

ORIGINAL PAPER

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Enabling a green just-in-time navigation through stakeholder collaboration

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Abstract

Background: The shipping industry has grown spectacularly during the last 50 years transporting nowadays, approximately, the 80–90% of goods worldwide. However, maritime transport remains a highly inefficient industry. Only in the last 10–15 years has the industry started studying how to optimize navigation speeds and digitization is just entering ports. Consequently, institutions like the International Maritime Organization (IMO) are pressing towards the adoption of measures that increase the industry efficiency, like Just-In-Time (JIT) operations.

Methods and Results: This paper shows why the Sea Traffic Management (STM) concept, based on stakeholder collaboration, is a JIT enabler. To do so, we analyze 1 year of navigation data of 33 ships, estimating the impact of JIT barriers on shipping and showing the benefits that the adoption of STM, with different maturity levels, could provide to the industry. Our evaluation shows that, only for containerships, STM can help reducing by 15–23% of fuel consumption and GHG emissions.

Keywords: Just-in-time navigation, Port call synchronization, PortCDM, Sea traffic management

1 Introduction

Over the last 50 years, seaborne trade has seen a remarkable development. Shipping carries approximately 80–90% of goods worldwide [6]. During this period, maritime transport and their logistic infrastructures have been essential for the global economy development and its competitiveness. The impact of this strategic sector in the quality of life of citizens is crucial, as maritime transport is a powerful key driver for job creation and economic growth. Promoting innovation on efficiency, sustainability, safety and (cyber) security within the maritime transport sector is a fundamental issue.

The significant economic growth before the global financial crisis and the increase of trade volumes in recent years have driven maritime transport into developing their capacities in unexpected ways. Infrastructures, services and equipment have achieved a significant

growth of capabilities and complexity. This evolution has provided remarkable benefits for the performance of the sector. However, operational missing links and bottlenecks remain, resulting in significant negative effects like performance inefficiencies, income loss, increased energy consumption as well as pollutant and Greenhouse gas emissions (GHG) among other externalities.

Prospects for seaborne trade are positive with projected volume increases of a 4% in 2018 and following years. Continued favourable trends in the global economy are also expected with a forecasting of 3.8% compound annual growth [32]. The total volume of cargo transported by seaborne trade is expected to surpass 10.7 billion tons and, if growth in seaborne trade continues at the above-mentioned rates, it is foreseen to see 32 billion tons of cargo being shipped annually by 2050, producing 3 billion tons of CO₂ in the process.

The IMO has been developing a strategy to reduce the shipping sector's emissions since 2003. Resolution A.963(23) [10] *'urges the Marine Environment Protection Committee (MEPC) to identify and develop the mechanism*

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or mechanisms needed to achieve the limitation or reduction of GHG emissions from international shipping'. Resolution MEPC.203(62) [11] on July 2011 developed mandatory technical and operational measures for the energy efficiency of ships. In October 2016, MEPC70 agreed on a Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships, which foresaw adoption of an initial GHG reduction strategy that was later approved during MEPC 73 on 13 April 2018.

The adopted strategy envisages a reduction in the total GHG emissions from international shipping of at least 50% by 2050 if compared to 2008. Emission reductions should start as soon as possible and those efforts should be pursued to phase out carbon emissions entirely. One of the proposed efforts that is gaining track is the concept of 'Just-in-Time operations' (JIT) as a specific e-Navigation instrument to mitigate the environmental impact of shipping and contribute to the GHG reduction objectives established by IMO. The shipping industry is far behind in terms of JIT efficiency. Recent findings by DNV GL [7] indicate that ships spend roughly 50% of their time in berth, anchoring or manoeuvring. Moreover, this implies more than the 15% of their annual fuel consumption and GHG emissions. Like for aviation, bringing in JIT operations would lead to a reduction on trading waiting times, a maximisation of ports utilisation and a reduction of costs for the ships in fuel or costs associated to their stay at port. Moreover, it would allow a substantial reduction on the GHG and other gasses emissions.

As part of the international mobilisation in the shipping sector to establish actions for mitigating the environmental impact of maritime transport in the coming years, the Sea Traffic Management (STM) initiative has been gaining momentum during the last decade. STM is a concept that aims to bring maritime transport into the digital era, thus obtaining remarkable benefits derived from this digital transition. In particular, STM aims to facilitate a better synchronisation of operations in maritime navigation and in the ship-port interfaces by increasing real time information exchange, thus leading to better decision making and increasing efficiency of operations with the associated reduction of environmental impact. As an e-Navigation initiative, STM is fully aligned with the IMO strategy on the reduction of GHG emissions through the digital transition of the shipping sector.

Other examples of this increasing awareness are other local proposals like Pronto, PitStop, or SmartPortLogistics in the ports of Rotterdam, Algeciras or Hamburg. Pronto [26] provides port actors with a shared platform to exchange data about their port calls, showing information related to a vessel in real time since an ETA is provided. It is aimed at improving the coordination of

actors and resources management in the port, increasing predictability and reducing CO₂ emissions. Similarly, the PitStop project in Algeciras [24] aims to improve port efficiency through the application of the Port Collaborative Decision Making (PortCDM, a communication standard from the STM initiative) concept to optimize ETAs, berth management and port visit management. With Smart Port Logistics [25], the Port of Hamburg aims to optimize traffic flows, infrastructure and the flow of goods to improve port efficiency. It also provides actors in the port with a platform to exchange data, involving even the truck companies operating in Hamburg.

These proposals share the fact of providing platforms to ease the communication between port actors to optimize how each portcall is served, but this hardly goes beyond a local optimization. Given the nature of the shipping business, all actors must be synchronized and that there must be an exchange of information between ports and ships, but also between ports. Ports must exchange key information like Estimated and Actual Times of Departure (ETDs and ATDs). Having this information in real time allows to evaluate the feasibility of reported ETA at the next port. That knowledge will allow ports to perform a better planification of resources that goes beyond several hours, reaching days in advance and, hence, improving the planning of port agents and reducing the waiting times.

In this paper we evaluate the role of STM as an enabler for JIT operations. The contributions of this work are two-fold. First, we enumerate some of the barriers to JIT operations and quantify their impact on regular shipping lines. To do so, we evaluate aspects like cruising speed dispersion, anchoring times and Estimated Time of Arrival (ETA) deviations. On the other hand, we estimate the potential benefits of having a STM-enabled ecosystem with different levels of maturity on fuel consumption and GHG emissions.

The rest of the paper is structured as follows. Section 2 introduces some previous work related to greening navigation. Section 3 defines JIT navigation, the barriers preventing it and how STM-based systems can overcome them. The impact of these barriers on navigation is quantified in Section 4. Section 6 evaluates the potential impact that STM can have in the shipping industry at different levels of maturity. We discuss some aspects of the evaluation on Section 7. Finally, we present our conclusions in Section 8.

2 Literature review

Historically, there have been multiple efforts in quantifying navigation-related pollution, specially in ports [31] [1] [35] [33], and in greening navigation. Many of these efforts are mentioned in [28], that analyzes issues related to road, maritime and other means of transportation.

Chapter 9 [27], in particular, focuses on Speed and Route Optimization and its subproblems like slow steaming, speed and route optimization, or weather routing. These techniques, respectively, consist in adapting the speed of the ship to reduce its fuel consumption, optimizing the route the ship has to follow in terms of distance, navigation time or expected consumption, or considering aspects like weather forecasts to avoid events, like storms, that may affect navigation and force the ship to catch up later, overspending fuel. Tu et al. collect in their survey [30] multiple examples of these techniques leveraging Automatic Identification System (AIS) data. These techniques have a great impact on fuel consumption and navigation, due to the non-linearities on the speed/power relation of engines. For instance, in a containership, a reduction on the engine load of a 10% means navigating at about half of its design speed [27]. This has additional benefits beyond reducing fuel and emissions, reducing the voyage costs as well, or helping to absorb fleet overcapacity [3]. Digitization is also an enhancer for the introduction of these techniques into production systems, making navigation more efficient and greener [18], and acting as an enabler for autonomous navigation even in the toughest conditions [16].

However, addressing only the voyage part is not enough. The community has become aware that to optimize navigation, ports have to be in the loop and that every stakeholder in the shipping ecosystem has to be involved [23]. Only recently ports have started to digitize, to leverage the advances in Information Technology (IT) and to tackle the problem of portcall synchronization [5]. Optimizing routes or speeds becomes useless if the ship arrives at port and has to wait in anchoring for several hours or, oppositely, needs to speed up to leverage a slot at berth. The main requirement for portcall synchronization is collaboration among port stakeholder. Despite of the ample variety of port simulation models [20], they cannot be used in production without (near-)real time data and collaboration of the port stakeholders. Collaborative planning [22] is gaining track in the research community in the last years, thanks to the enablers provided by IT [19]. Collaboration leads to synchronization of efforts and actors within the port. This synchronization enables an efficient resource management and planning [2], avoiding situations where ships have to wait to enter or leave the port because not enough tugs, or moorers or other actors are available. It also helps reducing the turn-around time, improving the port efficiency.

Along these lines, the Monalisa and Monalisa 2.0 projects [4] [15] [13] defined the STM concept, studying vessel-to-vessel awareness and information sharing, voyage management or laying the foundations of PortCDM. STM [29] extends and implements Monalisa. STM

provides tools to improve the communication between actors in the port and arriving ships, and also between ports or ships. It also offers on-demand services to ships (e.g., route optimization, weather routing). Altogether, STM will allow an end-to-end optimization of navigation and will boost ports efficiency, giving room additional savings in fuel consumption and GHG emissions. The STM concept is explained in Section 3.

3 Just in time (JIT) navigation

3.1 Concept

The concept of Just-in-Time (JIT) arose in the 1960s and 1970s as a management strategy that aims to adjust the required supplies and production rate to consumer demand [14]. This results in an increment of production efficiency, of inventory turnover and, hence, reducing the storage space, as less stock is required, reducing also wastage due to obsolete or damaged stock, among other advantages. It requires, though, an accurate planning, demand forecasting and synchronization, as supplier delays can cause a stock shortage. If properly implemented, rewards tend to largely compensate for the risks, reason why this management philosophy has been applied in many organizations in very different sectors [34].

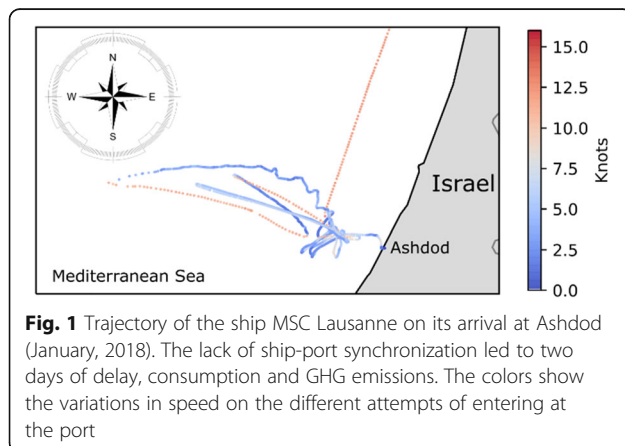
According to the IMO Global maritime energy efficiency partnerships - Global Industry Alliance (Glo-MEEP-GIA) [8], the shipping industry should be one of these sectors in the near future. Implementing JIT operations in the shipping industry will improve the industry average efficiency, leading to significant reductions in fuel consumption and GHG emissions. Similarly, JIT operations will help to eliminate inefficiencies like idle times in navigation or in ports. We refer, for instance, to anchoring times, time at berth when no cargo is being (un)loaded or any task is being performed but there are no resources to let the ship out of the port, or stop-by times due to congestion in canals. This can be achieved through investments on digitization and IT technologies to improve the communication among the actors involved in navigation and port operations. For instance, to have ports and ships negotiating ETAs so one can meet it and the other assures that the ship will be allowed into the port at that time, to have port technical-nautical services assuring that they will be available to serve an incoming ship, to coordinate the arrival of ships at a port or at the entrance of a canal. This coordination will also help ships to optimize their navigation speed, taking more advantage of slow steaming, reducing fuel consumption and GHG emissions, and allowing companies to improve their fleet allocation strategies. In general, JIT operations will result from collaboration and the resulting improved coordination and synchronization among stakeholders.

3.2 Barriers

The IMO GloMEEP - GIA working group is looking into the operational and contractual barriers that forbid ships, port authorities and others to implement JIT operations. Some of these barriers relate to the absence of standardized automated ship-port, ship-ship and port-port digital communications in real time and beyond the VHF range; the lack of coordination among the different actors within ports; or how man power is organized around a portcall.

Nowadays, most communications are performed through shipping agents that provide ETAs that are rarely updated. Only when ships get into the VHF range they communicate through VTS systems or radio and make ports aware of their proximity. Consequently, ports cannot make any solid resource planning beyond a few hours as they rely on ETAs, and ETAs are not reliable. This result is ships arriving early and finding their unavailable berths, busy/congested port entrances, or not enough technical operators (e.g., moorers, tugs, pilots, ice-breakers) to let them in/out, or even having to wait in the middle of the entrance/departure operations because some of these operators are not aligned or delayed. Figure 1 shows an example of the effects of this lack of synchronization. There, we show route followed by the MSC Lausanne, that had to wait for 2 days before being allowed to enter in the port of Ashdod (January 2018). The color of the path indicates the speed variation.

Similarly, ships can be informed that there may be a short window to enter in the port, or to be served earlier in berth if they arrive earlier, forcing to abrupt increments of speed that could have been distributed during the entire voyage; find narrow areas or canals congested instead of coordinating a staggered arrival, or finding themselves in collision routes to another ships that force stop-and-go operations. All these situations force variations in the cruising speed leading to additional consumption and GHG emissions.



3.3 STM as a JIT operations enabler

The Sea Traffic Management (STM) initiative focuses on offering services that allow real time digital exchange of information between ships, between and within ports, and between ships and ports as well as with shore centres. Examples of the information that can be exchanged are voyage plans between ships, ports and shore centres, continuous ETA reporting, real time tracking of when operations associated to these ships port call will take place. Similarly, other services are offered to ships, like route optimization or weather routing.

One of the most ambitious tasks in STM has been the elaboration of the Port Call Message Format (PCMF), based on PortCDM, accepted by IALA¹ as the S-211 standard [9] for Ship-to-port, port-to-ship, port-to-port, as well as port actor-to-port actor communication protocol. PortCDM has been deployed in the ports of Valencia, Barcelona and Sagunto (Spain), Goteborg, Umea (Sweden), Stavanger, Vaasa (Norway) and Limassol (Cyprus), among others, as well as being used in other projects like PitStop.

STM not only provides real time exchange of standard information, but also aligns ports and shore centres to share information, breaking the VHF range frontier and allowing to pull ahead the time limits for resource management in ports. Altogether, STM helps to overcome many of the operational JIT barriers, becoming a strong enabler and helping to green the shipping industry.

4 Methodology

In this section we describe the methodology followed in Section 5 to measure the impact of JIT barriers and in Section 6 to perform an estimation on the potential savings that can be achieved through solutions like those proposed by the STM initiative.

To measure the impact of JIT barriers we acquired 1 year of AIS data (2017/06/01–2018/05/31) of 33 ships in regular itineraries from MarineTraffic [17]. These data include timestamp, latitude, longitude, speed, IMO and reported ETA, among others. The data correspond to Car-Carriers (CC), Containerships (CS), RoRos (RR), RoPax (RP) and Pax (Px) ships. Within each type, ships are also divided in segments. The ships are anonymized and denoted as XXY_Z, where XX denotes the type, Y the segment, and Z the ship, e.g., CS1_3. Table 1 provides some information about the ships in these segments. To separate the different navigation phases (i.e., cruising, berth, anchoring, ...), estimate consumptions and emissions, etc., we based our calculations on [21], with subtle modifications required by the dataset.

¹IALA-AISM: International Association of Marine Aids to Navigation and Lighthouse Authorities

Table 1 Some of the characteristics of the different ship types analysed, including the number of ships of that type, ground tonnage, year of build, capacity (in the corresponding units) and main and aux engine power

| Segment | Number of Ships | Ground Tonnage [Tn] | Year of build | Capacity | Main engine power [KW] | Aux Engine Power [KW] |
|-----------------------|-----------------|---------------------|---------------|-------------------------|------------------------|-----------------------|
| Car Carrier (CC) | 2 | 59,835 | 2011–12 | 6700 CEU | 16,600 | 1540 |
| ContainerShip 1 (CS1) | 3 | 6326–7946 | 1995 | 646–660 TEU | 6600 | 375 |
| ContainerShip 2 (CS2) | 5 | 62,702–66,526 | 2000–07 | 5468–6336 TEU | 39,952–55,700 | 4000–6200 |
| ContainerShip 3 (CS3) | 9 | 94,000–95,500 | 2013–16 | 8800–9403 TEU | 47,430–54,900 | 7000–9000 |
| Ro-Pax 1 (RP1) | 2 | 51,837–57,958 | 2001–03 | 3980–4100 (lane metres) | 24,000–25,920 | 375 |
| Ro-Pax 2 (RP2) | 2 | 31,678–34,384 | 2013–14 | 1350 (lane metres) | 21,600 | 1463 |
| Ro-Pax 3 (RP3) | 2 | 34,384–35,492 | 1988–92 | 970 (lane metres) | 23,760 | 4280 |
| Ro-Ro 1 (RR1) | 3 | 5627–9708 | 1988–96 | 375–830 (lane metres) | 2960–5280 | 350–650 |
| Ro-Ro 2 (RR2) | 3 | 20,154–20,186 | 1996 | 1900 (lane metres) | 9000 | 1220 |
| Ro-Ro 3 (RR3) | 1 | 10,585 | 1998 | 616 (lane metres) | 14,480 | 640 |
| Pax (PAX) | 1 | 34,924 | 2004 | 1534 PAX | 23,388 | 2880 |

We use three different KPIs to estimate the impact of JIT barriers on navigation: cruising speed, anchoring time, and ETA deviation. We evaluate the cruising speed of a ship using the Interquartile Range (IQR)-to-median (ITM) coefficient of dispersion. The lowest this coefficient, the lower dispersion and more constant the cruising speed. High dispersion results from sub-optimal weather routing, lack of ship-port synchronization, on-route congestion, unexpected detention due to collision avoidance protocols, or bad planification, among others. To evaluate anchoring time, we use the anchoring time per call and aggregated for each ship. Anchoring time occurs when a ship is not allowed into port, usually due to a lack of ship-port synchronization. Usual causes are unavailability of technical-nautical agents (e.g., pilots, moorers, tugs) to let it in, or because the berth is not available. Ideally, the anchoring time in regular lines should be zero. Finally, we evaluate the ETA deviation using the difference between the initially reported ETA of a vessel and its ATA. We differentiate the cases where $|ETA - ATA| \leq 1$, $ETA - ATA > 1$ and $ATA - ETA > 1$. This KPI shows how good/bad is the ETA upon ship's departure and inherently reflects how difficult is for a port to make a resource planification beyond a few hours.

In section 6, we evaluate the potential of a hypothetical STM-based system as enabler for JIT and estimate the reductions in fuel consumption and GHG emissions that could result at different stages or maturity levels of its deployment. We define three scenarios that intend to represent the benefits that this STM-based system could achieve at three different, but incremental, maturity levels. We focus on the case of containerships for a) conceptual reasons, as according to IMO [12], it is the most pollutant traffic and, hence, the one where achieving JIT would be more beneficial; and b) practical

reasons, as it is the most important traffic for the Port of Valencia and, hence, the one for which we acquired more data. The scenarios are the following:

4.1 Scenario 1: improved port-ship synchronization

This translates into more reliable ETAs and reduction or elimination of anchoring. The ship adapts its speed to arrive at the agreed time at port and navigates at relatively constant speed. The port assures that the ship will be let in upon its arrival. We simulate this scenario by removing the anchoring time (if any) and adapting the cruising speed of the ships so they arrive at port at the time they commenced their anchoring. The time at berth is kept constant and its departure is moved ahead, so the anchoring time saved is used for slower navigation on the next leg. A ship cannot cruise at very low speeds, so we fix the minimum cruising speed to the first quartile of the speed distribution for that leg and ship. If the speed at which the ship had to cruise to use all the anchoring time saved was below that minimum speed, we assume the ship negotiates an earlier ETA with the next port and arrives earlier, leaving the remaining extra time to the next leg.

4.2 Scenario 2: improved port operations

PortCDM is already integrated in port and stakeholder operations, improving their efficiency and reducing the time at berth. For this scenario we had to estimate what was this margin of improvement. To do so, we analyzed data from port calls from the ports of Valencia and Sagunto as well as from other 5 large European ports involved in the STM project. We processed more than 6000 port calls for which the completeness of the data was sufficient to estimate the idle time spent in berth, i.e., not in operation. We classified these data per types of traffic. The average idle time for containerships in

these ports was roughly 15% of the time at berth. For this reason, we assume that reducing a 10% of the time at berth is feasible thanks to the improved actors' synchronization. We shortened berthing times, but not allowed this time as extra navigation time.

4.3 Scenario 3: elastic shipping

We assume that mature STM systems will lead to ships being able to adopt optimal navigation speeds and ports adapt to them seamlessly. For this reason, in this scenario we will study two different subcases. First, assuming that the median speed case observed for a ship in a leg is the right cruising speed. Second, the low speed case, where we fix the cruising speed to the first quartile of the ship-leg speed distribution.

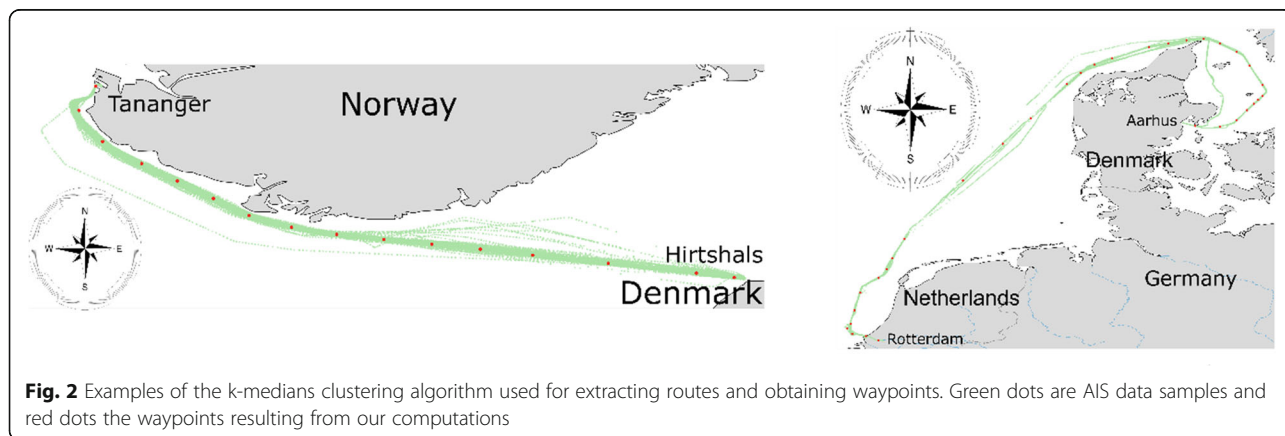
4.4 Common aspects

We apply a route extraction algorithm in all the scenarios. To compute the routes, we devised a K-medians based clustering algorithm that uses AIS data to obtain a series of waypoints for each route, we do not provide more details due to space limitations but show two examples in Fig. 2. This figure shows, in green, all the AIS data samples collected for several ships over two routes, Tananger-Hirtshals and Rotterdam-Aarhus, and, in red, the waypoints the algorithm extracted to characterize them. Similarly, we assume that congestion at the port entrance or in canals is avoided thanks to the improved ship-to-ship and port-to-ship communication and synchronization. In our simulator we consider ECA zones, different engine consumptions according to them, speed restrictions in canals, e.g., Kiel, or proximity to coast. The computation of GHG emissions and fuel consumption is based on the formulas provided in Olmer et al. [21]. Figure 3 presents an example of the engine related data included in the JSON input file used for each ship used to perform these computations.

5 Measuring the impact of the barriers to JIT navigation

Figure 4 shows the distribution of cruising speeds over a year for the 33 ships studied. Each violin includes median, IQR and, above, ITM. The color of the violin indicates the type and segment of a ship. We can see that, except for 5 ships from CS1, RP1 and RR1, the rest have a dispersion coefficient above 0.15, as intuited from the violins' shape. This evidence leads us to discard that large dispersion is associated to a type of traffic. Intuitively, it could be claimed that dispersion may be low for a leg, but that having different legs requiring different navigation speeds, results in large dispersion. Figure 5 inspects the per leg speed distributions of two of these cases, CS1_3 and CS3_9, CSs from different segments, with low and high dispersion respectively. Fig. 5 (left) shows that even when having different legs has an impact, the speed distribution can be bi or multimodal even for the same leg, e.g., USOAK-USLGB. Moreover, Fig. 5 (right) shows that dispersion appears even for ships that apparently have homogeneous legs. Other causes for dispersion are anchoring or delays upon departure in previous legs that may force the ship to recover time in the following legs; the presence of open windows at berth, causing the ship to speed up to take advantage of them; or unexpected congestion on-route or at the port entrance, for instance. These issues have a major impact on the fuel consumption and GHG emissions, as they depend superlinearly on speed. High speed dispersion and high speeds lead to an excess of fuel consumption and GHG emissions.

It is worth noting that other possibly relevant aspects, like leg distance or departure/destination port size are not necessarily causes for the dispersion. For instance, CS2 ships follow medium distance routes, CS3 and CC follow long distance and transoceanic routes, and RP2 ships short distance ones. Similarly, the ports called by CS2 and CS3 ships are relatively large ports while those called by RP2 and most called by CC are not. However,



```

{"engine_power": {
  "Cruising": {"main": 55700,"aux": 3100,"boiler": 0},"Maneuvering": {"main": 55700,"aux": 6200,"boiler": 450},
  "Anchor": {"main": 0,"aux": 6200,"boiler": 450},"Berth": {"main": 0,"aux": 6200,"boiler": 450},
  "IdleTime": {"main": 55700,"aux": 6200,"boiler": 450}},
"engine_emissions": {
  "ECA": {
    "main": {"CO2": 593,"NOX": 15.98,"SOX": 0.37,"PM": 0.19}, "aux": {"CO2": 696,"NOX": 12.22,"SOX": 0.43,"PM": 0.19},
    "boiler": {"CO2": 962,"NOX": 2.0,"SOX": 0.57,"PM": 0.1}},
  "NO ECA": {
    "main": {"CO2": 607,"NOX": 17,"SOX": 10.29,"PM": 1.42}, "aux": {"CO2": 707,"NOX": 13,"SOX": 11.98,"PM": 1.44},
    "boiler": {"CO2": 950,"NOX": 2.1,"SOX": 16.1,"PM": 0.93}},
  "constants": {
    "SAF": {"Cruising": 1.07,"Maneuvering": 1.43,"IdleTime": 1.43,"Anchor": 1,"Berth": 1}, "vmax": 26.1,
    "HFFI": 1.02595, "K1(um)": 120, "K2(um)": 400, "L(m)": 277.23, "coast_Wt": 1.1, "internat_Wt": 1.15,
    "DAF": 0.868940, "CO2_res": 3.114, "CO2_dis": 3.206}}
    
```

Fig. 3 Example of the JSON input data file regarding engine information. This information is used to estimate fuel consumption and GHG emissions using the models proposed in [21]

although at different levels, their dispersion results are beyond our 0.15 reference.

Figure 6 shows the Cumulative Distribution Function (CDF) and aggregated anchoring times for CCs, CSs and RRs over a year. In general, ports apply a First-Come First Served policy to allow ships into the port, independently on the accuracy of their ETAs. Hence, a ship arriving 3 h after its reported ETA but minutes before another one arriving on time, will be served first. The exception is passenger traffic, that has priority over any other traffic, causing other ships to wait even if arriving slightly before. For this reason, we omit RP and Px traffic in Fig. 6, as they barely ever go to anchoring.

Hence, we would expect that anchoring times are uniform across the other types. The reality is that CSs and CCs had to wait in anchoring many more times and for longer than RRs. Our intuition is that this is caused because these RRs mostly call at smaller and less congested

ports. On the other hand, CCs anchoring time is below 1 h in 50% of the times and less than 10 h in slightly more than a 60% of the time. However, they call at multiple central-African ports where they experience very long anchorings, causing the degradation in their results. CS2 and CS3 ships wait more than an hour 80% of the times they anchor. In their case, most of the times they call at hub ports with higher congestion at the entrance, which jointly with the presence of passenger traffic, extend their stays in the anchoring areas. Note that in some cases these ships spend more than a month per year in anchoring. Most of these waiting times could be avoided with better port-ship synchronization, leading to speed reductions and to a better management of resources in ports.

Figure 7 analyzes ETA deviations for CC, CS and RRs. RoPax and Pax traffic follow tight schedules and their deviation is typically within plus minus 20–30 min of

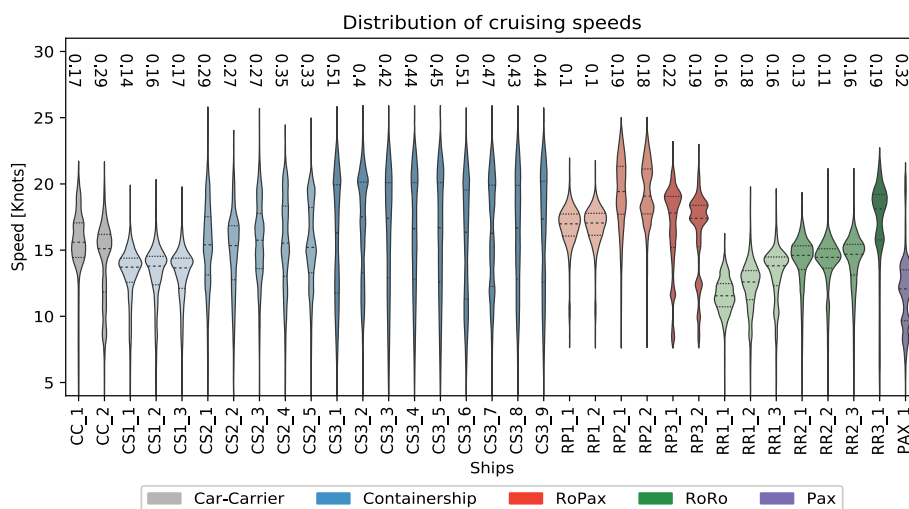
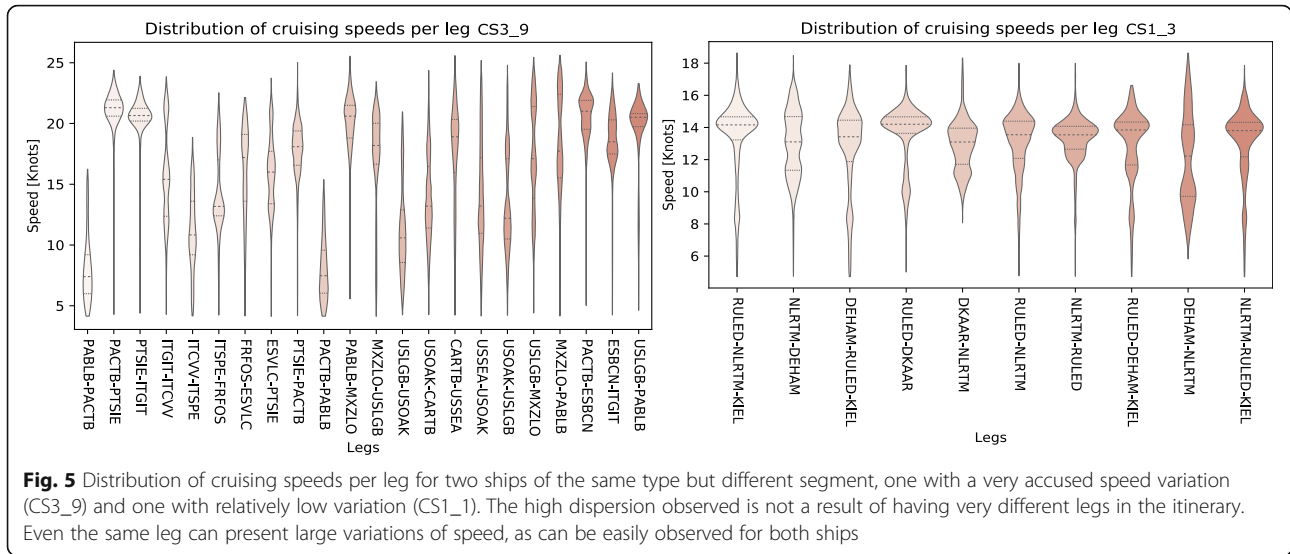


Fig. 4 Distribution of cruising speeds over a year for 33 ships. Each ship has a violin and an ITM. ITMs go beyond 0.15 in 28/33 ships, reaching 0.51 in CS3 Containerships, showing how inefficient, in terms of speed, navigation is nowadays



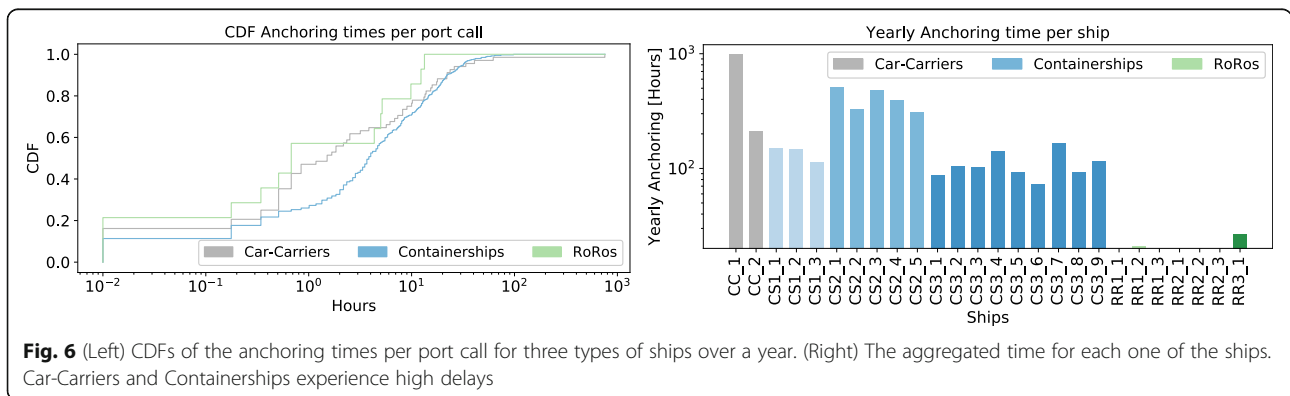
their ETA, so we excluded them from this analysis. We assume as acceptable a deviation of ± 1 h. Figure 7 shows that CSs and CCs only arrive within the hour in less than a 20% of the calls. The times they are late or early are also similar, being late a 65–70% of the times. RRs arrive within the hour more than 50% of the times and almost a 25% of the times they are early. The late arrival tails are bad for all three traffics, going CSs and RRs beyond the 24 h in more than a 20% of the times, per around a 35% for CCs. These delays difficult the planification of resources in the ports, not being realistic to plan beyond one or two hours ahead in most cases. At the same time, this results in longer stays in anchoring or increasing the congestion on the arrival and departure of ships, reducing their overall efficiency.

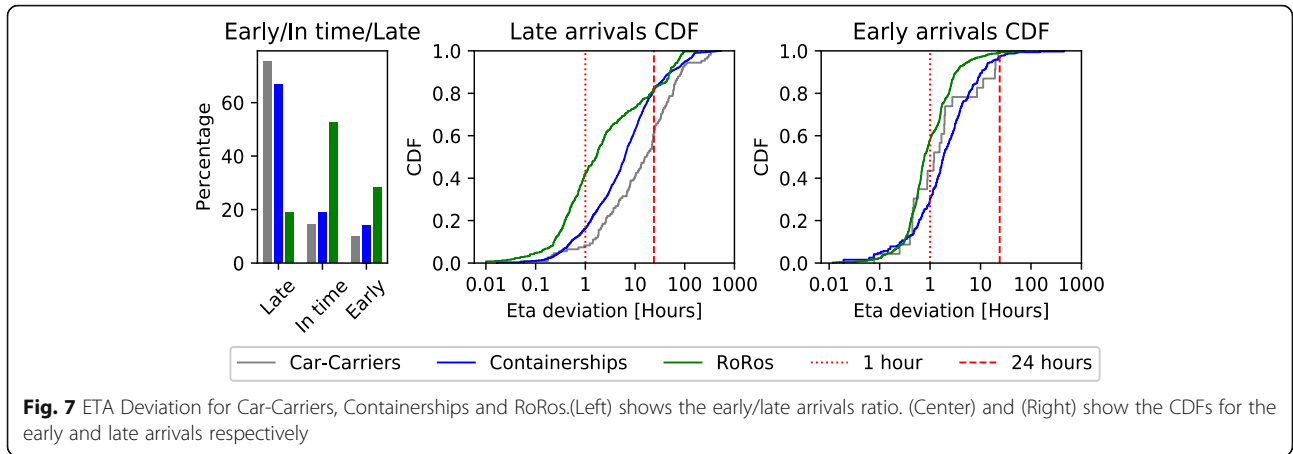
6 Evaluating the potential solutions

We estimate the reductions in fuel consumption and GHG emissions for each of the CS segments presented in Table 1. Figure 9 presents the results for CS1 ships.

The ships in CS1 carry less than 1000 TEUs and follow short routes in the north of Europe. Figure 9 (left) shows the potential fuel savings in the different scenarios versus the impact on the navigation time. Note that cruising speed depends on the scenario and this affects the time required to cover the route. The positive x axis represents the number of days by which the navigation time is reduced. The most remarkable result in CS1 is seeing how Sc 3 Low achieves 13–17% fuel reduction while also reduces the days of navigation between 10 and 22 days. CS1 ships go through the Kiel Canal. Due to congestion, many times surround Denmark with a great cost in time and fuel. Better synchronization would coordinate the arrival at the Canal entrance and optimize its use, avoiding this issue. For this same reason, in Sc 3 Med, the reduction in time can reach almost 50 days. It is also interesting to remark the difference in time between Sc 1 and Sc 2 results of the large amount of time these ships spend in berth.

Figure 8 (right) shows the average savings and standard deviations in CS1 for the fuel and GHG pollutants.





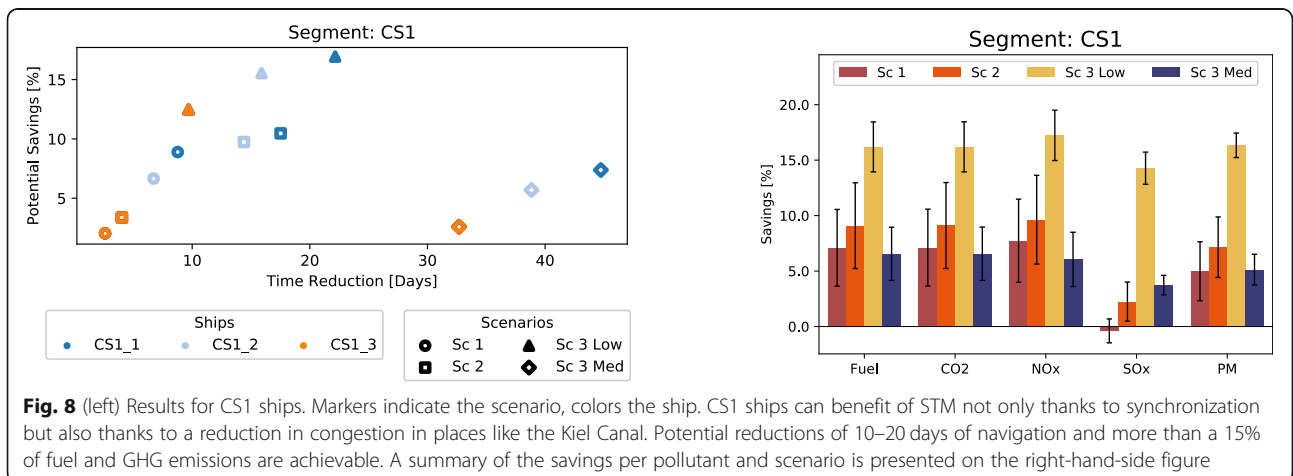
All of them are similar except for SOx. There is a 20X difference in SOx emissions of CS1 ships between ECA and non ECA zones. This causes that savings within ECA zones have lower impact, leading to a lower percentage of savings. In any case, the results for Sc 3 Low are clearly superior to the other scenarios.

CS2 ships carry around 6000 TEUs and follow long distance routes within Europe. Figure 9 (left) shows that Sc 3 Low achieves the largest savings, followed closely by Sc 2. CS2 ships navigate at low speeds and suffer large aggregated anchoring times. Large anchoring times result in large extra navigation times, low speeds and large savings in Sc 2. Sc 3 Low savings reach the 23% and is able to reduce between 10 and 25 days of navigation. The Sc 3 Med scenario can reduce consumption in 12–13% in 4 out of 5 cases but also days of navigation in 35–45 days. Figure 9 (right) shows that results for the different pollutants and fuel are very similar. This homogeneity is different to CS1 due to the absence of ECA zones in the routes of CS2 ships.

CS 3 ships cover transoceanic routes between America and Europe. Due to length of their routes, have less port

calls and spend less time at berth or in anchoring. For this reason, as shown in Fig. 10, Sc 1 and Sc 2 barely achieve any time savings and even negative results in terms of consumption, due to speed adjustments. Moreover, even when navigating at low speed supposes large savings in terms of consumption or GHG emissions, it can imply more than a month of extra navigation time. We must note, though, that these results are also consequence of the huge dispersion the speed distribution has for these ships, all of them in the order of 0.4–0.5. However, The Sc 3 Median case still achieves reductions of fuel and time, leaving the intuition that a good selection of speed, between our low and median speeds, can still achieve savings in the order of 5–10% in fuel and GHG emissions.

The most important takeaways from this evaluation are that, first, even in scenarios like Sc 1, STM and JIT can suppose substantial savings in fuel and GHG emissions, at least in short and medium distance routes, as shown for CS1 and CS2. Second, synchronization will help to lower speeds, if needed, and possibly lead to savings between 15 and 20% in fuel and GHG emissions. Third, that even when Sc 3 Low may be too aggressive



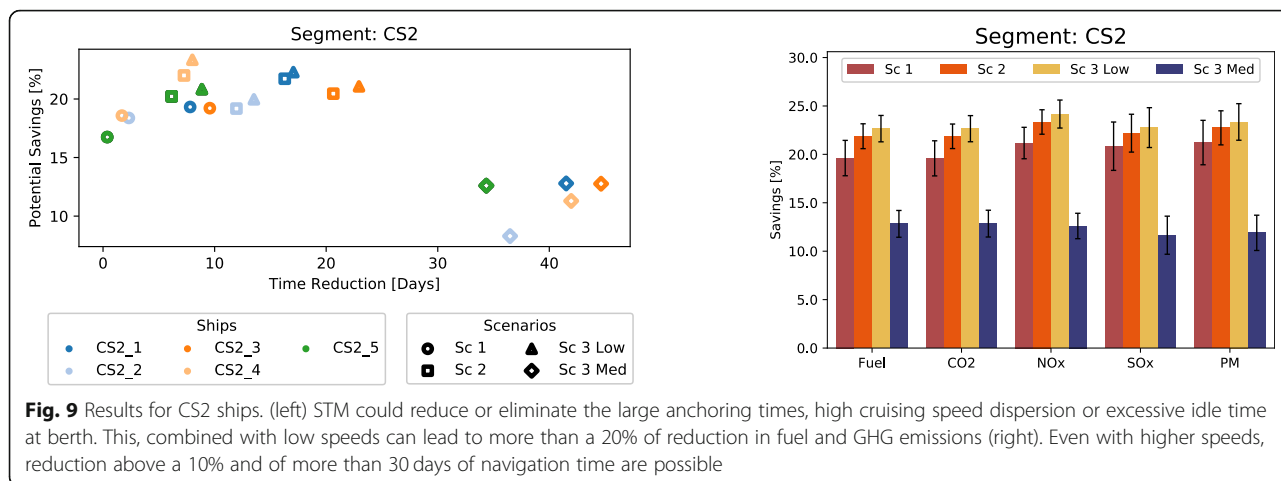


Fig. 9 Results for CS2 ships. (left) STM could reduce or eliminate the large anchoring times, high cruising speed dispersion or excessive idle time at berth. This, combined with low speeds can lead to more than a 20% of reduction in fuel and GHG emissions (right). Even with higher speeds, reduction above a 10% and of more than 30 days of navigation time are possible

in the speed reduction, both Sc 3 Median and Low act as upper and lower bounds on the possible achievable reductions and, thanks to STM, right-speeding and synchronization can lead to substantial benefits without increasing navigation times.

7 Discussion

The proposed method for estimating fuel consumption and GHG emissions is not perfect. However, we validated the accuracy of our results with cruising companies and crews within STM, in fact one of them is one of the ships under study, and our estimations were almost exact. Still, changes in the engine configurations, weather conditions, and several other causes can reduce the accuracy of our method. Similarly, our waypoints computation can introduce a small error in the consumption and GHG emissions while maneuvering. Similarly, some assumptions during the computation of the different scenarios, like the low speed variation, may reduce the realism of their results.

However, we believe this impact is acceptable and serves our goal of at least establishing an upper bound on the achievable savings. The effects of these

inaccuracies are not expected to be as substantial as to affect the order of magnitude of the savings that can be achieved through the implementation of approaches like those proposed in STM. Hence the upper bounds provided should be tight enough and reflect the impact these techniques can have in our environment. Thus, they show and quantify the problems inherent to lack of synchronization between agents within ports, and ports and vessels and their consequences. Reducing these issues would largely improve the efficiency of ports, reducing turnaround time. As a byproduct, they would also allow for a reduction on the fuel consumption and GHG emissions of vessels calling at those ports. Hence, investing in IT solutions, like those proposed by initiatives like STM, to improve the collaboration would not only not imply a cost but lead to larger profits and to more competitive ports and shipping lines.

8 Conclusions

In this paper we have presented the ways in which STM can be an enabler for Just-In-Time (JIT) navigation and

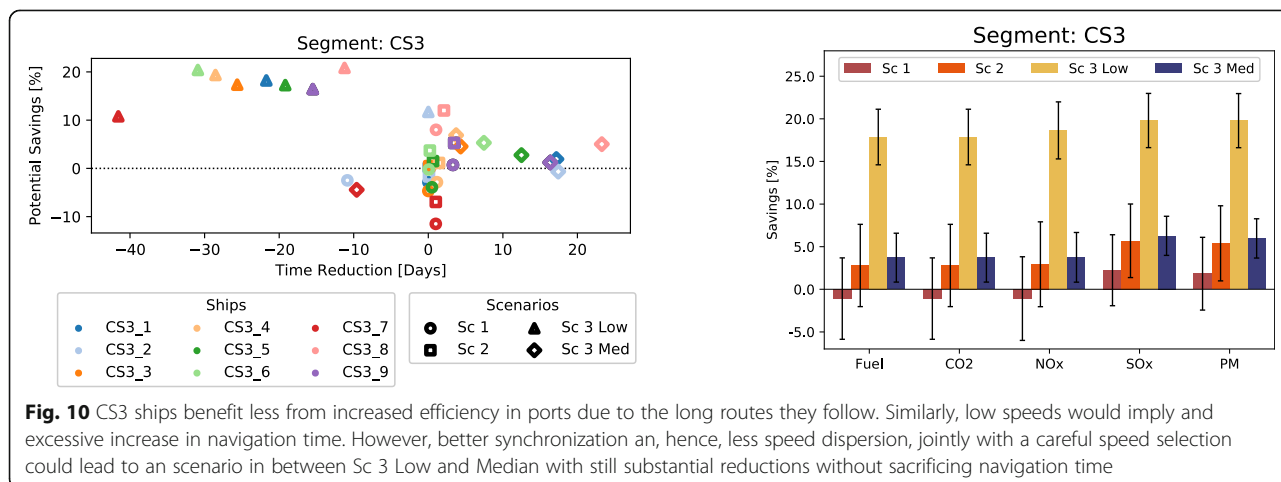


Fig. 10 CS3 ships benefit less from increased efficiency in ports due to the long routes they follow. Similarly, low speeds would imply and excessive increase in navigation time. However, better synchronization and, hence, less speed dispersion, jointly with a careful speed selection could lead to an scenario in between Sc 3 Low and Median with still substantial reductions without sacrificing navigation time

port operations, helping to overcome some of the barriers that nowadays avoid its adoption or, at least, a wider one. We have also estimated the impact of some of these barriers in the shipping industry, analyzing the dispersion of the cruising speed of ships, the time they spend in anchoring and the poor accuracy of the ETAs ships can provide nowadays when they leave departure ports.

Finally, we have estimated the impact that STM can have on greening the container shipping industry by reducing fuel consumption and GHG emissions at different maturity levels. Results show that potential reductions of fuel consumption and GHG emissions in the order of 15–23% may be achievable, what should make enforcing JIT and supporting initiatives like STM a priority for the IMO and shipping industry in general.

Acknowledgements

Not applicable.

Authors' contributions

JAA Every section, development of the evaluation framework. Reviews of the paper. JAGM Most of the introduction. Supervised the team. GFC Part of section 3, Just In Time (JIT) Navigation. NAG Helped adapting the methodology, devising the scenarios and in the use case selection. LC Helped in the analysis of the results and use case selection. JL Helped on the use case selection. The author(s) read and approved the final manuscript.

Funding

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 12 July 2019 Accepted: 19 March 2020

Published online: 15 April 2020

References

- Adamo, F., et al. (2014). Estimation of ship emissions in the port of Taranto. *Measurement*, 47, 982–988.
- Agussurja, L., Kumar, A., & Chuin Lau, H. (2018). *Resource-constrained scheduling for maritime traffic management*. In *Thirty-Second AAAI Conference on Artificial Intelligence*.
- Alphaliner, 2013. Extra and super slow steaming help absorb 7.4% of fleet. *Alphaliner Weekly Newsletter*, 44, October.
- Andreasson, B. & Holmberg, P. E., 2015. *STM Master Plan*, s.l.: Monalisa 2.0.
- Ascencio, L., et al. (2014). A collaborative supply chain management system for a maritime port logistics chain. *Journal of Applied Research and Technology*, 12, 444–458.
- Brooks, M. R., & Faust, P. (2018). *50 Years of Review of Maritime Transport, 1968–2018: Reflecting on the past, exploring the future*. (No. UNCTAD/DTL/2018/1).
- DNV, G. L. (2018). *Maritime Forecast to 2050. Energy Transition Outlook 2018*, s.l. DNV GL.
- GloMEEP-GIA. (2013). *GloMEEP-GIA* [Online] Available at: <https://glomEEP.imo.org/>.
- IALA-AISM. (2018). S-211 Available at: <https://www.iala-aism.org/technical/data-modelling/iala-s-200-development-status/s-211/> [Accessed 30 May 2019].
- IMO. (2003). *IMO policies and practices related to the reduction of greenhouse gas emissions from ships* [Online] Available at: [http://www.imo.org/blast/blastDataHelper.asp?data_id=26597&filename=A963\(23\).pdf](http://www.imo.org/blast/blastDataHelper.asp?data_id=26597&filename=A963(23).pdf) [Accessed 23 May 2019].
- IMO. (2011). *Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto* Available at: [http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-\(MEPC\)/Documents/MEPC203\(62\).pdf](http://www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Marine-Environment-Protection-Committee-(MEPC)/Documents/MEPC203(62).pdf) [Accessed 23 May 2019].
- IMO. (2014). *Third IMO GHG study*. London: International Maritime Organization (IMO).
- IMO-CONCASAR. (2014). *Sub-committee on navigation communications and search and rescue: Development of an E-navigation strategy implementation plan. Results and recommendations from the MONALISA and MONALISA 2.0 projects* [Online] Available at: <https://s3-eu-west-1.amazonaws.com/stm-validation/uploads/20160420153614/NSCR1-INF18-Italy-and-Sweden.pdf>.
- Javadian Kootanaee, A., Babu, K., & Talari, H. (2013). Just-in-time manufacturing system: From introduction to implement. *International Journal of Economics, Business and Finance*, 1(2), 07–25.
- Lind, M., Hägg, M., Siwe, U., & Haraldson, S. (2016). *Sea traffic management – Beneficial for all maritime stakeholders* s.l., Transportation Research Procedia.
- Liu, X., Sattar, S., & Li, S. (2016). Towards an automatic ice navigation support system in the Arctic Sea. *ISPRS International Journal of Geo-Information*, Volume, 5, 36.
- Marine Traffic. (2019). *Marine traffic* Available at: <https://www.marinetraffic.com/> [Accessed 28 05 2019].
- Neumann, T. (2018). Enhancing safety and reduction of maritime travel time with in-vehicle telematics. In *Management Perspective for Transport Telematics* (pp. 352–365).
- Ockedahl, C. (2016). *Trucker apps help drivers save time, reduce port congestion* Available at: <https://www.trucks.com/2016/05/16/trucker-apps-help-drivers-save-time-reduce-port-congestion/>.
- Olba, X. B., Daamen, W., Vellinga, T., & Hoogendoorn, S. P. (2018). State-of-the-art of port simulation models for risk and capacity assessment based on the vessel navigational behaviour through the nautical infrastructure. *Journal of Traffic and Transportation Engineering*, 5, 335–347.
- Olmer, N., Comer, B. R. Y. A. N., Roy, B. I. S. W. A. J. O. Y., Mao, X., & Rutherford, D. (2017). *Greenhouse gas emissions from global shipping, 2013–2015*. The International Council on Clean Transportation, 1–38.
- Pahl, J., & Voß, S. (2017). Maritime load dependent Lead times - an analysis. In *Computational Logistics* (pp. 300–305).
- Porathe, T. (2016). A navigating navigator onboard or a monitoring operator ashore? Towards safe, effective, and sustainable maritime transportation: Findings from five recent EU projects. *Transportation Research Procedia*, 14, 233–242.
- Port of Algeciras. (2017). *PitStop port operations Algeciras* Available at: <http://innovacion.apba.es/en/pit-stop-port-operations-algeciras/>.
- Port of Hamburg. (2014). *Port of Hamburg –digital gateway to the world* [Online] Available at: https://www.hamburg-port-authority.de/fileadmin/user_upload/140401_HPA_Broschuere_spl_web.pdf.
- Port of Rotterdam. (2018). *Pronto – port call optimisation* [Online] Available at: <https://www.portofrotterdam.com/en/tools-services/pronto>.
- Psarafitis, H., & Kontovas, C. (2016). Green maritime transportation: Speed and route optimization. In *Green transportation logistics, S.l.:International series in operations research & management science* (pp. 299–349).
- Psarafitis, H. N., 2016. *Green transportation logistics*. S.l.:Springer.
- STM. (2015). *Sea traffic management validation project* [Online] Available at: <https://www.stmvalidation.eu> [Accessed 19 Dec 2019].
- Tu, E., et al. (2018). Exploiting AIS data for intelligent maritime navigation: A comprehensive survey from data to methodology. In *IEEE Transactions on Intelligent Transportation Systems* (pp. 1559–1582).
- Tzannatos, E. (2010). Ship emissions and their externalities for the port of Piraeus–Greece. *Atmos Environ*, 44(3), 400–407.
- UNCTAD. (2018). *Review of maritime transport 2018*. New York & Geneva: United Nations.
- Winnes, H., Styhre, L., & Fridell, E. (2015). Reducing GHG emissions from ships in port areas. *Res Transp Bus Manag*, 17, 73–82.
- Yasin, M., Wafa, M., & Small, M. (2004). Benchmarking JIT: An analysis of JIT implementations in the manufacturing service and public sectors. *Benchmarking: An International Journal*, 11(1), 74–92.
- Zis, T., et al. (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics & Logistics*, 16(4), 371–398.

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