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HÅLLBAR
SJÖFART

BRAVE ECO - Benchmark for Reduction of Anchoring Vessels' Emissions - Enabling Change of Operation

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Summary

This feasibility study aims to evaluate the possibilities to reduce air emissions from ships anchored in port areas and, then especially the Port of Gothenburg. For this purpose, the study uses two main approaches. Firstly, it analyses the reasons and legal/business aspects for anchoring. Secondly, this study develops a reproducible calculation model for anchored vessels' CO_2 emissions. Regulation of anchoring sites are not entirely clear since international regulation partly applies, also it is not clear who is responsible for the anchoring sites. This implies that the port´s scope of action is limited mainly to the ships that are calling the port. However, also emission from other ships at in the port area has been evaluated in this study to get a broader perspective.

This pre-study provides both qualitative and quantitative findings and it is produced using mixed methods, including workshops with relevant port stakeholders. It also involves different scientific disciplines and several authors from the Port of Gothenburg Authority, IVL Swedish Environmental Research Institute, Maritime Studies at Chalmers University of Technology and the School of Business, Economics and Law at the University of Gothenburg. Furthermore, in connection to this study, one bachelor's thesis and two master's theses have been carried out.

The results show that it is mainly tanker ships that are anchoring in Gothenburg and that their main reasons for anchoring are related to awaiting *Laycan* or waiting for an available berth. The companies involved in the study generally combine time charter and voyage charter contracts to access vessel capacity. The inputs from the workshops, the interviews conducted with stakeholders and the international literature are "rather" consistent: combining just in time arrival with slow steaming has a great potential for making a business case and to reduce fuel consumption and thereby emissions. However, there are many barriers which needs to be addressed, such as: lack of trust, improving information sharing (actors now communicate via phone or email), loss of income (due to demurrage), attitudes in the industry, the "first come, first serve" concept, risk of missing estimated time of arrival and port infrastructure. Even if there are many barriers, several actors in the port already have experience of combining just in time arrival and slow steaming.

In this study, we develop a reproducible emission calculation model that calculates CO_{2eq} emissions. The emissions are partly calculated by using the ships' positions (AIS-data) from 2019, to extract the time spent at anchor. The emission model calculates the anchored vessels' total CO_{2eq} emissions, but the model also calculates the theoretical potential for avoiding emission by using the time at anchor to slow steam. The results show that all tanker ships that anchored outside the port in 2019, could theoretically have reduced their emissions with about 30 ktonnes CO_{2eq}, if they would have been notified of delays 24 hours before arrival and then reduced their speed to 10 knots. The results also show that using time to slow steam have a much greater potential to reduce emissions than if the ships would only reduce the

time at anchor (by using fewer ships to perform the same transport work). This is especially true for the initial speed reductions (10-14 knots).

This study also evaluates the emission calculation methods and assesses the uncertainties, by comparing different sources and underlying assumptions with real world data. The study argues that it is problematic to just use default values proposed in the global emission inventory issued by the International Maritime Organization (IMO). Using default values for estimating emission makes it harder to estimate the real effect of a new policy, regulation, or incentive in the port. However, a better emission inventory requires that on-board visits are made or that data is obtained digitally. The largest calculation uncertainties now are for boiler fuel consumption and bunker ships fuel consumption at the anchorage areas.

Keywords: Anchoring, emission calculations, models, shipping, slow steaming, just in time arrival, virtual arrival, voyage charter contracts, demurrage, AIS-data, IMO

Sammanfattning

Denna förstudie syftar till att utvärdera möjligheterna att minska luftutsläppen från fartyg som ligger ankrade i hamnområden och då särskilt i Göteborgs Hamn. För detta ändamål använder denna studie två huvudsakliga tillvägagångssätt. Dels analyserar vi de juridiska/affärsmässiga aspekterna bakom ankring, och dels utvecklar vi i en reproducerbar beräkningsmodell för de ankrade fartygens CO_2-utsläpp. De förordningar och regler som finns för ankringsplatser är inte tydliga eftersom internationell lag delvis gäller, dessutom är det inte heller helt klart vem som är ansvarig för ankringsplatserna. Detta innebär att hamnens handlingsutrymme i huvudsak begränsas till de fartyg som anlöper hamnen. Trots det har även utsläpp från andra fartyg i hamnområdet utvärderats i denna studie, i syfte att få ett bredare perspektiv.

Denna förstudie ger både kvalitativa och kvantitativa resultat och är framtagen med olika metoder inklusive workshoppar med relevanta hamnintressenter. Den involverar också olika vetenskapliga discipliner och flera författare från Göteborgs Hamn, IVL Svenska Miljöinstitutet, avdelningen för maritima studier vid Chalmers Tekniska Högskola och Handelshögskolan vid Göteborgs universitet. Vidare har en kandidatuppsats och två masteruppsatser genomförts i samband med denna studie.

Resultaten visar att det främst är tankfartyg som ankrar i Göteborg och att det främsta skälet för ankring är relaterat till att vänta på *Laycan* eller vänta på en tillgänglig kaj. De företag som är involverade i studien kombinerar i allmänhet tidsbefraktning (time charter) och resebefraktning (voyage charter) för att få tillgång till fartygskapacitet. Resultaten från workshoppar, intervjuerna med intressenter och den internationella litteraturen är relativt konsekventa: att kombinera *Just in Time* ankomster (JIT) med sänkt fart (*slow steaming*) har stor potential att bli en bra affär, minska bränsleförbrukningen och därmed utsläppen. Det finns dock många barriärer som måste adresseras, såsom: brist på förtroende, förbättrat informationsutbyte (aktörer kommunicerar nu via telefon eller e-post), förlorad inkomst (på grund av *demurrage*), attityder i branschen, "först till kvarn”-konceptet, risk att missa beräknad ankomsttid och hamninfrastruktur. Även om det finns många barriärer har flera aktörer i hamnen redan erfarenhet av att kombinera *JIT* ankomster med *slow steaming*.

I denna studie utvecklar vi en reproducerbar utsläppsberäkningsmodell som beräknar CO_{2eq}-utsläpp. Utsläppen är delvis beräknade genom att använda fartygens positioner (AIS-data) från 2019, för att extrahera ankringstiderna. Utsläppsmodellen beräknar de ankrade fartygens totala CO_{2eq}-utsläpp, men modellen beräknar även den teoretiska potentialen för att undvika utsläpp genom att använda ankringstiden till att i stället sänka farten. Resultaten visar till exempel att alla tankfartyg som ankrade utanför hamnen 2019 teoretiskt skulle kunna ha sänkt sina utsläpp med omkring 30 kton CO_{2eq}, om de hade få en notis att det skulle bli förseningar 24 timmar före ankomst och sedan sänkt sin hastighet till 10 knop. Resultaten visar

också att användning av tid för att sänka hastigheten har en mycket större potential att minska utsläppen än om fartygen bara skulle minska ankringstiden (t.ex. genom att använda färre fartyg för att utföra samma transportarbete). Detta gäller särskilt för de initiala hastighetsreduktionerna (till 10–13 knop).

Denna studie utvärderar också metoderna för beräkning av utsläpp och bedömer osäkerheterna genom att jämföra olika källor och underliggande antaganden med verkliga data. Resultaten indikerar till exempel att det är problematiskt att rakt av använda de standardvärden som föreslagits i den globala utsläppsinventeringen som genomförs av *International Maritime Organization* (IMO). Att använda standardvärden för att uppskatta utsläpp gör det svårare att uppskatta den verkliga effekten av en ny policy, förordning eller incitament i hamnen. En bättre utsläppsinventering kräver dock att ombordbesök genomförs eller att data erhålls digitalt. De största osäkerheterna för utsläppsberäkningarna i ankringsområdena är nu för bränsleförbrukning hos fartygens pannor och bunkerfartygen.

Keywords: Ankring, utsläppsberäkningsmodeller, sjöfart, *slow steaming*, *just in time arrival*, *virtual arrival*, *time charter, voyage charter*, *demurrage*, AIS-data, IMO

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Abbreviations and terminology

AIS	Automatic Identification System – Technology and standard for vessel identification where an onboard transponder continuously transmits the ship´s position.
BIMCO	Baltic and International Maritime COuncil
Charterer	Cargo owner, shipping line or person that hires a ship for a certain voyage or time period.
Charterparty	Contract between charterer and shipowner
CO_{2eq} emissions	Carbon dioxide equivalent emissions, including two others relevant GHG emissions: Nitrous oxide (N_2O) and Methane (CH_4)
Demurrage	Compensation from the charterer to the shipowner if the vessel has not been able to discharge with agreed time.
GHG	Greenhouse Gas
IMO	International Maritime Organization
JIT	Just in time - Delivering at a specific time, neither before nor after. In a shipping context, a voyage in which the ship speed is adjusted according to time of terminal readiness. For voyage charter, special clause can be utilized enabling the vessel to adjust speed.
Laycan	Laydays and Cancelling – A period in which the vessel must arrive at the port, if not the charterer can cancel and charter another vessel
Laytime	The time agreed for loading and discharging in a voyage charter contract.
Port Authority	Organization responsible for port facility infrastructure and port regulations, its role and mandate varies to a large extent depending on size, tradition and national laws.
Port calls	In this study: a ship is making a port call if it is visiting a quay in the Port of Gothenburg. In contrast to a ship in transfer (see below).
RTA	Requested Time of Arrival – The time in JIT-voyages where the terminal estimates terminal readiness for the vessel to load or discharge.
SMA	The Swedish Maritime Administration (*In Swedish: Sjöfartsverket*)
Slow steaming	In this context ship going bellow their design speed to save fuel.

STA	Swedish Transport Agency (*In Swedish: Transportstyrelsen*)
Time charter	Charter of a vessel for a set period of time
Transfer	In this study: ships that are anchoring in the traffic area without calling the port.
Voyage charter	Charter of a vessel for a single trip
WTT	Well-to-Tank emission, in this study upstream emissions of producing, refining, and transporting the fuel.
WTW	Well-to-Wheel, in this study rather Well-to-Propeller, all emission occurring during the fuel's entire life cycle

1 Introduction

1.1 Background

The Port of Gothenburg is one of several ports with strategic climate goals. The Port Authority is heading towards harmonizing its goal with the national goal for domestic freight transport, which is to reduce CO_2 emissions with 70% by 2030 (the Port of Gothenburg, 2020). This goal also includes emissions from ships. The geographical scope for this goal includes the port area and the fairway to the Vinga lighthouse. The ambition for reduced emissions is not limited to ship movements and berthing, but also emissions occurring at anchor for ships calling the Port of Gothenburg are included. However, regulation of anchoring sites is not entirely clear since international regulation partly applies, also it is not obvious who is responsible for the anchoring sites (see Section 2.3). This implies that the port's scope for action is limited to the ships calling the port.

A contributing factor to shipping's CO_2 emissions in connection with port calls is the time at which ships are at anchor. The size of the emissions largely depends on the port's location and operations. Reported values from some ports are 8% of the ships' CO_2 emissions, in the port of Los Angeles, 15% in the port of Long Beach, about 15% in the Port of Gothenburg, and 26% in Incheon, South Korea (The Port of Los Angeles, 2018; Winnes & Parsmo, 2017; Chang, et al., 2013). In some ports with limited access to quay locations, the proportion may be over 50%, but for Swedish conditions it is often significantly lower.

Previous experience shows that some ships anchor due to waiting time at the quay but also for operations that take place at the anchoring site such as bunkering, tank cleaning or provisioning; operations that in themselves account for additional emissions, or legal/commercial aspects(Johnson & Styhre, 2015). However, it is not known at which degree different factors influence and as far as we know, there has not been any previous study considering this analysis for the Port of Gothenburg before. In the port´s yearly emission inventory the Port Authority has noted a marked increase in anchored vessel emissions since 2010 (Winnes & Parsmo, 2017). However, the underlaying data and assumptions in this inventory are not sufficiently detailed regarding ship types or reasons for anchoring to draw concrete conclusions about emission reduction measures.

1.2 Purpose

This feasibility study aims to investigate what opportunities there are to reduce ships' emissions to air of mainly carbon dioxide equivalents (CO_{2eq}) when they are anchored in port areas. Specifically, the study has two purposes:

1. To present a reproducible calculation model for anchored vessels' CO_2 emissions in terms of total emissions, based on AIS data. The calculation

model must be able to show which types of ships leads to the highest emissions and quantify the uncertainty in the emissions for these ships. With minor adjustments, the model should also be possible to apply to other anchorage areas.

2. To develop a draft of proposals for emission reduction measures that can be implemented in collaboration between the Port Authority and the shipping industry, based on analysis of causes of anchoring. Measures should be proposed that can form the basis for direct implementation by industry players or be developed through new projects or new scientific studies.

1.3 Method

This pre-study provides both qualitative and quantitative findings and it is produced using mixed methods. It also involves different scientific disciplines and several authors from the Port of Gothenburg IVL Swedish Environmental Research Institute, Maritime Studies at Chalmers University of Technology and the School of Business, Economics and Law at the University of Gothenburg. Reasons for anchoring, the legal framework and commercial aspects of anchoring is further described in Chapter 2, while the methods for calculating emissions at anchor are further described in Chapter 3. In addition to what's mentioned above, three different degree projects and three workshops were included as part of this study, and these are described in the following two subsections.

1.3.1 Theses

In connection to this project, one bachelor's thesis and two master's theses have been carried out. In these theses, shipowners have been interviewed about why the ships are at anchor and how they use the ships' engines and boilers during the stay (Florez & Betancur, 2021; Therman & Wass, 2021). One study further investigates how the emissions at anchor could be reduced from a commercial perspective, mainly through interviews with stakeholders (Kristiansson & Wall, 2021). These studies were done prior to this report and their results are independent. However, this report summarizes and further develops some of the results and concepts that the students have produced. The "raw data" from the interviews and the questionnaires are well presented and further examined in this study.

For more quantitative data on anchoring in the Port of Gothenburg, the students carried out one survey about the reasons for anchoring and one survey investigating how the ships' engines and oil-fired boilers are used while at anchor. The methodology, the questionnaires and templets are further described in the theses (Florez & Betancur, 2021; Therman & Wass, 2021). The data from the questionnaires has been used in this study and been embedded into the calculations, which are further described in Chapter 3. Almost all answers were from product tankers smaller than 40 000 dwt.

1.3.2 Workshop with port actors

The results from the surveys were used in workshops with shipping lines Furetank and Terntank as well as the terminal Preem. In the three workshops the results from the student thesis were the framework of discussion.

It was known prior to the project that the liquid bulk segments represent a high share of the total anchored hours. Therefore, the composition of the group of industrial partners in this project was concentrated to shipping companies and terminals from this segment. The companies were chosen based upon their relevance for the Port of Gothenburg, their environmental focus, and their experience with just in time (JIT)-arrival, a management philosophy further described in chapter 2. Both Furetank and Terntank have expressed interest in utilizing slow steaming to reduce emissions and bunker consumption and they have experience from JIT-voyages with specific cargo owners.

The workshops were conducted with each company individually, with questions based on the project purpose and the results from the student thesis. With the terminal, the focus was mainly on how to reduce time at anchor, while with the shipping companies the focus instead were on the possibilities for technical solutions for emission reduction and emission evaluation.

1.4 Report outline

After this introduction, the rest of the report is organized as follows: Chapter 2 outlines the main reasons for anchoring at the Port as well as the results from the student´s survey on reasons for anchoring in waters close to Gothenburg. Additionally, some countermeasures are presented and discussed including legal implications. Chapter **Error! Reference source not found.** describes the methodology used for estimating the emissions; Chapter 4 provides an analysis applied to the context of anchoring in Gothenburg. Finally, Chapter 5 is devoted to summarizing the main findings and discussing the main conclusions and further research.

2 Reasons for anchoring and measures for reducing it

Even though anchoring of vessels could be due to, e.g., weather conditions or unforeseen events, some reasons for anchoring could be linked directly to port operations. In turn, port operation could potentially be improved by a changed port framework, for example by improving commercial and legal practices, which will be further elaborated on in this chapter.

Generally, ships lay at anchor for several different reasons such as:

- loaded or empty, waiting for berth to be allocated
- shortcomings in other segments of the transport chain
- loaded, waiting for orders where to discharge the load
- loaded as floating storage
- non-trading in short term ("warm") or long term ("cold") layup
- for operations such as maintenance and bunkering to be finished
- empty after discharging cargo, waiting for next trade

To cope with these types of uncertainties, master mariners tend to plan for arriving at port ahead of time as a safety measure.

Anchoring is a phenomenon mostly concerning vessels active in tramp shipping, in which each transport assignment is individually managed and often for a single or a few shippers with a need for moving large volumes of goods. It can be compared to a taxi or full truck load and predominantly concerns the tanker and dry bulk segments. Vessels trading in liner shipping in segments such as container, Roll-on-Roll-off (RoRo) and RoRo-Passenger (RoPax) shipping generally follow strict and published itineraries with pre-booked berths and port handling capacity (Woxenius, 2021). The service is available to most shippers, also those with small shipments. Shipping lines, agents and forwarders cooperate to consolidate smaller consignments to use the vessels efficiently. In that sense it is like a passenger train with an allocated slot time at tracks and stations. Liner vessels often stay berthed when there is time left in the timetable (also called "slack") and slow steam rather than arriving early risking waiting at anchor.

Nevertheless, anchoring in the liner shipping segment has been uncharacteristically common during the current pandemic-induced disturbances in the global container shipping network. During 2021, up to 75 container vessels have waited in San Pedro Bay for a berth in Port of Los Angeles/Long Beach, many of which drifting when the 60 anchoring positions were full. One of the ships' anchors might even have caused a crude oil pipeline to start leaking (Curwen, et al., 2021). Temporary closures of Chinese container ports during pandemic lockdowns or weather reasons have also induced anchoring of vessels (Clark & Varley, 2021) as shown in Figure 1.

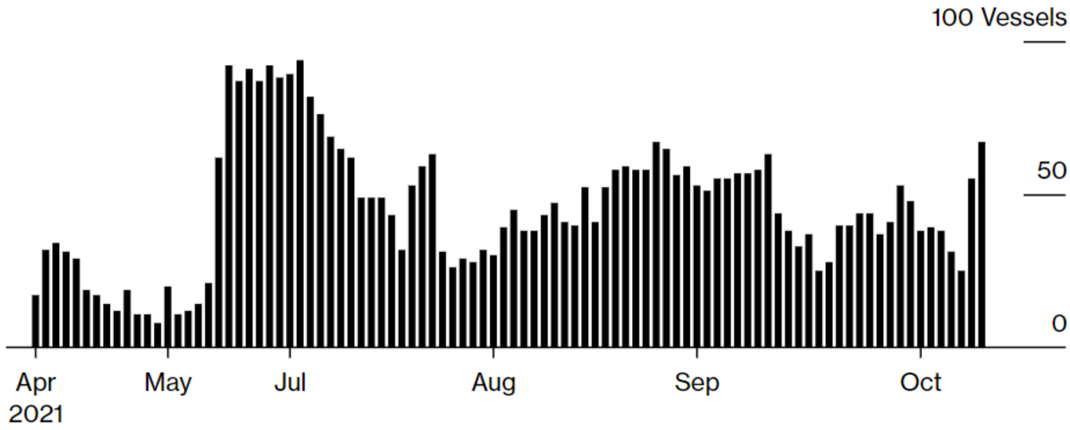

Figure 1. Number of ships waiting outside Shenzen Yantian port, China, April-October 2021. Source: (Clark & Varley, 2021).

In addition, the blockage of the Suez Canal in spring 2021 forced many ships to wait at anchor on either side of the canal. In Gothenburg, however, liner vessels are rarely seen at the anchoring areas. Instead, most traffic concern one sub-segment of tramp shipping, tanker shipping.

2.1 The effect of charterparties on time at anchor

Those familiar with logistics and buying transport services, but not particularly with shipping, might find tramp shipping using voyage charter contracts a bit contra-intuitive. Shippers are used to get compensation if a delivery is late, but the risk is shared as the shipowner cannot control weather, port capacity and some other unanticipated risks of delays. To illustrate, a trick to understand the principles is to view it as car rental rather than a taxi ride. In a taxi, you want to pay less or at least not give a tip if the ride is too slow but find it reasonable to pay an extra fee if you do not hand in the rental car on the agreed time.

As mentioned by Furness Wilson (2010), one of the most crucial clauses between the shipowner and the charterer is, like for most transport services, the agreed timing of the transport assignment. Since loading and discharging takes long time in comparison with other modes, the duration of the process of loading and discharging the ship is of particular interest and is referred to as *Laytime*. If the charterer fails to complete discharging and loading within the specified Laytime they are obliged to compensate the owner to cover for the extra costs, what is referred to as *demurrage*. As a safety for the shipowner, the demurrage rate is often fixed in the contract between the shipowner and the charterer, which is referred to as the *charterparty*. This usually implies that the charterer wishes for a longer Laytime, to prepare for unforeseen events, while the shipowner wishes to reduce this time, as it enables him/her to save cost by slow-steaming or earn extra revenues by using the ship elsewhere. Nevertheless, charterers often also have the possibility to earn *dispatch*, a payment they get if completing the operations faster than the specified Laytime. This is usually also a fixed rate, stated in the charterparty and can be considered an incentive for faster handling in port, which also benefits the shipowner (Furness Wilson, 2010). Considering the example of car rental or a flight, for the case of shipping this clause is different, as it is not obvious to get a rebate if delivering the car before the agreed time or to pay extra if the flight arrives early.

What is considered difficult is agreeing on when the Laytime starts. When arriving at the port, the shipowner gives a *notice of readiness*, indicating that the ship is at place and ready to load or discharge. However, if there is no berth available at arrival, the shipowner risks not being economically compensated for the loss of time, if not agreed upon differently in the charterparty. Therefore, it is of importance that the charterparty covers the aspect of when the ship can be considered arrived at port, for example it being in the port area or at a berth.

The charterparty also stipulates the estimated date of arrival of the ship, and a period for when the ship should arrive. In contrast to Laytime, the shipowner usually wishes to have as long time as possible for this, due to unforeseen events such as bad weather. To ensure the safety for the charterer, this period is often set with an expected date of arrival of the ship and a cancelling date. It means that if the ship has not arrived within the set time period, the charterer has the right to cancel and instead charter another ship. This period is often referred to as *Laycan* (Laydays and Cancelling) (Furness Wilson, 2010).

The oil market has a clear impact on the charterparty. Thus, under the positive sentiment in the oil market, shipowners expect a higher voyage charter. However, in practice, the voyage charter contracts incur a higher cost for them at times. In contrast, in an uncertain situation, shipowners engage in time charter contracts to control their revenues. Charterers and shipowners regard time charters as a mutual way of hedging risks.

2.2 Just in time and virtual port arrivals as measures for reducing time at anchor

The concept of just in time (JIT) manufacturing is tightly connected to Toyota. The company introduced the principles and the term already in 1938, but it became more commonly used in the logistics literature in the 1980's as Toyota and other Japanese automotive firms became manufacturing and logistics role models. A common misconception is that JIT deliveries should be small and frequent and over short distances, but the concept itself just implies reliable planning and precision of deliveries (Lumsden, et al., 2019).

For instance, airlines, and particularly low-cost airlines, have generally relaxed their timetables moving the estimated time of arrival ahead. The motive for this practice is to avoid being officially late risking reputation, missed connections and financially crediting travellers. Thus, it is common that planes arrive early nowadays, but in fact, that also violates the idea of JIT. Operationally, European air traffic management does not allow intra-European flights to start until the capacity in the airspace and at the destination airport is secured. In Europe, prior to this decision, planes started according to timetable and if there was a problem at the destination airport, planes circulated in so called "hotels" close to the airport waiting to be allowed to land. This is still the case for many inter-continental flights.

2.2.1 JIT in shipping

Whereas JIT is a widely adopted concept in the wider domains of manufacturing, logistics and supply chain management, the term seems surprisingly new within shipping. Arriving on time is obviously as important in shipping as in other modes and the cost of delays increase by size of ship and value of cargo. Furthermore, precision of delivery time often come on top in surveys of shipper preferences and shippers most often agree with the statement that delivery on time is more important than transport time.

Improving precision was a motive for Maersk when it implemented Daily Maersk for its container shipping services in 2011. By relaxing the timetable and managing the shipments more closely using different departures, Maersk could offer guaranteed delivery times. The high-precision service was more costly to produce and came at a higher price, and as enough shippers were not willing to pay for it, Maersk discontinued to offer it in 2015 (Porter, 2015). Nevertheless, precision is obviously highly debated following the current disruptions in the container shipping networks and global supply chains.

JIT arrival is far less used as a term in tramp shipping, but the phenomenon of matching ship arrival with the next step in the transport chain has a long history. When discussing the inertia of efficiency improvements, experts often bring forward a conservative industry and how contracts are designed. To speed up change, IMO issued a "Just In Time Arrival Guide" (IMO, 2020) lining out what barriers impedes JIT arrivals and some solutions to the problems. IMO states that current operations can be described as "Hurry up and wait", meaning that the ships are going on full speed to the port, to realize that there is no free berth, forcing them to anchor while waiting (see Figure 2).

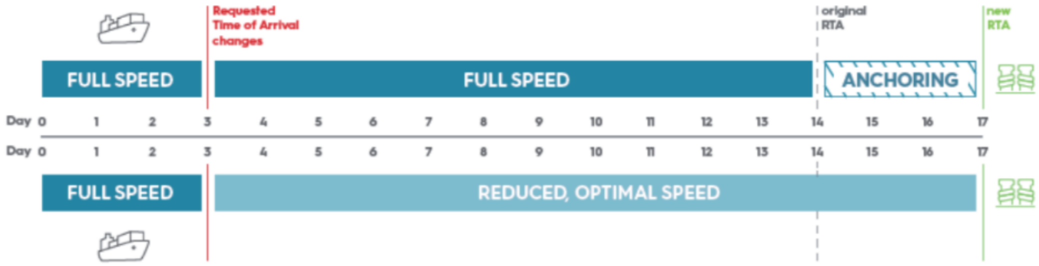

Figure 2. An example of just in time transport (IMO, 2020).

To prevent this, the operation would need better communication of information about the availability in the port. If the master mariner is fed updated information about availability in the port, the ship can slow steam and thereby use less fuel (IMO, 2020; Johnson & Styhre, 2015). However, as further mentioned by Styhre, et al. (2014), the policy of "first come, first serve" incentivises master mariners to race to reach the port first to be first in line for a free berth.

IMO (2020) does not argue for shortening the total time needed for the whole operation. Instead, they propose a more optimized speed, to reduce waiting time and the time spent at anchor. Another important aspect mentioned by IMO (2020) for the voyage charter market is that, depending on when the charterparty states that Laytime starts, the shipowner might lose the income of demurrage, as the ship instead will reach the berth without waiting time (Poulsen & Sampson, 2019). If the possible demurrage exceeds the potential cost savings of fuel, the shipowner is obviously motivated to arrive early at the port (Andersson & Ivehammar, 2017).

By introducing JIT arrivals, CO_2 emissions are not only reduced during the voyage, as speed is optimized, it also reduces local air pollution in cities near the port. In this regard, if the ship arrives at a time when there is an available berth, it does not have to wait at anchor and thereby no emissions are induced (IMO, 2020). Reducing the time that a ship spends waiting at anchor can also be seen as something that benefits the environment as well as the business, with lower costs and emissions (Poulsen & Sampson, 2019).

To increase its competitiveness, it would therefore be in the port's own interest to enable ships to arrive JIT, since JIT arrivals potentially involves cost savings. The process of planning port operations, such as loading and discharging of goods, is complex and can be made further complicated if needing to replan (Pratap, et al., 2018). The importance of improving these operations is further emphasized by Styhre, et al. (2014), stating that this is one of the most crucial aspects in reducing waiting time at port. Knowing the more specific arrival time of each vessel would enable port and the terminal operators to better plan and schedule berths and port equipment. Nevertheless, implementing JIT arrivals requires that they change the way of operating by improving information sharing between the stakeholders (IMO, 2020) and it also requires trust among the stakeholders.

2.2.2 Virtual arrival

To enable JIT arrival, actors can introduce a virtual arrival system such as the agreement between the energy company BP and Maersk Tankers (Poulsen & Sampson, 2019). They implemented a virtual arrival clause in their voyage charter contract implying that when being informed that the oil terminal is not able to accommodate the ship at the agreed day, the ship could slow steam. However, the ship could arrive "virtually" at the time it would have arrived if continuing in the same speed. Without this clause, the ship would need to be physically in place to be considered arrived at the port. For the extra time the charterer made use of the ship, i.e., the difference in time between the original arrival and the actual arrival, the shipowner received compensation. The savings in bunker fuel cost from slowing down was then shared between BP and Maersk Tankers (Poulsen & Sampson, 2019). BIMCO has prepared a virtual arrival clause in its model contract for voyage charter (BIMCO, 2013) and a slow steaming clause for time charters (BIMCO, 2011).

2.2.3 Barriers of JIT and virtual arrival

In the IMO report (2020) several obstacles in implementing JIT arrival are discussed. In the case of contracts, introducing JIT for voyage charter is more complex than for time charter. In practice, the time charterer controls the vessel and can manage fuel consumption through speed reduction. In the case of voyage charter, shipowners are the main ones responsible for any delays, and it would be more difficult to determine the effect of JIT arrival (IMO, 2020).

Likewise, demurrage can be an important source of income and some shipowners are averse to implement a virtual arrival system (Poulsen & Sampson, 2019). For instance, a ship with a voyage charter contract might risk missing its Laycan and thus give the business to another vessel. Consequently, it might not implement slow steaming (Styhre, et al., 2014).

Finally, information sharing can become an issue due to a lack of confidence among actors (Poulsen & Sampson, 2019). The authors suggest that the "first come first serve" method applied by several ports can be the reason why shipping companies are not implementing the virtual arrival system. Three main factors can explain this situation. Firstly, as mentioned before, the time-dependent cost of the cargo transported by ships, such as cost of tied up capital and shortage cost, can be higher than the fuel cost savings of speed reduction (Jivén, et al., 2020). Secondly, some shipowners can be averse to changing their operations or sharing information among the actors (IMO, 2020). Implementing a new communication process can be confusing or unacceptable for some operators (Flodén, 2018). Thirdly, the shipowner does not want to risk late arrival if it coincides with a crew change.

2.3 Regulation of anchoring sites in Sweden

This section contains some legal aspects that relates to the short time anchoring of ships. From the research there are three different areas that are of interest when it comes to reducing time at anchor. The first relates to international law and the law of the seas, which relates to the United Nations Convention of the Law of the Sea (UNCLOS), the second one is of interest from a national legal perspective and the third relates to the environmental impact of anchored vessels and thus environmental law.

Nevertheless, establishing anchoring sites is not well regulated and preceded by careful investigations and administrative decisions. The Swedish Maritime Administration (SMA) is responsible for surveying the Swedish territorial waters and by that to establish and publish sea charts for the safe navigation of vessels. The SMA was established as a governmental administrative authority in 1956. In the preparatory works that proceeded the establishment of the organization, SOU 1954:21 p. 17, anchoring sites are mentioned, for the first and last time since, in official documents from the Swedish Government. It is here mentioned as a site surveyed for the safe use by one of the organisations that formed the SMA, the Nautical Chart Department (Sjökarteverket). A recent interview with the SMA revealed that the SMA only makes repeated surveys at these sites to establish if the floor bed and the water column at normal water level are safe for anchoring. It was further understood in this interview that no new anchoring sites have been established as could be remembered by the administrators at the SMA. All Swedish anchoring sites, one of which is shown in Figure 3, are thus to be considered as there by historic reasons.

Figure 3. Anchorage area Charlie (Photo: Port of Gothenburg).

The first legal issue relates to the point of international regulation, and it regards the right to anchor inside territorial waters and internal waters. The key word is innocent passage. This concept refers to that a voyage through a nation's territorial waters, see dashed line in Figure 4, is accepted if the voyage is carried out without stops and in an orderly manner. International rules play an important part when it comes to regulating the use of such areas for international shipping, but the territorial waters are also subject to national legislation by for instance limiting some of the rights to passage, protected areas as one example. In this sense one major area of concern is the question whether anchoring on territorial waters could fall under the concept of innocent passage or not (See UNCLOS Section 3, art 17 - 19).

International literature is divided in this question whether anchoring is to be considered part of a normal operation of the vessel or not.

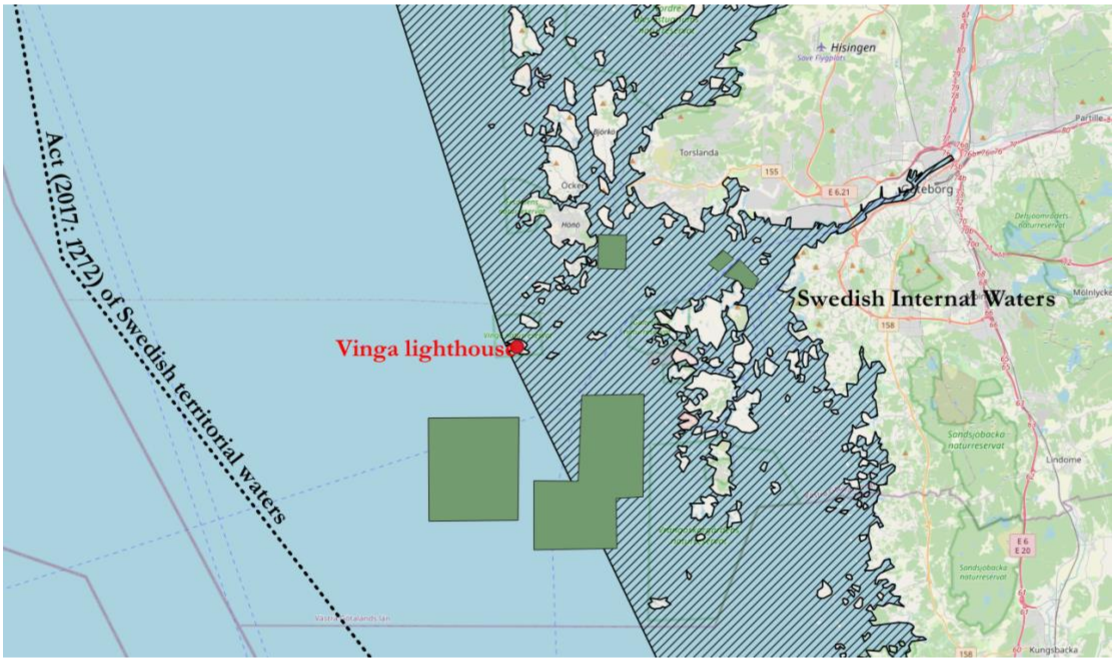

Figure 4. Illustrating Swedish internal and territorial waters in relation to the anchoring sites (green) used in this study.

The second issue of importance regards national legislation on anchoring. In a recent court case from the supreme land and environmental court (DOM 060107, 2021-03-12 in case M 2771-20) the responsible administration for anchoring sites has been questioned. SMA has as its standpoint raised that anchoring is a decision and under sole responsibility made by the commander of the vessel. Participation of a pilot does not remove such responsibility. Furthermore, the anchoring sites are just a mark on the navigation chart with no actual and physical marking on the site. The administration puts forward several other reasons backing the position that SMA lacks responsibility regarding the anchoring sites. Mainly that according to environmental legislation, an environmental investigation and permission to develop and maintain an anchoring site does not exist, which is different from developing and maintain a shipping fairway. Without going deeper in the arguments, which is outside the scope of this pre-study, it could be said that the court did not share the view put forward by SMA and there is room for a further discussion on the matter. As said before, anchoring sites have not been subject to neither an administrative decision, nor an environmental legal exercise.

A third area regards the environmental impact from anchoring vessels. As said above there are no preconditions at the time of an establishment of an anchoring site. Information from the SMA makes it clear that they are carrying out surveys of the seabed with some sort of regularity. These surveys aim at making sure that the water column is deep enough according to the sea chart and that the seabed is firm enough for safe anchoring. But there is no pre-study based on damage to the habitat on the seabed, i.e., there are more environmental impacts than just the greenhouse gas emissions that needs to be studied regarding the short time anchoring, but that is outside the scope of this pre-study.

2.4 Anchoring in the vicinity of the Port of Gothenburg

Almost all major ports in Sweden have an anchor mark on the navigation charts, so also outside the Port of Gothenburg. Anchor marks indicate that anchoring is allowed and mainly that the seabed allows for a firm anchoring at a sufficient water column for safe anchoring to be obtained.

2.4.1 The anchoring sites in the Port of Gothenburg

In the Port of Gothenburg six anchoring areas are marked in the navigation chart. These anchorage areas are marked in purple in Figure 5, however, two of the areas in the navigation chart are combined into one (1). The small black dots in the figure represents ship positions during 2019. The clustering of dots creates visual pattern such as the shipping navigation channel (the black line between site 3 and 4) and anchoring sites (the black rings), which is futher described in Section 3.2.5.

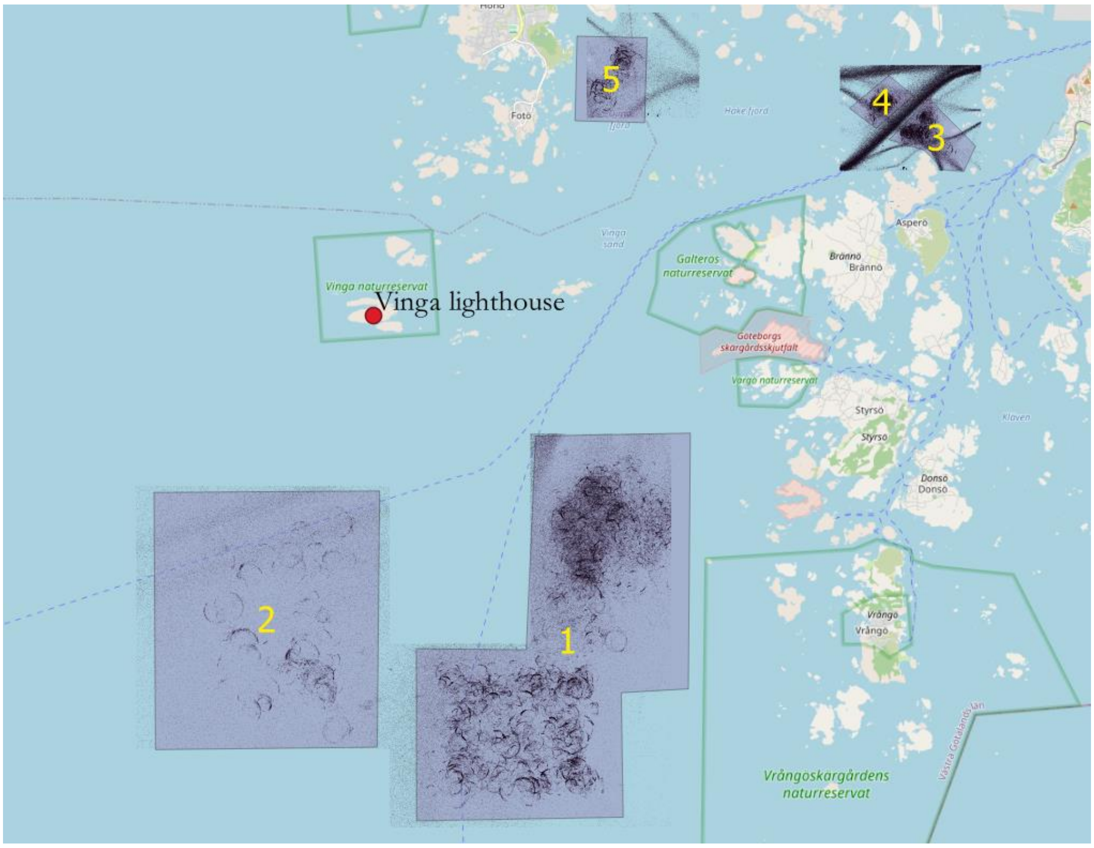

Figure 5. The anchorage areas from which AIS signals were analysed in this study. Each black dot in the figure represents one AIS signal which is futher described in Section 3.2.5. See Table 1 for a decription of each anchoring site.

The names and the intended purposes of the anchoring sites are detailed in Table 1.

Table 1. Description of the anchoring area outside the Port of Gothenburg

Area	Name	Intended purpose
1	Trubaduren B (a.k.a. "Bravo")	Northern part of area is designated for bunkering operations.
	Trubaduren C (a.k.a. "Charlie")	The southern part of the same area for vessels awaiting berth. See Figure 3.
2	Trubaduren A (a.k.a. "Alpha")	is designated for larger vessels.
3	Rivö N	The inner anchorages areas are preferred when strong winds are expected and used for all purposes. Because of the lee provided by the archipelago they are popular but for most vessels requires pilot.
4	Rivö S	
5	Dana	

2.4.2 Reasons for anchoring in Gothenburg

One of the surveys conducted by thesis students (Therman & Wass, 2021) concerned reasons for anchoring. The survey got 16 responses in total, all in the product tanker segment. Reflecting the current situation in the port, with product tankers dominating the anchorage areas at the Port of Gothenburg (Parsmo & Winnes, 2020). Out of eight reasons for anchoring, the respondents only gave two main reasons for anchoring, *awaiting Laycan* or *awaiting free berth*. For all vessels, 56% answered awaiting free berth and the remaining 44% answered awaiting *Laycan*. Only the ten vessels waiting to load in Gothenburg is represented in Figure 6. These anchor visits are generally considered the ones that the Port of Gothenburg can influence.

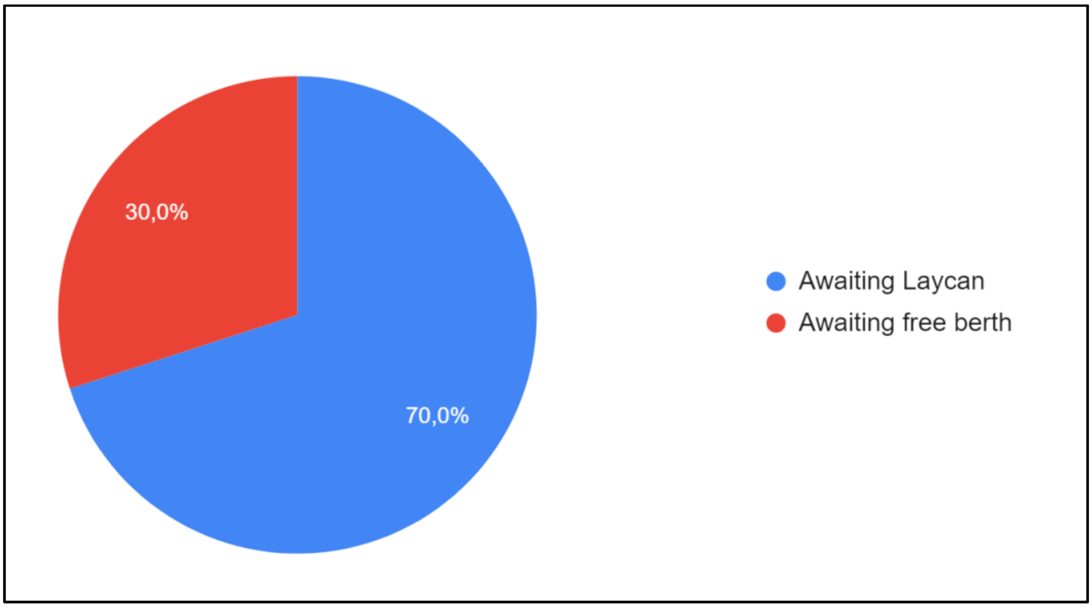

Figure 6. Share of vessels due to load in Gothenburg answering "Awaiting Laycan" and "Awaiting free berth" (Therman & Wass, 2021).

This sub-set differs in the sense that more vessels (70%) wait for Laycan than for a berth, showing a comparatively good access to berths, which also limits the Port of Gothenburg's prospects of reducing anchoring. Although it is a relatively small sample size it gives an indication that JIT-arrival in combination with slow steaming have a potential to reduce time at anchor (Therman & Wass, 2021). Some of the vessels reported that they were also partly conducting other activities such as bunkering while at anchor, but the main purpose was indicated as business terms or congestion as driving forces.

2.5 The insight of stakeholders in the energy terminal on reducing anchoring in Gothenburg by changing commercial and legal terms

As part of the master's thesis, Kristiansson & Wall (2021) interviewed eight persons, representing five stakeholders regarding anchoring in the vicinity of the Port of Gothenburg. Specifically, four companies and the Port of Gothenburg. For confidentiality purposes, the authors have not revealed the company names. Shipper 1 and 2 represents the oil sector (both with refineries in the Port of Gothenburg) and Shipping provider 1 is a shipping company and Shipping provider 2 is a logistics service provider.

2.5.1 Shipper 1

Four persons from Shipper 1, a company active in the energy sector, were interviewed. In general, the company combines time charter and voyage charter contracts. Time charter contracts are normally renewed on a yearly basis. The company often hires ships from a set of companies, with which they have established a long-term relationship. These ships are in full use and under full control by Shipper 1. In the case of voyage charter contracts, the company generally contracts reliable shipowners, normally Shipping provider 1, or signs new contracts for each voyage to get the best ship for the best price.

The company has access to extensive information about all vessels it uses. Even under voyage charter contracts, some of the master mariners frequently use slow steaming to get to berth on time, while others try to avoid being late at berth. This depends on if they have a good relationship with the shipowner, and if the ship arrives to a berth that Shipper 1 controls. The clause used is similar to the BIMCO voyage clause, implying that, for instance, the charterer and shipowner divide the earnings from saved fuel. Shipper 1 states that it is willing to adjust to JIT, as there is no point in having ships anchoring. JIT can also reduce the risk of paying demurrage. As stated by two interviewees representing Shipper 1, the reasons for other shipowners not wanting to agree on an optimized speed could be uncertainty of arrival time and if they will profit from it. Another issue is the "first come, first serve rule", which prevents speed optimization for ships that are going to a berth not controlled by Shipper 1. Nevertheless, still lacking a virtual arrival system, two representatives of Shipper 1 claim that it at present is the fairest system.

One of the main differences between ships under voyage charter contracts and ships under time charter contracts is that the operators of the former have a possibility, or risk, of demurrage. With time charter there is a running daily charter rate and thus an incentive to keep the ship busy. For voyage-chartered ships, a representative for Shipper 1 says that Laycans can be considered flexible in favour of both parties. If the berth and cargo is available, there is no need to await the certain Laycan date.

As Shipper 1 has a long and tight collaboration with a Swedish shipowner, it is willing to let the shipping company use slow steaming. Interviewees state that JIT transports function well as an agreement between Swedish companies and emphasises the importance of trust and that it is an efficient way to reduce anchorage time. Trust is also mentioned as a requirement for virtual arrivals to work in practice. Nevertheless, Shipper 1 must still acknowledge its obligations to the buyer or seller of goods. If the shipping company would slow steam and miss the estimated time of arrival, the financial loss of the buyer could be significant as it might in turn already have sold the cargo or planned for its use in a production process.

Moreover, as mentioned by two of the interviewees, the operations in the port cause anchorage in two main ways. Firstly, the specifications of mixing the right oil products are often very narrow leading to a difficult process. If the specifications are not met, they could have an immense impact on the loading time, which further creates queuing for other ships. They state that better port infrastructure would reduce the problem, for example by having more pipelines for the products or infrastructure to speed up the loading. Two other interviewees representing Shipper 1 suggest a more direct measure. If the product does not meet specifications, it could sell it anyway, but at a reduced price. Lastly, they also mention the lack of berths as a reason for increasing waiting time.

Finally, the company considers that information sharing is a complex issue as it requires trust among actors. Shipper 1 thinks that virtual arrival could complicate this situation. Thus, if the port aims to develop a new communication system, it must be easy to implement, which is further detailed in the master's thesis (Kristiansson & Wall, 2021).

2.5.2 Shipper 2

Shipper 2 is a company with a refinery in the vicinity of the port and to sort out its transport needs, it implements time charter contracts through Shipping provider 1. The company has a sophisticated loading method and, specifically, it must consider different terms for liquid fuels in different countries like Finland or Norway. Shipper 2 does not mind if ships arrive too early if the shipowner agrees to skip Laycans and, if possible, load earlier. However, this is sometimes refused by the shipowner who motivates this by referring to the contract and "that it has always been that way" as stated by an interviewee representing Shipper 2.

Shipper 2 differentiate itself from Shipper 1 by using an economical speed for the ships instead of slow steaming. As most of these ships are time charted by Shipping provider 2 on behalf of Shipper 2, there is deeper collaboration between the actors. Depending on the situation at the port, Shipper 2 can have a ship to slow down or speed up as an option to reduce the anchorage time for the vessel, as it can lead to demurrage. The cost of demurrage can be expensive and the main reason for the increasing demurrage cost is, according to an interviewee representing Shipper 2, the lack of infrastructure at the Port of Gothenburg.

Shipper 2 manages one berth (refinery) in the port, enabling it to be more flexible in managing the ships arriving, as in terms of being flexible on agreed dates and times. However, for ships that must make use of another berth in the port, owned, and operated by the Port of Gothenburg, the ships often must hurry to the port to ensure their place in the queue. Another barrier for JIT mentioned by Shipper 2 is that the buyer of the goods is not willing to change its contract accordingly, as was the case for Shipper 1.

Finally, in the case of communication, the company does not consider virtual arrival as a practical solution unless it is implemented through a validation system to guarantee that the information shared between the actors is correct.

2.5.3 Shipping provider 1

Shipping provider 1 is a family-owned shipping company. Time charter contract is the most common system implemented by Shipping provider 1. Although shipowners prefer to manage their vessels through voyage charter contracts, because of the higher revenues mainly derived from demurrage, Shipping provider 1 manages its vessels through time charter. The company mainly signs these contracts over a one-year period to ensure stable income rates. Furthermore, the company offers an efficient end-to-end process to get better economic and environmental outcomes. In general, Shipping provider 1 implements slow steaming and virtual arrival schemes to reduce time at anchor.

Through voyage charter contracts, Shipping provider 1 has implemented a virtual arrival system. The company considers that the port's queue approach of "first come, first serve" can be a barrier to implementing the virtual arrival system. Thus, the company suggests that it is essential to enhance information sharing between actors, i.e., vessel and port. As a result, through better information and a proper verification system, vessels will be able to adapt their speed to the situation at the port and consequently increase their efficiency by reducing waiting time and air emissions.

Finally, the company suggests that focusing on reducing the vessels' speed can negatively affect the use of alternative fuels and energy-efficient vessel technologies. Nevertheless, they did not elaborate on why or how this could be the case.

2.5.4 Shipping provider 2

Shipping provider 2 is a logistics company within the oil industry that manages the charters for Shipper 2. Thus, Shipping provider 2 acts as carrier for Shipper 2 and are thereby in charge of contracts and handles communication with the ships to and from the port area while Shipper 2 decides when a ship will call a port. Shipping provider 2 implements a combination of voyage charter and time charter in its services. Usually, the company has short-term (one-year) time charter contracts. However, thanks to a successful collaboration with Shipping provider 1, some contracts have been renewed for longer periods. Sometimes, to manage the capacity gap of the time charter, the company implements a voyage charter. Due to the volatility in the oil market, it is not considered commercially beneficial to only make use of time charter, as there might be a scenario where the company does not need the vessel but is still obliged to pay for it. The principle is to cover the expected minimum demand by time-charters and complement with voyage charters to cope with demand peaks.

Ships chartered from the spot market are chosen and determined by more criteria than price. Choosing a ship with a previous successful operation is preferable as more trust has been established. As the ship is chartered from the voyage charter market, Laycans still apply and these ships will not slow steam, which can be considered a higher financial risk for the shipowner. According to Shipping provider 2, the entire industry is based on Laycans. Shipping provider 2 is a logistics service provider acting on behalf of Shipper 2, but if it was given the full control of the transport chain, the Laycans would be more flexible. Shipping provider 2 has tried to reduce the anchorage time by adapting the speed of the ships but sees the port capacity at the Port of Gothenburg as one of the main contributors to increased anchorage time.

Based on the company's answers, communication is a key factor in adjusting a vessel's speed. In general, actors communicate via telephone or email, and the method depends on the type of contract. In the case of a time charter, the information is shared directly with the captain of the vessel, while in the case of a voyage charter, the agent is responsible for communicating any changes. In the case of information exchange, it seems difficult to implement a virtual arrival system due to a lack of confidence among actors.

2.5.5 The Port of Gothenburg

Gothenburg is an attractive anchoring location for vessels trading in the Baltic Sea, considering that its anchorage places are protected from adverse weather conditions, and it offers excellent bunkering infrastructure. Good travel connections also make Gothenburg attractive for crew changes. The port implements a "first come, first serve" order method and considers the method to be fair for all vessels, but it would like to use an alternative scheme as a virtual arrival procedure, supported by a system for validation and decision-making enabling JIT-arrival. With this approach, the port could use AIS data for validating the position of the vessel and artificial intelligence for estimating the time of arrival. Port of Gothenburg does not consider building new berths in the energy port, for the specific purpose of reducing time at anchor, due to high costs and lack of suitable areas. Nevertheless, the capacity and flexibility might be increased by investments in new berths, pipes, pumps etc and that infrastructure is continuously developed.

3 Assessing emissions while anchoring

As anchoring is neither achievable nor fully wanted, emissions need to be reduced during anchoring. Anchoring can be reduced but not eliminated, and hence another aim is to reduce CO_2 emissions while at anchor. Acting towards sustainability often relies on awareness (Macharis, et al., 2014) and one way of raising this is to assess the emissions released by ships at anchor. The fuel consumption at anchor for ships is calculated with different datasets and underlying assumptions, as described in the next section.

3.1 Emission calculations: data sources and models

The greenhouse gas (GHG) emissions at anchor are mainly generated by the auxiliary engines and boilers, since the main engines generally are turned off. The emissions are caluclated by estimating the fuel consumption and then multiplying the fuel consumption with an emission factor (equation 1) or by multiplying an emission factors with power output of the engine/boiler (equation 2). This study uses different datasets and compares these to make the best possible estimate; the datasets are summarised in Table 2.

$$Emissions_1 = EF \cdot fuel\ consumption\ rate \cdot time \qquad (1)$$

$$Emissions_2 = EF \cdot power\ output \cdot time \qquad (2)$$

Where:

EF	is the emission factor, which is either fuel based (gCO_2/g fuel) or based on the power output of the auxiliary engine or boiler (gCO_2 fuel/kWh).
time	is the time the ships is at anchor.
power output	is either the assumed average power (kW) at anchor or culculated by multiplying the installed power of the engine with an assumed load factor

The emissions are calcuated for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide N_2O and these results are combined as greenhouse gas equivalents calculated with a 100 year perspective (CO_{2-eq}). The data on the upstream emissions are from a study evaluating the environmental impacts of marine fuels (Brynolf, 2014). The background to the selection of data sets, methodologies and comparions between these can be found in the following sections.

Table 2. Data sources used in this study

Type of data source	In final results	Sources
Emission factors fuel based [gCO_2/g fuel]	yes	IMO´s 4th GHG study (MEPC 75/7/15, 2020).
Emission factors [CO_2g fuel/kWh]	yes	Ports yearly inventory (Cooper & Gustafsson, 2004; Winnes, et al., 2015; IHS Markit, 2019)
Auxiliary power demand 1	no	IMO´s 4th GHG study. (MEPC 75/7/15, 2020)
Auxiliary power demand 1 modified	yes	IMO´s 4th GHG study, surveys, and own work (Florez & Betancur, 2021; MEPC 75/7/15, 2020)
Auxiliary power demand	no	Ports yearly emission inventory (Entec UK Ltd., 2002; Sjöbris, et al., 2005)
Boiler fuel consumption 1	no	IMO´s 4th GHG study (MEPC 75/7/15, 2020)
Boiler fuel consumption 2	yes	Ports yearly inventory (The Port of Los Angeles, 2010)

3.2 Methodology development

The methodology to calculate the emissions at anchor is evaluated and further developed as a part of this project. We have done this in three ways:

1. using the feedback from the workshops as criteria for estimating the emissions when slow steaming.
2. included the results from the survey in the emission inventory, to improve the inventory and assess the uncertainty. However, only tanker ships are included in the analysis since almost all responses and most ships anchoring outside the port were tanker ships. The focus is on product- and chemical tankers smaller than 40 000 dwt.
3. we examine the method for extracting the time spent in the area and then compared the AIS-data with the port call statistics.

3.2.1 Reduction of emission during the slow steaming scenario

In this study we have assumed that all tanker ships except the bunker ships are slow steaming. The baseline emissions at sea are calculated with the following formula for each individual ship:

$$Emissions = (\,load_{ME} \cdot Power_{ME} \cdot EF_{ME} + load_{AUX} \cdot Power_{AUX} \cdot EF_{AUX}) \cdot time_{sea} \quad (3)$$

where $\mathrm{load_{ME}}$ and $\mathrm{load_{AUX}}$ are the assumed load factors on the main engines and the auxiliary engines at sea, in this study set to 80 % and 30 % respectively.

The $\mathrm{time_{sea}}$ (h) each ship can know beforehand that there will be delays is set for four different scenarios: 6 h, 12 h, 24 h and 36 h. These scenarios are selected since it is hard to know how much time before arrival that the port actors could be aware of delays and queues to the quays in a first implementation of JIT. Secondly, some ships could have made a shorter voyage since previous port than assumed. The corresponding distances and an exemplification of a port at that distance is described for each scenario in Table 3.

The maximum distance at sea for each ship is therefore also individual since the ships have different service speeds:

$$distance_{sea,\ max} = time_{sea} \cdot service\ speed \qquad (4)$$

Table 3. Descriptive statistics of slow steaming scenarios

Scenario	Time [hours]	Calculated average maximal distance* [NM]	Approximation of correspond arrival destination**
1	6	80	Port of Falkenberg
2	12	170	Port of Nyborg [DK]
3	24	330	Port of Kalmar
4	36	500	Port of Rotterdam [NL]

*The average is based on the 808 tanker ships that anchored outside the port in 2019.
** Distance according to vesseltracker.com

It is also important to note that although the slow steaming potential theoretically can be utilized in most cases, an initial JIT-approach will not include all ships. Furthermore, the earliest possible Requested Time of Arrival (RTA) will vary between voyages due to barriers in the JIT-implementation. As briefly mentioned in chapter 2, barriers of the JIT implementation are linked to for example trust issues, business cases and system support, which is further elaborated upon elsewhere (Kristiansson & Wall, 2021; Jivén, et al., 2020). Additionally, the actual possibility to lower the speed is not always possible since some ships are already slow steaming (Jivén, et al., 2020).

In the slow steaming scenarios, the time at sea increases for each ship, implying that the energy consumption of the auxiliary engine will increase. The power requirements for propulsion in the slow steaming case is estimated using the following model (The Port of Los Angeles, 2010):

$$Propulsion\ engine\ load\ factor = \left(\frac{speed_{slow\ steaming}}{speed_{service}}\right)^3 \quad (5)$$

Where $\text{speed}_{\text{slow steaming}}$ is the ship's assumed slow steaming speed, and $\text{speed}_{\text{service}}$ is the ship's speed when the engine is operating at maximum continuous rating (MCR), during average conditions. This relation is a highly simplified representation of reality and for example the actual speed may sometimes be higher than the speed in the denominator in equation 5, since e.g., winds and waves also influence the speed. The propulsion engine load factor when the ship is sailing at design speed is generally assumed to be about 80% (i.e., $\frac{P_{\text{"max"}}}{P_{\text{installed}}} = 80\%$) (Jalkanen, et al., 2009). The emissions in the slow steaming case are calculated by combining equation (3-5), resulting in equations 6:

$$\text{Emissions}_{\text{slow steaming}} = \left(\text{load}_{\text{ME}} \cdot \text{Power}_{\text{ME}} \cdot \text{EF}_{\text{ME}} \cdot \left(\frac{\text{speed}_{\text{slow steaming}}}{\text{speed}_{\text{service}}}\right)^3 + \text{load}_{\text{AUX}} \cdot \text{Power}_{\text{AUX}} \cdot \text{EF}_{\text{AUX}} \right) \cdot \left(\frac{\text{distance}_{\text{sea, max}}}{\text{speed}_{\text{slow steaming}}}\right) \quad (6)$$

where the $\text{speed}_{\text{slow steaming}}$ is varied between 4 – 10 knots. This range was chosen based upon the service speeds stated by the stakeholders in the workshops. One of the participating shipping companies stated that their newest generation of tankers has a possibility to slow steam at a speed of 4 knots while their older generations of vessels could slow steam at an approximate minimum of 9-10 knots. However, it is important to note that the relation in equation 6 does not consider that the efficiency of the engines is reduced when the ship is slow steaming (Jivén, et al., 2020; MEPC 75/7/15, 2020).

A boundary condition in this study is that the overall transport work is not reduced in the system, implying that each individual ship is only allowed to slow steam during the time it otherwise had been anchored (distance must be the same). The minimum speed for each ship is therefore determined by the following equation:

$$speed_{slow\ steaming,\ min} = \frac{distance_{slow\ steaming}}{time\ assumption + time_{anchor}} \quad (7)$$

The $time\ assumption$ in Equation 7 correspond to the four scenarios in Table 3 and $time_{anchor}$ the time each individual tanker ship was at anchor 2019 according to the statistics.

3.2.2 Auxiliary engine demand at anchor for surveyed ships

One of the parameters investigated in the questionnaire in Gothenburg (Florez & Betancur, 2021) was the auxiliary engine power used at anchor (black dots in Figure 7). These ships represented about 43 % of the time at anchor of the product- and chemical tanker segment during the survey period. The results from the survey in Gävle is also included in the figure as a comparison. In the figure both the results from the survey in Gothenburg (black dots) and in Gävle (red dots) are clearly below the modelled auxiliary engine power used in the yearly emission inventory report (dashed line) and the power demand used in the IMO's 4th GHG study (straight line).

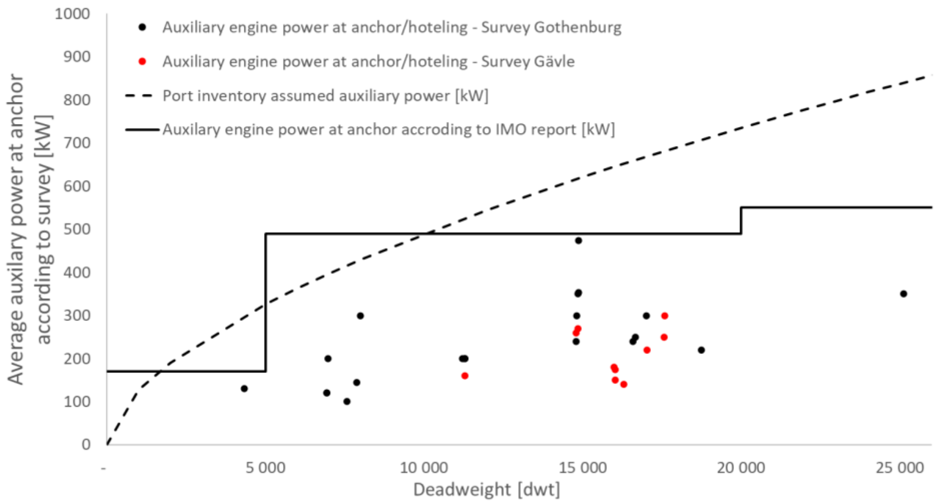

Figure 7. Modelled and surveyed auxiliary power used at anchor as a function of ship size. The dots represent all surveyed chemical/products tanker ships smaller than 40 000 dwt (31).

The results from both surveys are summarized in Table 4. In the UN guidelines for emission inventories, it is recommended to first and foremost use site specific data if possible, in order to reduce uncertainty (Frey, et al., 2006), we have therefore used 245 kW for this ship segment as a base case in this study, even though the sample is small adding risk of biases. A bias could for example be that ships with lower energy use are more likely to answer the questionnaire. However, the data from the survey is more transparent than the IMO data and more recent than the assumed 40% load factor of totally installed power of the auxiliary engines that is used in the yearly inventory report (Entec UK Ltd., 2002; Sjöbris, et al., 2005). Furthermore, both the qualitative and quantitative results from the survey in Gothenburg suggest that the ships are only using one of their auxiliary engines while anchoring (Florez & Betancur, 2021); see next section for further information how this affects the efficiency of the auxiliary engine.

Table 4. Survey results, descriptive statics for 31 surveyed Chemical/Products Tanker ships smaller than 40 000 dwt.

Product and chemical tankers smaller than 5 000-40 000 dwt	The Port of Gothenburg	Port of Gävle	Both studies
Average auxiliary power at anchor according to survey [kW]	245	211	233
Standard div [kW]	110	57	97

3.2.3 Specific Fuel Oil Consumption (SFOC) for surveyed ships

23 tanker ships in the study responded to the question of their specific fuel consumption (SFOC) during their time at anchor. Two of the replies were removed from the dataset since the SFOC value were lower than what is theoretically possible, i.e., more electric energy was generated than energy content of the fuel used. All other replies were in a reasonable range, between 176 g/kWh and 250 g/kWh, see Table 5. These data were only extracted from the questionnaire performed in Gothenburg.

Table 5. Descriptive statistics of SFOC for the auxiliary engines at anchor

# replies	Min	max	Average	Median	Std
21	176	250	216	210	21

In the 4th GHG IMO-study it is recommended to use 185 g/kWh as a baseline for SFOC for auxiliary engines built after 2001 (MEPC 75/7/15, 2020). In the pre-inventory to this report the IMO baseline value was used, 185 g fuel/kWh for almost all ships (Florez & Betancur, 2021), since all tanker ships in the survey were built after 2001 and used marine gas oil or marine distillate oil for their auxiliary engines. The results in Table 5 indicate that IMO's recommended value is low. However, IMO also suggest correcting the power demand for load factors on the engine according to equation 8 bellow, this relation is visualized in Figure 8.

$$SFOC_{Load} = SFOC_{baseline} \cdot (0.455 \cdot load^2 - 0.71 \cdot load + 1.28\,) \quad (8)$$

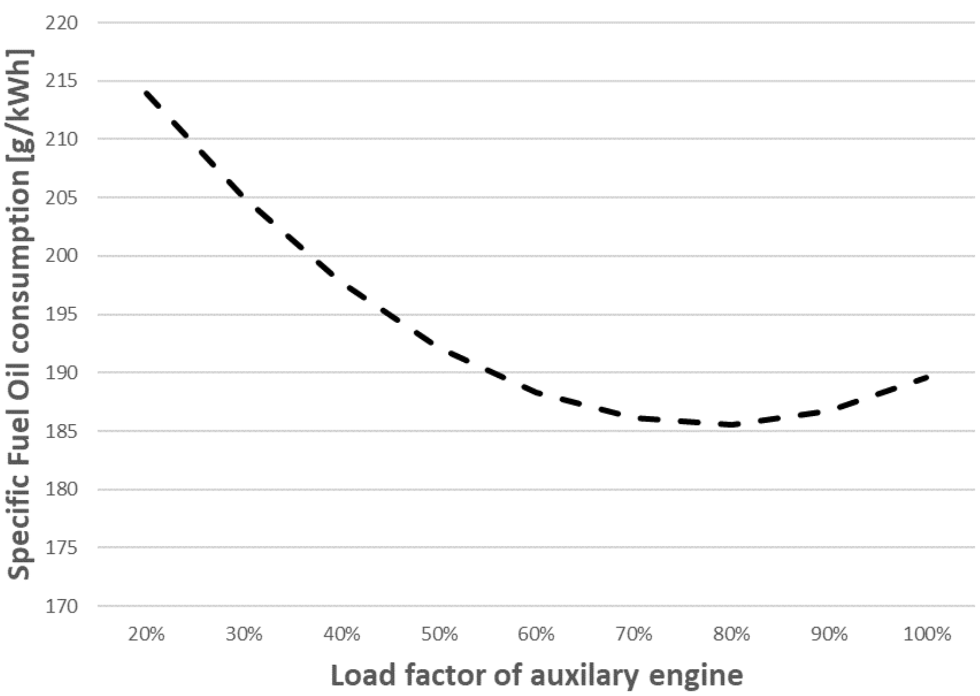

Figure 8. Specific fuel oil consumption for different load factors assuming a baseline SFOC of 185 g/kWh

Figure 9 shows that the load factors for the surveyed ships are lower than 80 % for all product tanker ships (assuming that only one auxiliary engine is used). We have therefore calculated the SFOC for different loads using equation 1 proposed by IMO (MEPC 75/7/15, 2020) to compare the results with 21 replies in the survey. This comparison is illustrated in Figure 9.

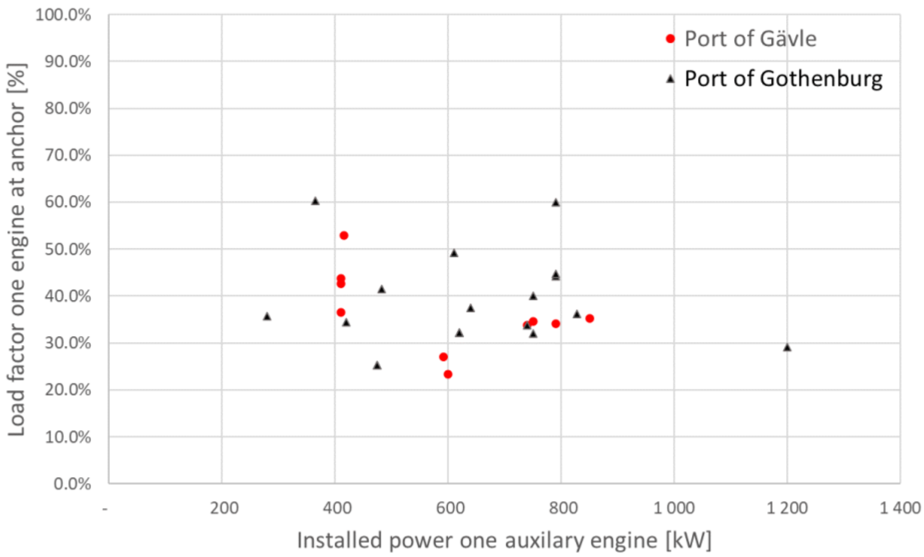

Figure 9. Illustrates the load factor at anchor as a function of installed power, assuming that only one auxiliary engine is used to meet the power demand. Each point represents one tanker ship.

The comparison between the results from the survey and the model in Figure 8 shows that the model underestimates the fuel consumption, i.e., the efficiency of auxiliary engines is consistently overestimated. The SFOC values were revised in the IMO's 4th GHG-study from 225 g/kWh to 185 g/kWh for ships built after 2000. In the report the main reason suggested by the authors was that SFOC should: "reflect the current mix of marine engine ages and types" (MEPC 75/7/15, 2020). However, the references for this data change are product guides from engine manufactures, which in turn are based on measurements in laboratory environment (Pavlenko, et al., 2020; ISO 3046-1, 2002). When the engines are used at sea, other parameters than engine load could affect the fuel consumption, we will therefore use a higher SFOC (216 g/kWh), for all ships at anchor in this study. This is very close to the SFOC 217 g/kWh estimate by Cooper (2003), on which the emission factors for auxiliary engines at berth in the port inventory are based. This study is based on measurement on 22 auxiliary engines.

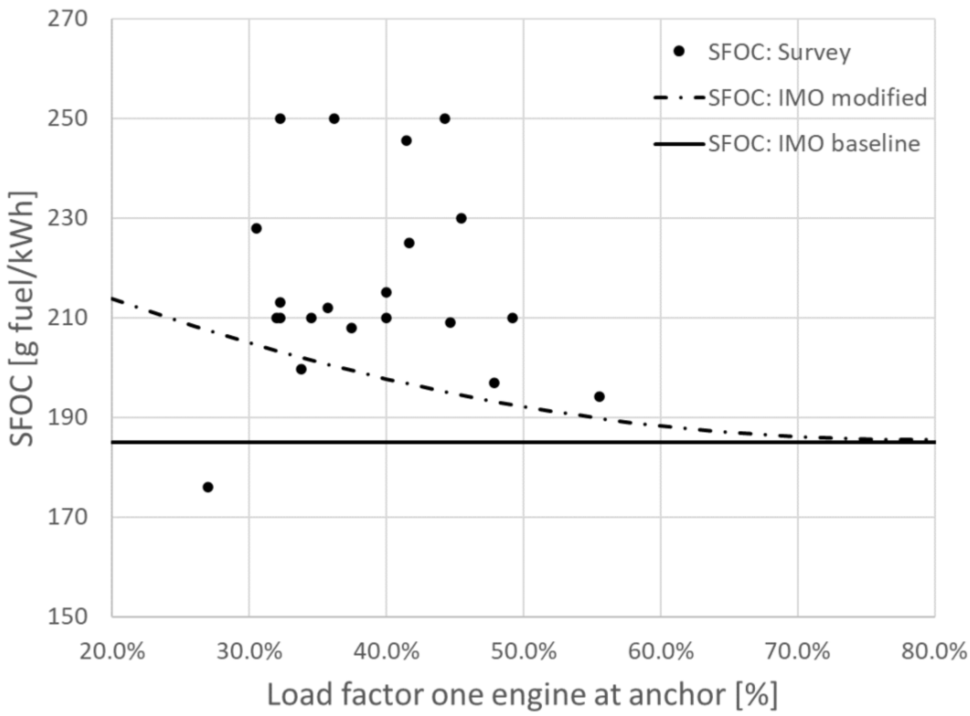

Figure 10. Comparison of SFOC for different engine loads between surveyed ships and average values provided by IMO.

Figure 11, all ships in the survey are built after 2000 and most of them between 2003 and 2010. It is therefore difficult to assess any fuel improvements over time. Only 4 of the ships (not tankers) anchoring during 2019 were built before 2000.

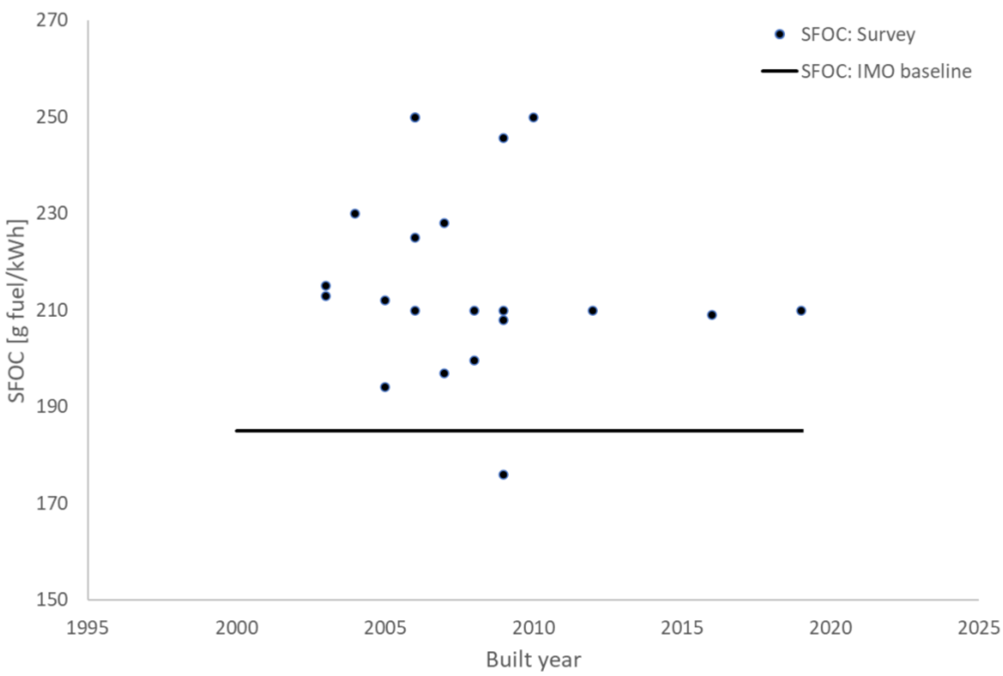

Figure 11. Specific Fuel Oil Consumption as a function of the building year of the ship.

3.2.4 Fuel used by auxiliary boilers

In the emission inventory study conducted prior to this report (Florez & Betancur, 2021), the data for fuel consumption from auxiliary boilers were gathered from IMO's 4th GHG study (MEPC 75/7/15, 2020). In the IMO study the calculations were done in the same way as for the emissions from the auxiliary engine, i.e., the fuel consumption was derived by multiplying the specific fuel oil consumption (SFOC, g fuel/kWh) with the assumed power outputs (kW) for different ship categories. IMO recommends using the same SFOC for auxiliary boilers as for steam turbines. However, steam turbines are used for propulsion and have a much lower efficiency than an auxiliary boiler.

For example, the suggested SFOC for boilers using MGO was 320 g fuel/kWh in the IMO report, this would correspond to an efficiency of about 27 % for a boiler which is very low. Old oil boilers generally have an efficiency around 60-70% and new ones could have an efficiency above 90%, that would correspond to a SFOC between 90-140 g/kWh. Furthermore, it is rather strange to calculate the fuel consumption based on the power and the SFOC. Typically, emission calculations from boilers are based directly on kg·fuel/hour since the boiler is producing heat. Since, it is not clear how the SFOC is used in the IMO study, this pre-study instead uses a methodology that is based on the generic value of the fuel consumption (kg fuel/h) for different ship categories and sizes, see Table 6. This methodology is further described in other studies, such as the port emission inventories in Gothenburg or Faxafloahfnir (Winnes, et al., 2015; Merelli & Parsmo, 2021).

Table 6. Fuel consumption in oil fired boilers at anchor. Fuel consumption is given per thousand gross tonnes and hour (Port of Los Angeles, 2010).

Ship type	Fuel consumption (1000 GT *hour)
Bulk carriers	1.4
Oil- and chemical tankers	4
Container ships	2.9
Cruise ships	4
General cargo ships	0.9
Other ships	4
Reefers	5.4
RoRo/Ferries	2

3.2.5 AIS data: time at anchor for ships

The speeds and the positions of ships have been analysed with help of the ships' Automatic Identification System (AIS) data and satellite data from the sea surrounding the Port of Gothenburg (MarineTraffic, 2021). The AIS data cover signals from 4 380 ship that visited an anchoring site in the port during 2019. In total about 495 700 signals were extracted from the areas. The AIS data contains information about IMO number, position, course, speed and a timestamp. About 53 900 of these signals were not included in this analysis since it was not possible to link them with the ship database (IHS Markit, 2019). However, only 3 156 of these 53 900 signals had a speed below 2 knots, indicating that most of these ships were not at anchor. A study of the missing signals shows that most were from small vessels, coastal gards or military ships. Two methods have been used to extract a ships time at anchor from the AIS data:

1. The time difference between when the ship leaves the area and when it enters the area.
2. The sum of the time difference between the two closest signals for each ship.

The results from the first method have been used in the final emission calculations in Chapter 4. However, the results of the two methods have been compared, to tune the assumptions and verify the method. The resulting assumptions are that the anchoring is consider as "new unique anchoring" if:

- It is not the same ship
- It is not in the same zone
- The maximum time difference between two signals is longer than 5 hours
- The distance between the two closest signals is larger than 2 km, i.e., it is seen as the ship has moved and makes a new unique anchoring.

Furthermore, if the ship had a higher speed than 1 knot it is assumed to be sailing instead of anchoring. Using method 1, this for example implies that the time the ships spend manoeuvring in the area before and after a unique anchoring is excluded from the time spent at anchor.

The ships that are "passing" an anchorage area are also excluded from the analysis. A ship is categorised as "passing" if it is in an anchorage area for a shorter duration than the time limit in **Error! Reference source not found.**. The time limit is calculated by assuming that a ship passes through each zone at four knots on the diagonal.

Table 6. Time limits for each anchorage area.

Anchorage areas*	Distance [NM]	Time limit [h]
1	5.4	1.35
2	3.9	0.975
3	0.9	0.225
4	0.6	0.15
5	1.3	0.325

*See Figure 5 for illustration of the zones

Usually, a ship at anchor shows a clear pattern, illustrated Figure 12. However, sometimes the ships have moved within the zone, even though there is no reason to believe that they left the zone during the period. These manoeuvres are also defined as one "unique anchoring", even though the ship can be anchoring several times during the same time interval, since it is not leaving the area, see next section for a more detailed description.

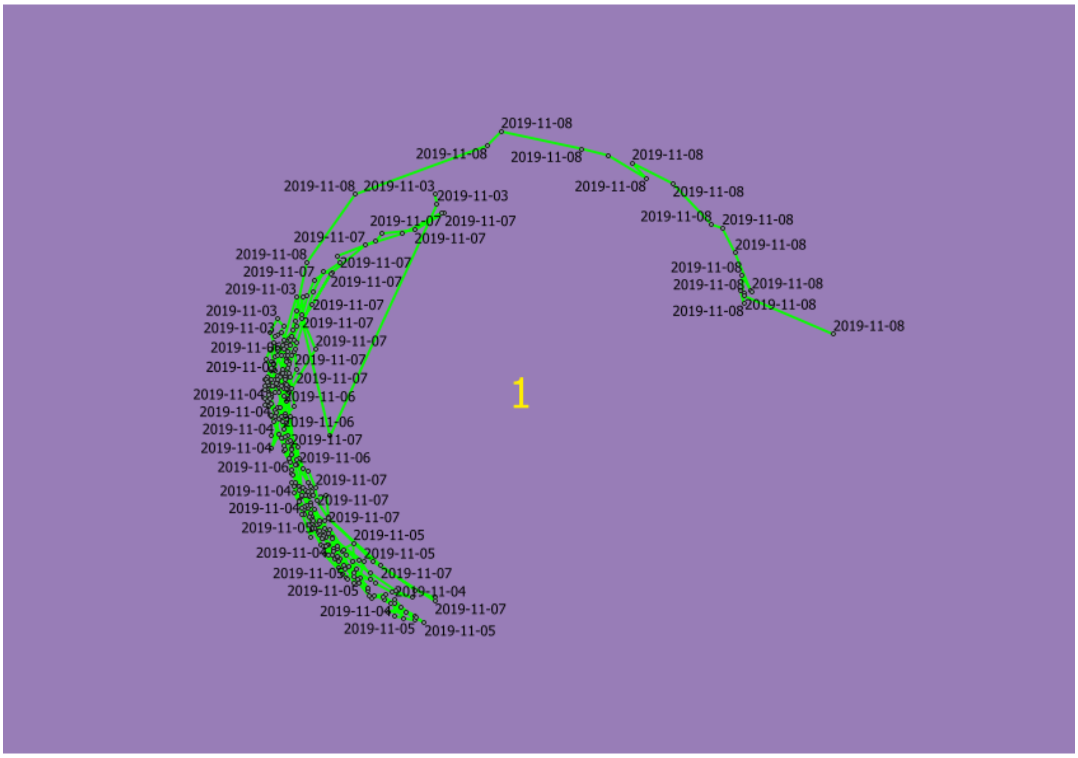

Figure 12. Illustrates a typical anchoring pattern at an anchoring site the anchor is in the middle and the ship "oscillates" depending on the wind direction. The ship arrived on the 4th of November and left on the 8th of November. Each dot represents one AIS-signal, and the line shows how the ship was moving during the period.

To be able to compare and verify the results, the AIS data have been linked to the data in PortIT. PortIT is the system which the Port of Gothenburg uses to collect information about all ships visiting the port. These statistics provide information about each ship's time of arrival & departure, the ship identity and at which quay it berths. These data are normally also used in the yearly emission inventory (Winnes & Parsmo, 2017).

The two datasets are linked by taking the port call identfication number from the PortIT system and adding it to the AIS-data, when the time and the IMO number matches. In some case the ships had several unique anchorings for the same port call number. The results from this comparision are described and futher analysed in Section 4.4. There are also anchored ships that are not included in the port statistics as they never call any of the port's quays. These results will be referred to as "*in transfer*". All anchoring operations that can be linked to a port call is instead referred to as "*port call*".

It would be difficult to look at patterns in the data and manage dataset that are order of magnitudes larger than the data used in this study, with the method used to extract times at anchor in this study. If one wants to make a deeper analysis it could be useful to use some type of clustering technique instead (Ahlberg & Danielsson, 2016).

3.2.6 Comparison between port call statistics and AIS data

A comparison of the time at anchor between the official port call statistics and the one used in this study (based on the AIS data) is shown in Table 7. The total time at anchors differs with about 10%.

Table 7. Comparison between the AIS data and the official port call statistics for the anchorage areas.

Ship type	Total time at anchor		Time difference	
	Port call statistics	AIS Method 1	In AIS (method 1) and not in port call statistics	In port call statistics (method 1) and not AIS
Product tankers	23 859	24 455	1 362	832
Crude oil ship	3 026	3 004	106	148
Bunkering ship	10 065	13 317	3 475	882
Container ship	1 282	1201	1	90
Vehicle carrier	296	288	0	10
General cargo	2 266	2 334	135	50
Other	58	174	124	8
Bulk	75	77	3	1
Total	40 928	44 850	5 206	2 021

The comparison in Table 7 show that about 5 200 hours of the time at anchor that were found in the AIS data were not found in the official port call statistics, even though it was possible to link this time to an official port call. The AIS data and the official port call statistics were linked by comparing the position and time stamp for each individual ship in the two datasets. It has not been possible to check all these discrepancies manually. However, a check of a small sample shows the port statistics in these cases typically jump between different unique anchoring occasions, even though they have been at the anchoring site during the entire period according to the AIS data. For example, the ship illustrated in Figure 12 has conducted three unique anchoring events according to the official port calls statistics and was at the anchoring site for 52 hours in total, but according to AIS data it was spending more than 5 days at the site without leaving. In this case the AIS seems like a better fit, since the ship has a very typical anchoring patter and there is no indication that the ship has changed her position during this period. Furthermore, the time interval between the points in the AIS data is 21 minutes at most. Another problem is that the time of arrival in the port calls statistics is later than that identified in the analysis of the AIS data.

As shown in Table 7 the largest gap between the port call statistics and the time at anchor extracted in this study is for bunker vessels (3 475 of 5 206 hours). The example in Figure 13 illustrates this issue. The example is from a bunkering vessel that has been in the area for about 140 h according to the AIS data but only 45 hours according to the port call statistics. The ship has probably moved during the period to perform bunkering operations at different locations, but it was not possible to verify this within this study.

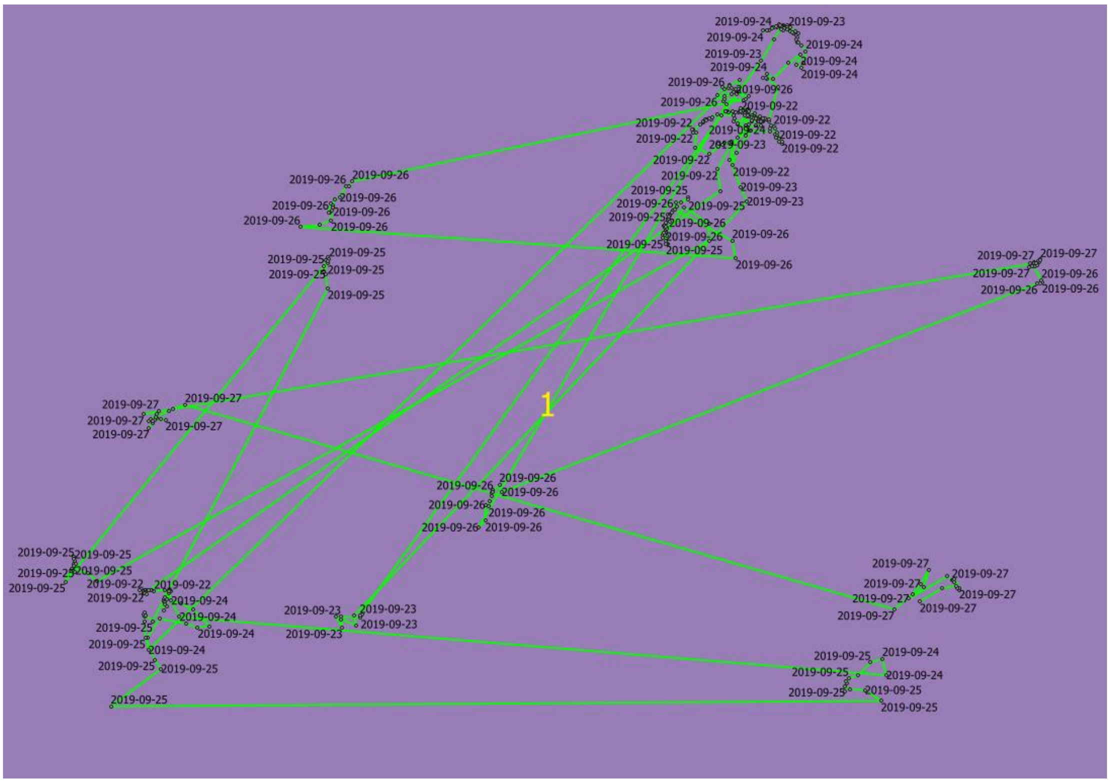

Figure 13. Illustrates a typical pattern for a bunkering ship.

The comparison in Table 7 also shows that about 2 000 hours of the time at anchor are missing in the AIS summary statistics but was present in the port call statistics. 515 of these hours were due to that it was not possible to connect the port call data with the AIS data. Other discrepancies are generally harder to evaluate since it is time consuming and we do not know exactly all the criteria used in PortIT, the differences could have several explanations. A control of 10 different examples showed the following:

- Jump for several days in AIS data, unclear if it is because the signal is turned off or if is because the ship left the area.
- The anchoring has taken place at the edge of a zone, which means that they are not or are only partly included in the AIS statistics.
- The time at anchor was too short, implying that it was not identified as an anchoring according to the definition in this study.

4 Case study: Emissions in the Port of Gothenburg

The Port of Gothenburg is the largest port in Scandinavia with terminals handling cars, container, RoRo, RoPax, liquid and dry bulk. The high traffic density of ships can occasionally lead to congestion on berths with high berth occupancy. The primary alternatives for ships are to adjust speed or to anchor awaiting an available quay. It is not possible to see any downward trend in the time spent at anchor during the last decade (2010-2020), as can be seen in Figure 14. Since the port strives to reduce CO_2 emissions from port operation on land and at sea defined from the municipal borders to Vinga Lighthouse (the Port of Gothenburg, 2020), including emissions from anchoring ships calling the port, this anchoring time needs to be addressed. The combination of multiple types of ship categories, high density in anchorage areas and the ambition to reduce emissions makes Gothenburg a suitable location to base emission models and investigate measures for emission mitigation. The results from this study give important insights on emission values and give suggestions on emission reduction based on input from the industry. The results from the case study in port is presented in the following sections.

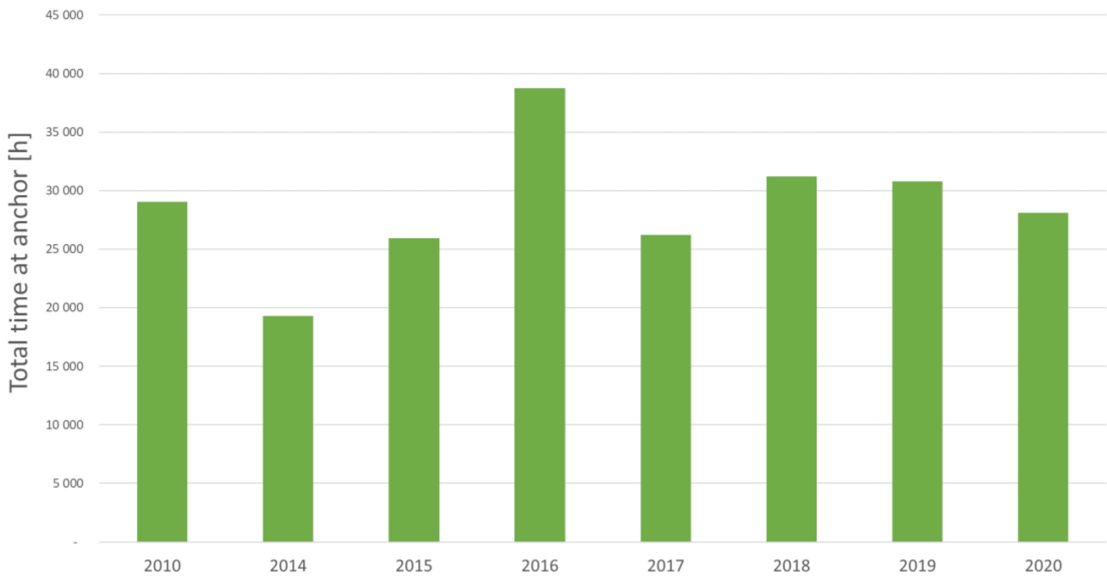

Figure 14. Total time at anchor for all ships visiting the Port of Gothenburg 2010 and 2014-2020, excluding all known bunkering ships. The system extracting statistics was updated in 2015 and the statistics for 2010, 2014 and 2015does not have the same quality as from 2016 and onwards.

4.1 Results from workshops

The workshops were performed with the shipping lines Furetank and Terntank and the terminal Preem. In general, the output from the workshops were in line with what has been said in the interviews with other parties in the theses (see Section 2.5) and in other studies (IMO, 2020). What was perhaps clarified in the workshop was that both shipping companies disregarded technical measures onboard, such as using batteries, as the most cost-efficient measure for emission reduction. Current technical development makes other solutions for CO_2-reduction more effective in relation to the ship's total emissions (at sea, at anchor and at berth). As an example, they mentioned alternative fuels being a more suitable option.

Regarding reduction of time at anchor all parties expressed willingness to increase efforts. According to the respondents, the main way of reducing time at anchor is by allowing for slow steaming in accordance with terminal readiness, i.e., with just in time arrival (JIT). However, they also argued that even though it may sound like a "simple task" there are many barriers for a JIT approach. But, regarding transparency and lack of trust in new commercial clauses for JIT, the participants were convinced that these could be partly bridged with different port regulations and systems for port to bridge team communication. The participants where convinced that, by an approving attitude, the stakeholders can overcome the barriers.

On a port or terminal level, systems for communication and verification of Estimated Time of Arrival (ETA) and adjustments to local rules and queuing order, could be a first steppingstone.

4.2 Time at anchor

The ships' time at anchor has been summarized in Table 8 below. As can be seen in the table the ships calling the port were spending more time at the anchorage areas (*port call: 44 850 hours*) than the ships that were not calling the port (*in transfer: 35 770 hours*). Bunker ships were spending much less time per anchor occasion than other types of tanker ships.

Table 8. Total time at anchor outside the Port of Gothenburg 2019 for different ship categories (hours). The estimates are based on AIS-data.

Ship type	Time [h]		Number of times at anchor [#]		Time per anchor occasion [h/#]	
	Port call	*In transfer*	*Port call*	*In transfer*	*Port call*	*In transfer*
Product tankers	24 455	19 124	766	879	32	22
Crude oil ship*	3 004		42		72	
Bunkering ship	13 317	5 434	1 384	915	10	6
Container ship	1 201	347	56	44	21	8
Vehicle carrier	288	93	4	3	72	31

General cargo	2 334	5 646	245	853	10	7
Other	174	807	15	161	12	5
Bulk	77	4 318	12	465	6	9
Total	**44 850**	**35 770**	**2 524**	**3 320**	**18**	**11**

*Crude oil tankers are only categorized for ships visiting the port

4.3 Emissions at anchor

The emission estimates in Table 9 show that tanker ships accounts for most of the emissions at anchor. 83 % of total emissions were emitted by tankers ships. Since tankers ships are dominating the emissions at anchor, they are further analysed in this section.

Table 9. Calculated well-to-propeller greenhouse gas emissions (tonnes CO_{2eq}/year) at anchoring sites outside the Port of Gothenburg in 2019 for different ship categories

Ship type	Port call	In transfer	Total
Product tankers	9 400	11 620	25 320
Crude oil tankers*	4 300		
Bunkering ship**	2 390	1 060	3 450
Container ship	1 720	700	2 420
Vehicle carrier	370	110	480
General cargo	110	990	1 100
Other	30	130	160
Bulk	10	1 530	1 540
Total	**18 330**	**16 140**	**34 470**

*Crude oil tankers are only categorized for ships visiting the quay 800 or 801

** The emissions for bunker ship are calculated the same way as other tanker ships. However, since they could be bunkering for some time their emissions are probably underestimated.

It is also worth noting that the total emissions were much higher from ships not calling the port (*in transfer)* that hade an anchor time between 0-10 hours, compared to ships that were calling the port, as can be seen in Figure 15. This shorter anchor duration could be an indication that these ships more frequently were doing some type of service at anchor, such as bunkering, rather than waiting for Laycan or time slot at another port, that were the main reasons stated in the survey (Therman & Wass, 2021).

A large share of the emissions was also emitted by ships *in transfer* that were at anchor for a longer time interval. It could be that they were waiting for a new assignment. However, it may as well be that they were waiting for a time slot in another port, due to suboptimal route planning, but preferred waiting at one of anchorage areas outside of Gothenburg. This anchor time could perhaps, partly, also be avoided with JIT- arrival, but in that case by initiatives independent of the port. The reason behind why ships *in transfer* were at anchor in Gothenburg has not been investigated in this study, however since it seems like much of the emissions comes from these ships it may be interesting to investigate this further in another study.

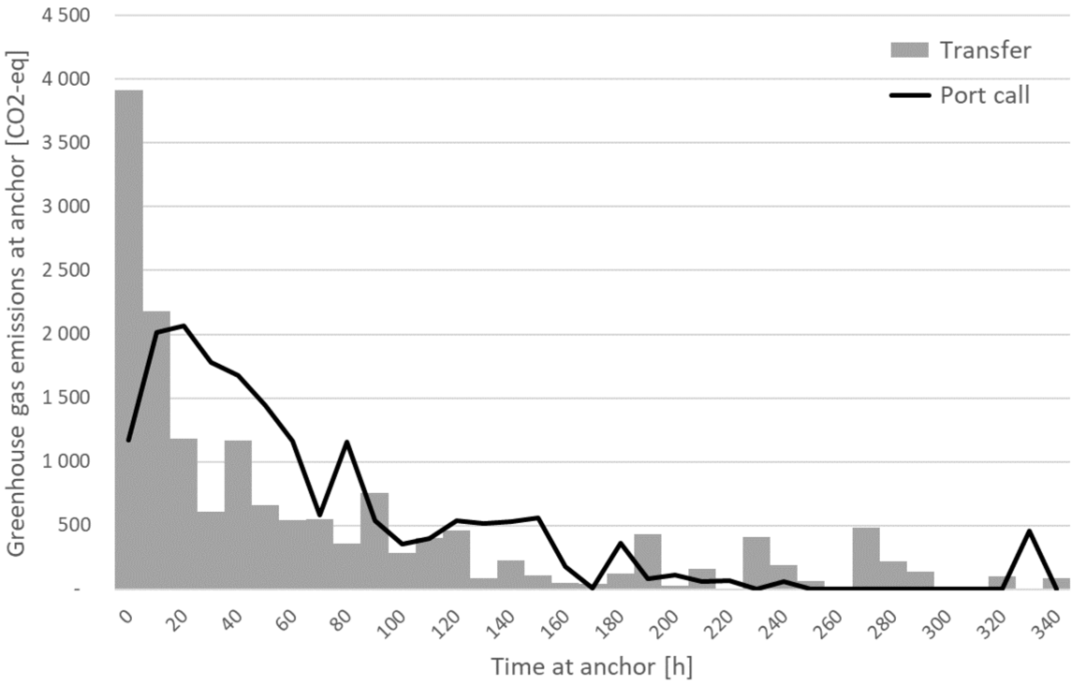

Figure 15. Emissions as a function of time at anchor (2019). Calculated well-to-propeller greenhouse gas emissions (tonnes CO_{2eq}/year) at anchoring sites outside the Port of Gothenburg.

4.3.1 Emissions from auxiliary engines and boilers

If the emissions are separated between what is generated by the auxiliary engines and boilers respectively, one can see that boilers constitutes about half of the emissions for product tankers, and 66 % of the emissions from crude oil tankers, see Figure 16. This is because most crude oil tankers are large and the model for calculating emissions from the boilers are directly proportional to the size of the ship, while the model for calculating the emissions from the auxiliary engine is separated into different size bins of the ship category. This is a flaw in the model, and we have therefore also calculated the emissions from boiler based on the data in the IMO report to compare the results, see Table 10.

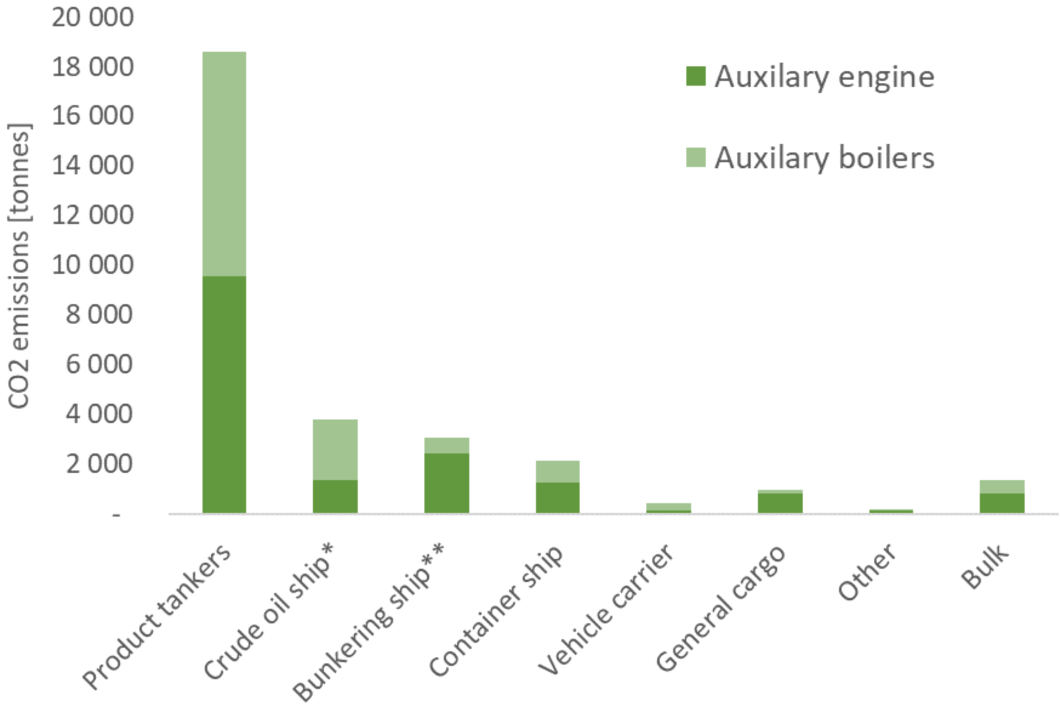

Figure 16. Comparison of tonnes CO_2 emissions (2019) from auxiliary engines and boilers for ships at anchor.

The comparison in Table 10 shows that the total emissions from the boilers would increase with about 23 % if the assumption and the data from the IMO report were used instead of the continuous function that have been used in this study. This is mainly explained by the higher emission estimates from product tankers, general cargo, and bunkering ships in the IMO data. It is rather unexpected results considering that the IMO report used a very high SFOC for the boiler, see section 3.2.4. This implies that the assumed power of the boiler in the IMO study probably is adapted to the SFOC, so that the average fuel consumption is in a reasonable range.

Table 10. CO_2 emissions 2019 (tonnes) from boiler using different data sources. Note that the comparison only is for direct CO2 emissions, i.e., it is not including other greenhouse gases and Well-Tank/upstream emissions.

Ship type	Method for calculating fuel consumption	
	As a continuous function of ship size (used in this study)	Average kW and SFOC (IMO)
Product tankers	8 995	10 656
Crude oil ship*	2 462	1 249
Bunkering ship**	613	3 093
Container ship	889	608
Vehicle carrier	277	117
General cargo	123	758
Other	33	69
Bulk	554	650
Total	**13 945**	**17 200**

Only some few respondents in the survey answered how they had been using their boilers during their time at anchor. These replies indicated that boilers were only partly used during their stay at the anchoring site, in contrast to the baseline assumption in this study is that the ships are using their boiler during their entire visit. However, it is unclear how this would affect the overall result, since no information about actual fuel consumption was gathered in the survey, information that could have been compared with default values proposed in study in LA and in the IMO report (Port of Los Angeles, 2010; MEPC 75/7/15, 2020).

The few replies in the survey and the comparison in Table 10 show that a larger survey is needed to make a better estimate and assess a reasonable uncertainty range. A new study would also need to reformulate some questions compared to the survey preformed prior to this report (Florez & Betancur, 2021). The survey should, e.g., ask about the average fuel consumption per hour and not the power use and the SFOC, since most ship are only measuring the fuel consumption for the boilers.

4.3.2 Emissions from tanker ships (except bunker)

The tanker ships are categories into three different sub-groups in the IMO report and the emissions results for each ship-category are presented in Table 11. As can be seen in the table, most of the LG tankers anchoring outside the Port of Gothenburg are not calling the port.

Table 11. Calculated well-to-propeller greenhouse gas emissions (tonnes CO_{2eq}) at anchoring sites outside the Port of Gothenburg for tanker ships in 2019

Ship type	Port call	In transfer
Chemical tanker	7 770	4 600
LG tanker	540	3 390
Oil tanker	5 390	3 620

*Products Tanker, Chemical Tanker, Nuclear Fuel Carrier, Shuttle Tanker, Molten and Sulphur Tanker
**LPG Tanker, LNG Tanker and Combination Gas Tanker (LNG/LPG)
***Tanker (unspecified), Crude/Oil Products Tanker, Crude Oil Tankera and Asphalt/Bitumen Tanker

The emission calculations also reflect which size category the ship belongs to. The results have therefore been plotted for different size bins in Figure 17. In this figure it is possible to see that for category *oil tankers,* the emissions are dominated by the larger ships, while for chemical tankers the results are more evenly spread.

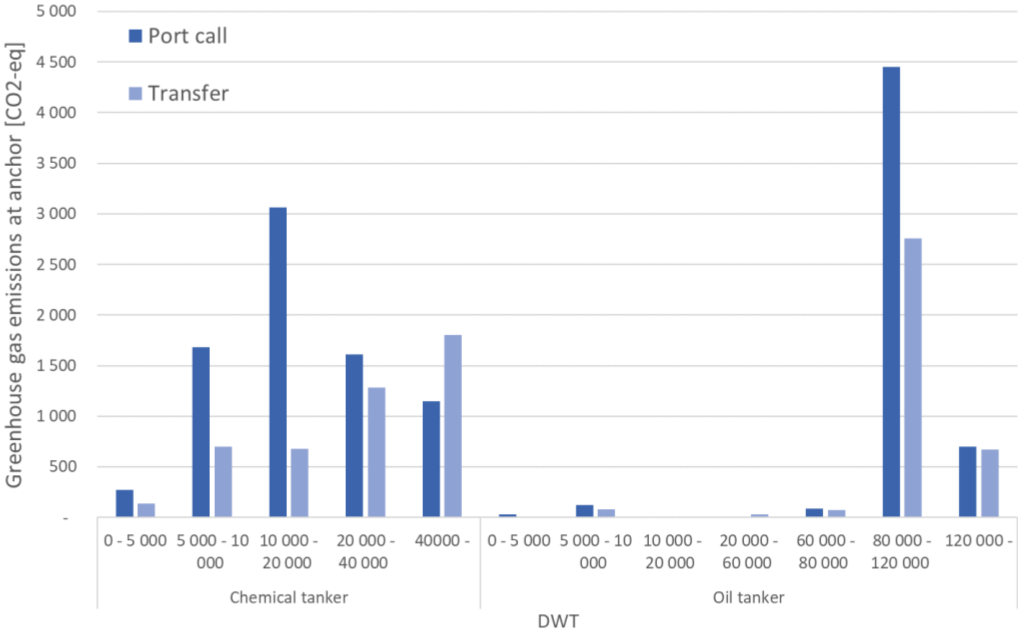

Figure 17. Calculated well-to-propeller greenhouse gas emissions at anchor for tanker ships of different sizes in 2019.

4.3.3 Emissions from bunkering ships

As shown in Section 3.2.6 the bunkering ships frequently have a very special pattern in the anchorage areas since they often are performing bunkering operation. A real-world bunkering operation is illustrated in Figure 18.

For bunker ships the breakdown between emission for ships calling the port and ships not calling the port is vague since all ships have their "home port" in Gothenburg. The categories "*in transfer*" and "*port call*" is only based on if it was possible to match AIS data with the official port call statistics from the Port of Gothenburg. One might as well argue that all or none of the emissions are associated with a port call.

Figure 18. Example on bunkering operation performed at Trubaduren (the Port of Gothenburg)

The power demand onboard when the bunkering ships are using the pumps and additional heat required for performing bunkering operation is not included in the calculated emissions in this study. One of the bunkering agencies operating in Gothenburg shared a rough estimate of the hourly fuel consumption for one of their bunkering ships. As shown in Table 12 the emissions would be about 3.5 times higher for this ship if the fuel consumption was based on this shipping agencies own fuel consumptions estimate instead of the modelled emissions in this study. Future studies should therefore try to:

1. separate the time bunkering ships are performing bunkering operations and when they are just operating in idle condition.
2. survey how bunker ships are using their engines during different operational phases.

The emissions from bunker ships could therefore potentially be very underestimated in this study. One study has tried to categorize bunkering operations through AIS-data, this methodology could potentially be used in a future study (Wu & Aarsnes, 2017).

Table 12. Example of emission from one bunkering ship. Note that the comparison only is for direct CO2 emissions, i.e. it is not including other green-house gases and WTT emissions.

Emissions of CO_2 [tonnes]		Time at anchor 2019 [h]
This study	Based on agency own estimate*	
31.1	108.1	251.5

*based on fuel consumption of 160 kg/h

4.4 Reduction of emissions

As shown in Table 9 (section 4.3) the potential to reduce greenhouse gases is about 13 700 tonnes $CO_{2\text{-eq}}$ if all tanker ship calling the port could avoid all time at anchor by an optimized port call process. This reduction potential would be theoretically possible if all the time at anchor were utilized by using fewer ships in the system 2019 (i.e. transport work and ship speed is still the same). However, one way to further reduce emissions would be if the ships used this time to slow steam for example by implementing JIT, as discussed in depth in Chapter 2.

The potential emissions reduction by using the time at anchor for slow steaming is illustrated in Figure 19. The emissions reduction potential has been calculated for four different scenarios, that all ships have the possibility to reduce their speed: 6, 12, 24, or 36 hours prior to arrival.

In the figure it is possible to see that if all tanker ships anchoring were using their time at anchor to slow steam instead, they could reduce the emissions with about 28 300 tonnes CO_2/year if they were reducing their speed to 10 knots instead of sailing at service speed, in the 24-hours scenario. This result can be compared with the speed that old ships is able to reach, according to what the shipping companies said in the workshop (9-10 knot). However, this reduction potential assumes that all tanker ships (except bunker ships) have the possibility to reduce their time at anchor with JIT arrival.

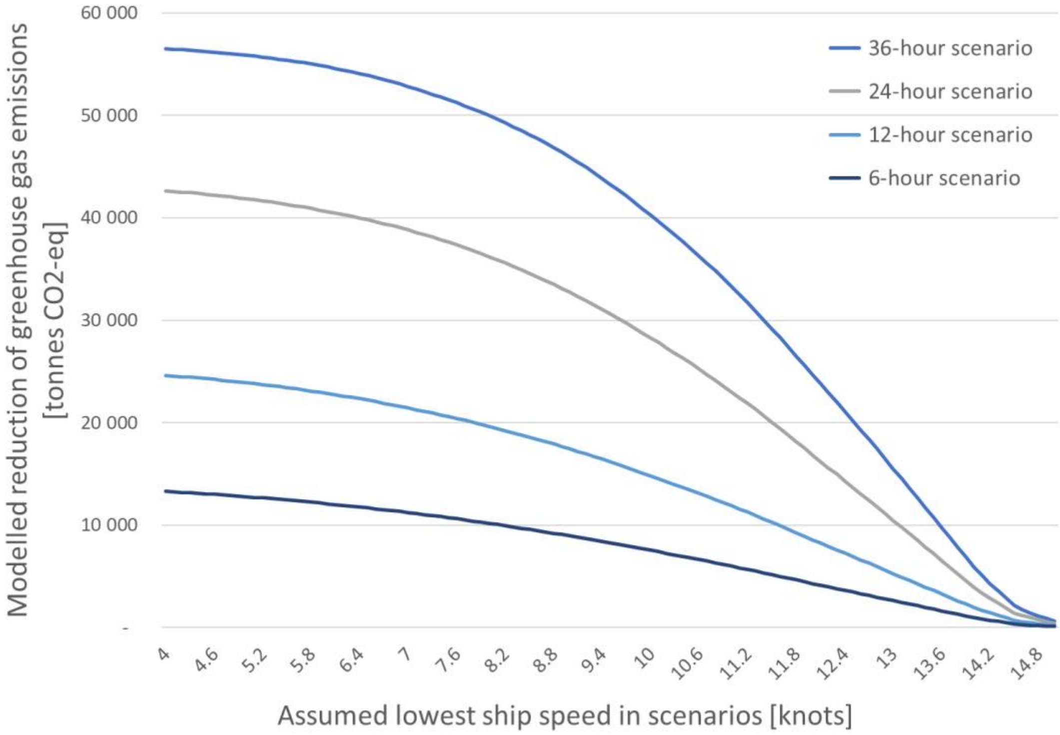

Figure 19. Modelled emission reduction potential for slow steaming and anchoring emissions (tonnes CO_{2eq}) for 808 ships, representing the tanker ships that were at anchors in the port of Gothenburg in 2019. Excluding emission reduction potential from bunkering ships.

The boundary condition in Figure 19 was set so that the overall transport work is not reduced in the system (see Chapter 3 Equation (7)). This implies that each individual ship is only allowed to slow steam during the time it otherwise had been anchored, since distance must be the same. I.e., a ship that was anchoring for 6 hours in 2019 was in the model only allowed to slow steam for 30 hours in the 24-hours scenario (24+6 h). For a service speed of 14.5 knots this corresponds to a new minimum speed of 11.6 knots in the model $\left(\frac{24\ h \cdot 14.5\ knots}{30\ h}\right)$. In practice this mean that the time at anchor will set the limit to reduction potential at lower speeds in the model.

The emission reduction potential is based on each individual ship's service speed, the reduction potential is set to zero at higher speeds. In Figure 19 it is therefore also possible to see that most tanker ship has a rather low service speed (below 14.8 knots[1]).

4.4.1 Discussion about the emission reduction potential

[1] 14.5 knots corresponds to 26.9 km/h. An average European RoPax ship for example has a service speed of about 21 knots (EMSA, 2021).

One issue with the theoretical potential calculated in the previous section is that ships could be at anchor for other reasons than delays. An indicator of this is that the ships spend many days at anchor. The potential of slow steaming for the ship that is laying at anchor for very many days could be questioned. Most ships spend less than three days at anchor, which is illustrated with a histogram in Figure 20. To visualize at which speed these ships is dominating the potential, the average time at anchor is plotted as a function of speed in Figure 21. The average time at anchor (dashed line) is only calculated for the ships that could use more time at anchor at that speed, according to the boundary condition in the model. The number of ships (straight line) that the average time is based on is therefore decreasing as the speed is decreasing. In Figure 21 it is for example possible to see that ships that could have decrease the speed below 5 knots is at anchor for over 100 hours on average.

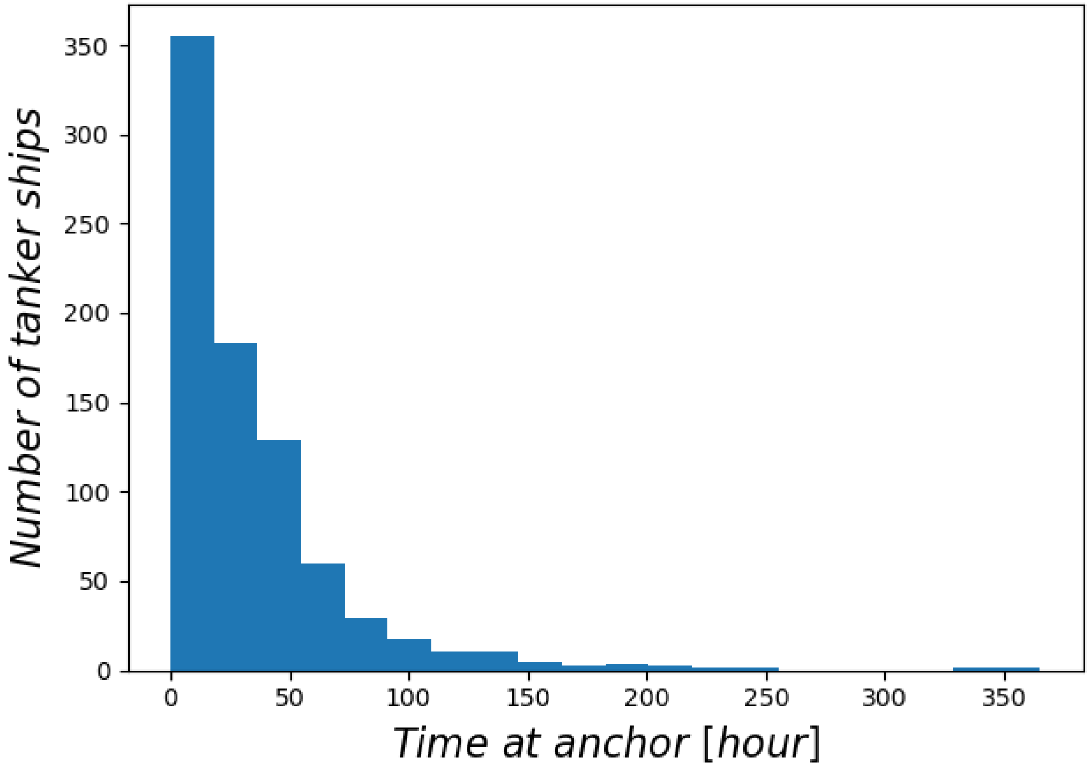

Figure 20. Histogram illustrating the distribution frequency distribution of the time the tankers ships spend at anchor in the slow steaming scenario.

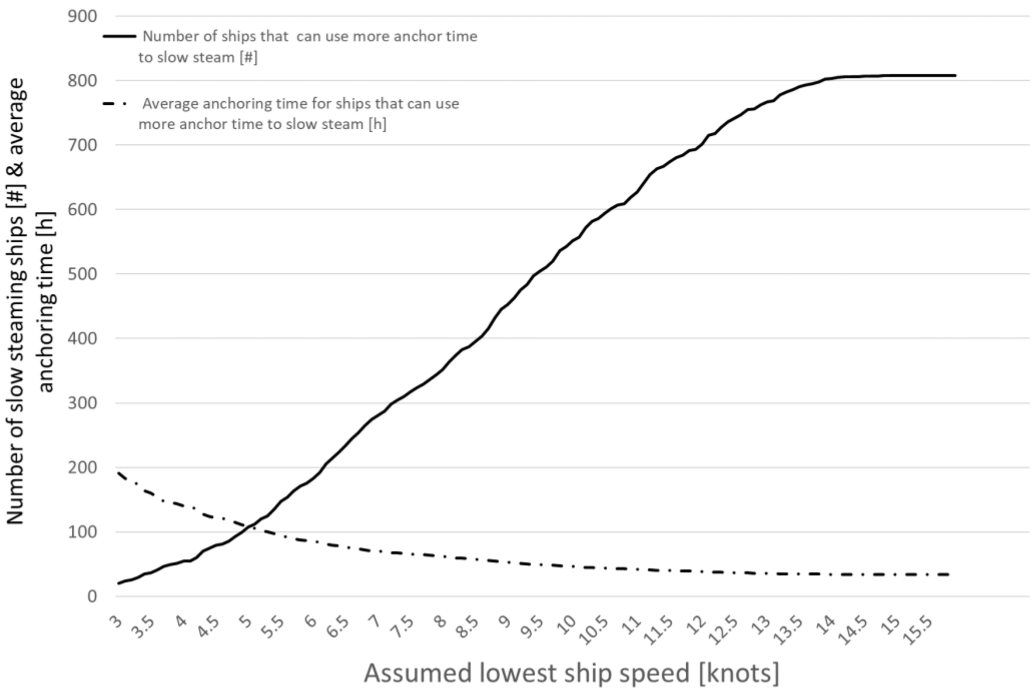

Figure 21. Illustrates the number of ships that can and the average time at anchor for these ships at that speed in the 24-hour scenario.

The emissions reduction potential is broken down between reduced time at anchor and slow steaming in Figure 22. The results in the figure illustrate that the largest potential is for slow steaming, compared to the emission at anchor, especially at minor speed reductions. At very low speeds the slow steaming emissions (dashed line) will instead start to increase for the ships that have very long anchoring times. This is due to the relation between modelled emissions from the main engine (emissions decreases as the speed decreases) and the auxiliary power (emissions increases as the speed decreases), see Chapter 3 Equation (6). However, this increase in emissions, decreases as the speed goes towards 0 knot, since the time at anchor is then limited by how slow the ships can go ($\text{time}_{\text{anchor}} \rightarrow \text{inf if speed}_{\text{slow steaming}} \rightarrow 0$).

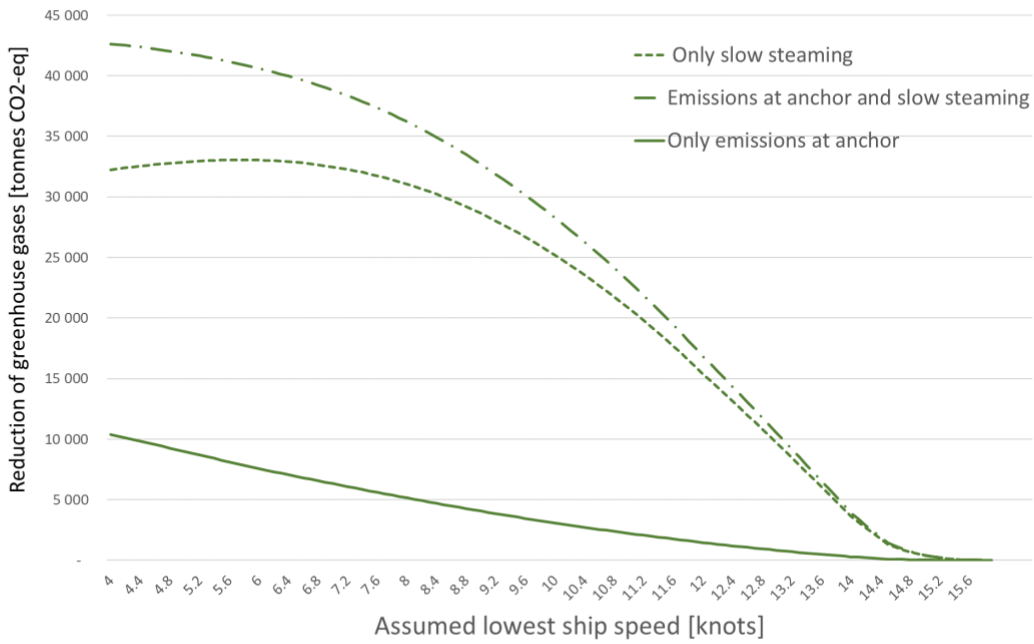

Figure 22. Breakdown of emission reduction potential between reduced time at anchor (straight line) and by slow steaming (dashed). Reduction of greenhouse gases, in the 24-hour scenario. The scenario is based on the extreme case that all tanker ships that were at anchors in the Port of Gothenburg 2019 had the possibility to decrease their speed instead of laying at anchor.

It is important to note that the modelled emissions reduction potential above may be overestimated, since it is assumed that all tanker ships are sailing at service speed in the baseline. Some ships may already have reduced their speed. Which was indicated both in the workshop (see section 4.1) and in the interviews performed by the students (see section 2.5). Another uncertainty is that the engine load and the power of the auxiliary engine are based on modelled values. However, the comparison in Figure 23 between the modelled emissions at service speed and the emissions from officially report data (MRV data) from ship larger than 5 000 GT shows a rather good agreement, *assumed distance: 519 NM* (for further information about the MRV data set see Appendix A). The comparison could be an indication that most ships are not slow steaming. The total emissions estimated to 71 506 tonnes CO_2 when the calculations are based on the average yearly CO_2 emissions per nautical mile in the MRV data and 72 971 tonnes CO_2 when the emissions are modelled (assuming 80 % load on main engine and 30 % load on the auxiliary engine). The comparison is based on the 542 ships that were in the MRV-dataset and were calling the Port of Gothenburg in 2019.

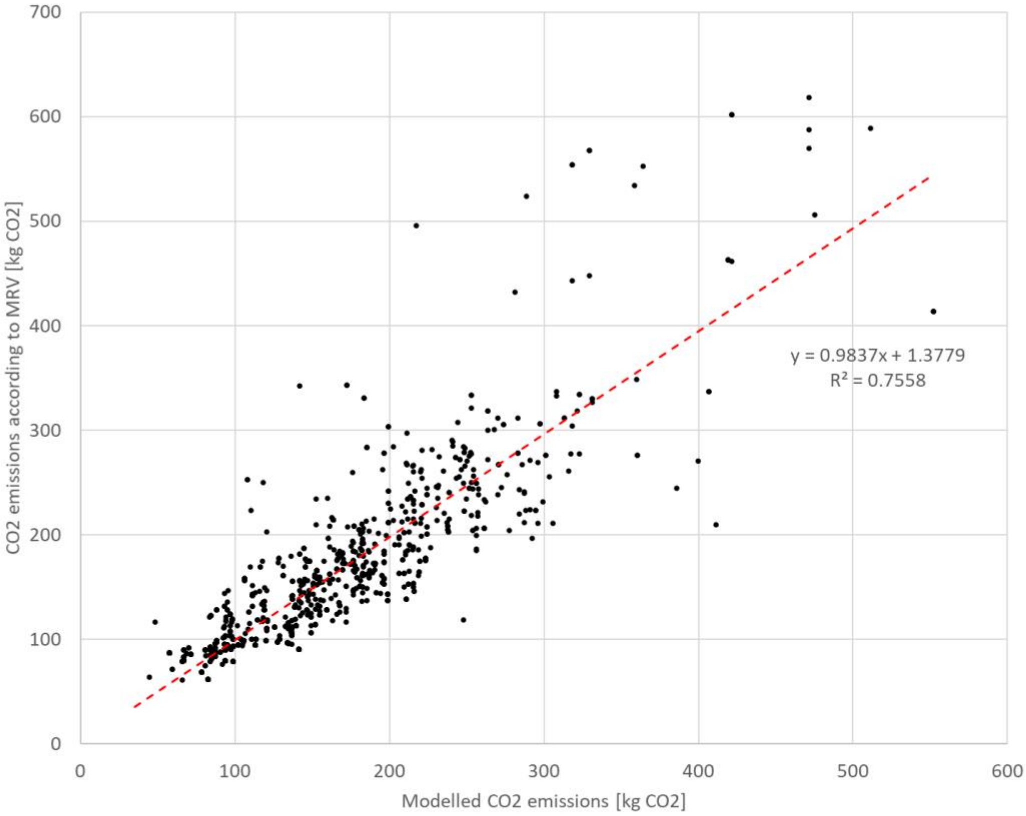

Figure 23. A comparison between the estimated emissions based on (1.) the reported emissions in the MRV data and (2.) the modelled emissions (assuming 80 % load on main engine and 30 % load on the auxiliary engine). The comparison represents the 542 tanker ships were at anchors in the Port of Gothenburg 2019 and were in the MRV database (IHS Markit, 2019; EMSA, 2021).

5 Conclusions and next steps

This pre-study evaluates the possibilities to reduce ships' air emissions, mainly CO_2, from ships anchored in port areas, and is focused specifically on two main objectives. Firstly, it aims to develop a reproducible calculation model for anchored vessels' CO_2 emissions in terms of total emissions, based on AIS data. Secondly, based on analysis of causes of anchoring, this study intends to elaborate on proposals for emission reduction measures that can be implemented in collaboration between different actors.

5.1 Commercial terms, policies, regulations and incentives in the port

Causes of anchoring can be related to weather conditions, unforeseen events, or shortcomings in other segments of the transport chain. While at the same time, these causes can be linked directly to port operations, maintenance and bunkering operations. Commercial and legal improvement aspects can help to optimise anchoring practices. Although the concept of JIT in shipping is relatively new, it is as essential in shipping as in other modes, and the cost of delays increases by the size of the ship and the value of cargo. Generally, JIT operations require efficient communication and information sharing among actors. Thus, to be able to implement JIT arrival, several players have introduced a virtual arrival system. However, in practice, most ports still apply the "first come, first serve" method.

Based on previous knowledge and confirmed by our results, the product tanker segment accounts for most of the anchoring in the port area. Considering the reasons for anchoring in Gothenburg, the results show that awaiting Laycan or waiting for an available berth is the most common reason.

In the case of commercial and legal aspects, companies generally combine time charter and voyage charter contracts to access vessel capacity. Finally, in the case of communication and information sharing, it is suggested by the industrial partners to be an important area of development to bridge the barrier of trust. Since legal and commercial praxis is not established, virtual arrivals currently require a significant amount of trust between the stakeholders. A validation system to guarantee that the information shared by the actors is correct, is one type of measure suggested by the workshop participants.

Enabling JIT by adjusting local rules, and providing necessary digital infrastructure is one steppingstone for a port's approach to using JIT-arrival as an emission-mitigating measure. Connecting incentives to JIT-voyages and/or vessels with lower slow steaming thresholds constitutes another type of measure. Both approaches used jointly can allow for a first cap of the potential, elaborated on in section 4.4 in this report.

In this study we take the methodology to calculate the emission reduction potential of slow steaming further than Parsmo & Jivén (2020) do by relating the slow steaming potential to the ship's time at anchor. This makes it possible to see what the reduction potential is and still have the same transport work. The results indicate that the potential for speed reduction is great. However, to utilize the full potential, the ships need to be modified so they can slow steam at lower speed than 9-10 knots, which was the optimal speed according to the stakeholders in the workshop. One of the stakeholders stated that their newest generation of product tankers could slow steam at a speed of 4 knots.

5.2 Improving emission estimates at anchor and future studies

In this study we have improved the emission estimate at anchor by including the results from the survey conducted in the Port of Gothenburg. As also showed in other studies the auxiliary demand can vary a lot (Parsmo & Jivén, 2020; Hulskotte & Denier van der Gon, 2010). However, the results from the survey clearly indicate that the used auxiliary engine demand at anchor for product tankers are consistently overestimated for both alternative models suggested, see the comparison in Figure 24 bellow. For example, the CO_2 emissions was about 7 200 tonnes lower if the average power demand in this study was used instead of the model used in the yearly port emission inventory, for product tankers that were calling the port in 2019.

The comparison shows that when analysing a particular ship, ship segment or operational mode, it is more important to get detailed information. Even though the overall relative errors in an inventory like the IMO's 4th GHG study or in the yearly port inventory are likely lower as other ship segments and other operational modes are added to the inventory. What is problematic with using the default values is that this makes it harder to estimate the real effect of a new policy, regulation, or incentive in the port. However, a better emission inventory requires that on-board visits are made or that data is obtained digitally.

Considering that boilers contribute to a large fraction of the total emissions (47.1 %) and that we can't conclude that the emissions from boilers at anchor is in a reasonable range, this constitutes the largest uncertainty of the emission inventory.

The second largest uncertainty in the emission estimate concerns the bunkering ships that constitute a large fraction of all anchoring time. The comparison in this study shows that the emissions from one bunkering ship could be underestimated with a factor of 3.5. If this is representative for all bunker ships, the overall emissions from bunkering ships in the anchorage area would increase from 3 450 CO_{2eq} to about 12 000 CO_{2eq}, making bunker ships one of the largest emitters in the area.

A comparison of the time at anchor shows that the official port statistics and the times extracted from the AIS data differs. However, the error range in the activity data (time at anchor) seems to be rather small compared to the uncertainties associated with estimated fuel consumption at anchor.

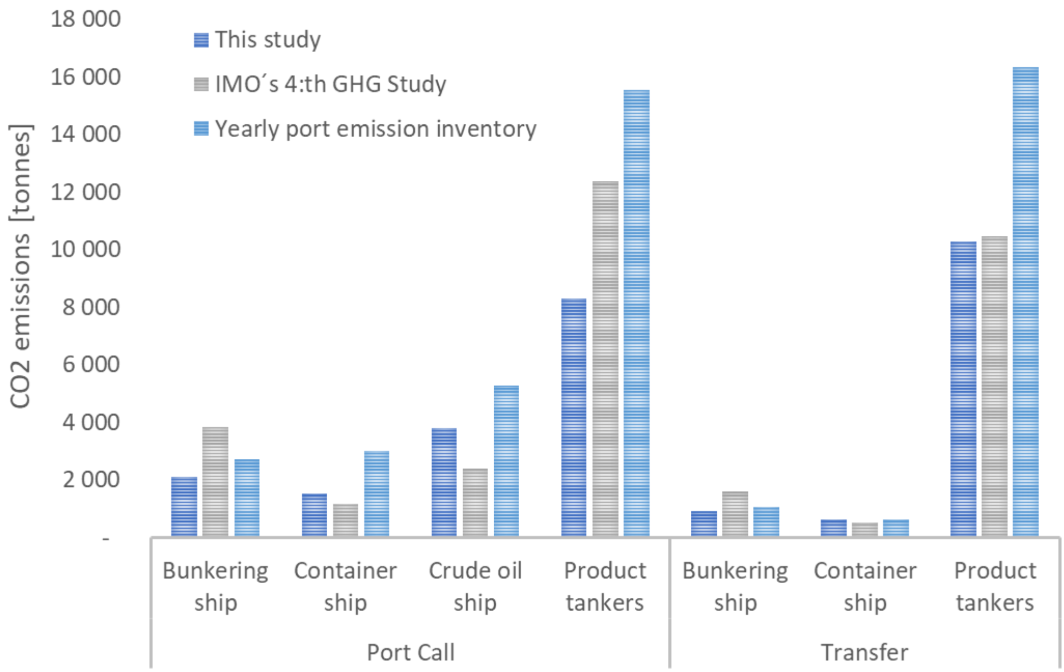

Figure 24. Comparison between total emissions using three different datasets. Note that the comparison only is for direct CO_2 emissions (2019), i.e., it is not including other greenhouse gases and Well-To-Tank emissions, since these haven´t been estimated in all studies.

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Appendix 1 Comment on MRV statistics

Fuel statistics for individual ships often give a better picture of the CO_2 emissions for the specific vessels than the modelled ones, as it can vary greatly how engines are used in different operating phases. One study compared the modelled CO_2 emissions (based on ship parameters) with the CO_2 emissions calculated using the average fuel consumption of individual ships at sea (Parsmo & Jivén, 2020). The results of that study showed that container vessels that called at the port of Gävle in 2017 had lower emissions when the calculations were based on fuel statistics, which the authors primarily believe may be due to container vessels slowing down to a greater extent than other vessel categories.

The average fuel consumption is compiled by the European Union (EU) in a database (MRV database). The EU has a goal of reducing greenhouse gas emissions from ships and has therefore created a new monitoring program that collects data since the first of January 2018 (Erbach, 2019; EU, 2016). The monitoring program compiles fuel and cargo statistics from all ships larger than 5 000 GT entering a port within the EU (DNV-GL, 2019). The statistics are aggregated and presented on MRVs website and contain information on approximately 14 000 different vessels (EMSA, 2021). However, the focus the reporting to MRV is only on the emission of carbon dioxide emissions, as this is the most relevant greenhouse gas emission from ships. We have therefore primarily used these statistics to estimate ship fuel consumption and CO_2 emissions at sea in this study.