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Green Deal: data driven operations

Data driven operational advice for reducing ship emissions

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EXECUTIVE SUMMARY

In this project the overall research goal can be summarised as:
"Reduce the uncertainty for the ship owner in the investment decision of operational data acquisition and/or monitoring/advisory tools, that help the ship owner to achieve further fuel efficiency and emissions reduction. The focus in this project will be on greenhouse gas emissions and the propulsion fuel use."

To mitigate a part of the uncertainty related to this investment decision, the following two research questions were addressed in respectively work package 1 and 2:

1. What is the operational performance of the ship and how does that change over time?
2. What are the realistic operational measures and how much fuel reduction can this achieve?

This report considered the second question.
A flowchart was developed to help in the process of decision making. It leads through the various decision steps and can help to increase understanding between ship owners and tool makers.
Onboard insight based on a survey shows large variation in fuel use between sailing days. Information and tools can help the crew to make better decisions during operations. There is an interest in such tools as long as training or a clear introduction is given.
A literature review shows that operational measures can have a significant impact on fuel use and emissions. However, due to large variations in both ship and environment the actual impact is difficult to predict and to prove.
Several operational advise tools exist, however the easy accessible information does not give enough information on how they perform. The instrumentation, presentation, validation and uncertainty is often unspecified, especially taking into account specific ships and their circumstances. This makes the investment choice difficult for ship owners, as they look for what works within their fleet (+ what they need – data sources, or how they are tested (validation etc)

Following the investigated uncertainties and needs, two use cases were carried out on how to make steps towards uncertainty reduction and operational improvement.
One case study shows that there are saving opportunities and operational engine data can give insight on where the best improvement can be achieved. In the second use case voyage simulations showed helpful to gain insight in possible gains when operational measures are taken, taking into account the variation in circumstances over specific routes. Comparison with operational data gives trust in the method and shows that the effect of operational measures is difficult to quantify in operation due to the high variability in environmental circumstances and crew behaviour.

This report presents part of the work done within the Green Deal project "Data Driven Operations". Two other reports are available:

1. Report 70138-7-PAS [42]: Operational speed power analysis: Using Bayesian modelling. This report describes an approach to determine the speed power relation from operational data. This provides a cost effective method to detect changes in fuel efficiency, either due to fuel saving measures or due to e.g. maintenance issues.
2. Report 70138-8-RD [43]: WP1: in-service performance test protocol. In this report novel steady state zig-zag runs are compared to the reciprocal runs according to ISO15016 and the current conditions and sea state (recorded in the area).

1 INTRODUCTION

1.1 Research questions

In the Green Deal validation, it was decided end of 2023 to start up three studies that focus less on specific products/suppliers (to validate a specific product) and more on the technology behind those specific products. This proposal is one of those three. It focuses on the technology to gain insight in ship performance and the accompanying fuel use in operation, leading to operational changes that will reduce the fuel use and with that, emissions. This technology can be used either by the shipowner directly or with the help of existing monitoring and/or advisory tools.

Ship owners who want to improve their operational fuel use and with that lower their emissions, need information on the ship performance. They can invest in (a) their own operational data acquisition and intelligence and/or in (b) a monitoring/advisory tool that supports this. However, there is a lot of uncertainty on the possible and realistic gains. The main consideration from a shipowner perspective can be simplified to:
What is the return on investment and environmental gain of the operational measures and/or required instrumentation?
To mitigate a part of the uncertainty related to this investment decision, the following two research questions are considered crucial:

1. What is the operational performance of the ship and how does that change over time?
2. What are the realistic operational measures and how much fuel reduction can this achieve?

The overall research goal of this project can be summarised as:

“Reduce the uncertainty for the ship owner in the investment decision of operational data acquisition and/or monitoring/advisory tools, that help the ship owner to achieve further fuel efficiency and emissions reduction. The focus in this project will be on greenhouse gas emissions and the propulsion fuel use.”

This Green Deal project is a concrete first step to get insight in the emissions reduction potential by operational monitoring/advisory actions and the tools linked to that. It helps the ship owner to reduce their uncertainty in the ships fuel efficiency / performance. Also, it concretises the possible effects that operational monitoring and/or advice can have in specific operational situations for specific ships.

We hope that this project will facilitate the start of a broader cooperation between different parties in the sector and possibly lead to a follow-up joint project once the GD Validation comes to an end. By not specifically validating one product we aim to create an open research project where tool suppliers can join to provide their views, without being reluctant to reveal all tool details.

1.2 Scope

The work scope is divided into two main work packages, related to the two research questions. This report is related to WP2, focusing on research question 2 “What are the realistic operational measures and how much fuel reduction can this achieve?”.

Note that the first research question results are presented in [Ref 42.][Ref 43.]. A novel in-service performance test protocol was compared to the standard speed power trials. This method would make it possible to gain insight in the (change of) speed power characteristics of the vessel without dedicated trials [Ref 43.]. Next to that a Bayesian model approach was used to gain information on the speed power curves from (noisy) operational data, including uncertainty indication [Ref 42.].

This Green Deal project considers operational measures, i.e., changes in how the ship is used, not how the ship itself can be improved. Advisory tools we look at are mainly for onboard use, e.g., to adjust sailing speed, energy management settings, weather routing, and trim and draught. We focus on tools and methods that are based on data gathering and interpretation, possibly in combination with physics knowledge.

Technical solutions such as hull & propeller adjustments, engines, and alternative power systems are out of scope. Also, fleet strategies are out of scope, however, relevant secondary benefits of data availability for fleet development will be discussed.

This report is set up as follows:
In Chapter 2 the qualitative flowchart developed in this project is presented (Section 5.1). It aims to support the ship owner in his consideration on the question: What is the return on investment and environmental gain of the operational measures and/or required instrumentation?
As mutual understanding between ship owners and tool providers is critical to establish what instrumentation and tools can provide added value a workshop was facilitated to discuss the flowchart.
In Chapter 3 the state of the art is presented. Survey results on current views on operational measures and the possibilities are presented in section 3.1. Based on literature, possible operational measures and their impact are described (section 3.2) and a market survey of available tools is presented in sections 3.3 and 3.4.
Following the investigated uncertainties and needs, the following two chapters consider two use cases on how to make steps towards uncertainty reduction and operational improvement.
Chapter 4 presents investment considerations and consequences from a ship owners perspective in relation to operational measures. Based on interviews, we discuss the investment considerations (Section 4.1). in Section 4.2.we analyse the insights gained by a positive investment decision based on real life onboard data.
In Chapter 5, we investigate the insight voyage simulations can give investigating operational changes, within a highly variable environment. The simulation scenario results are compared with measured data from an actual trip.
Finally Chapter 6 summarises the overall conclusions.

2 GUIDING PRINCIPLES TOWARDS APPLICATION

As mentioned in the introduction, ship owners who want to improve their operational fuel use and with that lower their emissions, need information on the ships' performance. They can invest in (a) their own operational data acquisition and intelligence and/or in (b) a monitoring/advisory tool that supports this. However, there is a lot of uncertainty on the possible and realistic gains. The main consideration from a shipowner perspective is simplified to: *What is the return on investment and environmental gain of the operational measures and/or required instrumentation?*

Besides quantitative assessments to gather proof, mutual understanding between ship owners and tool providers is critical to establish what instrumentation and tools provide added value. Often heard is that "digital tools promise all encompassing solutions and applicability", whereas the operational practice of a ship owners requires "robust, safe, low operational complexity, and focused application to solve a specific issue". The rift between these two perspectives, combined with that the return on investment of tooling only occurs when properly used has often negative results. This dissatisfaction can result in delay in further adoption of data driven operational tools in the maritime domain.

Therefore, we aim to enable the discussion and alignment by developing a "data driven operations consideration chart", together with sector stakeholders. The scope of this chart considers the potential use of an *operational advice tool(s)* which is defined as a software package that takes input on a vessel's operation condition and provides advice on possible actions to the crew, including the required instrumentation. These actions may include – but are not limited to – adjustment of the sailing speed, the draught/trim (e.g., by changing the distribution of cargo, fuel, and ballast water), and the route. In addition, multi-use of the output for administrative or fleet development functions are also mentioned due to their natural overlap and added value. The flowchart is not intended to be complete, but a reasoning starting point.

2.1 Data-driven Operations Consideration Chart

Based upon the line of reasoning related to "*What is the return on investment and environmental gain of the operational measures and/or required instrumentation?*[1,2]. The goal of this chart is not to provide specific answers, but to create a mutual line of reasoning on the considerations between ship owners and tool/instrumentation providers when discussing what type of tooling could provide what kind of efficiency increase in the voyage, given the availability and use of (interpretated) data from onboard measurements.

Figure 2.1 shows five steps starting from the functionality towards the theoretical gains, operational output, required data input, via operational complexity to an assessment of the investment feasibility.

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1 Developed based upon available literature and four interviews with ship operators and tool providers.
2 Applied during the workshop for validation on completeness and applicability.

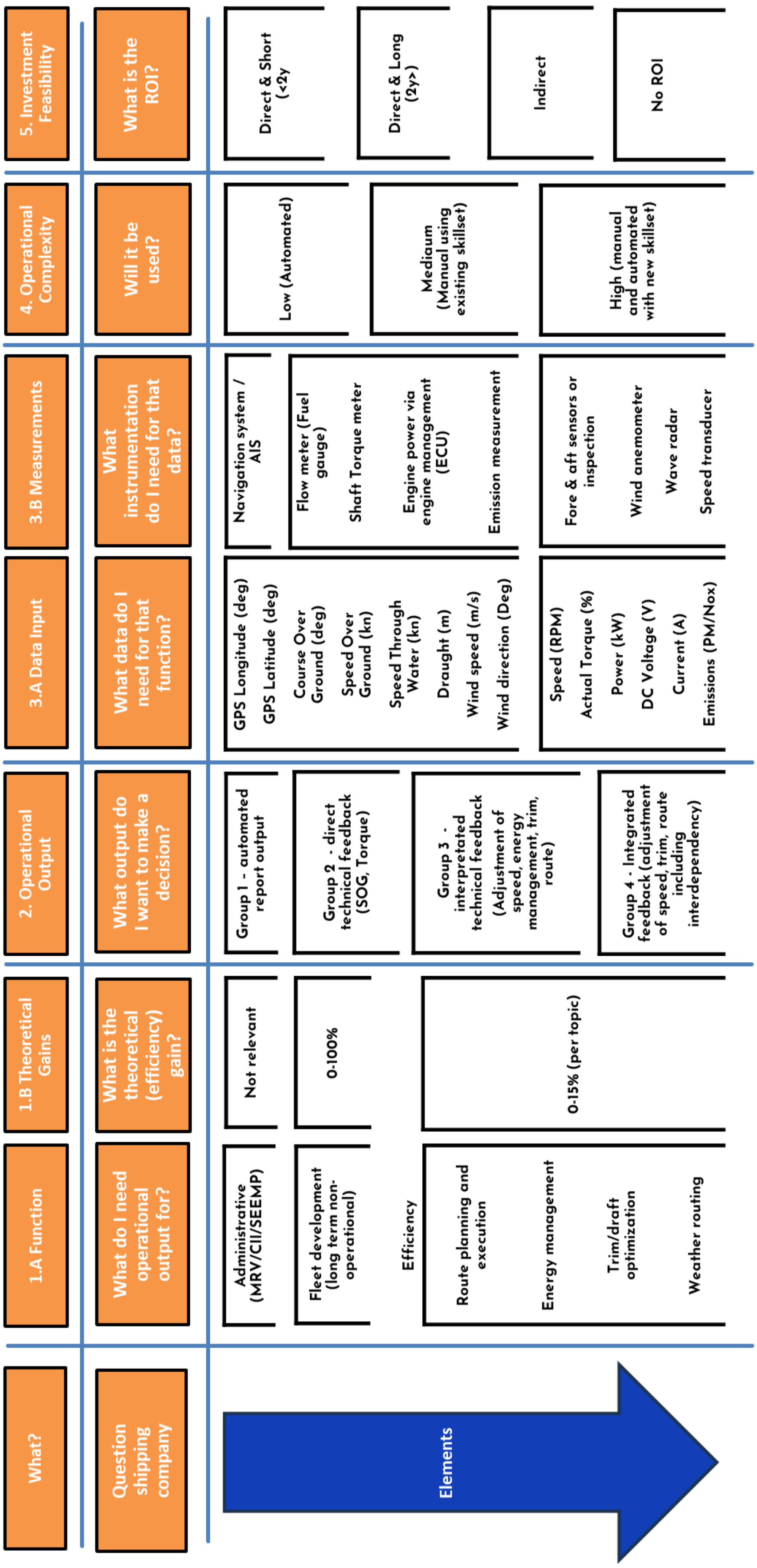

Figure 2.1: Flowchart to discuss the main considerations towards investing in operational advice tool(s).

2.1.1 Function & Theoretical Gains

The function defines the intended field of use for the tool. This can be to support administrative tasks, to provide long term data input for fleet development or efficiency increase as clarified in the introduction. Linked with the function and the solution types to be applied, a theoretical gain is possible. Whereas this is not the case for administrative efforts, in the field of fleet development new alternative energy carriers technologies can theoretically reduce up to 100% of the emissions. Finally, as the core focus of this research, operational efficiency via route planning (just in time arrival), energy management, trim/draught optimisation, and weather routing can reduce emissions up to 15% per topic, and a potential multiplication when applying various solutions together. However, the complexity increases rapidly for correct and integrated use, resulting in often lower than expected impact.

2.1.2 Operational Output

The operational output is the actual result of the operational advice tool that is to be used onboard or on shore. Operational output is defined in four groups of step by step increasingly higher complexity.

- Group 1: Automated report, which translate that available data into standardised reports for internal use or external reporting (e.g., MRV).
- Group 2: Direct technical feedback, which shows the data output of the measurement as-is in an understandable format, but lacks any form of advice or enrichment (e.g., SOG).
- Group 3: Interpretated technical feedback, which interprets the direct technical feedback into an operational advice. However, this is not directly integrated to other measures.
- Group 4: Integrated feedback, which provides based upon integrated technical feedback. Where, for example, the impact of a trim change is aligned with a speed trough water optimisation given a certain wave direction, for an economically ideal just in time arrival.

2.1.3 Data Input & Measurements

The data is the output of the instrumentation placed on board. The data can differ between transit and environmental data such as speed through water (STW) and wind speed, and powertrain data like torque, power, and emissions. To get this data instrumentation is required related to navigation, power train, and the direct environment of the vessel. The instrumentation and data shown in Figure 2.1 show a fundamental subset, which enables at least direct technical feedback.

2.1.4 Operational Complexity

The operational complexity describes the effort required toward implementation.

- For example, a limited amount of administrative automation such as MRV reporting enables crew to focus on core task of operation of the vessel, requires ‘low’ effort toward implementation.
- Technical feedback for an increase in energy efficiency that related to ‘normal’ operation of the vessel, such as speed adjustments, require a ‘medium’ effort towards implementation onboard. This is considered an incremental innovation, and requires mostly an open mindset and incentive, but no new ‘way of working’ or in depth expertise to handle.
- Complex new technologies, e.g., semi-autonomous skeleton crew sailing or non-intuitive operational output onboard for the crew, require a 'high' effort towards implementation. This is considered a ‘radical’ innovation and requires a new way of working and in depth expertise to handle.

2.1.5 Investment Feasibility

The investment feasibility considers the return on investment (ROI) of the tool(s). Four categories have been mentioned, based on the payback period.

- Short ROI (payback period less than 2 years) and has a highly specific use case, where the added value is direct and clear. For example, proven advice tool(s) with a limited cost, such as automated reporting for MRV.
- Long ROI (payback period more than 2 years), and has a more complex use case where the added value is direct. For example, partially proven tool(s) with possible a higher cost, such as data driven just in time arrival.
- Indirect ROI, where the added value comes from increased insight in the operation of the vessel. This is highly relevant when troubleshooting, or when considering fleet development. Most shipowners have not quantified the value of this insight, and therefore don't have a direct ROI or payback time to break even.
- No ROI or break even period, where the tool(s) are not implemented properly due to technical issues or operational complexity and no direct gain is obtained.

2.2 Workshop: Feedback flowchart

The flowchart was discussed in a workshop with 15 stakeholders. The goal of the workshop was to validate the elements in the flowchart, to determine whether it enabled discussion among stakeholders, and to assess which elements are considered enablers or barriers towards adopting operational advice tool(s). This varied group consisted of tool providers, large and medium shipping companies, captains and maritime sector associations. During the workshop the flowchart steps were discussed focussing on what helps or stops shipping companies to make decisions within the different steps.
The discussion itself proved to be helpful in the mutual understanding between ship owners, tool providers and other stakeholders.

The topics mentioned during the workshop are listed in Appendix 1. The topics in Appendix 1 show a wide range of concerns and possibilities, show-casing the high variation within the maritime sector. Depending on e.g. the fleet size, fleet variation, (variation in) sailed routes, technical and digital development, different concerns and opportunities can be encountered. This is one of the explanations for the large uncertainties that both shipping companies and tool makers face, as a solution will always be dependent on the situation it is developed for. Based on all the input we condense the mentioned issues into a listing of core factors that function as an enabler or barrier towards implementation of operational advice tool(s) (Table 2-1: Listing of core factors per step affecting the ship company readiness to implements an operational advice toolTable 2-1).

Table 2-1: Listing of core factors per step affecting the ship company readiness to implements an operational advice tool.

Step	Factor	Enabler	Barrier
Step 1: Function	Sufficient scale for impact. A single use case works for gaining experience, but major efficiency increase is aided by a fleetwide approach.	Large comparable fleet (between 100 and 1000 vessels) and routes	Small differentiated fleet (10 vessels) and routes
Step 2: Operational output	Complexity of the output (and operation) needs to be taken into account, so that it can support decision making.	Simple and direct output	Complex output

Step	Factor	Enabler	Barrier
Step 3: Data input & measurements	Data reliability, collection and accessibility are issues that need large scale	Robust software, hardware, and support.	Lack of robustness
Step 4. Operational complexity	Crew and office involved into the implementation to create cultural change/acceptance	Incremental steps enabling the existing skillset	Radical change with untested skillsets
Step 5: Investment feasibility	Improve the operation and demonstrate gains, both finance and sustainability.	Availability of (some) proof (beforehand) what the saving will be for specific case	Unclear and unproven impact
Other	Dealing with influences outside your own data collection (fuel price, market social and commercial opinions/possibilities)	Robustness by strategic embedding external factors into your strategy and tooling	Lack of awareness of external factors

When the shipping company and (external or internal) tool provider together conclude that a operational advice tool mostly functions as an enabler in the above-mentioned factors, then the feasibility of successful implementation increases drastically. Figure 2.2 concludes the qualitative guiding principles. In short, depending on a shipping company's strategy and readiness a qualitative differentiation can be made on what complexity level of tooling is feasible.

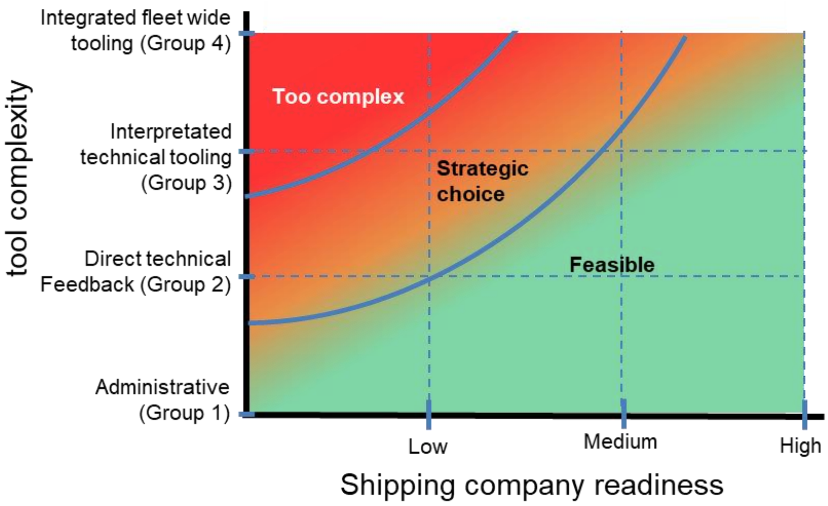

Figure 2.2: Qualitative guiding principles based upon the flowchart and feedback showing guiding principles in relation to the adoption of operational advice tools.

3 STATE OF THE ART

Next to the workshop we investigated literature for a wider view of current knowledge and available tools. A survey was conducted under both onboard crew and onshore staff to gain insight into the current views on emission reduction and using decision support tools.

3.1 Survey Results

During this project we set up a survey to investigate the current ideas on operational information and (advisory) tools. The survey was sent around via the KNVR (Royal Association of Netherlands Shipowners) network and resulted in 33 respondents. The questions were split up in different categories, starting with basic information to fuel consumption, interest in tools and what information is used or needed. Results are described in Appendix 2.

From the respondents reactions we can draw the following conclusions:

- There is a, sometimes large, uncertainty in the fuel use during a journey.
- There is an interest in tools and/or information on mostly the topics of fuel, speed and weather. This is also the tooling that is already most available and installed.
- The interest in information and advice indicates that there is an appetite for advisory or informative tools.
- Introduction of and training with the tools is a must to get them accepted, trusted and integrated in the operational activities.

The survey results show that both on board and onshore there is an interest in tools to save fuel/lower emissions. However, there is uncertainty about what tool to use for what goal (see investment considerations in next chapter). Next to that, the onshore (investment) decisions and onboard implementation and trust could be aligned further (see chapter 5).

3.2 Literature review

Although a lot of academic literature is available on weather routing and voyage planning, data on the application of algorithms in real-world operation is scarce. In particular no studies on the benefits of using operational advice tools could be found. In 2009, Corbett et al. [38] published a marginal abatement cost analysis for container ships and derived a simple formula to determine the (economically) optimum speed. They studied the impact of freight rates, fuel prices, and fuels tax on vessel speed of container ships calling at US ports in two scenarios: One without a change in total fleet size to compensate for the changes in freight capacity due to lower speeds and one which includes an increase of the fleet. Lindstad et al. [39] carried out a similar study and included, amongst other factors, weather conditions, capital costs of the transported goods, emissions at berth, and emissions for vessels that need to be built to compensate for the reduced freight capacity due to speed reduction. It was concluded that reducing CO_2 emissions at negative or zero abatement costs is possible.

3.3 Operational measures

In 2017, Bouman et al. [1] published a review-paper on the state-of-the-art of technologies and measures to reduce CO_2 from vessels. They summarised the findings of about 150 studies that were published after the Second IMO GHG Study of 2009 [2] to assess the potential impact. At fleet level, the estimated CO_2 reduction potentials differ significantly with large variances in the results of some studies, cf. [1, Tbl. 1]. The individual operational measures distinguished by Bouman et al. were speed optimisation, capacity utilisation, voyage optimisation, and “other” operational measures. The CO_2 reduction potentials are depicted in [1, Fig. 2]. According to this, capacity utilisation has the highest expected (median) reduction followed by speed optimisation, voyage planning, and other operational measures. In particular the calculated potential impacts of speed optimisation range from very low reduction to up to 80%. This indicates that a significant improvement is possible.

An automated fuel optimisation system developed by Lean Marine has been studied by Madureira et al. [24]. The tool was designed to maintain a preset daily fuel consumption and optimise propulsion output and efficiency by varying fuel rack position, engine and propeller speed, and propeller pitch. Madureira et al. studied operational data of one vessel equipped with this system over one year. They found that the actual fuel consumption showed good agreement with the target fuel consumption. Furthermore, a dependence on whether the shaft generator was used or not was noticed. If it was on, engine speed had to be maintained in a narrow window to obtain the right frequency of the generated electrical power. This left propeller pitch as the only manipulated variable and led to slightly different pitch angles than would have been attained with variable shaft speed. Unfortunately, no analysis of the benefits of using the fuel consumption optimisation system compared to manual operation has been carried out. Also, the study did only look at aggregated data over a full year and therefore impact of weather (wind and waves) averaged out.

3.3.1 Weather routing, voyage planning, and speed optimisation

Weather routing and the development of algorithms to find optimal routes has got increasing attention in the last 25 years. Hundreds of studies have been carried out and the results have been published in scientific papers. The problem of weather routing can be defined in different ways depending on the boundary conditions – e.g., time of arrival, way points, and (expected) weather conditions – and objectives – e.g., total cost, fuel consumption, emissions, or duration of the trip. Different mathematical models and optimisation algorithms have been proposed and the increased available computational power drives further research in the field. Recent developments are the increase in the number of model parameters, the combination of different approaches, and the use of artificial intelligence. [3]

To give an idea of recent developments in the research on weather routing, a few recent papers will be summarised below. This is, however, not intended as a complete review of the literature in the field. Simulation of an eleven-day trip of a dry bulk carrier [4], yielded a reduction of fuel consumption of 7.34% compared to a constant sailing speed regime. This is in good agreement with the median value depicted in [1, Fig. 2]. Weather routing algorithms might not always yield the optimum of a given problem. The novel algorithm presented in [5], for example, converges for the used problem, but not necessarily to its global minimum. The inevitable uncertainty related to a future voyage poses a challenge for planning. For cruise ships, Braidotti et al. [6] proposed a probabilistic method to forecast the emission in itinerary planning. In the test case discussed in the paper, the Carbon Intensity Indicator (a measure for a ship’s energy efficiency) could be reduced from E (inferior performance level) to C (moderate) in the most probable scenario. The possible improvement of the Carbon Intensity Indicator (CII) of a fleet by applying operational measures has been studied by Yuan et al. [7]. They aimed to optimise operations and profitability while complying to efficiency requirements. They conclude that reduction in sailing speed has the biggest impact on vessel efficiency. For a test-case fleet, the average reduction was about 7%, with a maximum speed reduction of 20.6%. [7]

Already in 2001, MARIN started the development of the voyage scenario simulation tool "Gulliver". It combines vessel and weather data to calculate ship motion during a trip. The modular setup makes it possible to compare different vessel layouts and support design decisions. Gulliver can be combined with a rerouting algorithm that proactively changes the route and sailing speed based on weather and sea state. The optimisation can be done to minimise fuel consumption and travelling time but also more complex cost functions are possible. [8]

3.4 Tools on the market

3.4.1 Definition of operational advice tool

The classification society DNV summarised operational measures to reduce GHG emissions in an online presentation [9]. The different measures were grouped into three categories with several sub-categories each. Note that not all sub-categories include operational measures. The ones which are most important for the study at hand are marked with an asterisk:

- Optimising machinery and system operation
  - Auxiliary systems
  - Auxiliary engine loads*
  - Steam plant
  - Main engine testing and tuning
  - Turbocharging
- Optimising hydrodynamic and propulsion efficiency
  - Hull cleaning
  - Propeller polishing
  - Trim/draught*
  - Autopilot*
  - Combinator curve*
  - Dynamic positioning*
- Optimising efficiency during voyages and in port
  - Voyage planning*
  - Fleet utilisation
  - Capacity utilisation
  - Slow steaming*
  - Time in port*
  - Weather routing*

In their Decarbonisation Strategy, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) defined several levers to improve the energy efficiency of seagoing vessels. One area of application are operational measures which are split up into 'Voyage optimisation' and 'Fleet strategies'. Examples of the former are [10, Tbl. 1]:

- Voyage planning and weather routing,
- Trim and draught optimisation,
- Energy management,
- Hull, and proper fouling management.

MMMCZCS estimates that gains in energy efficiency of up to 10% are possible through operational measures. [10]

Based on these definitions, for the purpose of and in the scope of this document an *operational advice tool* is defined as a software package that takes input on a vessel's operation condition and provides advice on possible actions to the crew. These actions may include – but are not limited to – adjustment of the sailing speed, the draught/trim (e.g., by changing the distribution of cargo, fuel, and ballast water), and the route.

In particular, the operational advice tool does not initiate measures independently, i.e., without involvement of the crew (or staff onshore). An engine speed governor would, for example, not be considered an operational advice tool. The input can origin from other systems onboard the vessel or from sensors that have been installed specifically to feed the tool. Examples for onboard systems are engine control units or bridge management systems. Since there is a large variety of possible (optional) sensor input that is accepted by a specific tool, sensors are not considered part of the tool.

During the market study it turned out that many of the available software solutions serve a broader purpose than operational advice. It is, for example, common that one software package covers operational advice and administrative tasks. Also, some tools interact directly and without action taken by the crew with onboard systems like the main engines. In these cases, the term operational advice tool in its strict sense will only refer to the functionality that meets the above definition. The hardware setup to run the tool is also not considered in this project, even if it is proprietary and the tool is not intended to or even cannot be run on different hardware than the one provided by the tool supplier.

3.4.2 Market survey on operational advice tools

During the project a market survey was conducted to get an overview of operational advice tools that are commercially available. In particular, information of the needed sensors/input, the output, and possible advice to the crew was investigated. An overview of the tools is given in Appendix 3.
The list is based on the available detail. According to the limited technical information, which is publicly available, the investigated tools have many similarities. Monitoring of fuel and performance of hull, propeller, and engines is available in almost all of them. Furthermore, route and speed profile optimisation based on monitoring data and weather conditions is widely offered. Reporting and compliance are also important aspects that are commonly addressed by these tools. To improve the planning of operations, data can be made available to onshore fleet management in real-time.

Due to a lack of easily available technical specifications, it is, however, not possible to compare them with respect to implementation costs, required sensors, possible cost savings, etc. Only few statements/claims on the possible savings of fuel and reduction of GHG emissions could be found. For none of them sufficient background information on the baseline, the ship type, the operating conditions, etc. were provided to enable a comparison and validation.

4 EVALUATION OF OPERATIONAL MEASURE: OPERATIONAL ENGINE DATA ACQUISITION

Following the investigated uncertainties and needs in this chapter and the next we will consider two use cases on how to make steps towards uncertainty reduction and operational improvement.
The goal of this chapter is to clarify investment considerations and consequences from a ship owners perspective in relation to operational measures with a focus on engine data. First, we shortly discuss the investment considerations in Section 4.1 based upon interviews. Thereafter, we analyse available operational engine data to show the insights gained by data from a positive investment decision (Section 4.2).

4.1 Clarification of the investment considerations

The main consideration from a shipowner perspective is simplified to: *What is the return on investment and environmental gain of the operational measures and/or required instrumentation?* Based on the interviews, the return on investment (ROI) can relate to lower administrative burden, value of insights for long term fleet development, operational efficiency gains, or a combination of the above. We will briefly discuss two basic investment considerations shared by interviewees, to clarify lines of reasoning.

4.1.1 Case 1: ‘Administrative and more’

The administrative burden is currently increasing. For example, the mandatory reporting for the EU MRV (Monitoring, Reporting, and Verification). This task can be automated with onboard measurements with a fuel gauge (e.g., flow meter), navigation system, and automated report software. For a shipping company, the ROI is direct and short (<2 years).

Depending on the level of detail, this information has additional added value for fleet development considerations (e.g., realistic energy consumption, or efficiency gains compared to current operations), thereby increasing the ROI even further.

4.1.2 Case 2: ‘Operational efficiency and more’

Obtaining maximum efficiency gains via operational measures (e.g., route planning for just in time arrival, energy management, trim/draught optimisation, weather routing, or the combination), requires interpreted and integrated feedback of (onboard) measurements. This means that not only the technical feedback must be made available, it must also be interpreted into operational recommendations, and integrated so that the recommendations by itself do not reduce the impact of another measures. Finally, the operational recommendations must be executed.

This requires an extensive set of instrumentation, complex software, active alignment with the onshore office for planning, and willingness and or capabilities onboard to implement the recommendations. In practice, the following challenges occur when implementing:

- Profitability & Safety > Sustainability: operational measures function when sustainability and profitability align via fuel savings. However, the financial incentive to be on time or the incentive to be safe result in other operational recommendations. This increases the difficulty to filter out the positive impact of operational measures considering sustainability.
- OPEX & CAPEX: The needed investment strongly depends on what sensors/datalogging systems already exist on board, what data is shared with the shore office, and the type of ship. An (new) extensive set of instrumentation for integrated operational efficiency measures is a considerable investment. Furthermore, an onshore team is still required to analyse data and optimise the operational recommendations balancing between safety, profitability, and sustainability increasing the operational expenses.

Operational complexity: the willingness and capability of the crew to implement the recommendations is the final and crucial step. Practice has shown according to interviewees on both shore and onboard, that differences of insight occur constantly.

Overall, the combined challenge is that the ROI based on the OPEX and CAPEX is unclear (between less than 2year, and no ROI), as it depends on the quality of the implementation. This quality depends on the integration of technical, operational and commercial considerations and implementation. The investment becomes “A so-called “ongedekte investering”, according to one of the interviewees. Gains of up to 15% are not out of the question, however difficult to prove in the short term.

Yet, all interviewees confirm the relevance and benefit. If not on operational measures, then on fleet development. Highly detailed insight form the basis for the design criteria. The consensus is that the combination of these benefits warrant the investment for at least some of the vessels in a shipowners fleet.

4.2 Analysis of operational data

A vessel outfitted with instrumentation and software is analysed in this chapter to show potential insights gained after a positive investment decision. For the discussion of the collected data in the following sections one general cargo ship will be used as an example, further referred to as Ship X.

4.2.1 Operational data – General Cargo Case

To gain additional insight in the operation of their fleet, the shipowner has installed instrumentation and software on several vessels. The gathered data is, however, not connected to an operational advice tools at the moment. The monitoring data is currently used as an indication of which information can be collected and how it can be used to improve the operations of oceangoing vessels. For the purpose of the study at hand, the shipowner provided operational data of seven general cargo ships and one multi-purpose ship. The monitoring tools installed on the different vessels differ in terms of number of signals/sensors and the quality of the logged data. The main engines are marine diesel engines driving the generators which provide electrical power to the thruster motors and auxiliary systems. Some engines can run at two speed levels which also leads to two values of MCR power.

4.2.2 A list of instruments and their output

The shipowner has equipped several vessels with automation software that monitors relevant operational data on vessel movement, weather conditions, engines, generators, thruster motors, and propellers. The data originates from control systems of installed equipment and additional sensors. An overview of signals and sources is given in Table 4-1.

Table 4-1: Overview of relevant measured quantities and their sources.

Device(s)	Measured quantity	Unit	Source
Voyage and Navigation	GPS Longitude	[deg]	Navigation System GPS
	GPS Latitude	[deg]	Navigation System GPS
	Course Over Ground	[deg]	Navigation System GPS
	Speed Over Ground	[kn]	Navigation System Speed
	Speed Through Water	[kn]	Navigation System Speed
	Draught	[m]	Navigation System AIS
	Wind speed	[m/s]	Navigation System Wind
	Wind direction	[deg]	Navigation System Wind

Generators	Speed	[rpm]	ECU
	Actual Torque	[%]	ECU
	Power	[ekW]	Sensor connected PMS PLC
	Load	[%]	ECU
	Fuel Rate	[L/h]	ECU
Thruster motors	Speed	[rpm]	Drive
	Actual Torque	[%]	Drive
	Power	[bkW]	Drive
	DC Voltage	[V]	Drive
	Current	[A]	Drive
	Power	[ekW]	Drive
Bow thruster	Speed	[rpm]	Drive
	Actual Torque	[%]	Drive
	Power	[bkW]	Drive
	DC Voltage	[V]	Drive
	Current	[A]	Drive
	Power	[ekW]	Drive
Propeller shaft	Shaft speed	[rpm]	Torque meter
	Shaft torque	[Nm]	Torque meter
	Shaft power	[kW]	Torque meter

4.2.3 Case study

Onboard Ship X, the fuel rate, electrical power, engine speed, and percent torque are logged for the four diesel engines that drive the generators. With this data, engine maps can be derived. An example is given in Figure 4.1 below. The generators run at constant speed to keep the frequency of the generated voltage/current constant. Therefore, engine speed is not an independent variable in the below engine maps. On the x-axis, the generator power is plotted whilst the y-values refer to the specific fuel consumption. The latter has been determined by multiplying the fuel rate in L/h by a constant fuel density. This partially explains the scatter in the plots. The impact of variations in fuel density on the actual vs. perceived consumption should not be underestimated, and requires further research in practice. As could be expected, the specific fuel consumption gets very high at low engine loads (low engine powers). At about 50% of the maximum continuous rated power the Specific Fuel Consumption (SFC) line becomes less steep, but the gain remains negative up to a 80% of MCR 8 which represents the optimum operation point of the diesel engines.

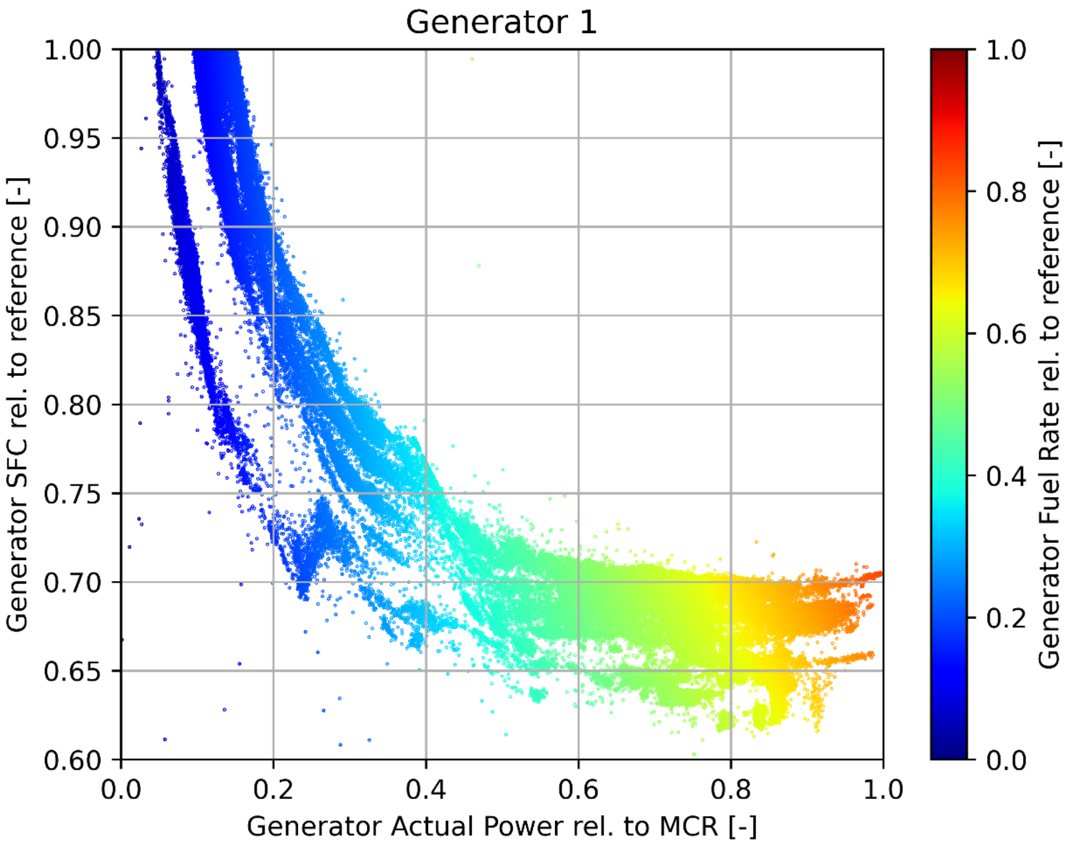

Figure 4.1: Engine maps of the four diesel main engines onboard Ship X.

As has been mentioned during the discussion of Figure 4.1, the work-specific fuel consumption of the main engines attains more favourable values at high engine loads. That's why it is interesting to take a closer look at how the power demand is shared between the engines. A more detailed illustration of the (electrical) power balance is given in Figure 4.2 below. In this plot the powers generated by the four generators are summed up. The data is sorted in descending order by the numbers of engines running and the total power generated. Black lines mark the MCR of one to four engines to give an indication of the minimum required number of engines to meet a certain power demand. Only samples with at least one running engine are considered in the plot. The numbering of the generators in the legend represents their power contribution – 1st Generator contributes the most and so on – and cannot be linked to a physical engine on the vessel. So, for example, when only one engine is running this could be any of the four installed on Ship X. The same applies for the thruster motors and the grids: They are sorted in descending order of their current power consumption. The losses have been calculated as the difference of generated and consumed power.

The time shares of four, three, two, and one engine running at the same time can be clearly distinguished in Figure 4.2 by looking at the different colours in the positive part of the plot but also by the short time shares of low total generated power that lie between the major areas. These are caused by short-time operation of many engines at low load which can happen during the start and end of a voyage or during deceleration of the vessel when the engines are kept idling in expectation of higher demand or shut-off. There is a clear trend to run as few engines as needed to (reliably) meet the current power demand. As a consequence, the engines deliver at least 50%, 67%, and 75% load in case two, three, and four engines are running at the same time, respectively. Only for a very low time share more than one engine run at low loads. These rare cases can be attributed to starting up and idling of the propulsion system before the vessel starts sailing.

Most of the time, the number of running engines is chosen as the minimum number required to meet a certain demand (cf. the black horizontal lines in Figure 4.2). The load is in general distributed evenly between the running engines. It is noticeable that the time share of one engine running is the highest. This is caused by the need to provide auxiliary power at anchoring or in berth. The second largest share is the one of three engines running at the same time. The time share of four engines running is about 40% less than the time that three engines are operated. The time share of two engines running is the lowest. This distribution can be explained by the vessel's operational profile. For economic reasons, most of the sailing does not happen at very high speeds and therefore three engines can provide sufficient power. Furthermore, the fourth engine might serve as a back-up and represent a margin for high sea-states. The operational conditions that can be covered by two main engines are rare: The power that can be provided is too low for sailing but too high for only auxiliary purposes.

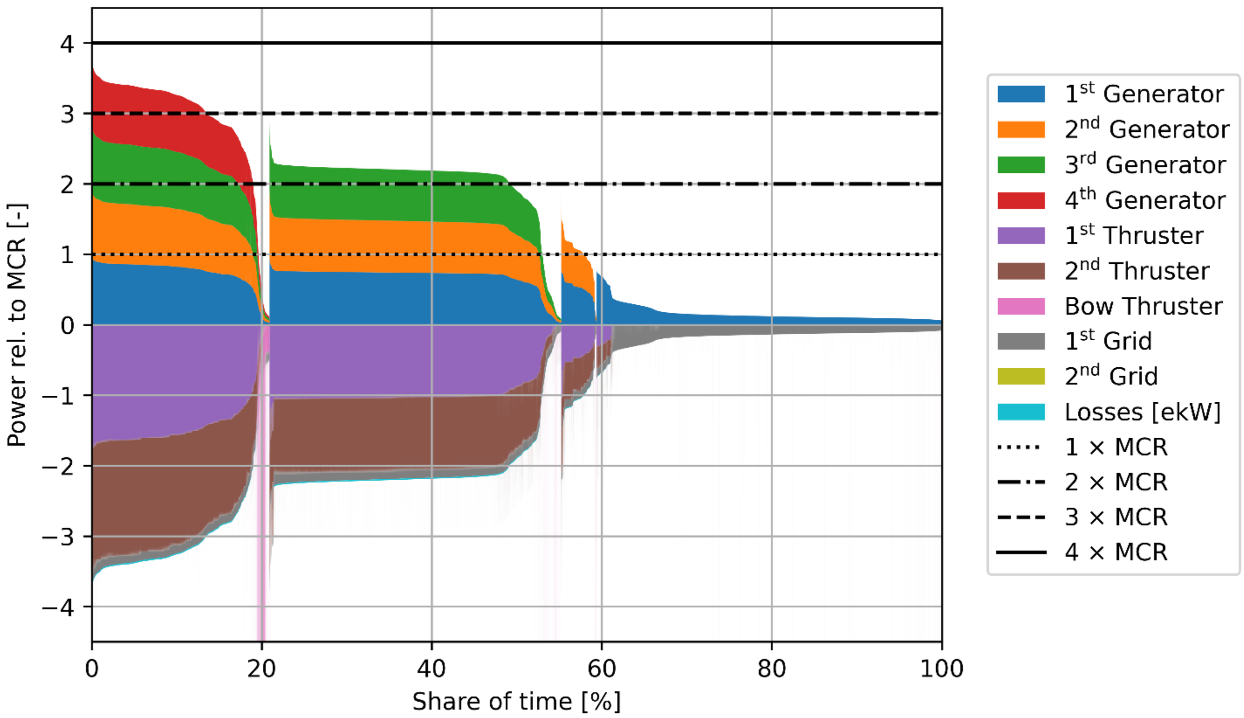

Figure 4.2: Comparison of generated and consumed power onboard Ship X.

The time shares of loads to the electrical system confirm what has been stated above. Similar to the main engines, the load of the thruster is evenly shared between the two motors. During most of the time when only one engine is running, the thrusters do not consume electrical power. This corresponds to the interpretation of these operations as providing auxiliary power at anchor or in berth. There is not much deviation in the power demand of the electrical grids. Only for a share of time in berth the demand is noticeably larger. The losses in the electrical system are negligible.
There are few small peaks pointing downwards from the accumulated power demand these are caused by (non-physical) artefacts that origin from the different sampling frequencies of the systems and the averaging during the download of the data.

4.3 Discussion of current operational data acquisition

The information provided in this chapter illustrates the data acquisition that is already used in the fleet of one operator. In general, the engines on board of Ship X are already operated in an efficient manner, i.e., at relatively high loads in order to reduce specific fuel consumption. Whether this was optimised with the data provided, or based on crew knowledge is not clear. Although not yet directly fed into an operational advice tool, the collected data gives a good insight in the engine use. It is difficult to assess how big a possible benefit of processing of operational data in an operational advice tool would be

because the particular reasons for running more engines than needed to provide the current power demand is not known. It could be that there are compelling reasons, e.g., safety, which overrule the aim for low fuel consumption and CO_2 emissions.
The focus of the case study was on the engine operation, in particular on the load sharing between several engines rather than on weather routing and speed optimisation. The latter will be part of an analysis in Chapter 5.

5 EVALUATION OF OPERATIONAL MEASURE: SIMULATIONS

Following the investigated uncertainties and needs in this chapter we consider the second use case on how to make steps towards uncertainty reduction and operational improvement.
In this chapter we investigate the insight that voyage simulations can give, within a highly variable environment. The simulations create a baseline of what is possible and can be compared against operational measurements. The theoretical gains and variability are simulated in detail for the same example cargo vessel as in Chapter 4, Ship X.

The example scenario we use is an optimisation on route planning with just in time arrival and both varying waypoints and varying speed, based on weather and ship characteristics. The simulated scenarios are modelled with SafeTrans. The results are compared with measured data from an actual trip.

Figure 5.1 presents different sailing scenarios. Here the Y axis shows the engine setting and the X axis presents the time of the trip. To assure in time arrival, the captain might choose to sail with a higher MCR for the first part of the trip, than either arriving to early or slowing right down the last part of the trip (1) Alternatively the MCR can be changed earlier and in a stepwise manner (3) or the MCR can be kept constant over the whole trip (2). In the simulation comparison in this chapter we will compare the simulated constant MCR option (2) versus the real time results (1, based on Figure 5.8). We compare the efficiency based on the total fuel consumption over the journey.

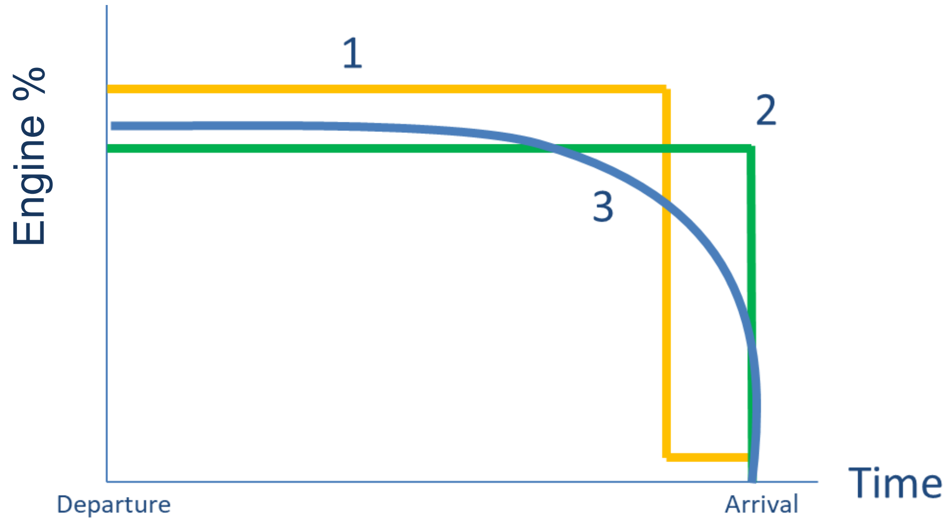

Figure 5.1: Different scenarios for sailing a trip. (1) Low efficiency: High speed start, low speed wait before port call, (2) Optimal efficiency: Exact average speed for just in time arrival, no low speed end, (3) Actual efficiency: changing speed over time based on onboard decisions.

5.1 Voyage simulation

A voyage simulation was performed using MARIN's in-house tool SafeTrans or Safe Transport (henceforth referred to as ST), which is a cloud-based integrated tool to design marine heavy transport in a safe and efficient manner. An illustration of the commercial application of ST is shown in Figure 5.2. ST combines a ship motion database, weather database, hurricane avoidance model, and captain mimic configurations. A schematic representation of the workflow of ST is shown in the Figure 5.3. The main inputs for this tool are hull lines, loading conditions, wind and manoeuvring coefficients, motion signals, resistance and propulsion, voyage route, engine settings, and forecast limits (see Figure 5.4). It provides estimates of voyage distance, duration, fuel consumption, significant wave height, wave period, wind speed, and wind direction as output.

a) Biglift ship carrying cranes [3] b) Optimised transport solution[4]

Figure 5.2: Illustration of commercial applications of the SafeTrans numerical tool.

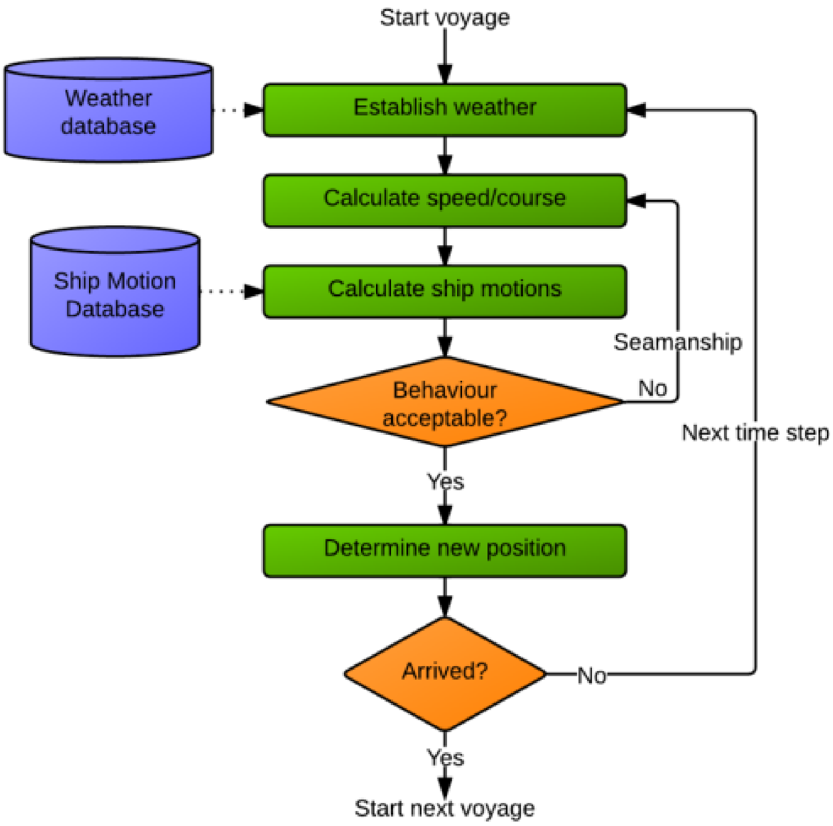

Figure 5.3: Schematic representation of the workflow of SafeTrans.

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3 https://www.bigliftshipping.com/en/rtgs-and-stc-crane-for-mombasa
4 https://rdtestsystems.com/cases/rds-specially-designed-transport-frame-optimises-coli-schiffahrts-blade-transport-2/

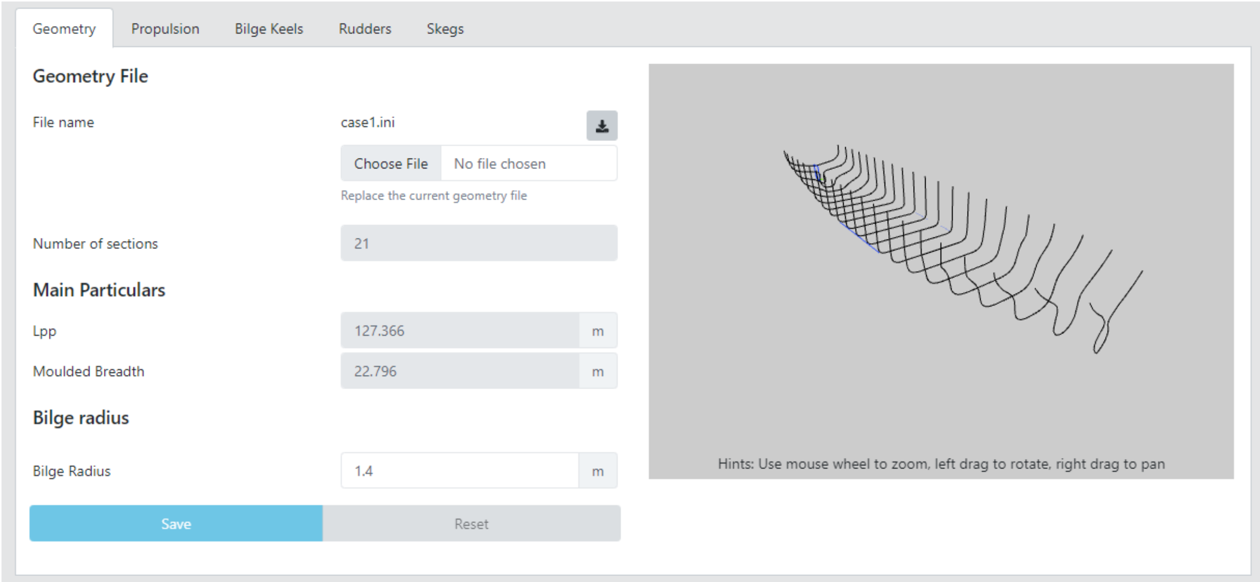

Figure 5.4: User interface of SafeTrans.

The user has the option to select the hard waypoints and wish waypoints in the route of voyage simulations. The former option, i.e., hard waypoints, results in the suppression of voyage simulations through the defined points. In contrast, wish waypoints attempt to initiate simulations through the defined points, without necessarily resulting in the suppression of voyages. Furthermore, the user has the capacity to define a forbidden zone, thereby restricting the simulations to a specified area. SafeTrans incorporates an integrated response amplitude operator (RAO) viewer as a constituent element of the tool. It uses 2D strip theory to generate the ship motion database (see Figure 5.5). It can also integrate higher fidelity models if required.

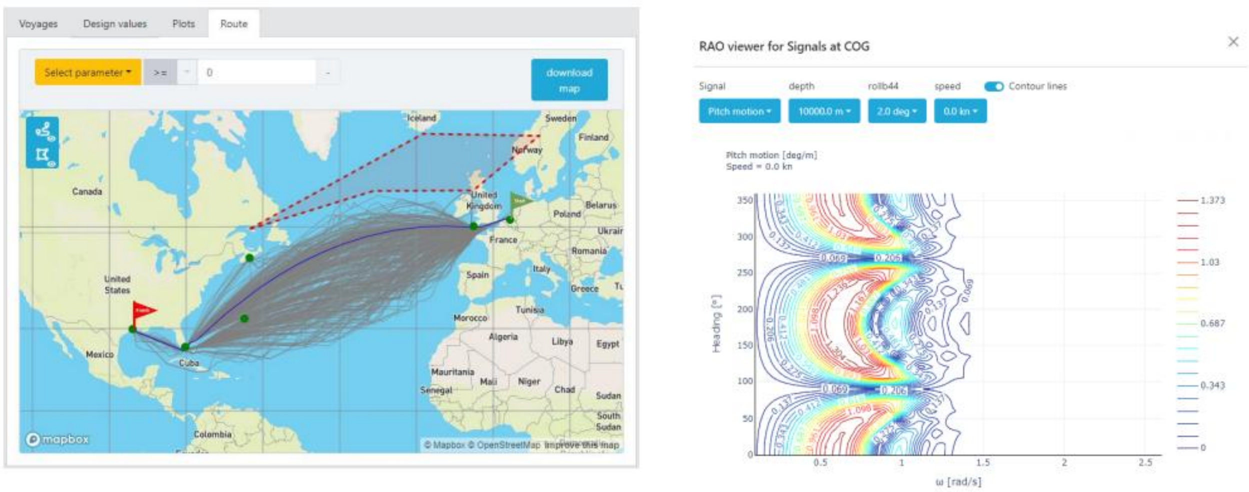

Figure 5.5: Route map for voyage simulation and RAO viewer in SafeTrans.

Based on the full-scale data availability of a commercial vessel, a SafeTrans simulation was carried out that closely mimicked the full-scale scenario in order to have a better comparison with the data. Conclusions were then drawn from the study.

5.1.1 Insights of operational data from Ship X

In this section the operational data received from Ship X is analysed and discussed The data received indicated that the vessel made a transatlantic voyage from Eemshaven (Netherlands) to Paramaribo (Suriname) between 10-09-2024 and ended on 28-09-2024. It covered about 4288 nm (7942 km) with a total duration of 418.90 hours. Figure 5.6 and Figure 5.7 show the location and timestamp of Ship X's voyage from Eemshaven to Paramaribo. Ship X sailed through the English Channel[5] between 10-09-2024 and 13-09-2024 and reached the open sea on somewhere between 13 and 14 of September 2024. From the Figure 5.8 and Figure 5.9 it can be clearly seen that the ship's speed over ground (SOG[6]) and course over ground (COG[7]) during the ship's departure from the port of Eemshaven and reaching the open sea and near the arrival to the port of Paramaribo were slower than in the other period, mainly due to the manoeuvring reasons. The average SOG during the whole voyage was about 10.2 knots and between 14 and 27 September 2024 it was about 10.5 knots. Similarly, the average COG during the entire voyage was 227 degrees and it was 225 degrees between 14 and 27 September 2024. Figure 5.10 and Figure 5.11 show the scatter plot and the time trace of the wind speed and direction respectively for the voyage period. The wind speed was predominantly between 5 and 15 knots acting in the range of 25 degrees to 360 degrees (earth fixed as reference).

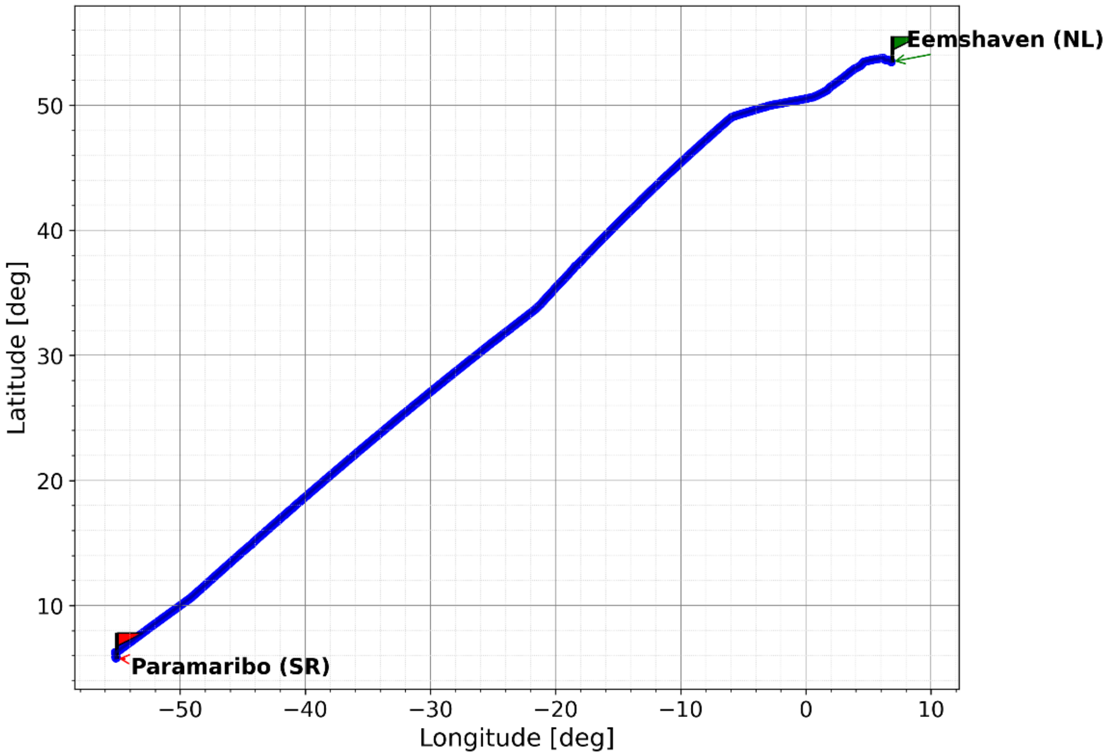

Figure 5.6: Latitude and longitude of Ship X during its voyage from Eemshaven to Paramaribo between 11 and 29 September 2024.

[5] a narrow channel that separates southern England and northern France

[6] actual speed at which a ship is moving across the ground, taking into account external factors such as currents and wind

[7] actual path that a vessel follows over the surface of the earth, relative to true north

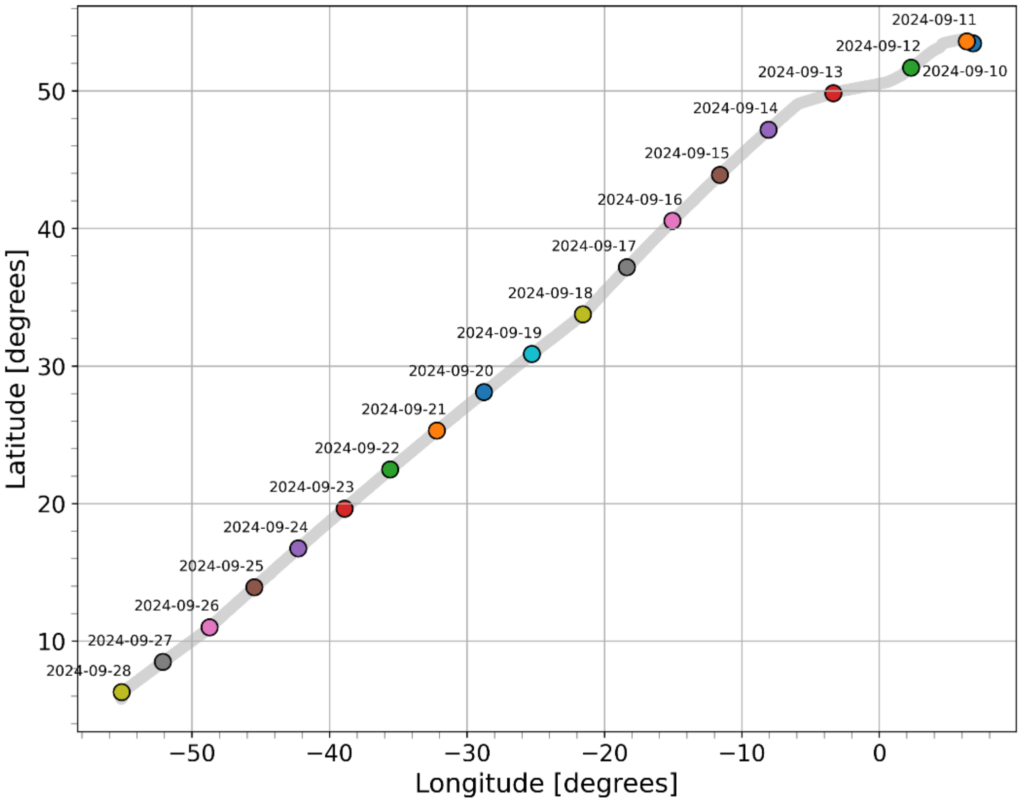

Figure 5.7: Time stamp of the location of Ship X during its voyage from Eemshaven to Paramaribo between 11 and 29 September 2024.

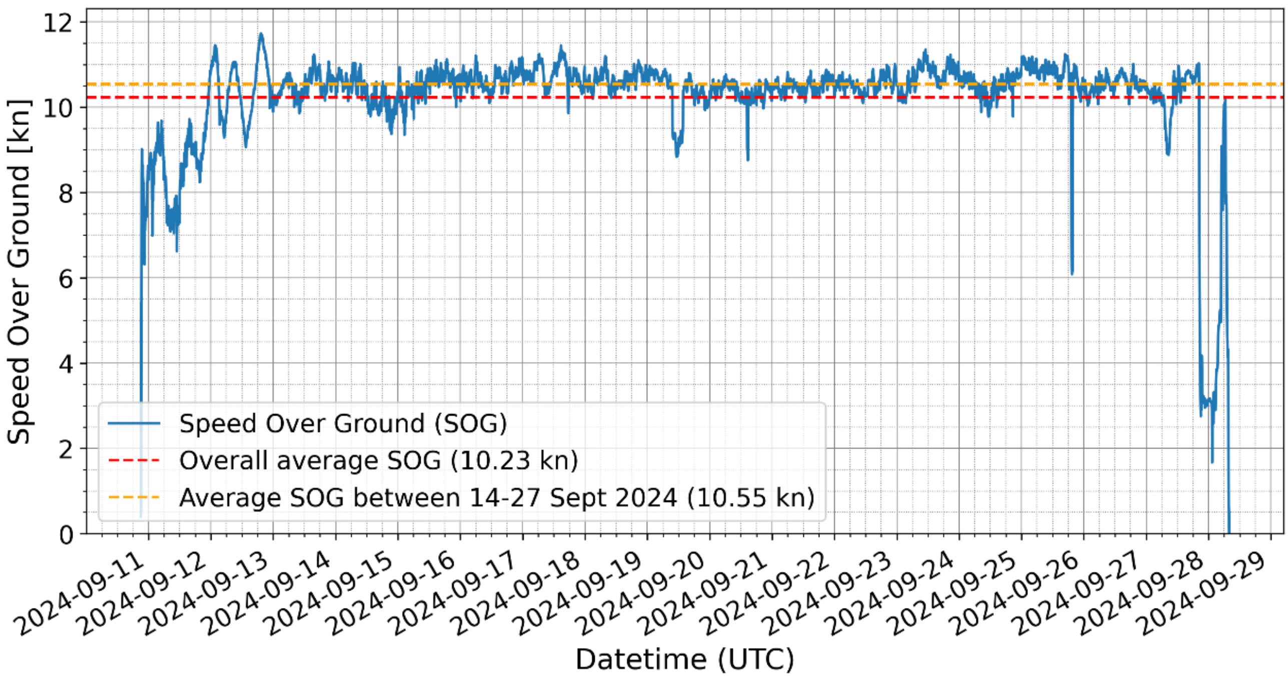

Figure 5.8: Speed over ground in knots during Ship X's voyage from Eemshaven to Paramaribo between 11 and 29 September 2024.

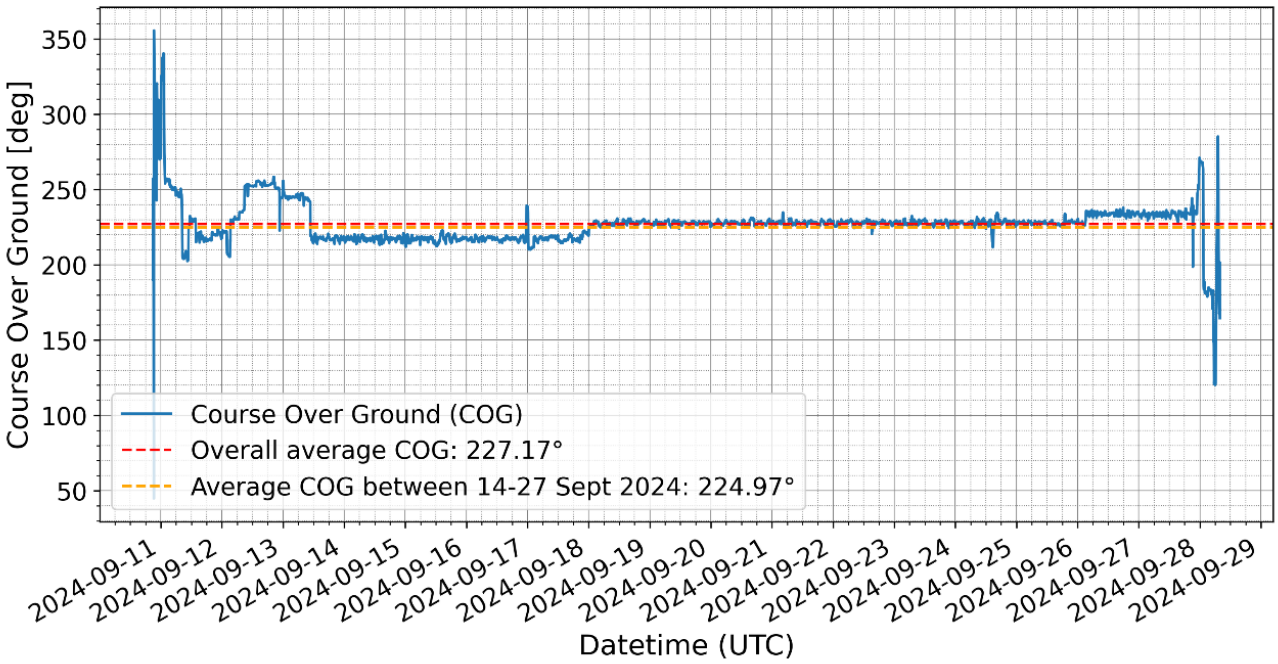

Figure 5.9: Course over ground in degrees during Ship X's voyage from Eemshaven to Paramaribo between 11 and 29 September 2024.

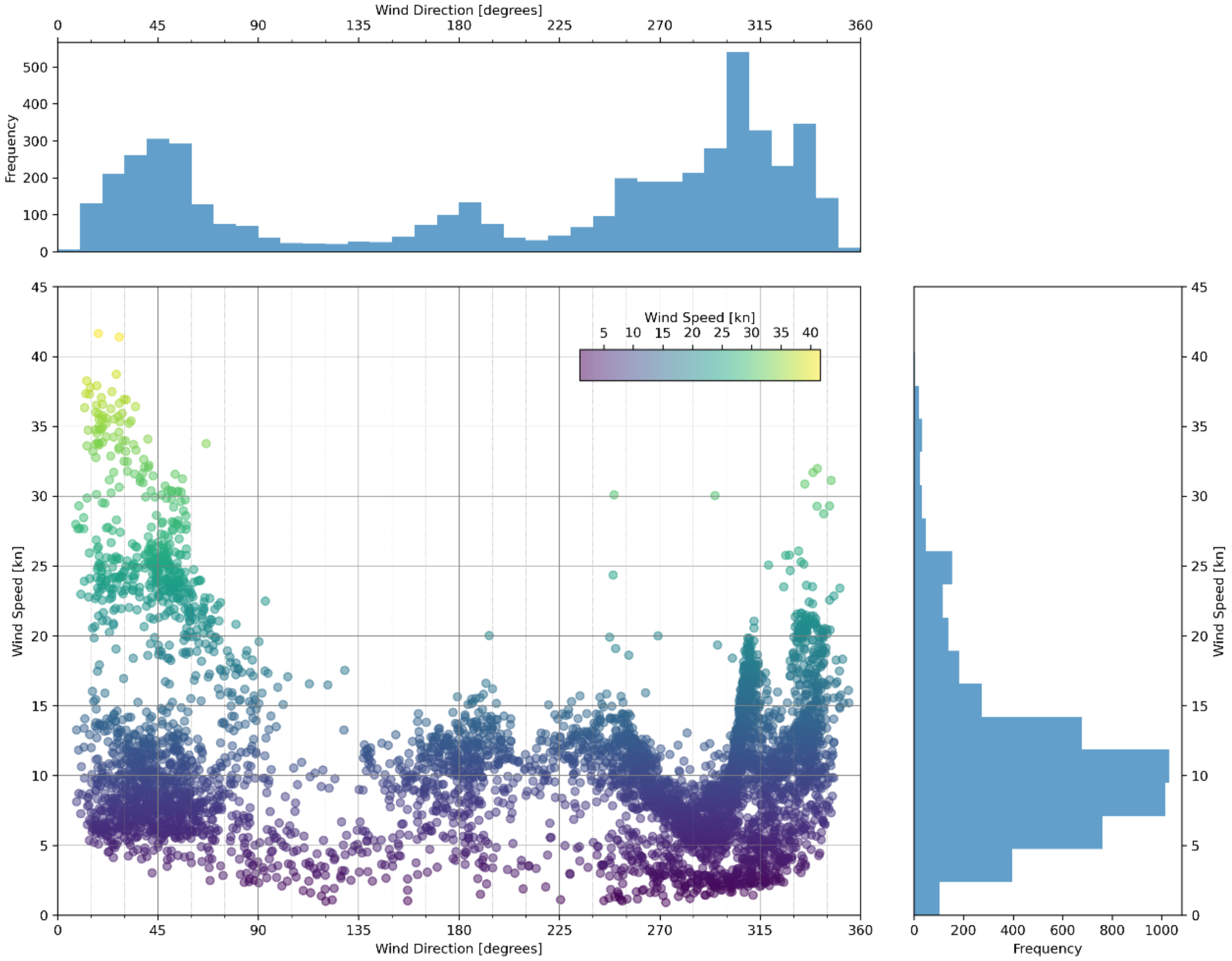

Figure 5.10: Scatter diagram of wind speed and direction during Ship X's voyage from Eemshaven to Paramaribo between 11 and 29 September 2024 (colour corresponds with the Y-axis value).

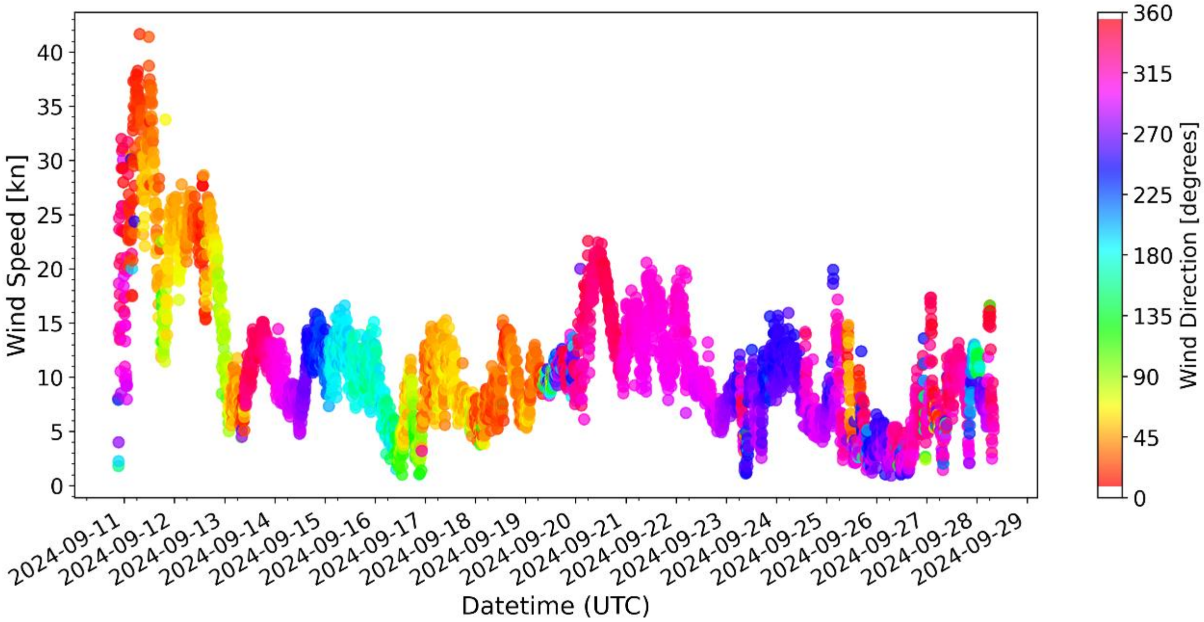

Figure 5.11: Wind speed and direction during Ship X's voyage from Eemshaven to Paramaribo between 11 and 29 September 2024.

5.1.2 Voyage simulation in SafeTrans

The voyage simulation was carried out with ST based on full-scale data provided by the shipowner between the voyage from Eemshaven (The Netherlands) to Paramaribo (Suriname). Note, that the Ship X was designed for short sea, but is used in a wider variation of contexts (e.g., transatlantic).

5.1.2.1 Speed resistance and speed power estimation of Ship X

Since the data of the speed resistance and speed power relation was not known it was estimated at MARIN using the inhouse calculation package DESP (Design Ship Powering) which uses the formulas obtained from a regression analysis on results of MARIN model test experiments and sea trials. The main input parameters are the main dimensions of the ship, displacement volume (based on known loading conditions or draughts), form coefficients CM (midship section coefficient), CWP (waterplane coefficient), LCB (longitudinal centre of buoyancy), bulb particulars, immersed transom area when at rest, and various parameters related to the propeller arrangement. DESP can be used for the early design phase to estimate the relation between ship speed and resistance. This tool gives a good estimate for large and comparatively slow ships (Fn[8] < 0.25) and because the considered ship type sails at Fn < 0.25, the values of the relation between ship speed and resistance should be a good approximation for operational values.

5.1.2.2 Simulation setup in SafeTrans

The main inputs for the ST simulations are listed in Table 5-1. In this study, the voyage was modified to cross the English Channel using hard waypoints. The shortest route between Eemshaven and Paramaribo is illustrated Figure 5.12. As Ship X is a general cargo vessel transiting the Atlantic Ocean, the selected sea state condition is set to 6[9], which means that the captain decision mimics will modify the heading and speed of the vessel aiming at limiting the wave height below 6 m and the wind speed below 47 knots. The season is chosen as September because the operational data received were from that period. 288 Monte Carlo Simulations (MCS[10]) were performed with the time interval between the

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[8] Froude number, Fn = $\frac{v}{\sqrt{g\,L}}$; where: v – ship forward speed [m/s], g – acceleration due to gravity [m/s^2], L -waterline length of ship [m]

[9] sea state 6, definition by NATO STANAG 4194 Annex D

[10] statistical technique use to model and analyse complex systems with inherent uncertainty

start of the voyage simulation set to 48 hours (or every 2 days). This incorporates a range of sea state conditions over the selected period, facilitating the simulation of various decision-making scenarios that a ship's captain might encounter, giving the study a wide coverage of possible outcomes and resulting in more realistic estimates of voyage distance, time, and fuel consumption.

Table 5-1: Main inputs for SafeTrans.

Particulars	Value	Unit
Route	Eemshaven (NL) to Paramaribo (SR)	-
Voyages through	English Channel	-
Significant wave height	4 (comfort) – 6 (maximum)	[m]
Wind speed	28 (comfort) – 47 (maximum)	[kn]
Weather data fetched	Between 1995 to 2012 (18 years)	-
Season selected	September	-
Total voyages	288	-

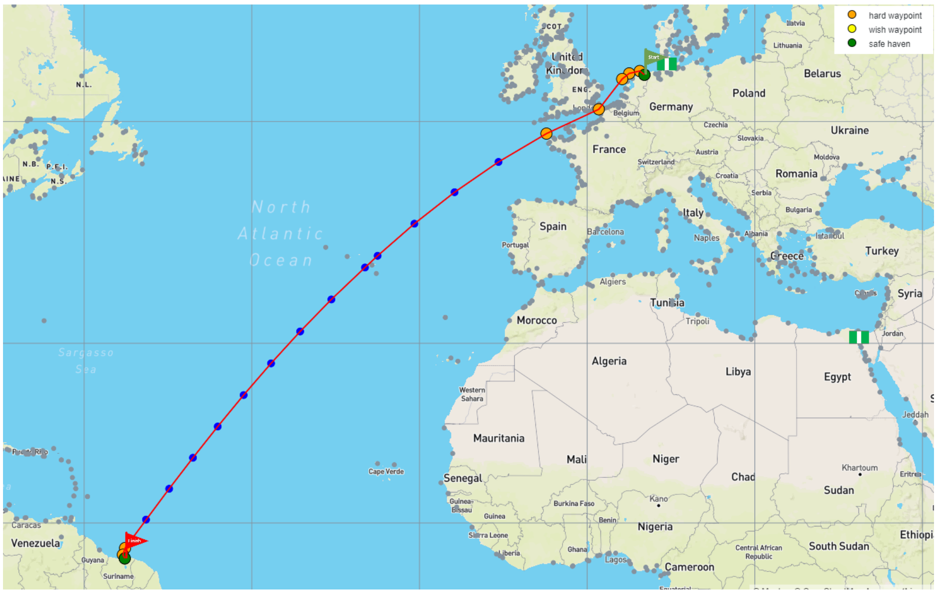

Figure 5.12: Shortest route in SafeTrans between Eemshaven (The Netherlands) to Paramaribo (Suriname).

5.1.3 Comparison of results from SafeTrans and operational data

Based on the insights obtained from the full-scale and ST simulations results were compared and analysed here. Figure 5.13 shows all the resulting 288 MCS ship tracks from the ST simulation for the investigated route. As can be seen from the figure a majority of realisations stay close to the shortest route, while some rare voyage deviates from the it, due to weather avoidance. In addition, all simulations pass through the English Channel due to the hard way points applied. Table 5-2 shows the comparison of the results from operational data and SafeTrans voyage simulations. The comparison shows that the average distance from ST is lower for the operational data, but the duration is higher, possibly due to the weather conditions. Figure 5.14 shows the box plots of distance, duration, and SOG. As can be seen from the box plots, despite the smaller scatter in the distance between the lowest and highest, there is a larger scatter in voyage duration data, which may explain the differences in the average between ST and operational data. The captain mimic model in ST took more time by avoiding certain weather conditions. Note that the small differences between the mean and the median from ST data give confidence that there is less variation between them and that therefore the average results can be compared with the operational data.

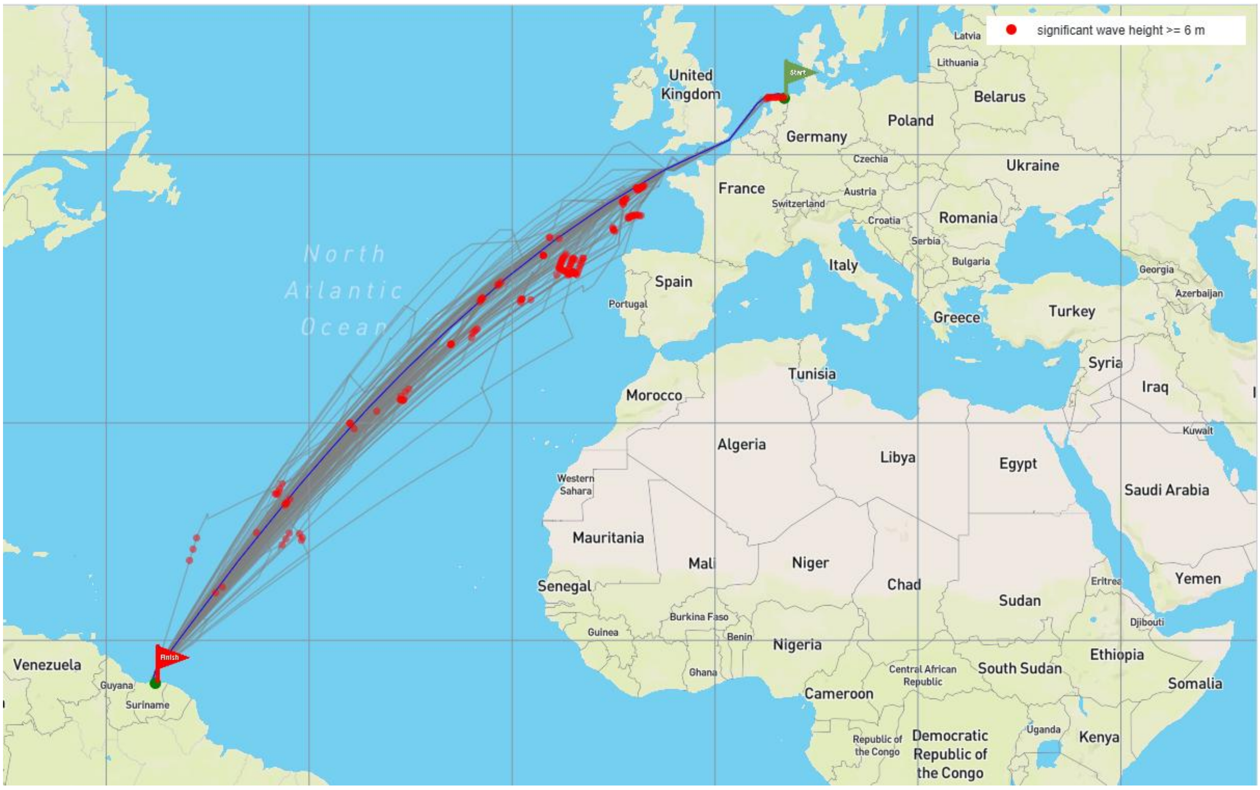

Figure 5.13: All scenarios of voyage simulations in SafeTrans between Eemshaven to Paramaribo. The red dots indicate a significant wave height of 6m or higher.

Table 5-2: Comparison of results from operational data and SafeTrans voyage simulations.

Particulars	From operational data	From SafeTrans (mean)
Distance [nm]	4288.1	4217.7
Duration [hr]	418.9	431.8
Speed over ground [kn]	10.23	10.02
Total fuel consumption [L]	139079	143750
Total fuel consumption [t]	115.8	119.6
Total CO_2 [t]	313.4	322.9

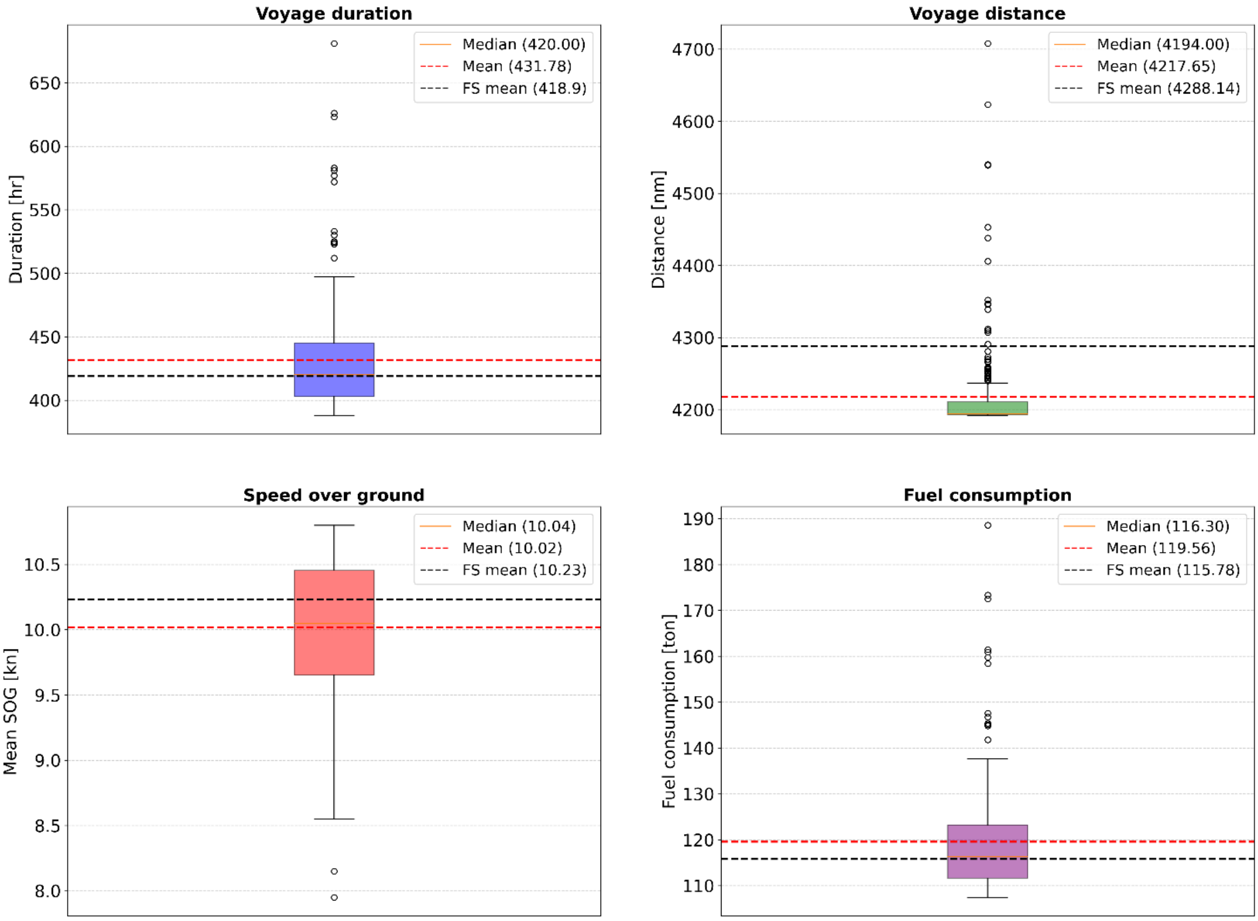

Figure 5.14: Box plots of duration, distance, speed over ground, and fuel consumption from ST simulations in comparison with the mean value from operational data.

5.1.4 Discussion of results

The comparison of operational data and ST simulation data shows that operational data results fall well within the variation of the ST results. In the case of these large trips, the variation over time due to e.g. weather makes it difficult to estimate the advantage of another sailing scenario (Figure 5.1). The ST variation gives an indication of the uncertainty when sailing large trips, both in time and speed and in fuel use and emission. This can help to distinguish effects of different sailing scenarios over a longer time period including the natural variation encountered in operational trips.

The ST simulations give an estimation of voyage distance, duration, and fuel consumption resulting in an idea of the cost of operating the vessel between two ports. Adaption due to operational measures based on data or a tool advice can be valued using the simulation with different restrictions or captain mimics. This can help both tool makers and ship owners for estimating operational costs, break-even, and return on their investment. In addition, the estimation of CO_2 emissions can be useful for regulatory compliance (IMO and local authorities).

The ST model used in this project had the following assumptions (moving to a higher fidelity model is not expected to change the presented trends):

- Speed-resistance and speed-power estimation is based on statistics and comparison with similar vessels from the model test database, assuming a clean hull and is estimated at a specific draught and displacement. This has a significant impact on the comparison with operational data. Firstly, we should be sure of the draught and displacement of the ship was sailing at, and secondly how clean the ship was at the time of data collection, as research has shown that fouling effect can have a significant impact on the ship's hull resistance (on frictional component of resistance at lower Fn[11] < 0.25) and propeller efficiency, giving a penalty on the fuel consumption and CO_2 emissions.

- SHIPMO or 2D strip theory method was used for the ship motion database or in other words a coarse empirical method was used to predict the wave added resistance, but in high sea conditions, research has shown that the wave added resistance can contribute to a significant percentage of the total ship hull resistance. Therefore, a higher fidelity model such as SEACAL can be used to better estimate it.
- The maximum continuous rating (MCR) is kept constant throughout the simulation, but the speed may vary during the voyage depending on the weather conditions in which the ship is sailing.
- The seakeeping and manoeuvring coefficients have been approximated from the known ship hull particulars, but can be improved by obtaining them from the ship designer, which helps to estimate the wave added resistance and the influence of the wind on the superstructure of the ship. Note, that Ship X is designed for short sea, however operates from time to time in deep sea.
- The weather database is retrieved between 1995 and 2012 (18 years) in SafeTrans and it is expected that the sea state conditions collected during the operational are a subset of the database taken during the same season (September).
- By default, the drive system in ST is a diesel engine and the choice of drive system and its influence on weight distribution and general arrangement is not modelled in the voyage simulations.
- Voyage simulations take into account only the fuel consumption of the trip and do not take into account any auxiliary systems installed onboard the ship.

[11] Froude number, Fn = $\frac{v}{\sqrt{g\,L}}$; where: v – ship forward speed [m/s], g – acceleration due to gravity [m/s^2], L -waterline length of ship [m]

6 CONCLUSIONS AND RECOMMENDATIONS

In this project the overall research goal can be summarised as:
“Reduce the uncertainty for the ship owner in the investment decision of operational data acquisition and/or monitoring/advisory tools, that help the ship owner to achieve further fuel efficiency and emissions reduction. The focus in this project will be on greenhouse gas emissions and the propulsion fuel use.”

To mitigate a part of the uncertainty related to this investment decision, the following two research questions were addressed in respectively work package 1 and 2:

1. What is the operational performance of the ship and how does that change over time?
2. What are the realistic operational measures and how much fuel reduction can this achieve?

This report considered the second question. The following conclusions summarise the findings of work package 2:

1. A flowchart (Figure 2.1) was developed to help in the process of decision making. It leads through the various steps and can help to increase understanding between ship owners and tool makers.
2. Onboard insight shows large variation in fuel use between sailing days. Information and tools can help the crew to make better decisions during operations. There is an interest in such tools as long as training or a clear introduction is given.
3. Literature shows that operational measures can have a significant impact on fuel use and emissions. However, due to large variations in both ship and environment the actual impact is difficult to predict and to prove.
4. Several operational advise tools exist, however the easy accessible information does not give enough information on how they perform. The instrumentation, presentation, validation and uncertainty is often unspecified, especially taking into account specific ships and their circumstances. This makes the investment choice difficult for ship owners, as they look for what works within their fleet (+ what they need – data sources, or how they are tested (validation etc)
5. There are different investment considerations for ship owners to invest in tooling or operational measurements. A case study shows that there are saving opportunities and data can give insight on where the best improvement can be achieved.
6. Voyage simulations can help to gain insight in possible gains when operational measures are taken, taking into account the variation in circumstances over specific routes. Comparison with operational data gives trust in the method and shows that the effect of operational measures is difficult to quantify in operation due to the high variability in environmental circumstances and crew behaviour.

Within work package 1, two methods were investigated that can lead to a ship performance baseline in time. Based on the WP1 reports ([Ref 42.]] and [Ref 43.]) we can further conclude:

- In mild conditions of Beaufort 3, sea state 3, a trial was carried out with (1) reciprocal runs according to ISO15016, (2) a novel steady-state zig-zag runs and (3) ground truth measurements for the current and sea state conditions. It is concluded that while the results from the reciprocal runs using iterative method is mostly satisfactory, the results from the zig-zag runs are not as accurate.
- The zig-zag runs could be executed during the ships operation to create a performance baseline in a non-invasive way. It is expected that the zig-zag runs will perform better in milder weather conditions, and in general need a lower limit on wind speed and wave height than the reciprocal run protocol. To find practical limits of application of the zig-zag protocol, further experimental work is needed to observe results at more conditions (ship, weather, current conditions). A desk study modelling all expected disturbing factors systematically could also yield valuable insights.

- A Bayesian approach was used to determine the speed-power relation from operational data. The results show that operational data can be used to determine the speed power relation as well as changes in this relation:
  - We can distinguish design and ballast draught.
  - We can reveal outliers between ships.
- This approach using operational data has some practical concerns:
  - The scatter in the operational data is large, as such long term measurements are needed to get a reliable fit.
  - Good communication with the vessel operator is needed to ensure the correct interpretation of measured values.
  - A good model helps in suppressing the impact of the scatter, but to set up a good model, understanding the dominant underlying physics is crucial.
  - Part of the scatter can usually be explained by confounding factors. Where possible, the model should include the dominant confounding factors. This requires some input on the time dependent magnitude of each confounding factor. If the confounding factors are sufficiently uncorrelated to the speed-power, we can suppress the related scatter in the fit.

Wageningen, June 2025
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APPENDICES

APPENDIX 1 WORKSHOP OUTPUT

Workshop topics

In the tables below the topics mentioned during the workshop are listed following the 5 flowchart steps.

Table A-1: Flowchart step 1: Function & theoretical gains

Topic	Barrier / Enabler / Other
Insight in efficiency	Enabler
Technical decisions	Enabler
Saving fuel = saving money	Enabler
Operational advice tool can: a. Relieve the captain b. Optimise port calls c. Lead to one system for route, dynamics, energy management	Enabler
Data for fleet development and for decision of ‘ideal ship‘ for me’	Enabler
Regulatory compliance	Enabler
Reducing emission = improving companies green social image	Enabler
Delaying refit or new build by operational changes that make ship comply with emission regulation	Enabler
Human behaviour (is it used the right way)	Barrier
Reliability of tool	Barrier
Trust in tool	Barrier
Access to data or missing (historical) data	Barrier
Uncertainty in how the ship is/will be used	Barrier
Small or diverse fleet	Barrier

Table A-2: Flowchart step 2: Operational output

Topic	Barrier / Enabler / Other
Ability to deal with higher project complexity	Enabler
Take into account ‘all’ influencing factors	Enabler
Reduce fuel use / emission with 5-10%	Enabler
Requirements for new builds	Enabler
Less dependency on experienced crew	Enabler
Option for captain operating the ship from shore	Enabler
Gap between wish and reality	Barrier
Advice needs to take into account interest and complex considerations within operational context	Barrier
Risk for crew in both directions: overload and underload	Barrier
Only raw data gives no insight due to lack of intertwining connections	Barrier
Captain/crew needs background, explanation and insight to make a choice (based on an advice)	Barrier

Table A-3: Flowchart step 3: Data input & measurements

Topic	***Barrier / Enabler / Other***
Needed: - Mass flow meter - Torque meter / power - Speed - Draught - Trim - Fuel measurement	Enabler
Rather 6 good sensors for what I want to know than many sensors (irrelevant and uncertainty)	Other
Integration of systems/installations	Enabler
Take into account more than propulsion alone	Enabler
Needed but not available in measured data: - Market expectations - Operational insight - Commercial data - Event based data - Dynamic draught - Insight on component level (fuel meters)	Barrier
Uncertainty in: - Measuring accuracy - Speed through water - Fuel measurement - Needed accuracy	Barrier
Data accessibility (central location)	Barrier

Table A-4: Flowchart step 4: Operational complexity

Topic	Barrier / Enabler / Other
Needed: - Automation: no to little manual input - Simplicity - Training	Enabler
Take into account psychological rewards	Enabler
Save fuel – reduce emissions	Enabler
Improve process and use ‘lessons learned’	Enabler
Needed: external party with skillset to analyse and advice over multiple parties / data sets	Enabler
Reliability	Barrier
Sharing data - Needed for enough scale/ data - Sector is fragmentated - Lack of trust in sector	Barrier
(lack of) Incentives	Barrier
Cost of ownership	Barrier
Uncertainty due to human impact	Barrier
Needed new skillset	Barrier
Change needed in organisation, crew and culture = difficult to achieve	Barrier

Table A-5: Flowchart step 5: Investment feasibility

Topic	Barrier / Enabler / Other
Potential profit is large with - Fuel use reduction - Less ballast journeys	Enabler
Needed: - Clarity what the profit is/can be under different circumstances (ship types, route, speed etc) - Quick and limited investment - Access and ownership of own data	Enabler
Profit dependent on vessel life cycle	Barrier
Investment needs to have (clear) pay back time	Barrier
Low total cost of ownership	Barrier
Incentive and fluctuating fuel prices	Barrier
Difficulty to demonstrate saving beforehand	Barrier
Scenarios are difficult to compare	Barrier

A.1.1 Feedback towards recommended next steps

To finalise the workshop all participants were asked what they required as a next (development) step in relation to data driven operational advice.

Table A-6: Output recommended next steps by workshop participants

Topic	Development level of (operational) output	Entity
Digital platform or service operational stability	Advanced (Group 4)	Shipping company (large)
Test and trials for small/medium sized shipping companies	Intermediate (Group 3)	Tool provider
Incentive feedback loop on fuel reduction	Intermediate (Group 3)	Knowledge institute
Focus on (digital) systems and instruments which or not there yet	Fundamental (Group 2)	Shipping company (medium)
Pre/post research to proof the (financial) feasibility of a system or tool	-	Tool provider
Robust (retrofit) 'starter' system that works	Fundamental (Group 2)	Shipping company (large)
Data quality assurance	Intermediate (Group 3)	Shipping company (large)
Development of robust fuel gage / flow meters for both bunkering and during operation	Intermediate (Group 3)	Shipping company (medium)
Raise the knowledge base line on instrumentation and data output in the sector	Fundamental (Group 2)	Branche organisation

APPENDIX 2 SURVEY RESULTS

Background information

The first survey section was on general background information. The majority of the respondents indicated to have a position on shore (N = 22). The rest of the respondents has a position on board (N = 10) or a combined position (N = 1). Most respondents have more than 10 years of experience working in their position. Figure A.1 shows the distribution of years of experience.

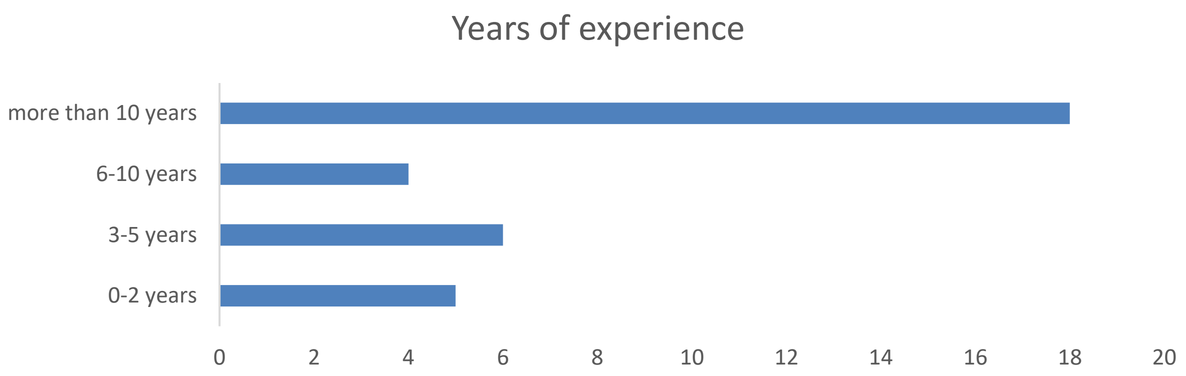

Figure A.1: How many years of experience do you have in this (and similar) position(s)?

The typical ship on which the majority of respondents work with is general cargo. Figure A.2 gives a distribution of the different ship types. The following ship types will be taken together for the further analysis (due to their general behaviour of sailing cargo over sea from one port to another, e.g. compared to offshore vessels that typically have other specific activities): general cargo, container, bulk carrier, Ro-Ro/PCTC, and chemical/oil tanker/gas carrier. This will be referred to as *combined.* The ships that do not fall within these categories will be referred to as *other*.

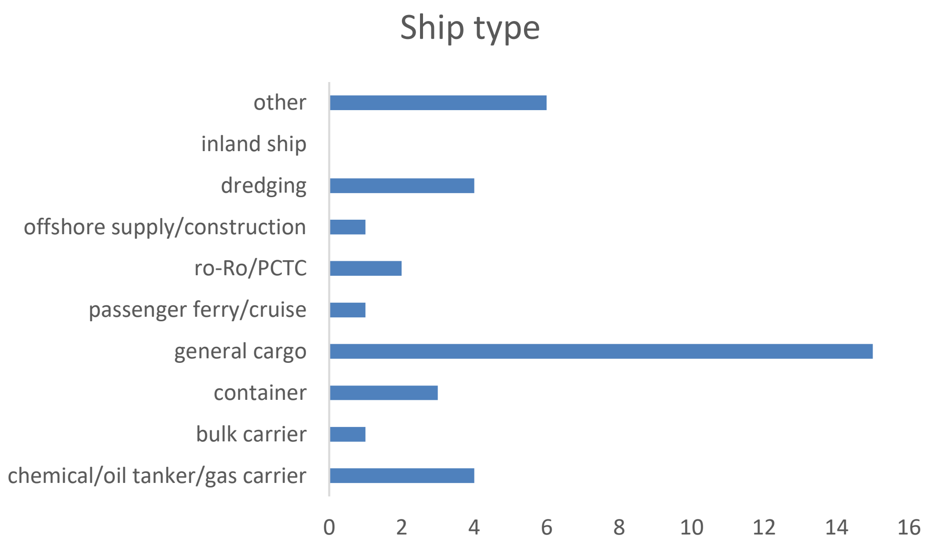

Figure A.2: What is a typical ship your work with or, if this question is difficult to answer, what is the last type of ship you worked with?

Fuel consumption

As indicated in Figure A.3, most respondents are aware of the fuel consumption of the ships they sail/work with.

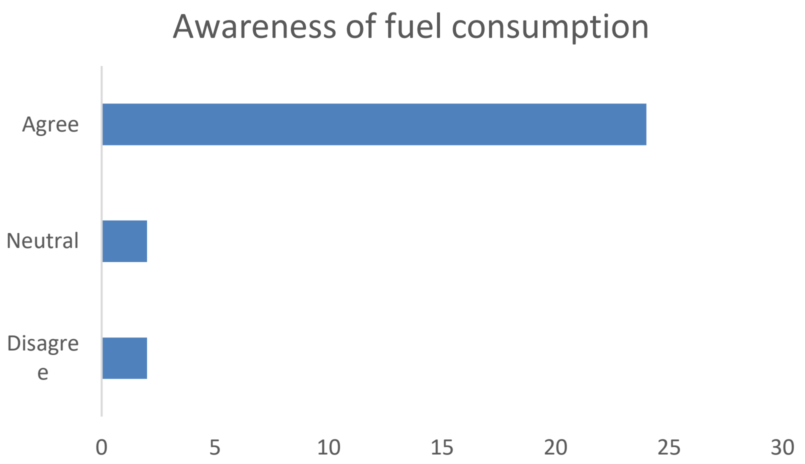

Figure A.3: I am well aware of the fuel consumption of the ship(s) I sail/work with.

When asked about the daily variation in fuel consumption, the majority of respondents reports a variation of 6-10%. However, a significant amount of the respondents report higher variation in fuel consumption, up to more than 30% (Figure A.4)

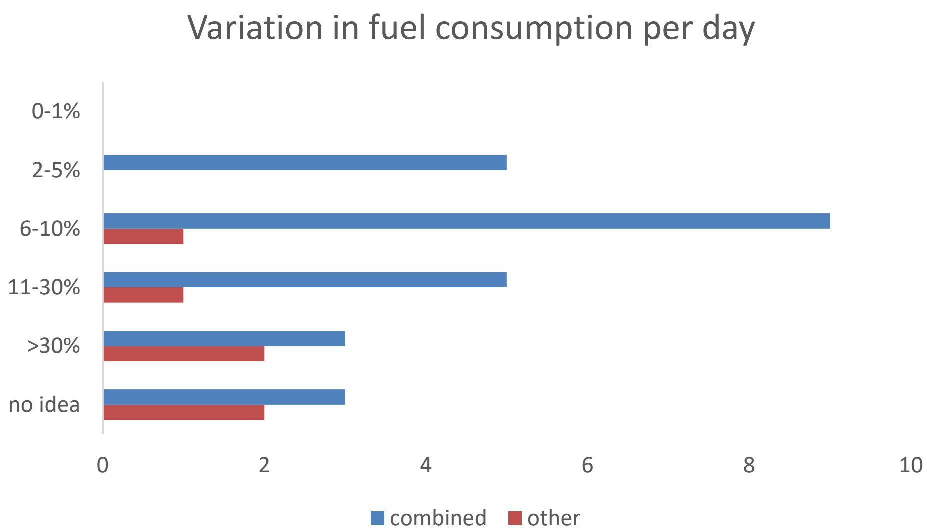

Figure A.4: Due to circumstances there is uncertainty/variation in fuel consumption. Looking at full sailing days over the past month, how much variation is there in fuel consumption per day?

Figure A.5 shows that, in most cases, MRV reports are already submitted or will soon be introduced.

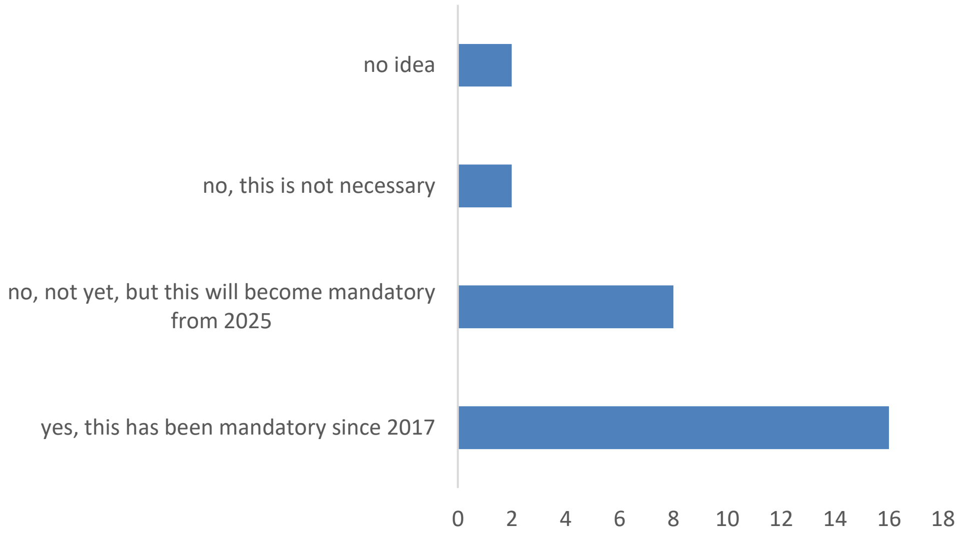

Figure A.5: Are MRV reports submitted for the ship(s) you work with?".

Interest in tools

The next section in the survey focused on the respondents interest in operational tools and how they would like to see this introduces in their way of working. Figure A.6 shows that most respondents are interested in having voyage optimisation tools. There is some spread in the area of interest for which the tool would be (primarily) used.

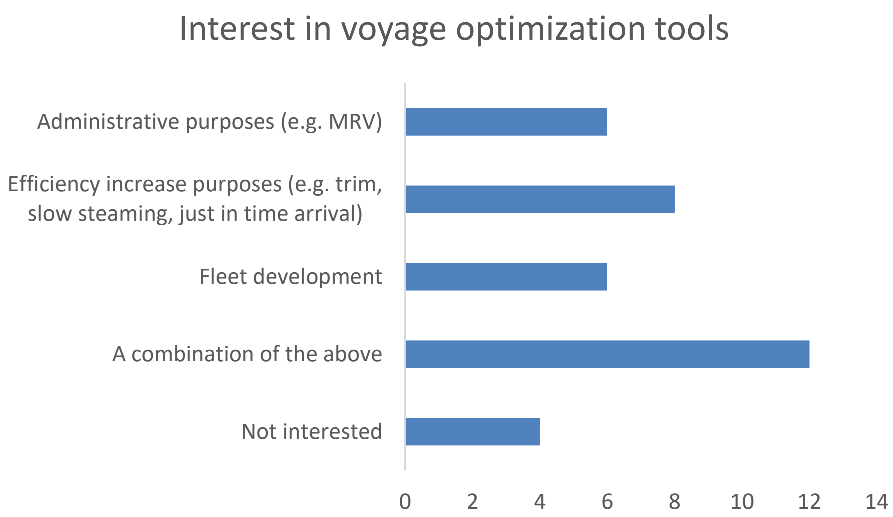

Figure A.6: Why are you interested in voyage optimisation tools?

Figure A.7 shows the respondents expectations for a potential new system. The graph shows some uncertainty in whether to trust a system or not. Furthermore, it shows uncertainty in whether a system or a training is preferred. There is a strong agreement that a new tool should be explained/introduced for (all) users. Also feedback on the system use and effectiveness would be largely appreciated by most respondents.

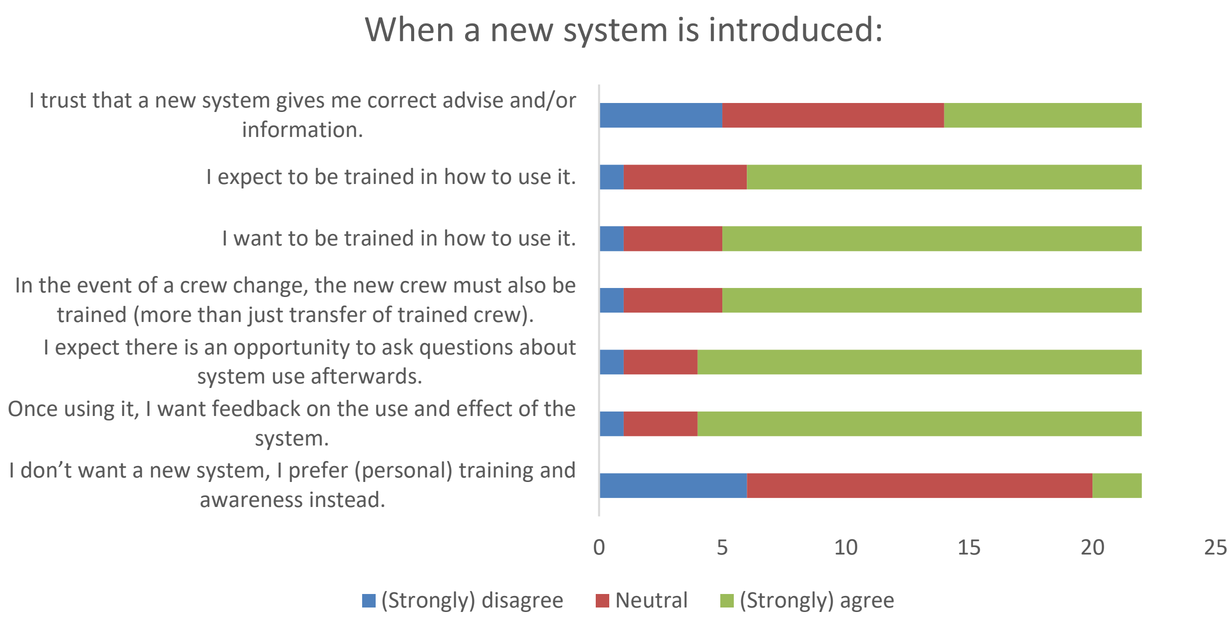

Figure A.7: What is important when introducing a new system?

The training preferences on different topics are shown in Figure A.8. This is not directly related to a specific tool but to various topics that are important for operational decisions. A slight preference can be seen for a training about dealing with data for fuel savings.

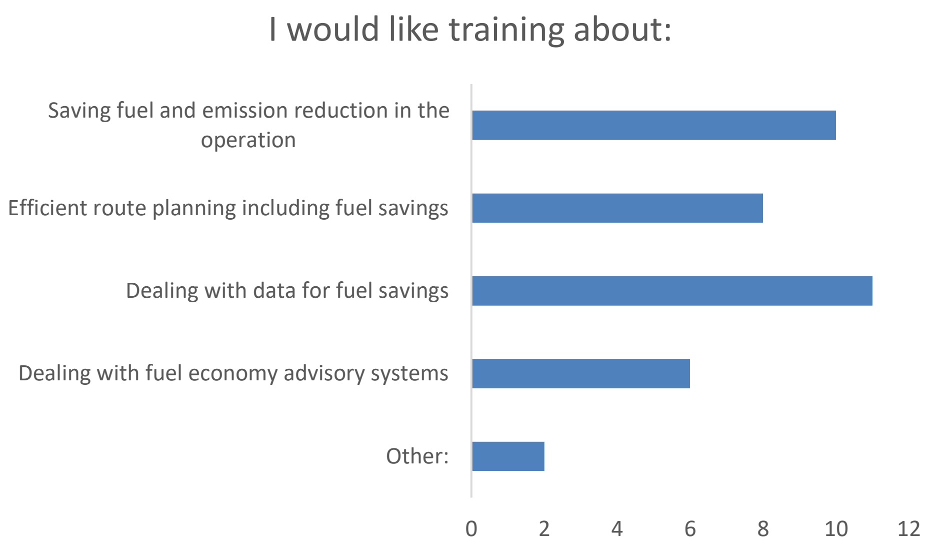

Figure A.8: interest in training

Information

Next, questions were about the kind of tools and information that is available and/or can be improved on. Figure A.9 shows the responses on how much influence different environment and ship factors have on fuel consumption. Sailing speed is considered the most influential factor, followed by draught and weather routing.

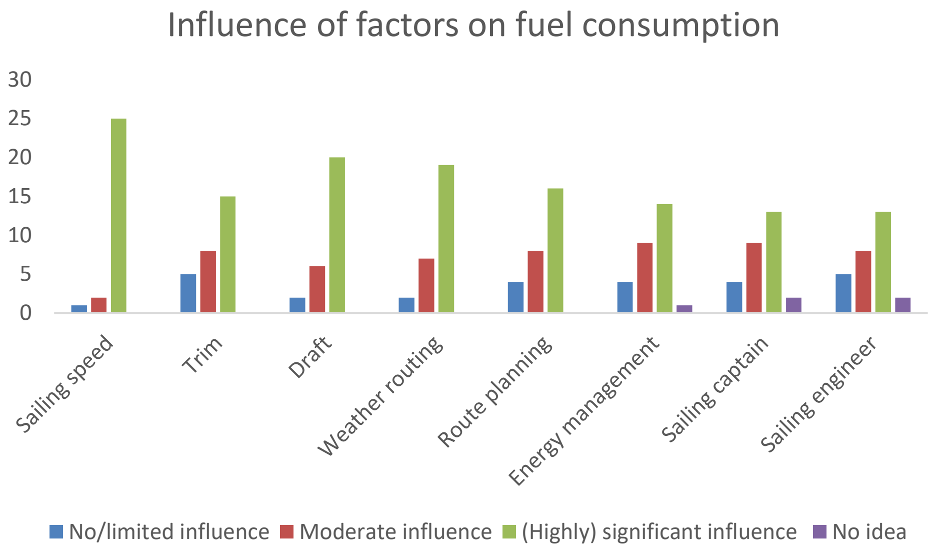

Figure A.9: How much influence do the following factors have on the fuel consumption of a ship?

Figure A.10 shows how helpful the respondents found certain types of information to save fuel during the operation. Generally, information about the current fuel consumption and information about weather conditions were seen as most helpful. Experience with/on another ship and information about GHG emissions were evaluated lowest.

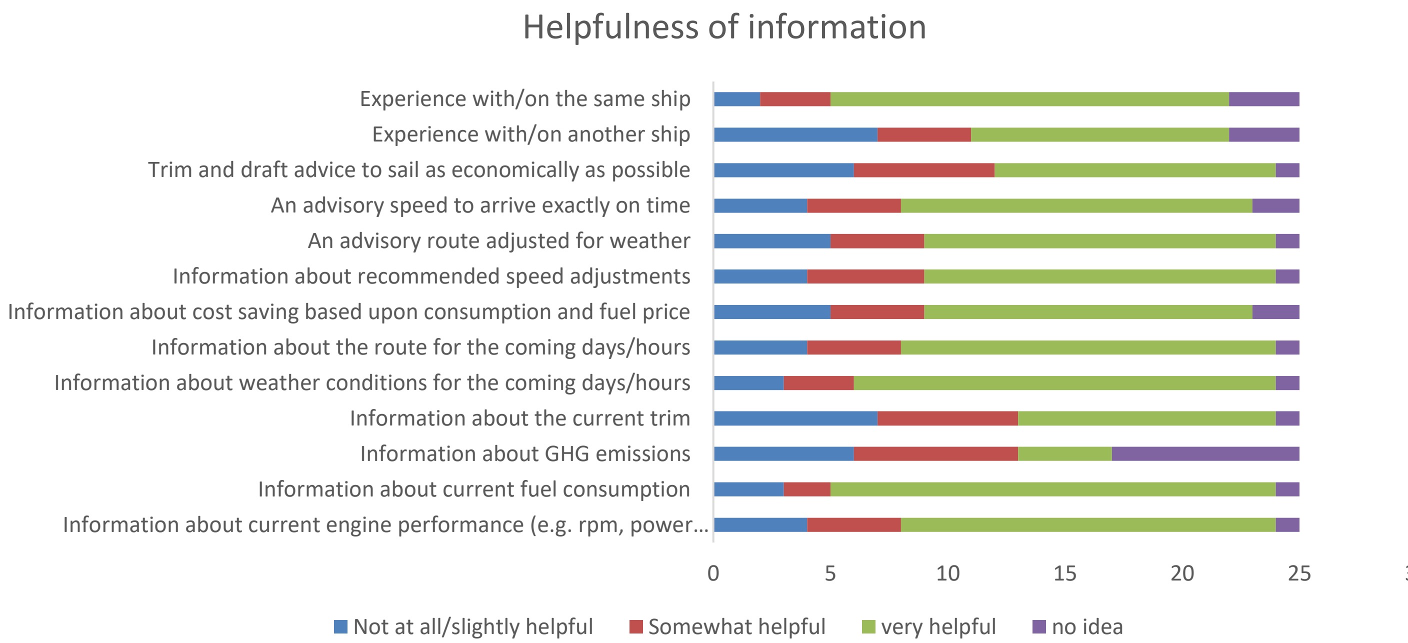

Figure A.10: How helpful is this information to save fuel during the operation?

Figure A.11 gives insight in the system preferences of the respondents. The graph shows that the majority of respondents has a preference for a system that gives information about:

- Current fuel consumption
- Weather condition for the coming days/hours
- Current engine settings

The least preferred information is current fuel price, followed by current GHG emissions. Note that the information that is valued highest is currently in most cases already available as shown in the Figure A.12.

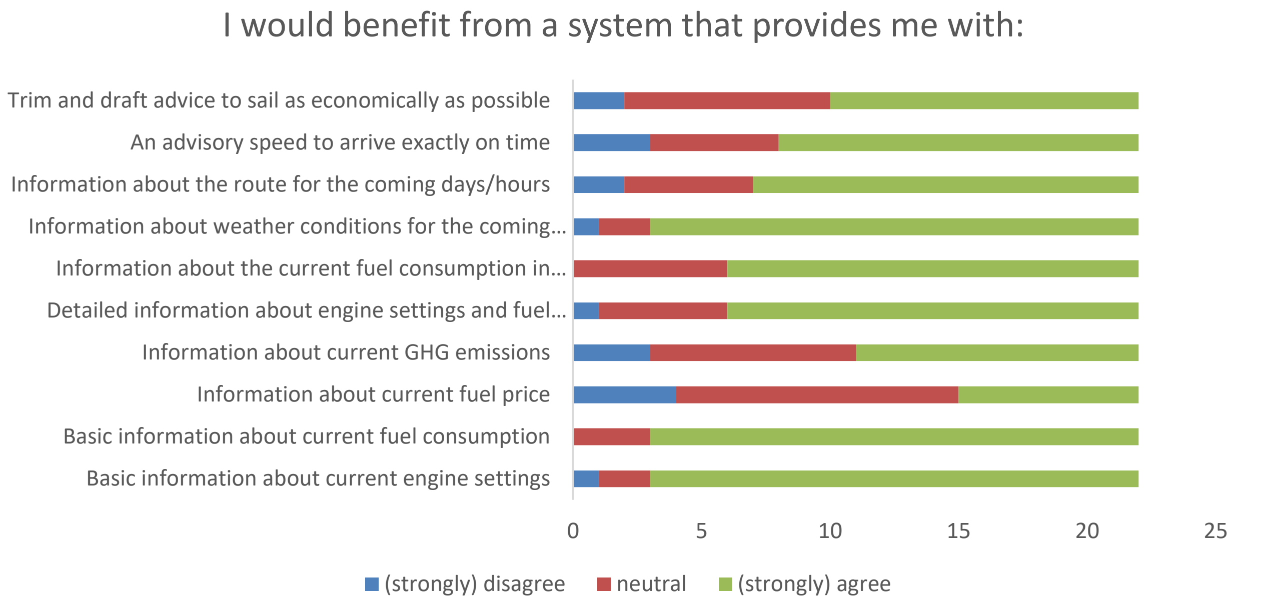

Figure A.11: Information preferences for system

Figure A.12 shows whether the respondents have the aforementioned information available or not. The data shows that all respondents have access to information about weather conditions for the coming days/hours. Information about current GHG emission is least available, followed by information about current fuel price.

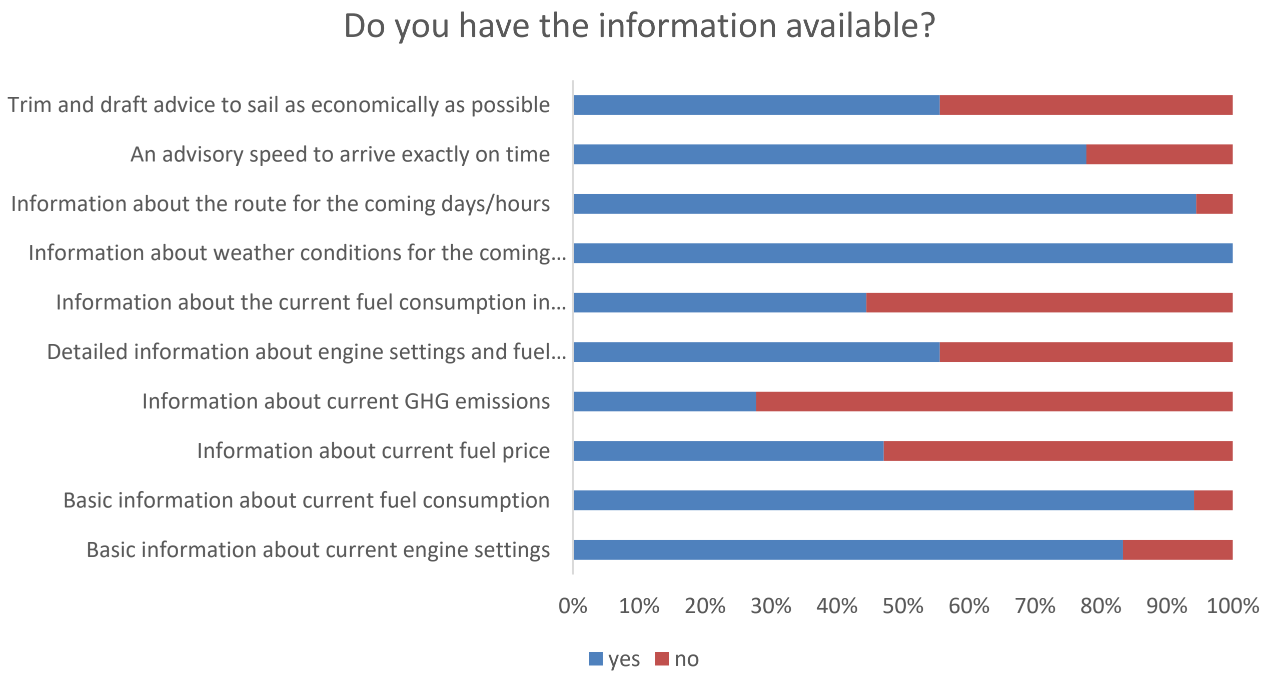

Figure A.12: Availability of information.

Figure A.13 shows the actions respondents already take on a regular basis to reduce emissions and save fuel. The majority indicated to do weather routing with regular adjustments. For the “other”-category, respondents gave the following answers:

- Only sailing with the tide as much as possible
- Keep the most fuel efficient engine rpm and calculate the ETA based on that. Not the other way around.
- Optimise trim and draught before departure and arrival once.

Finally Figure A.14 shows how the respondents would be most effectively encouraged to suggest improvements. This varies widely from cost saving to intrinsic motivation, climate change and regulations.

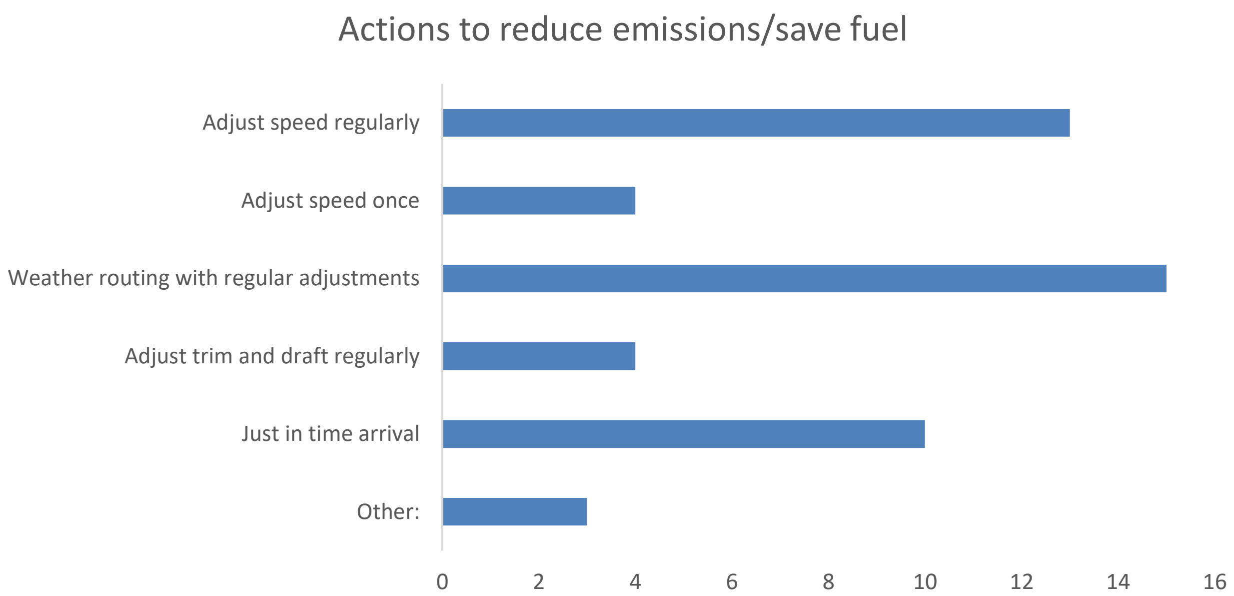

Figure A.13: What actions do you use on a regular basis to reduce emissions/save fuel?

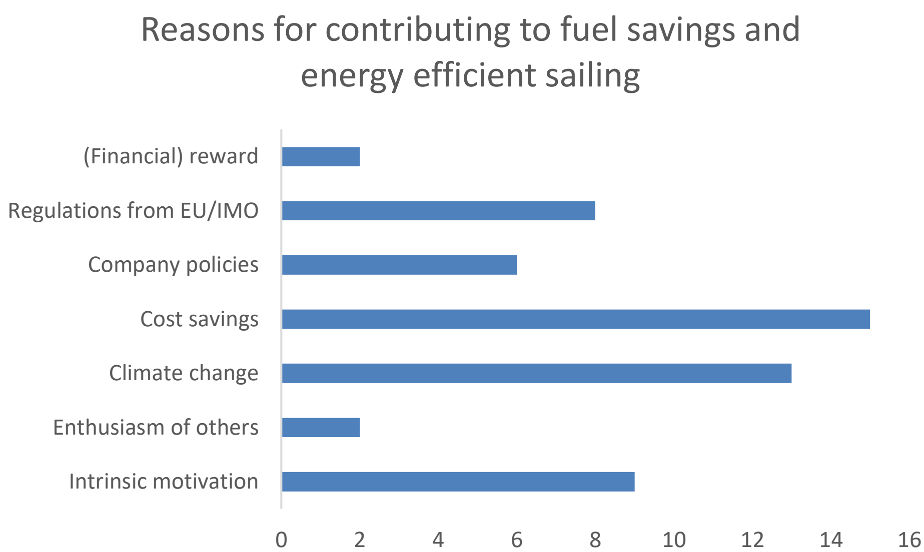

Figure A.14: How could you most effectively be encouraged to suggest improvements?

APPENDIX 3 COMMERCIALLY AVAILABLE OPERATIONAL ADVICE TOOLS

The list below makes no claim to completeness because no unique definition of operational advice tools is used in the market. In many cases, operational advice forms only a part of management systems that are used onboard of oceangoing vessels and is not prominently advertised. Many management systems also offer programming interfaces which, in principle, could be used to develop a custom-tailored operational advice tool. Furthermore, the market for these tools is growing and changes quickly. Suppliers are purchased by other companies, brand names disappear and new ones are launched. Therefore, the below list can only be a snapshot at the time when the survey was carried out (summer 2024).

ABB Ability™ OCTOPUS - Marine Advisory System

ABB Ability™ OCTOPUS is a product family for performance management in marine operations. It aims for reduction of fuel consumption and emissions by guiding crew decisions. [11]

Ascenz Marorka

Ascenz Marorka [12] develops software for marine applications. Their portfolio includes operational advice options like

- Electronic fuel monitoring,
- Vessel performance monitoring,
- Weather routing,
- LNG fuel and cargo management, and
- Shaft power limitation.

DNV

Navigator™ by DNV provides decision support related to port clearance, vessel efficiency, safety, and compliance. It comprises two modules, Navigator Port and Navigator Insight. The former supports the crew in managing port visits and voyages in controlled waters (e.g., SECA/NECA). The latter allows comprehensive fleet performance monitoring and analysis. Navigator Insight complies with the requirements of EU MRV (maritime regulation for monitoring, reporting and verification of maritime transport emissions). [13], [14], [15]

Insatech Marine

Fuel Consumption System (FCoS) by Insatech Marine [16] provides real time information on fuel consumption, which is preferably measured by Coriolis mass flow meters but the use of third-party sensors is also possible. It can help to detect leakages, increase crew awareness, and reduce fuel consumption. A Performance Monitoring System (PMoS) can be used on top of the FCoS and collect input from any sensors on board a ship, e.g., from power meters, speed logs, anemometers, or gyros. With the operator panel [17], default Key Performance Indicators (KPIs) can be logged and custom KPIs can be developed. [19], [20]

Kongsberg

The Vessel Performance Optimizer [21] by Kongsberg comprises of a set of tools for optimisation of vessel operation by providing decision support related to engine, hull, trim, and voyage planning. There are two main modules, one for the engines – an extension of the KONGSBERG AutoChief® bridge manoeuvring system (BMS) integrating the AVL engine performance and optimisation system (AVL EPOS™) – and one for the hull – KONGSBERG ShipLoad. For engine optimisation data of, amongst others, cylinder pressure, torque, fuel consumption, and turbocharger operation is logged. [21]

The EcoAdvisor™ is a decision support tool to optimise operation of vessels equipped with a Dynamic Positioning (DP) system. It gives real-time advice on measures to reduce fuel consumption and emissions. The tool also provides input for voyage planning based on weather forecast and sailing time/speed. [22]

Manta Marine Technologies

Manta Marine Technologies [23], formerly known as Yara Marine Technologies which has acquired Lean Marine, offers several tools for the optimisation of vessel operation, ranging from real-time data analysis to fuel and route optimisation.

Marine Digital

Fuel Optimisation System is the voyage and emission reduction planning tool by Marine Digital. Artificial Intelligence (AI) and big data are used to provide advice on route planning and operational measures like vessel speed. Weather and geo data can be used to plan optimised routes. The manufacturer claims that reductions of fuel consumption and CO_2 emissions of up to 12% are possible. [25]

Marpower

Marpower offers several automation options to monitor the systems and subsystems of a ship. The Marpower Automation System (MAS) collects and visualises the information of the various systems. If a concern or problem is detected, this is signalled to the user. As is the case for many of the tools described here, many modules can be added to MAS to enhance the scope of the tool. These modules include:

- Power Management System (PMS),
- Ballast Control System (BCS),
- Valve Control System (VCS),
- Tank Measurement System (TMS),
- Fuel Oil Monitoring System (FOMS), and
- Engine Room Reporting (ERR).

MAS does, however, mainly monitor the systems and raise alarms rather than give operational advice to the crew. Since, however, comprehensive data monitoring and visualisation may also trigger actions by the crew, MAS has been included in this study. [26]

NAPA

Another manufacturer of operational advice and optimisation tools is the Finnish NAPA Group. NAPA Voyage Optimisation [27] improves operational efficiency by weather routing and optimising speed profiles for different goals, e.g., arrival time, constant speed, or RPM.

Onboard

The Fuel Efficiency app by Onboard-Platform collects, stores and processes data obtained from different sensors on board a vessel. It is explicitly stated that the app offers operational advice beyond the optimum sailing speed. Which options are available is, however, left open and might depend on the vessel and the available sensors. The data can also be made available to fleet managers for further processing and analysis in real-time via an API. On the website they advertise with "16% increase in fuel savings" and up to 33% reduction of fuel consumption. The basis of these statements is not publicly available.[28]

TechBinder BV

Smart Vessel Optimizer by TechBinder BV gathers data from onboard systems, enriches it, and shares it via a Cloud system. It is advertised as being scalable from one asset to a whole fleet. The functionalities include trackers, basic and detailed analytics, video feeds, remote support, automated reporting, and automation of workflow. [30]

Shipmate

The Shipmate Vessel Performance System monitors operational data of a vessel and contributes to improving the ship's performance, energy consumption, and safety. Furthermore, the Shipmate software can be used for improving the SEEMP (Ship Energy Efficiency Management Plan). Like many other tools, the system can be accessed by the crew and fleet management staff ashore. [31]

Wärtsilä

Wärtsilä published a list of fifty options for shipowners to reduce GHG emissions [34]. Fifteen of these ideas are related to reduction of engine power demand and four deal with data utilisation.

Of course, Wärtsilä offers technical solutions to implement the measures recommended by them. Several modules are grouped in the Fleet Optimisation Solution (FOS). There is, for example, a web module for optimisation of hull and machinery [35]. Another one is the Voyage Optimizer tool [36] which supports fleet managers in route planning by calculating optimal routes and vessels speed profiles based on weather conditions, safety parameters, and commercial aspects.

Vessel Performance Solutions

The VESPER software monitors and logs data on the performance of hull, propeller, boilers, and main and auxiliary engine(s). Based on this data, it is possible to optimise the specific fuel oil consumption. Furthermore, the tool can assist in reporting related to environmental compliance. [37]

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