, less than 20 hours, except for Ponta da Madeira.

It is worth noting that even if the confidence intervals for the mean value are narrow, the results are widely distributed. This can be observed in figure 16 where the median and the quartiles of participant waiting time changes are plotted. Actually, there are 11 ports for which the waiting time does not change for most of the vessels. In addition, there are ports that do not benefit from the BVS at all or only minimally. On the other hand, examining medians reveals that for some ports, the resilience towards freeloaders may be even better than it seemed. For Dampier, Qingdao, and Panama Atlantic, the median value remains below zero until 90% of freeloaders.

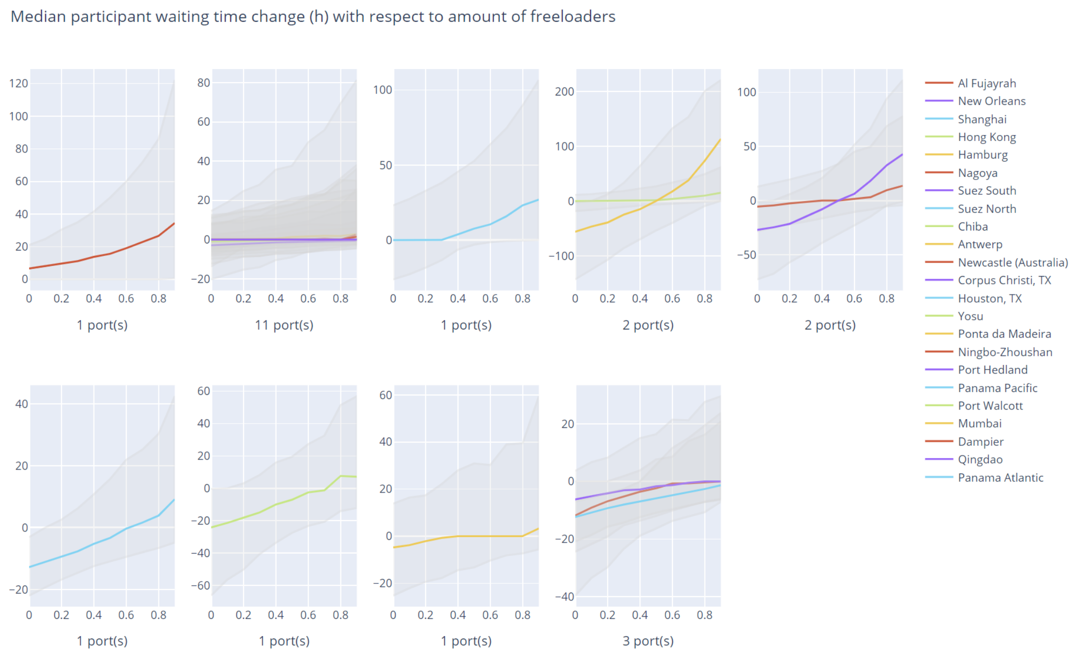


Figure 16: The participant waiting time change in hours plotted for each port so that the line presents the median value and the light grey area presents the first and the third quartile. The ports are divided into multiple figures based on the FL-% where the values exceed zero.

In general, it should be noted that many metrics presented in this section have very skewed distributions. When the histograms are examined in more detail, it can be concluded that for all the ports there are voyages that are not affected by the BVS and those for which the effect is significant. Therefore, using the mean value reveals the impact for those that are affected but might be overestimating the results in general. The examination of the waiting time change for participants and the BVS speed for each port can be found in appendix A.

Measuring the waiting time change relies on the port transit modeling. Therefore, it should not be used as the only metric when evaluating the impacts of freeloaders. This is why the number of overtakes per participant is presented in figure 17 where ports are divided in figures based on the FL-% where the values exceed one overtake per participant. This would mean that, on average, each participating vessel is overtaken once during a voyage by a freeloader. In general, it can be seen that for most ports the number of overtakes increases first rapidly and moderately slows down when the number of freeloaders is already high. Once again, there is considerable variation between ports. In Port Hedland and Ponta da Madeira, there are large numbers of overtakes. Additional 5 ports exceed one overtake per participant when the freeloader percentage is 20%. On the other hand, the largest group of ports is the last figure for which the values remain below one meaning that overtakes are rare even with a large number of freeloaders.

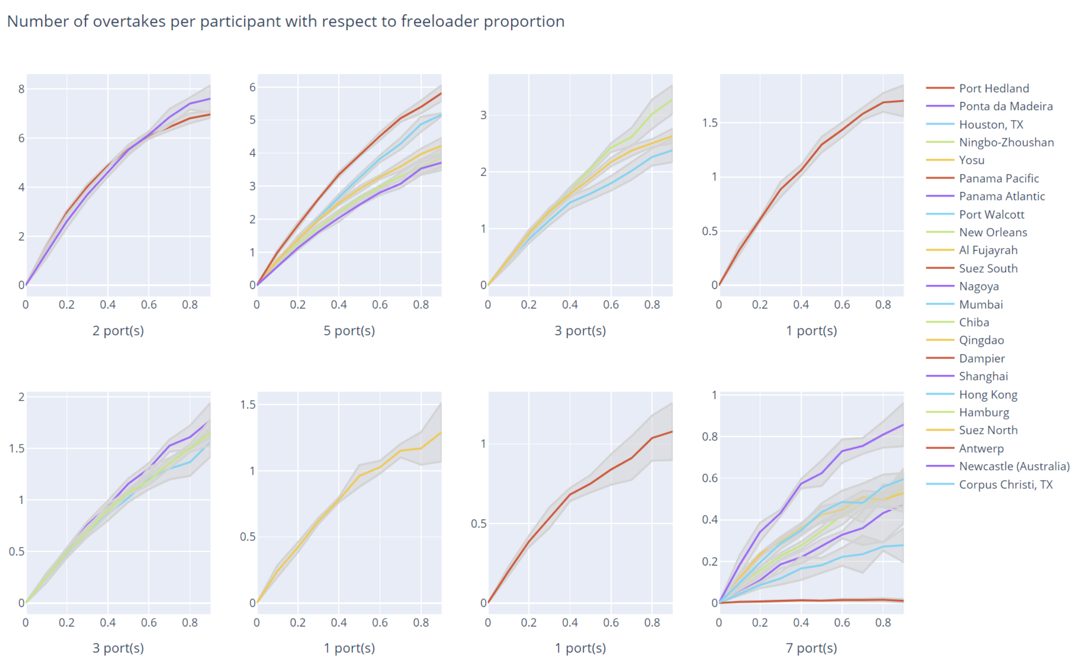


Figure 17: The number of overtakes per participant plotted for each port so that the line presents the mean value and the grey area 95% confidence interval. The ports are divided into multiple figures based on the FL-% where the values exceed one overtake per participant.

When the number of overtakes is scaled by the voyage distances, the results can be examined per 100 nautical miles. This development can be seen in figure 18. Interestingly, it can be noted that the growth is rather linear for all ports. In addition, the ports with the most overtakes are different than when the metric was presented per participant. Houston, TX and New Orleans have the highest number of overtakes per nautical mile even if they are not specially highlighted in figure 17.

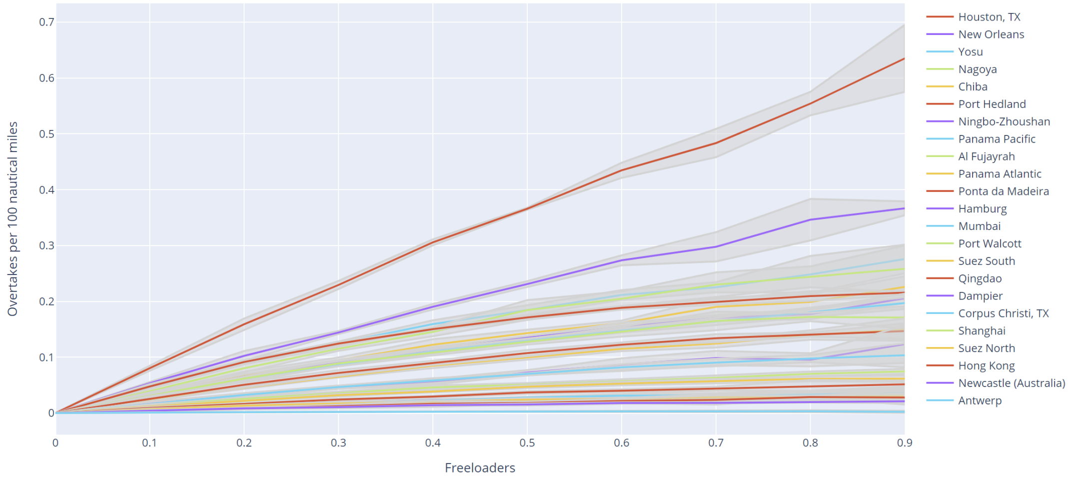


Figure 18: The mean and the 95% confidence intervals of the number of overtakes per 100 nautical miles for each port with respect to the freeloader proportion.

In figure 19, the number of overtakes per participant and the waiting time change are combined as a scatter plot. Colors present FL-% and the size of the dot reflects the total number of voyages to the corresponding port. Firstly, it can be seen that the relationship between the number of overtakes and the waiting time change is not linear and it varies between ports. For most ports, few overtakes do not yet prolong the waiting time significantly, but it accelerates for larger values of overtakes per participant. In general, this is realistic as ports may be operating using other than FCFS principal, or vessels might be served in groups due to tides or other factors.

In figure 19, the area, where participants can be expected to gain benefits from the BVS, is clearly below the zero line as the waiting time should not grow from the historical baseline. Preferably, it should decrease. This leads to the definition of the benefit areas. The strictest view for the number of overtakes is that only less than one overtake per participant can be tolerated. Therefore, the first benefit area is defined so that the waiting time change is below zero and the number of overtakes is below one. When this area is inspected, it is observed that all the ports can be found within it when the whole fleet is participating in the BVS. The values are presented in table 1. With 10% of freeloaders, 87% of the ports are still in the benefit area, and with 20% of freeloaders, half of the ports remain there. Interestingly, Dampier as a single port is within the strict area until 50% of freeloaders. The full list of the ports within benefit areas can be found in appendix B.

When only the participant waiting time change is used, a wide benefit area can be defined. In table 1, this area is defined as the third benefit area. Almost all of the ports are within this area for 10% of freeloaders, and for 30% of freeloaders, the number is still above 50%. However, the waiting time change is not as reliable as the number of overtakes due to ship-specific port transit modeling, but, at the same time, the relationship to the number of overtakes is not and should not be linear. Hence, both benefit areas should be taken into account when drawing conclusions.

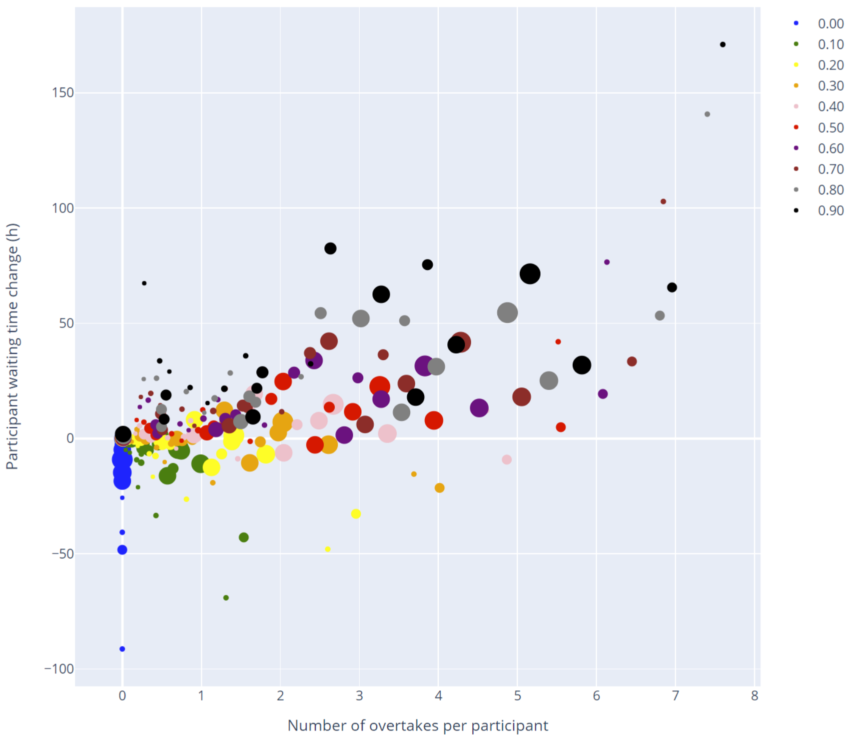


Figure 19: Number of overtakes per participant and the waiting time change are presented as a scatter plot. The colors present the proportion of freeloaders and the size of the marker the total number of voyages to the corresponding port.

			Freeloaders (%)					
Area	Waiting limit	Overtake limit	0	10	20	30	40	50
1 (ports)	0.0	1.0	23	20	12	8	1	1
1 (%)	0.0	1.0	100	87	52	35	4	4
2 (ports)	0.0	2.0	23	22	16	11	2	2
2 (%)	0.0	2.0	100	96	70	48	9	9
3 (ports)	0.0	-	23	22	18	14	4	3
3 (%)	0.0	-	100	96	78	61	17	13

Table 1: The benfit areas are defined for figure 19, and the number of ports and their percentage are presented. For all three benefit areas the waiting time change needs to be negative. The strictest benefit area 1 is defined so that the number of overtakes per participant needs to be less than 1. For the second area, the same constraint is loosened to less than 2 overtakes. With FL-% higher than 50% no ports can be found from any benefit areas.

Therefore, the number of overtakes should not be neglected altogether, and for this reason, a second benefit area is defined as a compromise. The allowed number of overtakes per participant is now less than two. This relaxes the constraint for overtakes, which takes into account that the impact of one overtake might be very small. The same ports are found within the area for 0% and 10% of freeloaders as for area 3.

The number of ports in the area for 20% and 30% of freeloaders is 70% and 48%. In conclusion, it seems that, in most ports, the vessels receive benefits from participating in the BVS when a maximum of 20% of the fleet are freeloaders. A little less than half of the ports still remain in the benefit area for 30% of freeloaders. On the other hand, some ports may tolerate even 50% of freeloaders.

A similar examination can be performed for the freeloader perspective as can be seen in figure 20. The waiting time change of a freeloader is now plotted against the number of overtakes per freeloader. Firstly, a similar relationship between these two metrics can be seen here as in figure 19. The relationship is not linear but more overtakes, of course, mean less waiting time in the anchorage. For all ports, it can be noted that the waiting times usually decrease significantly. However, only for a few ports, the changes are drastic. The number of overtakes grows from 2 to 5 per freeloader, but some exceptions exist as well. Once again, the destination port that the voyage is heading to has a great impact on the results.

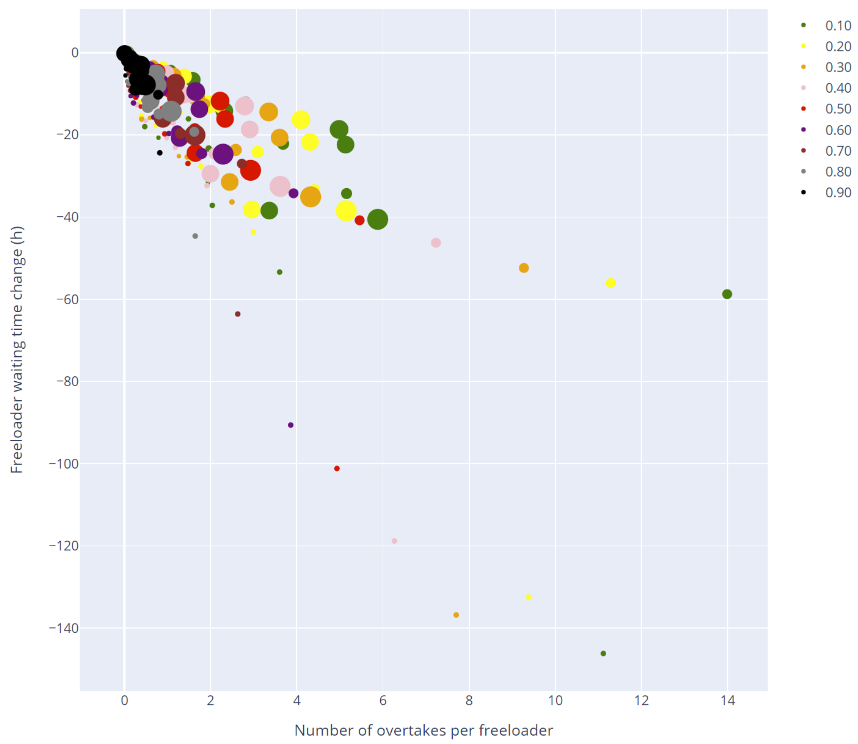


Figure 20: The number of overtakes per freeloader and the waiting time change of freeloaders presented as a scatter plot. The colors present the freeloader proportion and the size of the marker the total number of voyages to the corresponding port.

5.1.3 Queue development

One metric that describes the system behavior is the queue length. In figure 21, the mean value and the 95% confidence intervals are presented for the proportion of the queue length over the original average queue. The mean queue lengths seem to converge to 1.0, meaning that while the number of freeloaders grows the system approaches the historical state. With no freeloaders, queues are at least 10% shorter in all ports. For some ports, such as Port Hedland and Port Walcott, the queues are less than 50% compared to the historical data. It is noteworthy that the queues are in general lower whenever the BVS is used, even if most of the fleet would be freeloaders.

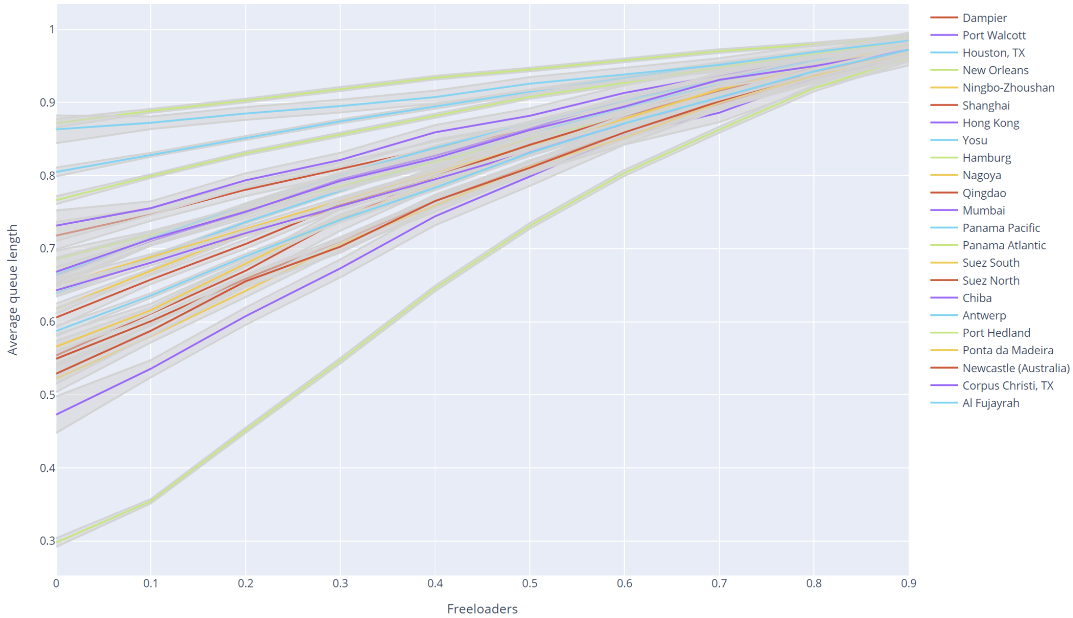


Figure 21: The mean value and the 95% confidence intervals of the queue length for each port with respect to FL-%.

In addition, the daily average queues are examined for each port. In figure 22, Port Hedland and Hong Kong are presented as examples while the rest of the ports can be found in appendix C. The results of daily queues also show that the queues approach the historical case when the number of freeloaders increases. Once again, there are large differences between ports. For Port Hedland, the impact of freeloaders can be seen clearly, and even if the queues follow the same trend, the magnitudes differ. In Hong Kong, the differences can hardly be seen but the queue is most of the time very short.

The queues are generally shorter when the BVS is used because the arrivals of the participating vessels are synchronized. The impact of this can be seen even if the number of participants would be small compared to the total number of voyages. However, the results depend on the estimates of the target inter-arrival times. These values are computed for each port using the historical inter-arrival times, and no additional information about the service rates is used. This means that there is considerable uncertainty, which is most likely reflected in the results. This might explain a part of the differences between ports. When the target inter-arrival time has been successfully estimated, the impact of the BVS can be seen realistically. This might be one factor to explain why good results can be obtained in Port Hedland using the BVS and not in Hong Kong.

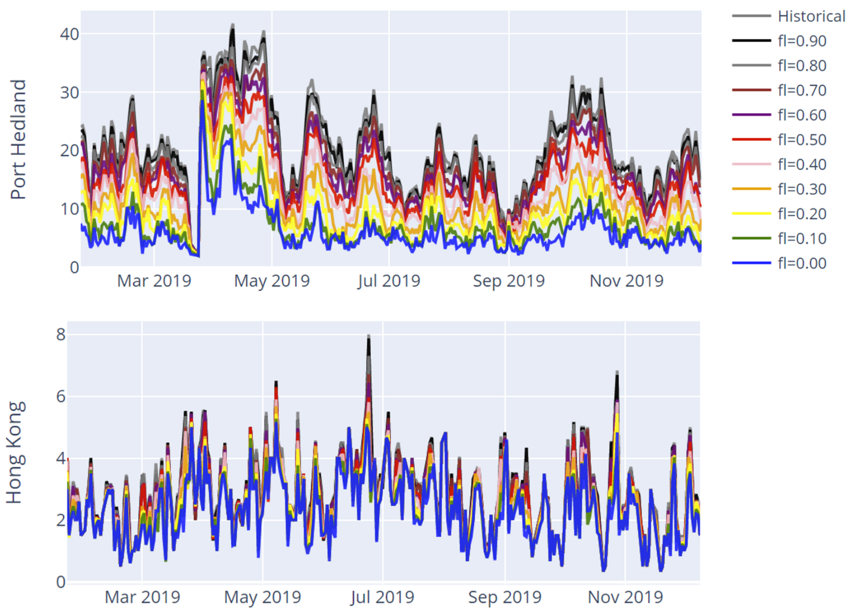


Figure 22: Daily average queues of Port Hedland and Hong Kong for all FL-% values as well as the historical baseline. Daily average queues of all of the ports can be found in appendix C.

5.2 Voyage analysis

In addition to the port-wise analysis, the results are examined from the perspective of single voyages. The aim is to shed light on the features of a voyage that benefits from participating in the BVS. The analysis is completed on voyages that were acting as participating vessels at least in one replication for all freeloader proportions. It should be noted that the number of voyages is still high in this case, 235 326 voyages in total due to different FL-% values. Therefore, this analysis is somewhat preliminary, and further ideas and approaches are presented in section 6.3.

In this part of the analysis, the attention is on the voyages and their features. This is why the metrics are computed voyage-wise so that if the voyage had been a participant in multiple replications, the mean value is used. All the metrics are examined but, as many of them are consequences of the decreased speed, more attention is paid to the BVS speed, the potential savings, and the waiting time change. In addition, static information about the voyage is included. This means a voyage distance, an original average speed, and a draft. Furthermore, JIT savings potential, which indicates the potential economical savings achievable by JIT arrival, is included.

5.2.1 Distributions of the metrics

The distributions of the metrics computed for the voyages are examined, and the related histograms can be found in total from appendix D. Figure 23 presents the distribution of the BVS speed so that the bottom figure shows the entire distribution and the top is a zoomed-in version to show the differences in more detail. It can be observed that almost 30% of the voyages are not affected by the BVS, and they use the normal service speed. This is an observation that can be done for all of the metrics. There is a large number of voyages that carry on as they used to regardless of the BVS. Although, the reason may be that for these vessels there is no congestion in the first place. The other group has a large variation and some may be impacted drastically by the BVS. Figure 24 shows the same for the waiting time change in the anchorage. There is a high peak of voyages for which the queueing time does not change. On the other hand, it can be seen that the proportion of freeloaders affects the distributions even if the impact may be hard to see in the big picture.

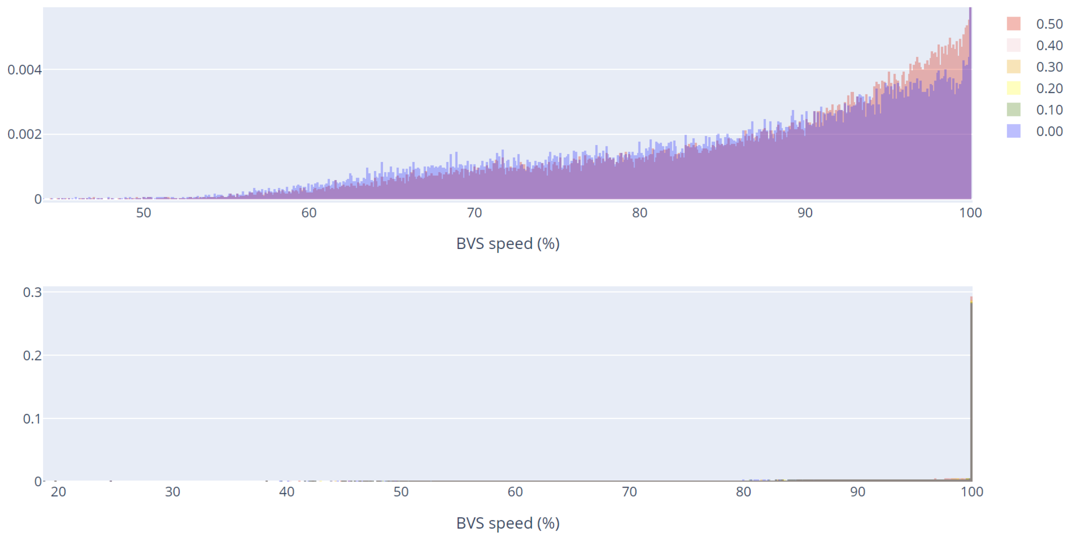


Figure 23: Overlayed histogram of the BVS speeds for different freeloader proportions. The top figure is a zoomed-in modification of the bottom figure only with FL-% values 0% and 50% to illustrate the differences in distributions.

As mentioned above, many of the metrics are results of the BVS speed, and hence, for example, fuel consumption has similar peaked distribution. Metrics that show somewhat differing results are the number of overtakes and the savings potential. Figure 25 presents the overtakes per participant for each FL-%. Note that when there are no freeloaders, there are also no overtakes. The distributions are left skewed and the tail to the right grows as the number of freeloaders increases. It should be noted that with half of the fleet participating in the BVS, 45% of the participants are not overtaken at all during their voyage. However, in this case, a small number of vessels are overtaken over five times and the number can grow as large as 30 overtakes.

The savings potential is computed from the fuel consumption and the prices of each fuel type. Figure 26a shows the savings for freeloader proportions 0% and 50% as well as the JIT savings potential for the corresponding voyages. The last metric is computed so that the vessel would arrive exactly at the same time as the port transit occurs. Therefore, this aims to present the optimal savings that can be obtained by reducing speed. However, as the fuel consumption for JIT arrival is computed using simulated weather conditions, it is possible that the JIT savings are not actually better than the savings from the BVS, or they even become negative.

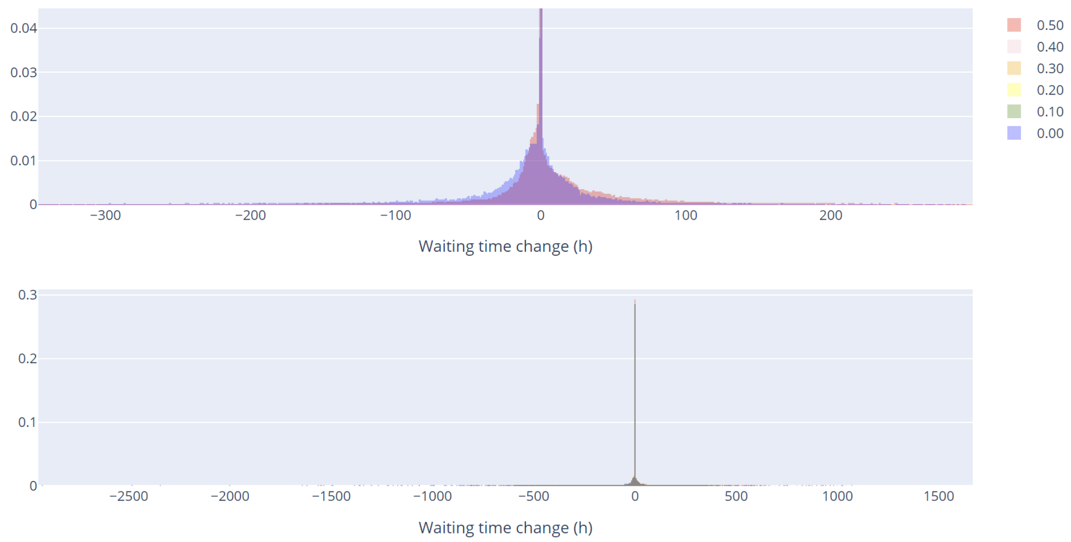


Figure 24: Overlayed histogram of the waiting time change in hours for different freeloader proportions. The top figure is a zoomed-in modification of the bottom figure only with FL-% values 0% and 50% to illustrate the differences in distributions.

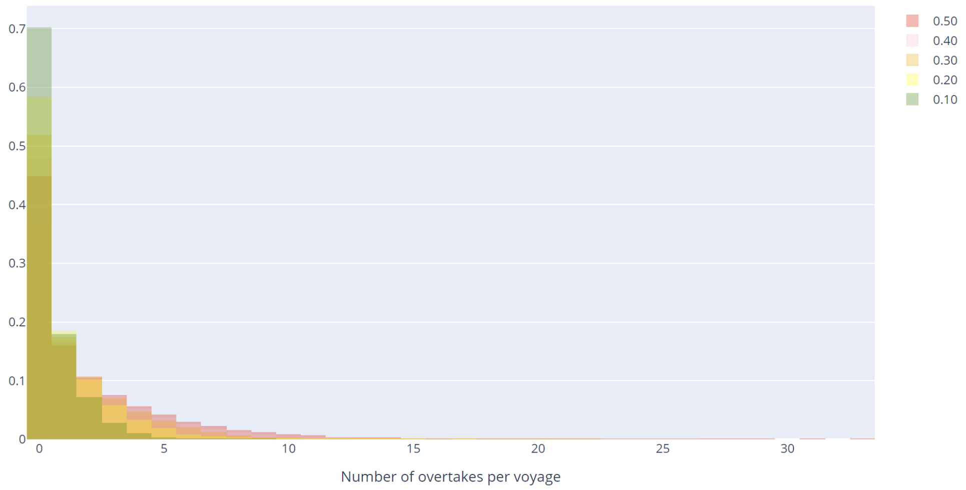
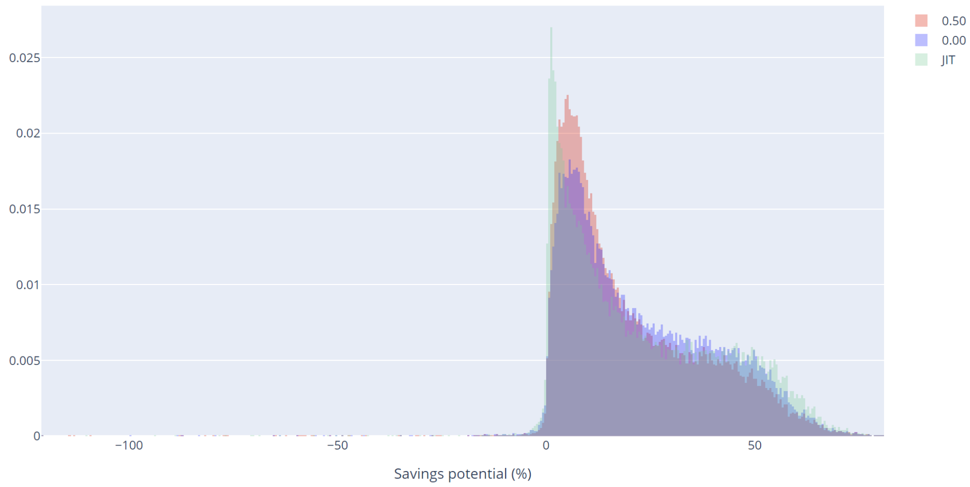
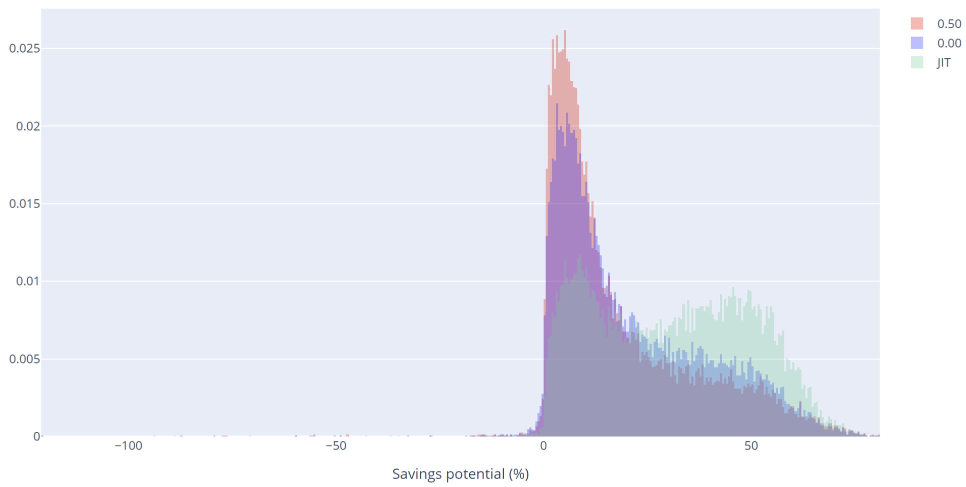


Figure 25: Overlayed histogram of the number of overtakes per participant for different freeloader proportions.

In addition, the late arrivals create a conflict in the results. Figure 26a shows clearly that the peak of JIT arrivals is worse than the simulated results. The tail to the right is slightly longer but overall it does not seem that the JIT savings are better. This is due to the mentioned late arrivals. It has been established that the simulation model has a built-in problem of producing arrival times that take place later than the original port transit time. This is partly a behavior that is wanted from the BVS, but it creates a bias for the results that can be seen clearly here. When a vessel arrives late it is possible for it to use a lower speed than it would use for JIT arrival. Hence, the JIT savings potential can be lower. Figure 26b presents the same savings potential but without the late arrivals, and now it can be seen that the JIT savings are indeed better. However, the shape of the distribution becomes almost bimodal. The reason might be that the voyages that arrive late have similarities and they are missing from this examination.



(a) All voyages



(b) Voyages without late arrivals

Figure 26: Overlayed histograms of the savings potential in $ for FL-% values 0% and 50%, as well as the JIT savings potentials for the corresponding voyages. In figure 26a, all voyages are included, but in figure 26b, the late arrivals have been removed.

5.2.2 Bivariate dependencies of voyage features

The above examined three metrics and some static features of the voyages are analyzed from a bivariate point of view. Figure 27 presents pairwise scatter plots so that the color of the marker reflects the proportion of freeloaders. The impact of freeloaders can be seen clearly in the number of overtakes per participant. For the waiting time change, the BVS speed, and the savings potential some variation of colors can be noted but, as there is considerable variation within one FL-%, points are mixed.

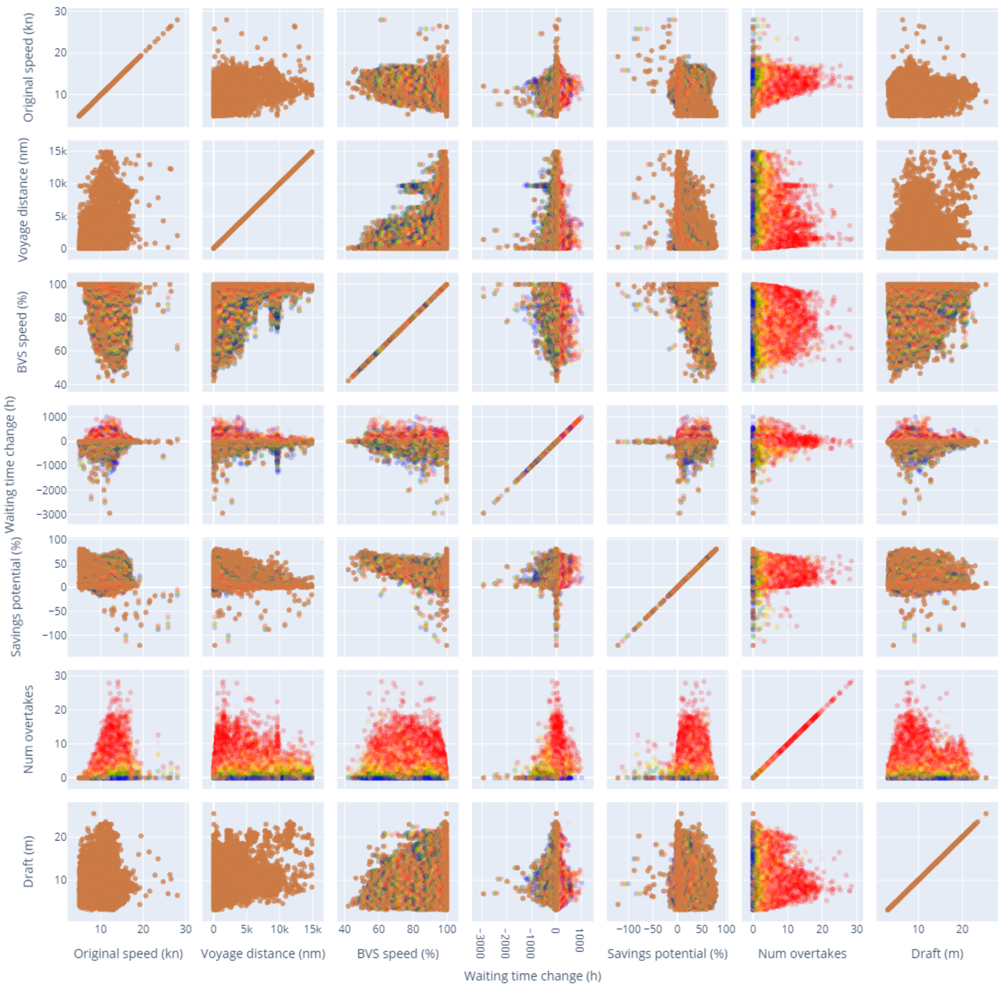


Figure 27: Scatter matrix presenting some static features of voyages and results of the simulation. The colors present the freeloader proportion such that blue = 0%, green = 10%, yellow = 30%, pink = 40%, and red = 50%.

The possible correlation between examined metrics is evaluated based on figure 27. The BVS speed seems to have an impact on potential savings, as can be expected. With lower speed, potential savings tend to be larger, but due to simulated weather conditions, there is variation. Rather unexpectedly, the largest variation in potential savings can be seen with speeds close to the original average speed. Freeloader overtakes and different waiting times occur across the whole BVS speed range. The largest variation in waiting time change is observed when there are very few overtakes. With a high number of overtakes the waiting time change tends to be around zero. Negative savings potential values seem to be correlated with vessels that have not been overtaken multiple times and whose waiting time has not changed.

Static features of voyages, such as original speed, distance, and draft of a vessel, do not seem to be correlated with each other significantly. In particular, the original average speed does not seem to have a great impact on the BVS speed as different speed reductions are observed on the whole original speed range. One might say that the largest speed reductions are not observed with the lowest and the highest speeds. A similar observation applies to the waiting time change, and the number of overtakes, as the vessels with very low or very high original speeds are not overtaken as often, and their waiting time is not changed. Interestingly, it is observed that the negative savings potentials mostly occur with exceptionally high speeds.

Voyage distance seems to have some effect on the results as well. Larger BVS speed reductions are actually observed more prominently in shorter voyages, which is surprising. There are generally more overtakes during shorter voyages, and the range of the waiting time change is wider. However, there are freeloader overtakes on all voyage distances. Potential savings are evenly distributed, but in general, it seems that lower potential savings are observed within the longest voyages.

A draft may indicate whether the voyage is in laden or in ballast conditions, or it may differ between different vessel types. It seems that vessels with higher drafts often do not have as small values for the BVS speed as vessels with lower drafts. However, there is considerable variation. With respect to the waiting time change and the number of overtakes, the results are similar to the original average speed. The most variation in the waiting time change and the most overtakes are observed with a lower draft of 10 meters. Potential savings do not seem to have significant dependence on the draft.

5.2.3 Impact of freeloaders to voyage-specific metrics

Due to a large number of voyages, a more detailed analysis of the impact of the number of freeloaders on single vessels would deserve its own analysis. Therefore, this part of the analysis is only shortly examined here. The difference in the BVS speed, the waiting time change, and the savings potential from no freeloaders to 50% are computed. This means the absolute change in the metric when the environment is modified from no freeloaders to half of the fleet participating in the BVS. These values are presented as histograms in figure 28. It can be observed that there is roughly one-third of the voyage not impacted by freeloaders.

Figure 29 present the same values but now with respect to the value of the metric when every vessel is participating in the BVS. In addition, different ports are marked with different colors, but it seems that the voyages are quite evenly distributed regarding this. Surprisingly, the figure reveals that the voyages that are not impacted by freeloaders can be found across the different BVS speed values. This implies that there are voyages that benefit from the BVS and remain to do so even with freeloaders. However, for the vessels that are not impacted by the system from the beginning, the speed is not modified when FL-% increases.

The waiting time change is an interesting metric as the data plot forms a cross. There is a group of voyages that have no waiting time change originally but are affected by freeloaders, usually so that the waiting time increases. On the other hand, there are voyages for which the waiting time prolongs almost linearly depending on the waiting time change with no freeloaders. This would mean that the waiting time grows similarly regardless of the starting value. Savings potential seems to be more grouped by the destination port than the other metrics. Savings potential increases for some voyages but the majority stays the same or the value decreases drastically.

In addition, the bivariate dependencies of these absolute changes and features defined in section 5.2.2 are examined in more detail as a scatter plot, which is presented in appendix E. In conclusion, it seems that there are voyages that are more tolerant of the freeloader proportion increase. On the other hand, there are vessels that suffer greatly from the increase meaning that they might have also a higher tendency to become freeloaders. The reasons behind these differences should be researched further, and the hypothesis should be verified with a more rigorous approach.

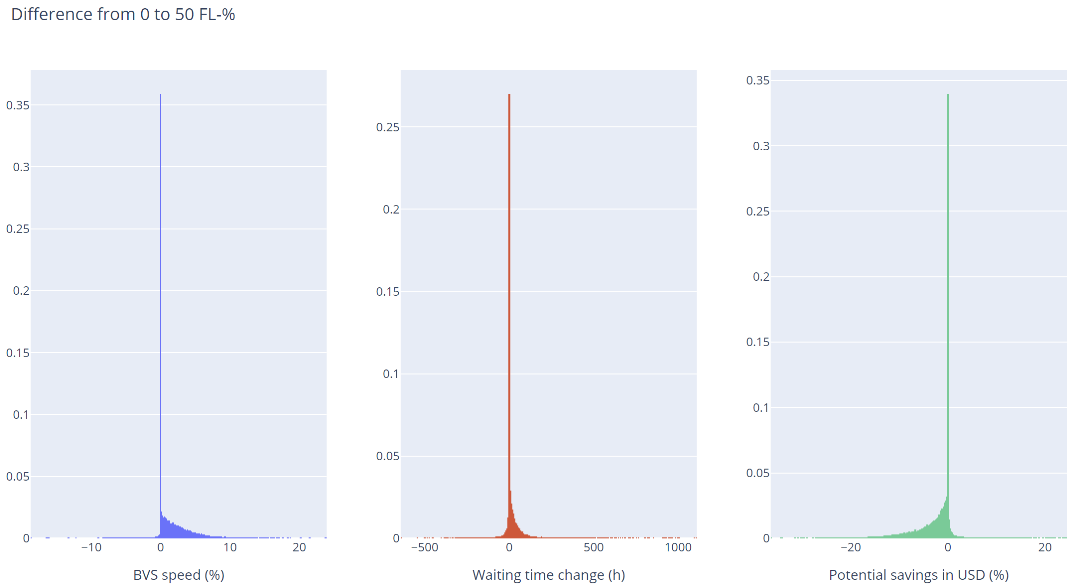


Figure 28: The differences from 0% to 50% of freeloaders are computed for the BVS speed, the waiting time change, and the savings potential in \$. The results are presented as histograms.

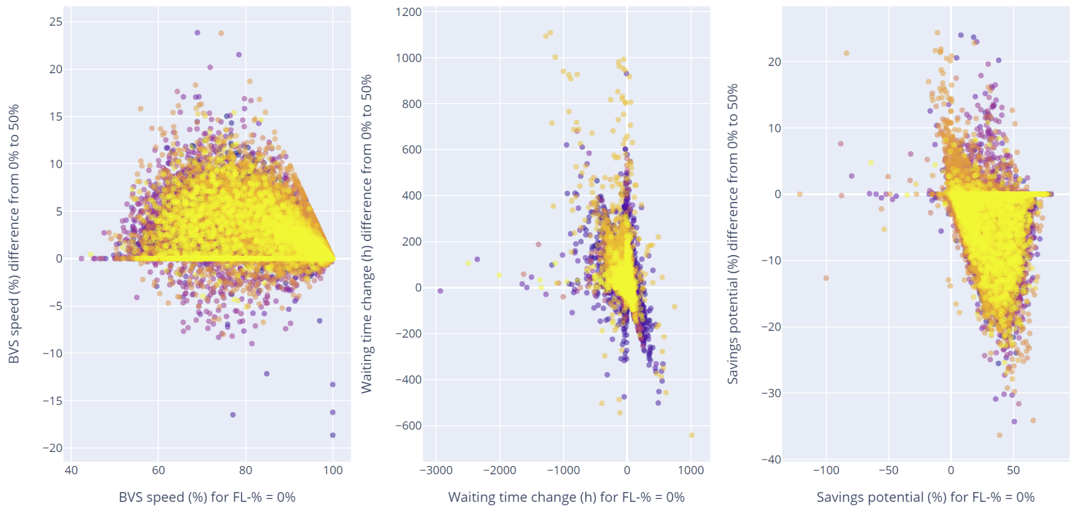


Figure 29: The differences from 0% to 50% of freeloaders are computed for the BVS speed, the waiting time change, and the savings potential in \$. The results are presented as scatter plots against the metric value when there are no freeloaders, and different destination ports are plotted using different colors.

6 Conclusion

6.1 Summary of the study

The Blue Visby Solution is a technical platform and a contractual framework to address the operational energy efficiency of cargo vessels. Energy efficiency has a growing importance in the shipping industry, which needs to work toward global emission reduction goals. The International Maritime Organization has established regulatory measures for both technical and operational energy efficiency, which increases the need for research in the field as well as practical innovations. The future zero-carbon fuels and energy systems are the main interests in the decarbonization of the shipping industry, but the operational measures can be used sooner for the current fleet to produce emission reductions. The BVS aims to synchronize the arrival times of vessels heading to the same destination port so that the queues in anchorage are reduced and idle time used for waiting will be diminished. This makes it possible for vessels to use lower speeds and, in this way, reduce fuel consumption and emissions.

The BVS has been studied as a system in two Proof-of-Concept studies. The first one has been published by Sung, Zografakis, and Nielsen (2022), and the second has been performed by Blue Visby Consortium coordinated by Napa Ltd. This study directly continues from the previous work and builds on the simulation model created for the POC2. The assumption that is addressed in this study is that previously the whole fleet has been assumed to participate in the BVS. This has resulted in promising conclusions regarding fuel consumption reductions and potential savings. However, it is clear that this is a very unrealistic scenario, and, to be able to evaluate the benefits of the BVS and possible future development needs, it is important to examine the behavior of the system when a part of the fleet follows the BVS and the other part is acting as freeloaders that operate using their normal service speeds. Therefore, the research question of this study is to find the proportion of freeloaders that the system can bare so that it is still beneficial for the participants.

As mentioned above, this study is an extension of the work done in the POC2. AIS data from the year 2019, including 23 different ports, is used to simulate voyages. Participating vessels' arrival times and speeds are updated according to the BVS algorithm, and fuel consumption is computed using the historical voyage track, simulated weather data, and ship-specific performance models. The model is extended in three ways. Firstly, a part of the fleet is randomly assigned as freeloaders. Freeloaders are assumed to use a historical track, speed, and arrival times. Secondly, the BVS algorithm is extended to trigger the update process when a freeloader arrives at the anchorage. This corresponds to a situation where the queue unexpectedly grows and the ongoing voyages react to that change. Lastly, the port transit modeling is developed so that the transit time of each vessel is recorded. The purpose of this development is to be able to understand how a freeloader overtaking a participant affects the queueing time.

The extended simulation model is run for different experimental scenarios. The freeloader proportion is varied from 0% to 90% with 10% step size. As the freeloader selection is performed randomly, each scenario is run multiple times. The fuel calculations are computationally intensive, and for these practical reasons, those are performed only until 50% of freeloaders. The system is analyzed in terms of the sensitivity under the freeloader selection, and the warm-up and cool-down periods of the simulation are determined. The final results are analyzed from the perspective of ports and the freeloader proportions. A variety of metrics are defined to understand the behavior of the system and consequent impact to the participants. Conclusions are drawn using, for example, the savings potential, the number of overtakes per participant, the waiting time change, and the average queue length. In addition, the reasons behind certain behaviors are examined from a perspective of a single voyage.

6.2 Main results

We observed that the BVS algorithm results in speed reductions for participants even when most of the vessels would be operating normally as freeloaders. This is an expected behavior, as the BVS aims for reducing the time in the anchorage by slowing down the participants regardless of the reasons behind the queues. When only a part of the fleet participates, the queues grow generally longer than what they could be with full BVS participation but, remarkably, remain shorter than without the BVS. This means that when the growing queue is observed, the ongoing participants slow down. However, the average speeds of the participants are higher when there are more freeloaders. The mechanism behind this end result is that the freeloaders are observed so much later than what they would be observed as participants that the prediction of the queue does not work anymore. As a result, the speeds are higher at the beginning of the journey, as it seems that there would not be as long queues. Consequently, average speed, fuel consumption, CO_2 reduction, and savings potential are not very good indicators of the impact of freeloaders.

Metrics that can be used to evaluate the impact on the benefits are the number of overtakes and the waiting time in the anchorage. Using these two metrics, three benefit areas are defined. The first area is defined so that the waiting time should not grow from the historical queueing time, and the number of overtakes per participant should be below one. The third area has only the first condition, and it relays heavily on port transit modeling. In addition, a second area is defined as a compromise so that the constraint of the first area is relaxed to two overtakes per participant. All of the ports are within the strict benefit area when there are no freeloaders. With a freeloader proportion higher than 50%, no ports are located in any of the areas. As the number of overtakes is a more reliable metric than the waiting time change but the impact of an overtake is not straightforward, the second area can be used to evaluate the benefits. In conclusion, the BVS can tolerate 20% of freeloaders in most of the ports but almost half of the ports can tolerate 30% of freeloaders.

As mentioned above, the average queue lengths are shorter in all ports when the BVS is used even in a fraction of the fleet. It is noteworthy that when the proportion of freeloaders approaches 100%, the queues converge to the historical queue lengths. Additionally, it is observed that the distributions of the chosen metrics are often skewed and there is a large group of vessels that is not impacted by the BVS. Their speed and, hence, also fuel consumption remain the same. These voyages are often not impacted by the freeloaders, but it should be noted that these are not the only vessels in that regard. There are voyages that can tolerate the environment with freeloaders better, whereas some voyages suffer from a great impact. This raises an interesting future research question. The vessels that are more drastically impacted by the freeloaders might have a higher tendency to become freeloaders themselves. The reasons behind this behavior should be examined more in detail to understand possible voyage features that affect the tolerance toward freeloaders.

The contribution of this work is relevant to the Blue Visby Solution. Although, it is significant that the BVS can systematically reduce average queues and produce fuel savings, the amount of tolerated freeloaders is not as high as would be beneficial. The most conservative view is 20% meaning that at least 80% of the fleet should be operating within the BVS. This creates a need to investigate cooperation opportunities with ports and develop technical aspects of the system so that the robustness can be increased. Additionally, this work provides more insight into port transit modeling, which has not been utilized in previous studies. The analysis of the results opens up new research questions and observations about the distributed benefits between vessels and the number of late arrivals produced in the system.

6.3 Limitations and further developments

This work nor the BVS as a system can avoid biases and weaknesses fully. One important bias in this simulation study has already been discussed in section 5, which is the late arrivals, and their impact on the results. It is observed that there is a large number of vessels that arrive later than their original port transit time, which results in that the used speed can be lower than it would be with JIT arrival. This has a false positive reflection on the results, meaning that the fuel consumption reduction and potential savings seem to be lower than what they maybe should be.

The second bias that has been discussed in the context of filtering the results is the voyages in the dataset that use speeds outside of the defined speed ranges. These may include voyages that have so low average speed that it is likely that the data has an error, or the data is mistakenly interpreted as one sea passage. Even if these voyages are not used in the analysis of the results, this indicates that the data is not always reliable and includes problematic voyages. The preprocessing of the data should be developed so that at least the vessels with unrealistic average speeds could be filtered out from the beginning. However, this may result in a different bias as the total number of voyages would in that case decrease.

The simulation is implemented so that the recorded tracks of the vessels are used but the speeds are modified. For the final results, the weather conditions for the new time at a historical position are simulated. This does not consider that the original speed may have been dictated by the weather, for example, to avoid storms. In addition, the path might have been chosen differently for the new speed. Consequently, there are voyages for which fuel consumption increases drastically. This is a clear weakness of the chosen method of simulation but one that does not have a straightforward solution. Weather routing could be considered for modifying the tracks of the vessels but this is not likely to produce more accurate results, especially because the computational load would be even higher.

One obvious development is the target inter-arrival time estimation. The current method is simply to observe the historical inter-arrival times and conservatively choose the target value from the distribution. This creates a bias in the results, especially when the ports are compared to each other. If the target is chosen close to the actual service rate of the port, the results can be expected to be good as the synchronization of the arrivals will match the operations in the port. If there are queues in anchorage, the BVS can then produce clear benefits. On the other hand, if the port is currently overloaded and the inter-arrivals are very small, the resulting target will also be smaller than the actual service rate. In this case, the BVS will not be used in an optimal way. If the estimation is too large, the BVS will slow down the vessels too much, which may be part of the reason for many late arrivals in some of the ports. Hence, it is of utmost importance to be able to estimate the target inter-arrival accurately, which might require cooperation with ports or more advanced analysis for the estimation. For example, both statistical and machine learning approaches could be taken to accurately model the service rates of the ports from available data.

In this study, the freeloaders are chosen randomly. This a useful and important baseline for future research, but it should be noted that this might not be a realistic case and, hence, might impose a bias on the results. For example, it is possible, and even observed in this study, that some voyages tolerate freeloaders more than others. These others may have a higher tendency for becoming freeloaders, which is also an interesting question to research further. Additionally, the market environment should be taken into account as it is possible that the vessels would be participating based on the operating company or that some companies have arrangements with ports about the transit times. Overall, it is possible that the results are affected by random choice, and other aspects could be explored in the future.

One of the most significant additions to the model created in the POC2 is the ship-specific port transit modeling. As discussed before, the approach taken is rather simple. It aims to preserve the historical port transit order as well as possible, but exceptions are made when a freeloader overtakes a participant or when a vessel misses its original port transit time. This modeling directly creates the waiting time metrics. On the other hand, this makes the metric less reliable as the modeling is not accurate or based on data about the ports' behavior. Rather, it is a reasonable estimate, which means that certain reservations about the results should be held. As this is not a relevant aspect of the real-time usage of the BVS, further research on the matter is not necessarily important, but if further analysis on the freeloaders should be made, the port transit modeling should be re-evaluated.

As it has been concluded, the BVS behavior metrics are not good indicators of the freeloaders' impact. In addition, the waiting time change is based on the port transit modeling. Therefore, the evaluation of the impact of the freeloaders on the benefits of a participant is rather difficult. The question at the end is how many overtakes are too much for a participant. Some ideas can be concluded from the waiting time change, but for a more comprehensive understanding of the benefits, more detailed monetary calculations should be completed. This could additionally include an evaluation of the economic impact of the prolonged sea passage time as well as the benefit-sharing framework that is the second part of the BVS.

The triggers of the BVS algorithm are extended in this work so that the arrival of a freeloader also triggers the BVS update. Firstly, this trigger could be extended even further, so that the update would be triggered by any factor that unexpectedly increases the queue. These kinds of disruptions could be strikes in the port or weather conditions. This clearly requires more advanced data input to the system. Secondly, the question of whether the event is unexpected or expected is important when considering the triggers. The current version of the BVS observes the queue and the ongoing voyages, and using this information computes the Blue ETAs. This means that arrival of a participant is an expected event, and does not trigger a BVS update. The arrival of a freeloader and a start of a new voyage are unexpected or something that is not known beforehand; therefore, a BVS update is triggered. This same logic does not directly apply to the port transit as a trigger. If the time between two port transits is rather close to the target inter-arrival time, the event is actually expected. This means that the BVS update should not be performed as it either is unnecessary or increases speeds, which is most likely not desirable. The triggering might be relevant if the time of the port transit is exceptional and in this way unexpected. This line of development should be investigated further and implemented in the BVS algorithm.

Currently, the queue in the anchorage is not actually predicted, it is only concluded from the ongoing voyages. This means that even with all of the vessels participating in the BVS, the speeds are at the beginning of the journey too fast, as the journeys that start later but arrive earlier are not yet observed. This mechanism is even more emphasized when the freeloaders are added as they are only observed when they arrive at the anchorage. Therefore, the system would benefit from a queue length prediction component. In the simplest way, this could be implemented so that a dynamic buffer would be added to the computed queue. This would mean that when a long voyage starts the arrival time would be defined with the expectation that an X number of the new voyages, which are not yet observed, will arrive at the anchorage before the arrival. The size of the buffer could depend on the distance to the port. More advanced approaches could and should be explored. The prediction should be port-specific, and, most likely, should be connected to the port transit modeling as well as the target inter-arrival time.

In addition, the ability to react to freeloaders could be increased by detecting them before their arrival at the anchorage. This could be possible through AIS data that is available already during the voyage. Detection requires further analysis as the identification of the ongoing voyages is not straightforward as the destination port might not be known beforehand or it might change. Consequently, this would increase the ability to predict the queue length accurately and might give additional benefits to the participating vessels. In general, it is assumed that the solution to long queues or traffic in the port is to slow down the ongoing voyages, which will decrease the waiting time in the anchorage. However, if the reason for the long queue is freeloader overtakes, decreasing speed might not be the optimal solution. Different reactions to the freeloader's impact should be evaluated from the perspective of fuel consumption.

The development of the BVS algorithm started from an optimization problem that is sequentially solved and ended up with a heuristics approach. When the algorithm is further developed, it might become relevant to re-evaluate this decision. For example, if a queue length prediction is added to the system and the target inter-arrival time estimation is developed, the optimization might bring new benefits and the dynamics of this approach would change. When more information about the system could be included in the problem formulation, the optimization of the arrival times could find better solutions than what the heuristics can, especially when the target inter-arrival cannot be fulfilled. This is, of course, also a question of practicality as the benefit that could be gained in this way can be so small that neither the work nor the computational cost would be worth doing.

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A Port-specific examination of the distributions of the metrics

The distributions of the metrics were examined on a port-specific level. Figure A1 presents the BVS speeds as a proportion of the original average speed. This means that the values close to one indicate minor or no impact from the BVS. It can be seen that the results differ significantly between ports. There are ports where there are clear speed reductions and benefits from the usage of the BVS. On the other hand, there are ports where the impact is minimal, for example in Antwerp almost 90% of the voyages use the original speeds.

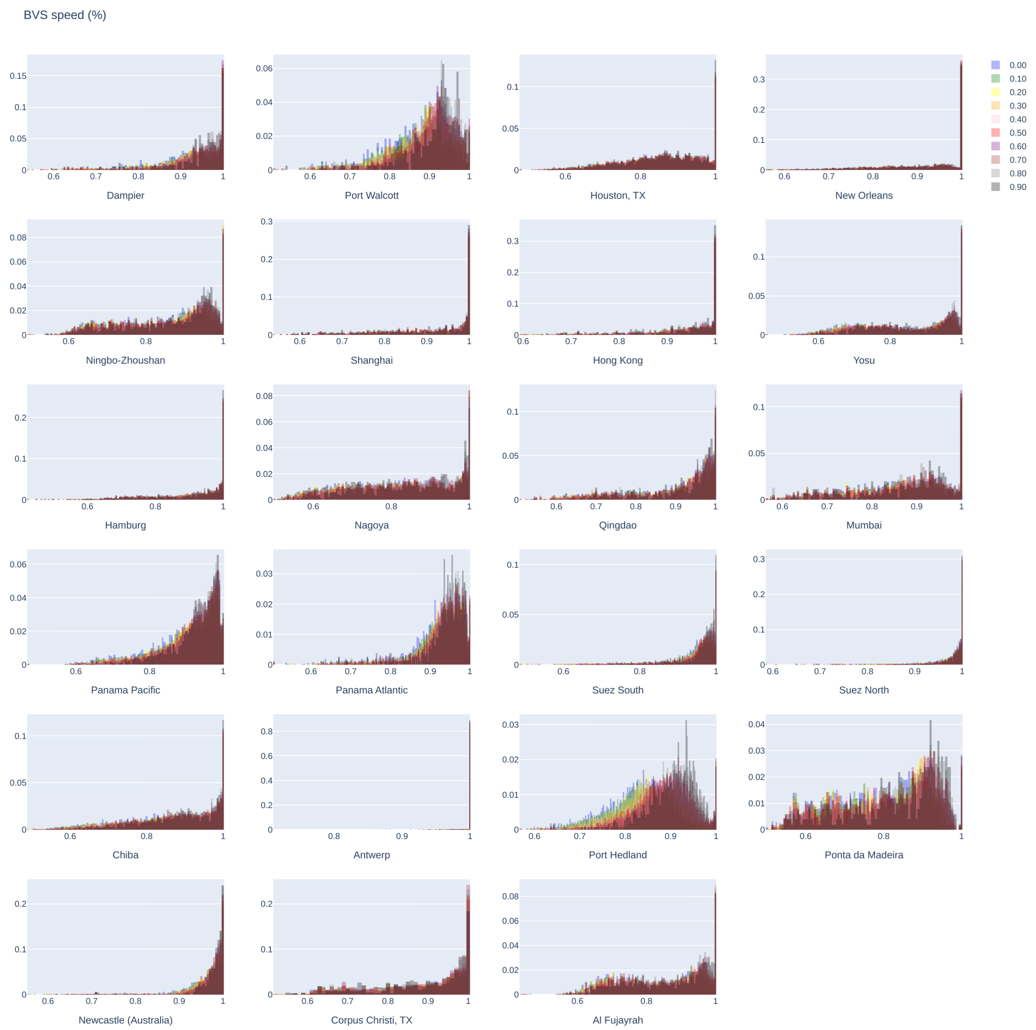

Figure A1: Distributions of the BVS speeds for each port so that the different freeloader proportions are presented as overlayed histograms.

Consequently, similar results can be seen in other metrics, such as the BVS delay and fuel consumption. In figure A2, the participant waiting times are plotted for each port. There is a peak at zero for all ports, meaning that the queuing time at the anchorage does not change. However, there are vessels that are affected drastically by the usage of the BVS.

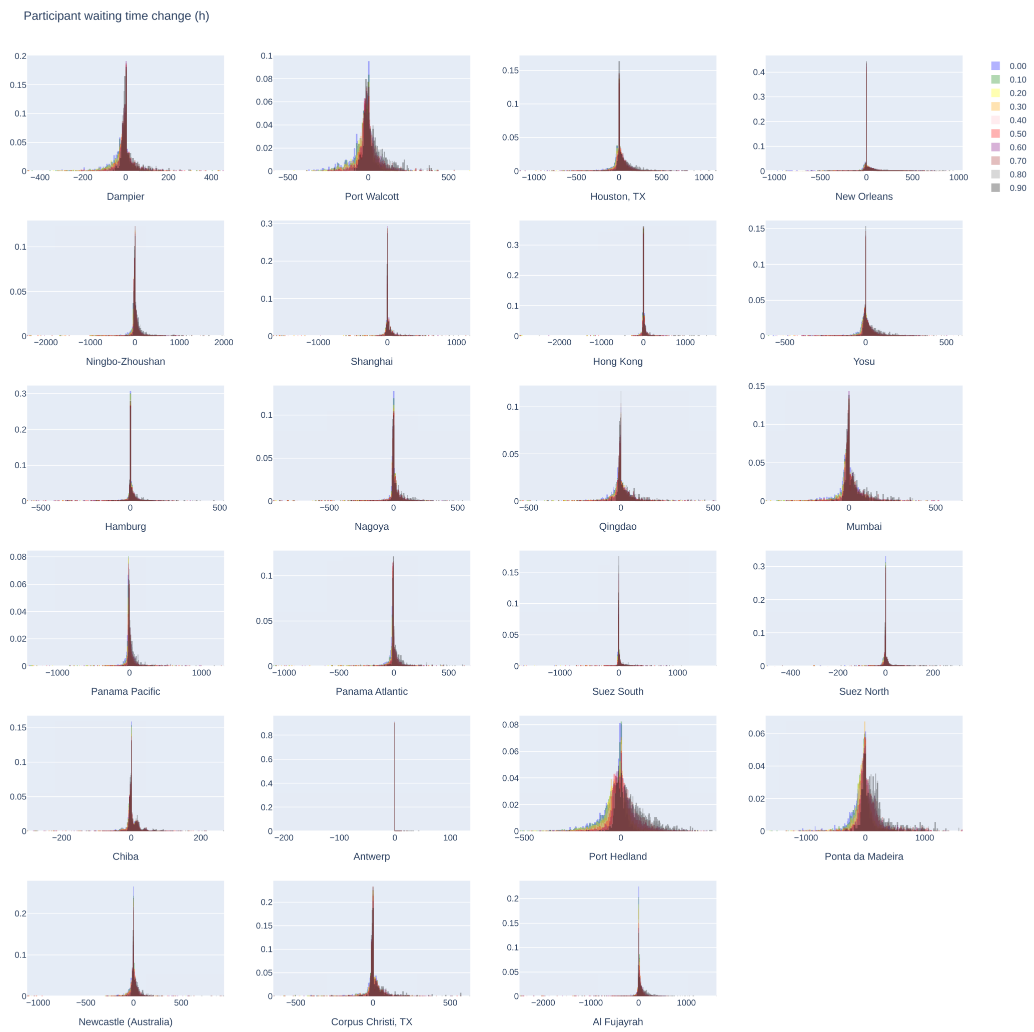

Figure A2: Distributions of the participant waiting time changes for each port so that the different freeloader proportions are presented as overlayed histograms.

B Ports within the benefit areas

The benefit areas are inspected so that the number of ports within each area can be computed. Table B1 shows in which of the three benefit areas each port can be found for different freeloader percentages. Note that none of the ports are within any of the areas when there are more than 50% of freeloaders.

Port	0%	10%	20%	30%	40%	50%
Al Fujayrah	1	1	-	-	-	-
Antwerp	1	1	-	-	-	-
Chiba	1	1	1	-	-	-
Corpus Christi, TX	1	1	1	1	-	-
Dampier	1	1	1	1	1	1
Hamburg	1	1	1	-	-	-
Hong Kong	1	1	1	1	-	-
Houston, TX	1	1	-	-	-	-
Mumbai	1	1	1	-	-	-
Nagoya	1	1	1	1	-	-
New Orleans	1	-	-	-	-	-
Newcastle (Australia)	1	1	1	1	-	-
Ningbo-Zhoushan	1	1	2	2	-	-
Panama Atlantic	1	1	2	2	3	3
Panama Pacific	1	1	2	3	-	-
Ponta da Madeira	1	2	3	3	-	-
Port Hedland	1	2	3	3	3	-
Port Walcott	1	1	1	2	2	2
Qingdao	1	1	1	1	-	-
Shanghai	1	1	-	-	-	-
Suez North	1	1	1	1	-	-
Suez South	1	1	1	1	-	-
Yosu	1	1	2	-	-	-

Table B1: Table presents the benefit areas for different FL-% values in which a port can be found. Note that if a port is in benefit area 1, it is also in areas 2 and 3. Similarly, if a port is in area 2, it is also in area 3. Therefore, only the strictest area is presented.

C Daily average queues

Daily average queues are computed for each port as presented in figures C1 and C2. In addition to different freeloader proportions, the historical queue length is plotted. In all ports, it can be observed that when the freeloader proportion is increased, the queue lengths approach the historical values. This means that the usage of the BVS is beneficial from the system perspective even with few participants. However, the impact of the BVS is very small in some of the ports, some of which have also long queues. For example, New Orleans has long queues but the BVS has not succeeded to reduce them.

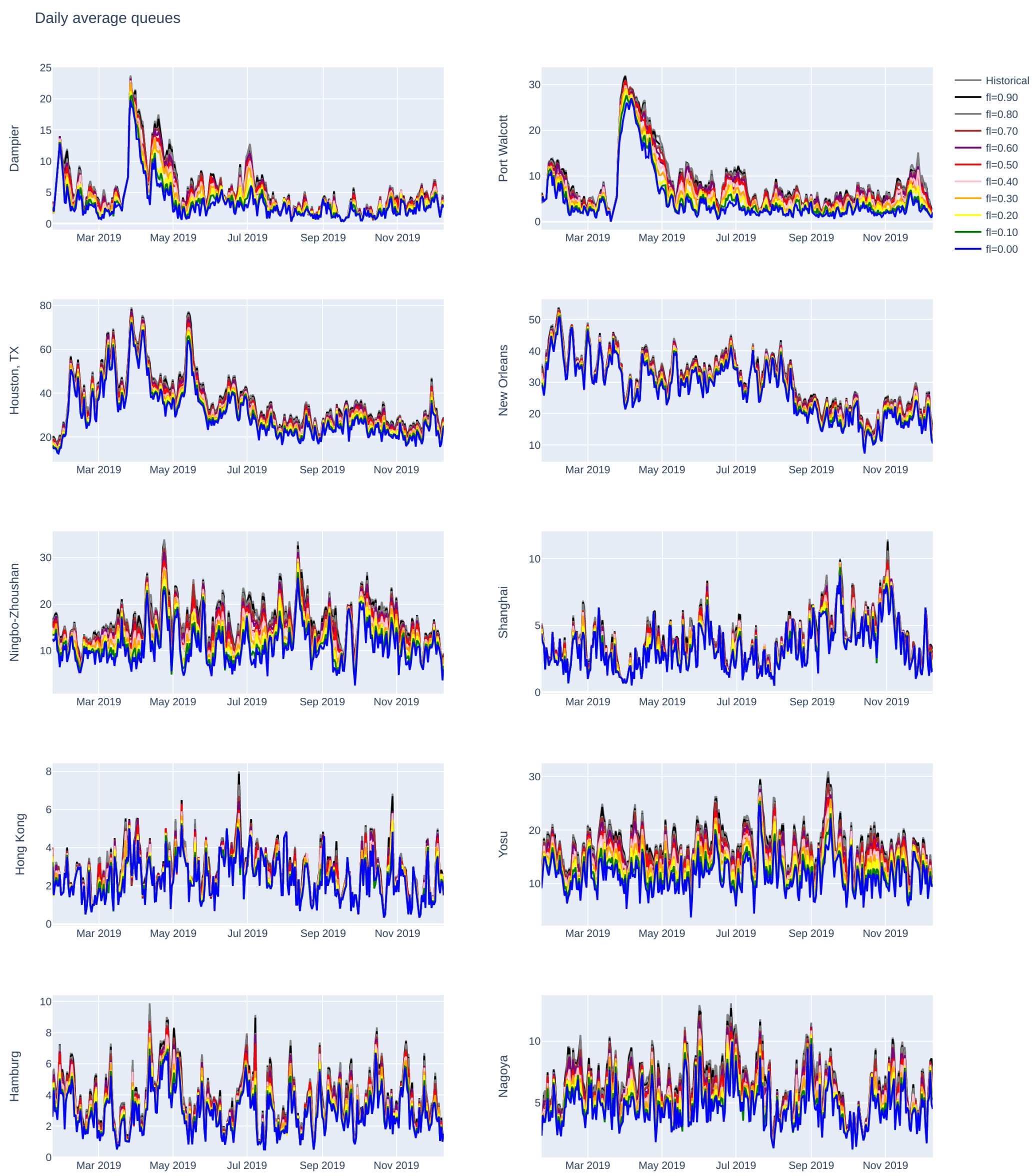

Figure C1: Daily average queues for different freeloader proportions and for the historical baseline for each port.

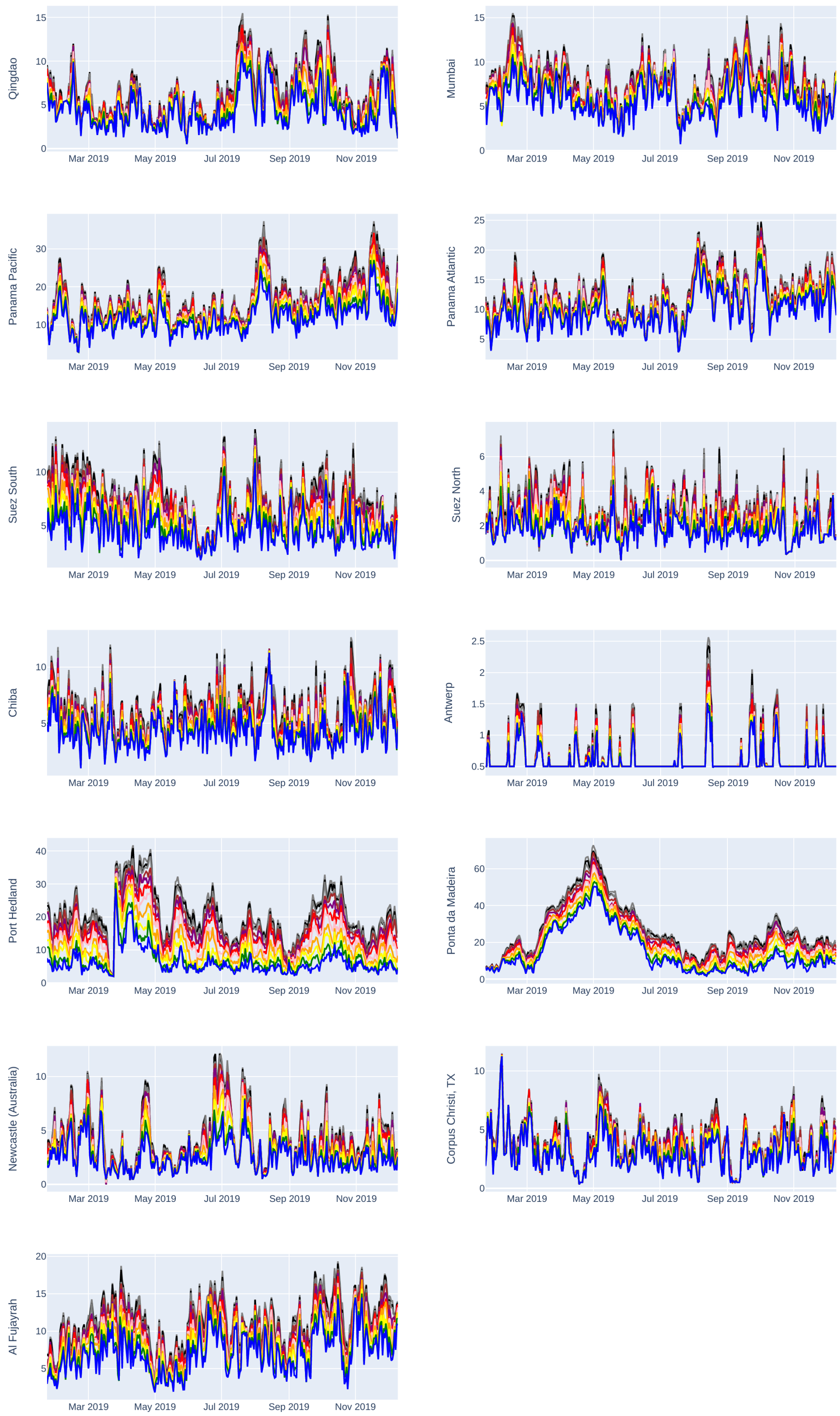

Figure C2: Figure C1 continued.

D Pooled histograms of the metrics

Figure D1 presents overlayed histograms for nine different metrics so that the results over all the ports and replications are pooled together. This is part of the analysis of the impact of freeloaders from the participant's perspective. Therefore, chosen voyages have acted as participants at least in one replication for each freeloader proportion. In figure D1, the arrival lateness is examined in a more general way using the transit time difference. This metric presents the difference between the original and the simulated port transit time. For most metrics, it can be observed that there is a high peak on the voyages that are not impacted by the BVS. Consequently, the differences between freeloader proportions are difficult to understand without a more detailed examination.

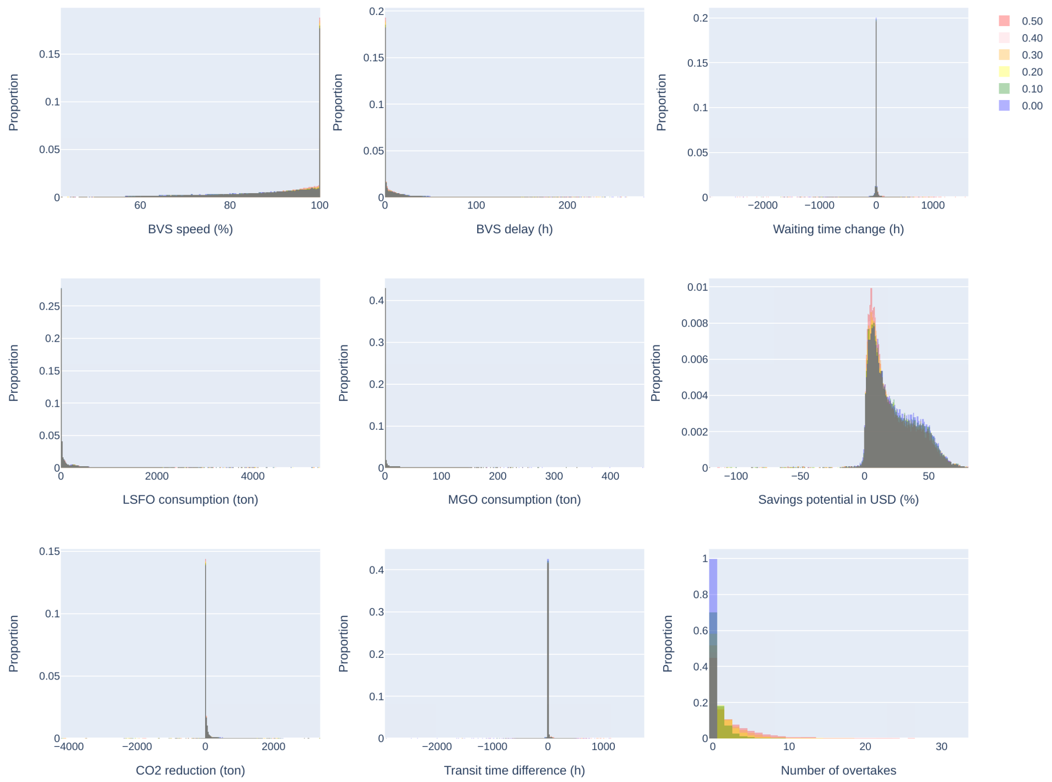

Figure D1: Overlayed histograms of different freeloader proportions for the following metrics: BVS speed, BVS delay, participant waiting time change, LSFO and MGO consumption, savings potential, CO_2 reduction, participant transit time difference, and the number of overtakes per participant.

E Bivariate dependencies of the changes in the metrics from 0% to 50% of freeloaders

The impact of the freeloader proportion is examined by computing the absolute change in the BVS speed, the participant waiting time change, and the savings potential from 0% to 50% of freeloaders. As this is part of the analysis of the freeloader impact on the single vessels, only voyages that have acted as participants at least in one replication for each freeloader proportion are included. Figure E1 presents the bivariate dependencies of the computed differences. Some clear correlations can be observed, for example, the difference in the BVS speed and the difference in the savings potential seem to be dependent. However, the reasons behind the impact of the freeloader proportion require a more detailed analysis. It is possible that there are features that can explain if a voyage is more sensitive or more tolerant to the number of freeloaders.

Figure E1: The absolute difference from freeloader proportion 0% to 50% in the BVS speed, the waiting time change, and the savings potential are computed and presented as speed difference, waiting difference, and savings difference. The bivariate dependencies within these metrics as well as the BVS speed, the waiting time change (BVS waiting), the savings potential (BVS savings), the original speed, the voyage distance, and the draft are presented as a scatter plot.