

TNO report**TNO 2021 R11732v2 | 1.1****Development of a fuel-optimal sailing time
method for Green Maritime Emission
Monitoring****Traffic & Transport**

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Summary

Motivation for the project

Worldwide, the maritime shipping sector accounts for 2.9% of all greenhouse gas emissions (4th IMO GHG study). In the 72th Marine Environment Protection Committee session in April 2018, a first milestone was achieved in the IMO greenhouse gas (GHG) roadmap. The industry agreed to an overarching objective of reducing GHG emissions by at least 50% by 2050 compared to the level of 2008.

Ship owners and operators have a key role in reaching the IMO goals, since they need to implement the changes that lead to the reduction of GHG. Basically, there are existing KPI's for monitoring CO₂ performance in place (see also §2.1.1), but implementation depends on the availability of reduction measures and their potential in real-world operations. To effectively reduce emissions, ship owners and operators need to be able to relate their actions to the effect on GHG performance. This requires an effective form of data collection, a means to relate changes in the data to their actions. Such data is also required for ship owners to prove achievements in GHG emissions and operational costs to other stakeholders, such as investors and policy makers.

CO₂ emissions are directly related to fuel consumption. To better understand fuel consumption, effects on fuel consumption and possibilities for accurate and reliable fuel consumption monitoring, several ship owners are currently experimenting with onboard monitoring systems. Matching this demand, there is an increasing number of suppliers of fuel and emission monitoring equipment. However, accurate and reliable monitoring of fuel consumption is rather complex, because of possible errors and uncertainties in measured parameters and due to the numerous ways in which sea, weather and cargo conditions can influence the actual fuel consumption. To support the maritime industry, a joint project is being carried out in which forces are bundled.

Objective of the project

The overall objective of the project was to pave the way for ship owners to perform effective monitoring of fuel consumption, assess fuel reduction measures and communicate achievements to external stakeholders.

The goals of this project were to:

- Develop know-how and guidelines for the technical lay out of onboard fuel monitoring;
- Develop data analysis and presentation methods to evaluate fuel consumption reduction measures for ship owners and operational planners;
- Investigate how industry partners can effectively take advantage from continuous fuel monitoring in their responsibility of effectively executing fuel saving strategies; and
- Develop Key Performance Indices (KPI's), which ship owners can use to communicate fuel saving achievements based on monitoring results to policy makers, investors and other stakeholders.

Innovation level

This TKI project Green Maritime Emission Monitoring (GMEM) aims to pave the way for ship owners to perform:

- Effective real-time monitoring of fuel consumption;
- Assess fuel reduction measures; and
- Communicate achievements to external stakeholders.

As also mentioned in the initial project plan, the current research is only a first phase in a possible series of research projects in the field of monitoring.

During the current research phase, a methodology was developed that integrates high quality data acquisition with a data-driven modelling approach for ship operation. In the data acquisition step, automated procedures were developed to monitor the ship's fuel mass consumption under a wide range of operating conditions and to perform systematic data analysis in order to monitor data quality. This data is crucial input to generate an actual ship operational model that captures the main dependency of the defined fuel-related KPI's on a wide range of operational conditions, such as ship parameters and water conditions. Based on the analysis of the modelled operational profiles and the actual weather and sea conditions, crew instructions for ship operation with minimal and economic viable fuel consumption can be derived. Besides the development of a methodology, as described above, a start was made with an on-board awareness program, by involving the crews in the execution of the experiments.

Project schedule

The project started at the end of 2019 and was finalised mid-2021.

The project concentrated on three main tasks:

- Validation of monitoring data and evaluation of external conditions;
- Development of a fuel evaluation method based on operational profiles; and
- Proof of emission reduction due to proposed measures.

Results and conclusions

With this project, a first step is made towards ship owners to perform effective monitoring and to make use of a fuel consumption evaluation method.

An elaborate analysis and review of the technical lay-out of an on-board fuel monitoring system is performed and resulted in the installation of such a monitoring system on two ships (PROGRESS and PERFECT). From these systems, an elaborate sailing dataset could be retrieved, and – based on a preliminary model to evaluate fuel consumption reduction – this dataset was even extended with additional data measured by the crew.

Based on detailed discussions, all partners agreed that cargo delivery time and operational costs (i.e. journey OPEX and crew costs) are essential KPIs. These KPIs generate the required insight in economical ship operation and are relevant for the commercial aspect of users. However, they can also be used to communicate fuel saving achievements to other stakeholders (like policy makers and investors). This research focused on the development of a central component: a fuel consumption evaluation method based on the ship's operation and external conditions. Ultimately, the wish is to assess the total operational costs.

This requires a detailed cost model, which was not available and outside the scope of the current study phase. Consequently, as a first step, this work focused on the trade-off between available sailing time and fuel consumption.

A crucial step towards the implementation and demonstration of the proposed fuel consumption evaluation method is the realisation of the measurement and data processing system. To realise this, the layout of the monitored ships' powertrains and their fuelling system was identified. In order to understand the ships' performance, it was crucial to acquire not only the data coming from the on-board measurement system, but also from Noon and Bunker reports to validate some measurements and to be able to bring external factors into account.

To obtain an integrated, high-quality data set from these sources, various data processing steps were introduced: first the integration of the various data sets, then post-processing of the data, including graphical interfaces and calculation of additional parameters and finally a check of the data quality. The resulting data set is essential for performance analysis and model development.

A central component in the fuel consumption evaluation method is a ship operational model. We aimed at determining the relationship between fuel consumption and sailing time for varying weather, sea and ship parameters and chose to follow a data-driven modelling approach. This was mainly motivated by the complex relationship between fuel consumption and weather and sea conditions. To gain sufficient data for the model, several experiments were executed taking into account a minimal impact on daily ship operation and safe operation at all times.

Using the derived model, two case studies were examined to show the potential of the fuel consumption evaluation method. For both cases a fuel consumption reduction was shown. From the first case, it was seen that even light weather conditions can have a significant effect on the ship's fuel consumption: 22% change in fuel consumption (for identical ship speed). The second case showed that alternative ship speed operation schemes can reduce fuel consumption by 4.6% reduction (for same sailing time) during bad weather conditions. Based on this second case, however, we conclude that knowledge of the best window of opportunity for the arrival time of the ships (i.e. also taking into account public holidays in visiting harbours) is essential to exploit the potential of the proposed method. Due to time and budget constraints, the fuel saving potential of the alternative ship operation is not validated by the crew in additional experiments.

The developed fuel monitoring method is seen as an important first step towards cost-optimal sailing and fleet optimisation. To reach this stage, more details and information on ship costs and logistics are needed to extend the optimisation framework. Also, the crew has to be taken into account in this integrated approach. Only then, the industry's wish to sail green and efficient as well as commercially viable can be fulfilled.

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1 Introduction

1.1 Background of the project

Worldwide, the maritime shipping sector accounts for 2.9% of all greenhouse gas emissions (4th IMO GHG study). In the 72th Marine Environment Protection Committee session in April 2018, a first milestone was achieved in the IMO greenhouse gas (GHG) roadmap. The industry agreed to an overarching objective of reducing GHG emissions by at least 50% by 2050 compared to the level of 2008.

Ship owners and operators have a key role in reaching the IMO goals, since they need to implement the changes that lead to the reduction of GHG. Basically, there are existing KPI's for monitoring CO₂ performance in place (see also §2.1.1), but implementation depends on the availability of reduction measures and their potential in real-world operations. To effectively reduce emissions, ship owners and operators need to be able to relate their actions to the effect on GHG performance. This requires an effective form of data collection, a means to relate changes in the data to their actions. Such data is also required for ship owner to prove achievements in GHG emissions and operational costs to other stakeholders, such as investors and policy makers.

Existing KPI's (Key Performance Indicators) used by IMO as an indicator of environmental performance are EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Indicator) for technical and operational performance on the ship level. EEDI gives an indication of the technical efficiency, including a limited number of technologies. EEOI is a tool to manage and monitor operational efficiency over time of a ship in operation and to determine the effect of changes in operation. EEOI cannot be used for non-cargo vessels. Although helpful, these KPI's give a rather bulky indication of efficiency, and the use for determining effectiveness of measures is therefore limited.

To better understand fuel consumption, effects on fuel consumption and possibilities for accurate and reliable monitoring fuel consumption, several ship owners are currently experimenting with on-board systems. Matching this demand, there is an increasing number of suppliers of fuel and emission monitoring equipment. However, accurate and reliable monitoring of fuel consumption is rather complex, because of possible errors and uncertainties in measured parameters and due to the numerous ways in which sea, weather and cargo conditions can influence the actual fuel consumption.

From the experience of several ship owners, it is concluded that:

- it is difficult to accurately monitor the desired parameters,
- the interpretation of the results is very complex, and
- convincing stakeholders of achieved reductions requires fact based arguments.

1.2 Project objectives

The overall objective of the project is to pave the way for ship owners to perform effective monitoring of fuel consumption, assess fuel reduction measures and communicate achievements to external stakeholders.

Although there is an increasing number of suppliers of continuous monitoring equipment, the acceptance, data quality and interpretation of the data is not yet developed well enough to be used reliably in operational conditions. The project therefore aims to provide shipowners and operators with guidelines and considerations when choosing for monitoring equipment.

Especially the task of assessing fuel reduction measures requires the development of new methods to analyse operational profiles and condense the outcomes into meaningful metrics raising awareness with the end-users.

The work during this research was driven by a mix of knowledge and industrial partners. TNO as knowledge partner of this project focussed on recommendations for data- and voyage analysis, awareness raising and fuel reduction reporting. The industry partners (Vertom, Rivermaas and Marlow) were responsible for obtaining monitoring data, organising and implementing alternative sailing strategies and involving crew and operators.

Project Objectives Vertom

Vertom UCS Holding B.V. (Vertom Group) is a medium-sized private company (B.V.) operating from the Netherlands. Vertom is an experienced and reliable partner for all companies who require professional services and support in organising and handling their sea transport. They present themselves as a maritime service provider for the European shortsea shipping segment, having almost all of their business activities in Europe and within the maritime service sector. Over 45 years, Vertom has been active in the international maritime industry and able to transport a large variety of bulk materials. Their fleet consists of 87 general cargo vessels, which enables them to safeguard a quick and reliable transport of goods. Common goods and materials transported by Vertom are steel, grain, fertilizer and project cargo.

In line with the strategic agenda of the IMO, Vertom is constantly looking for opportunities to invest in business activities that have a positive impact on the community and the environment. In this respect, the search for this positive impact is embedded in their business model and lies at the basis of their upcoming sustainable competitive advantage. By conducting their business activities, Vertom wants to make a positive contribution to the value chain of its customers. Therefore, they strive for long-term business relationships with mutual benefit for both their clients and their business partners. In this respect, green maritime monitoring and the reduction of GHG while handling the sea transport for its customers is becoming one of the fundamentals of their business model and their sustainable competitive advantage. Taking this into consideration, a direct relation can be identified between the strategic impact of GHG on their business models and the upcoming rules and regulation in respect of the taxation of GHG governmental institutions such as the European Parliament.

To begin with, taxation of the GHG by the EU is in line with a broader strategy of decarbonizing the economic activities within the EU in its entirety. As many industries, following up on the agreements from the Paris Agreement, also the maritime industry is compelled to steer towards its plan to become climate neutral by 2050. In that respect, the EU parliament voted in favour of including GHG emissions from the maritime sector in the EU carbon market as from 2022.

GHG emission from many industries were already included in the EU carbon market. In fact, the maritime sector was/is currently the only industry left which does not face EU targets to cut emissions.

It is safe to say that the industry is coming under increased scrutiny to enforce global decarbonizing ambitions which will, especially as from 2022, undermine and/or challenge the current business models within the industry. The IMO is aware of the fact that additional sustainable measurements are imminent. They introduced CO₂ reduction targets on their own. A few years ago, they introduced the ambition to reduce GHG with 50% by 2050. However, EU Parliament just underlined their ambitions to reduce GHG to 0% in 2050. Question is, who will draw the longest straw? Of course, this is a legal discussion, but a possible scenario is that the EU will impose the relevant rules and regulations helping them to enforce their ambitions. The imposed GHG taxation from the EU Parliament is currently presented by the EU Commission in the Fit for 55 working program. They will be responsible for presenting a series of dedicated rules and regulations that should enforce the GHG taxation.

The main conclusion of the above is that additional rules and regulations for the maritime industry to stimulate decarbonization and the reduction of GHG are imminent. A relevant question might be: How can shipowners, such as Vertom, turn the table and transform this upcoming treats on their business models into an opportunity, while safeguarding the interests of its stakeholders?

Within the Vertom Group, several opportunities are currently investigated to make these developments benefit the Vertom Group's activities, and its relationship with their customers/partners and other stakeholders. Becoming more sustainable is of strategic value and therefore also becoming an important foundation for a sustainable competitive advantage. For example, Vertom is currently pushing the boundaries with respect to sustainable propulsion systems and alternative fuels. Also this research on green maritime monitoring is supporting Vertom in its constant quest of acknowledging the impact of its business activities. By doing so, it is Vertom's ambition to facilitate its customers/partners with competitive sustainable transport solutions.

Project Objectives Rivermaas

Safe and sustainably profitable shipping is what Rivermaas aims for. This typically features strong cooperation between specialist partners. Rivermaas represents investors in the European short sea sector and has vessels in technical management. The contributions of our partners include crew management and commercial management.

Sustainability is driven by the willingness of actors in the chain to obtain and share data and for that reason Rivermaas decided to join the Green Maritime Emission Monitoring research. The objective was to assemble multiple data resources in order to create a set of KPI's, which would allow shipowners, commercial operators, technical managers and shippers to optimise each voyage by weighing various objectives. Moreover, unified data will allow managers to actively involve the crew in lowering our environmental footprint.

Project Objectives Marlow

Marlow Navigation Netherlands B.V. is a service provider to ship owners with regards to crew. They have no impact in any operational matters, neither have they the authority to give orders to the captain or the crew. However, they can support owners when it comes to fuel saving measures by creating awareness and providing extra training. This can only be performed in strict coordination with owners.

By joining this project, Marlow learns how they can support ship owners to achieve whatever goal they have. As a contracted service provider they will always act in the interest of the owner.

Concludingly, the goals of this project were to:

- Develop know-how and guidelines for the technical lay out of onboard fuel monitoring;
- Develop data analysis and presentation methods to evaluate fuel consumption reduction measures for ship owners and operational planners;
- Investigate how industry partners can effectively take advantage from continuous fuel monitoring in their responsibility of effectively executing fuel saving strategies; and
- Develop Key Performance Indices (KPI's), which ship owners can use to communicate fuel saving achievements based on monitoring results to policy makers, investors and other stakeholders.

1.3 Outline

In (this) chapter 1 an introduction is given containing the background of this project and the objectives from the different consortium members. In chapter 2 the fuel consumption evaluation method is described in more detail, with a focus on key performance indicators and a description of a method to evaluate fuel-optimal sailing time. Consequently, in chapter 3 and 4, we dive into the data acquisition and data processing details, respectively. Chapter 5 explains the development of a data-driven ship operational model and a first validation based on a set of experiments. In chapter 6 an effort is made to demonstrate the potential of the developed evaluation method by means of two case studies. Finally, the last chapter summarises the conclusions we can make based on this research and some recommendations for further work.

2 Fuel consumption evaluation method

This project aims to develop a new method to assess real-world fuel consumption.

This method has to pave the way to:

- Perform effective monitoring of fuel consumption;
- Assess the impact of fuel reduction measures; and
- Communicate achievements to external stakeholders.

In order to come to meaningful metrics, key performance indicators (KPI's) are firstly discussed in Section 2.1. This study is not limited to existing (technical) criteria, but is also done from a multi-stakeholder standpoint. Based on the identified KPI's, an evaluation method for fuel-optimal sailing time is proposed in Section 2.2.

2.1 Key performance indicators

2.1.1 Existing performance indicators

Besides logistical measures and use of low carbon and sustainable energy carriers, energy efficiency optimisation is an important step to address greenhouse gas (GHG) emissions from ships. As a first step towards realizing 40% CO₂ reduction in 2030 (compared to 2008 levels) in international shipping, IMO introduced two mandatory mechanisms to ensure an energy efficiency standard for all ships with minimal 400 gross tonnage (IMO, 2019):

- (1) **Energy Efficiency Design Index (EEDI)** gives an indication of the performance potential for new ships, including a limited number of energy saving technologies;
- (2) **Ship Energy Efficiency Management Plan (SEEMP)** is an approach for shipping companies to manage ship and fleet efficiency performance. To perform and monitor the operational efficiency over time of a ship in operation and to determine the effect of changes in operation, the **Energy Efficiency Operational Indicator (EEOI)** is introduced for voluntary use.

Definitions of EEDI and EEOI are shown in Figure 2-1.

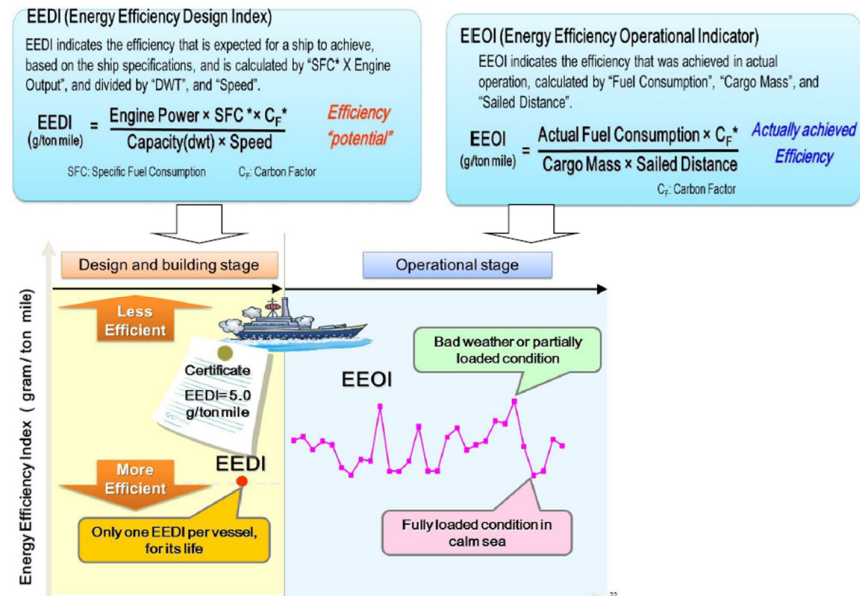


Figure 2-1: Illustration of EEDI and EEOI (Otsubo, 2010).

Both EEDI and EEOI specify ship performance in terms of fuel consumption per ton cargo and per covered distance. This gives a uniform, well defined framework. However, in order to assess real-world performance, it is crucial to understand the impact of both external factors, such as sea conditions and crew, and ship operation parameters (e.g. trim and ballast).

2.1.2 Key performance indicators for stakeholders

In order to specify the key performance indicators that are relevant for industry, various experts are interviewed. From these expert meetings, a complex multi-stakeholder picture emerged, see Figure 2-2. Focus is on individual journey level. Consequently, CAPEX investments and fleet level optimisation are not considered in this study.

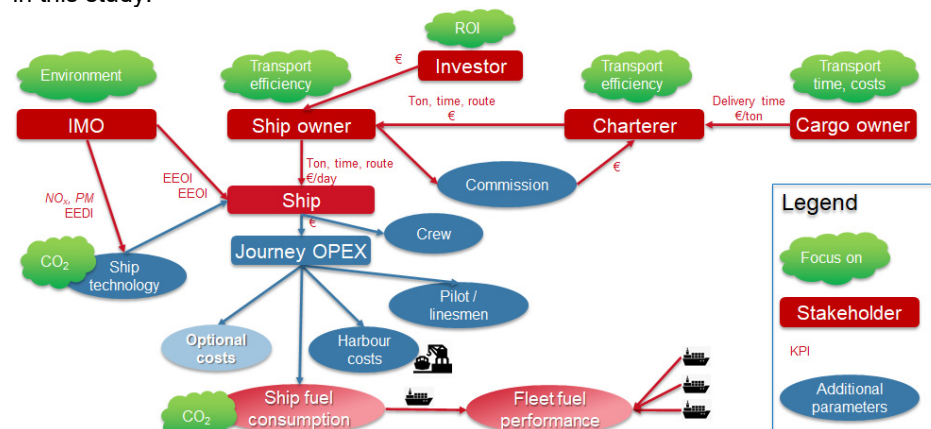


Figure 2-2: Overview of stakeholders and their KPI's.

Given a specific cargo (volume, ton) and destination (route), two essential KPI's are identified for all stakeholders: delivery time and operation costs.

2.1.2.1 Delivery time

Timely delivery of cargo is a key performance indicator parameter in the transport sector. Related to time, three main parts can be distinguished in the journey, see Figure 2-3: loading (in Harbour A), sailing and unloading (in Harbour B). Note that sailing time is directly related to the ship's speed and covered distance.

T_{sailing} = Sailing time
 v = Ship velocity
 X = Distance

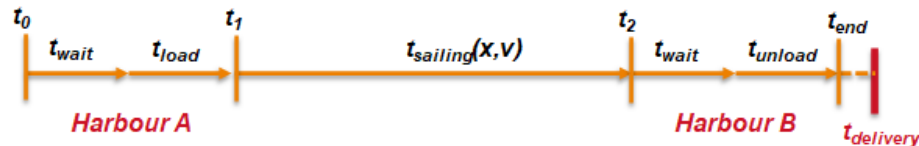


Figure 2-3: Illustration of different time parts in the journey.

2.1.2.2 Operational costs

By determining journey OPEX and crew costs, an essential economical KPI becomes available on ship level. This will generate better insight in economical ship operation as well as the commercial value of delivered transport services. More precisely, besides fuel costs, additional costs related to harbour stay play an important role. Note that optional journey-specific costs, e.g. materials, are not considered here. In the future, CO₂ taxes have been announced that will further stimulate green transport. In summary, for ship operation (with fixed cargo and journey), the following OPEX-related KPI is defined (in €):

$$\text{€}_{\text{OPEX}} = [\text{ship fuel consumption (in kg/h)} \times \text{fuel costs (in €/kg)} + \text{crew costs (in €/h)}] + \text{harbour costs (€)} (+ \text{CO}_2 \text{ taxes (€)})$$

Note that in EEOI focus is on fuel ship consumption only (for specific cargo and distance). This KPI requires detailed information and insights in harbour related costs, including costs for a pilot, linesmen, port dues, and unloading. This information was not available for this research.

2.2 Evaluation method for fuel-optimal sailing time

Given the scope of the project, it was decided to focus on the trade-off between fuel consumption and sailing time.

2.2.1 Ship operational model

A key element in the new evaluation method is the ship's operational model, which is illustrated in Figure 2-4.

This model describes the relation between the ship's fuel consumption and sailing time for various factors:

- **External conditions:** wind, sea conditions;
- **Ship operation:** propeller pitch α , trim, and ballast.

As the route (and thus distance) is fixed in this model, sailing time is proportional to the inverse of the ship speed ($1/v$).

This model is inspired from the work presented in (Bialystock & Konovessis, 2016). We focus only on the fuel consumption of the main engine, since this has the largest contribution to overall fuel consumption. However, the fuel consumption of the auxiliary engines and the boiler can be easily added at a later stage.

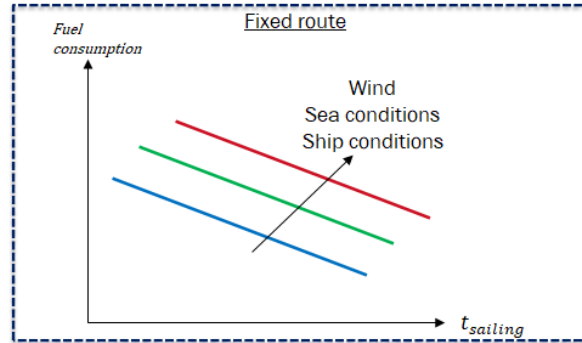


Figure 2-4: Schematic representation of the ship's operational model

2.2.2 Fuel consumption evaluation method

Having the ship's operational model available opens the route to determine fuel optimal sailing times. Given operational information, i.e. delivery time t_{end} and route, the ideal ship speed for the different parts of the journey can be determined based on *a priori* knowledge of the local weather and sea conditions. This operational information supports the captain (and the charterer's operators) to realise fuel-optimal sailing time.

The potential of this method is illustrated in the example shown in Figure 2-5. Note that arbitrary numbers are used.

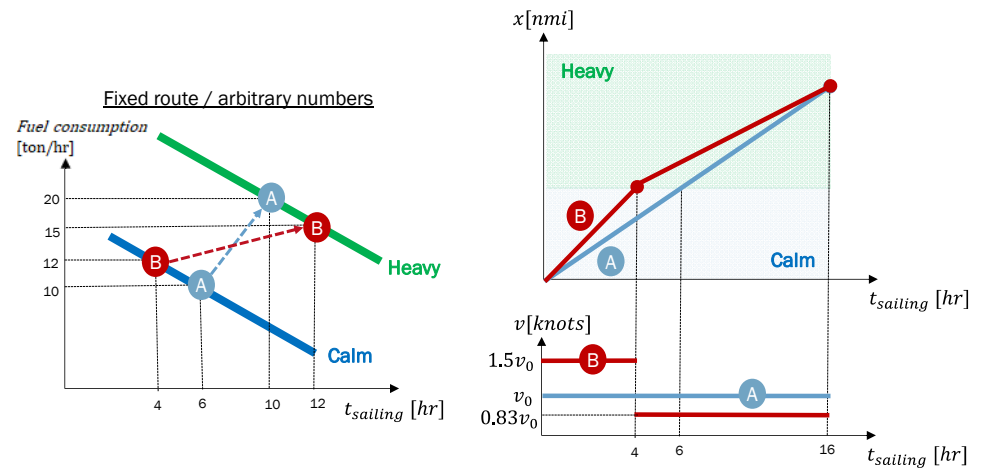


Figure 2-5: Illustrative example to demonstrate the fuel saving potential of the proposed evaluation method for fixed delivery time

We consider a journey where the ship starts in calm weather conditions (blue line). However, it encounters heavy weather (green line) during its journey after 6 hours of sailing time. In Case A, we assume that weather information was not available and the captain keeps travelling at a constant speed V_0 during the entire journey.

This results in a total sailing time of 16 hours and corresponding fuel consumption of $(10 \text{ ton/h} \times 6 \text{ h}) + (20 \text{ ton/h} \times 10 \text{ h}) = 260 \text{ ton}$. For Case B, we assume that an accurate weather forecast and operational model is available for the fixed route. Consequently, the captain first starts with increased ship speed $1.5 \times V_0$ during calm weather conditions. As a result, heavy weather conditions are encountered after 4 hours of sailing. Then, the captain adapts the ship speed, such that the total sailing time remains constant and the destination is met after 16 hours of sailing. Now, the total fuel consumption is $(12 \text{ ton/h} \times 4 \text{ h}) + (15 \text{ ton/h} \times 12 \text{ h}) = 228 \text{ ton}$. This 12% fuel saving clearly illustrates the potential of this new evaluation method.

In the future, this evaluation method can be further extended including the cost model to also consider OPEX in the optimisation, see Appendix A.

3 Data acquisition

Realisation of the measurement and data processing system is a crucial step towards the implementation and demonstration of the proposed fuel consumption evaluation method. In this chapter, first the powertrain layout with available sensors is presented in Section 3.1. In Section 3.2, the different data sources are described.

3.1 Powertrain layout

The performance of two ships was monitored: PERFECT and PROGRESS. The layout of the powertrain with their fuelling system is identical for both ships and is shown in Figure 3-1.

The ship propulsion system is driven by the main engine (ME), which provides power to the controllable pitch propeller and to the generator. Also, two auxiliary engines (AE1 and AE2), which deliver additional electric power, and a boiler are installed on both ships.

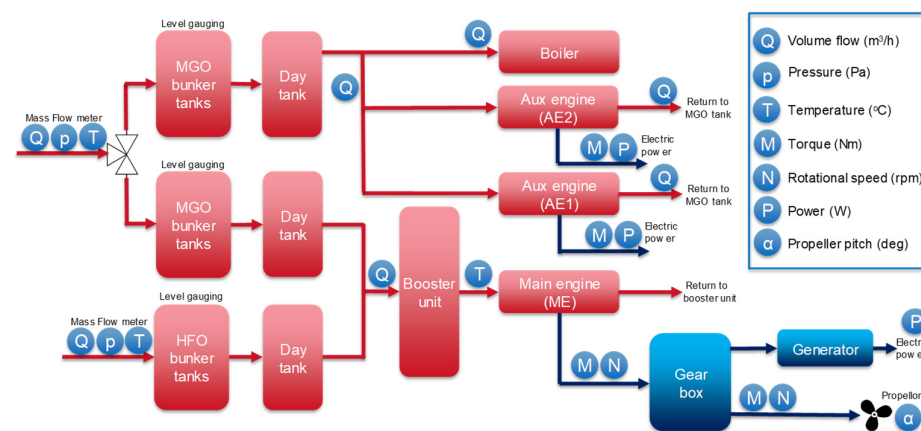


Figure 3-1: Powertrain layout with measurement system.

Both ships are equipped with bunkering tanks for Heavy Fuel Oil (HFO) and Marine Gas Oil (MGO). As illustrated in Figure 3-1, MGO is used for all engines, while HFO is only used in the main engine. However, the main engine only uses one fuel at the time. This fuel is pumped from the day tanks to the booster unit, which has a capacity of around 20 m³.

3.2 Data sources

Various data sources are combined and integrated to assess the performance of PROGRESS and PERFECT. In order to understand the ship's performance, it is crucial not only to focus on recorded ship parameters, but also to acquire data for external factors, such as crew, mission, location, ship condition, and sea condition. Figure 3-2 gives an overview of the data and processing flow. More precisely, it shows the various types of data that are recorded and processed.

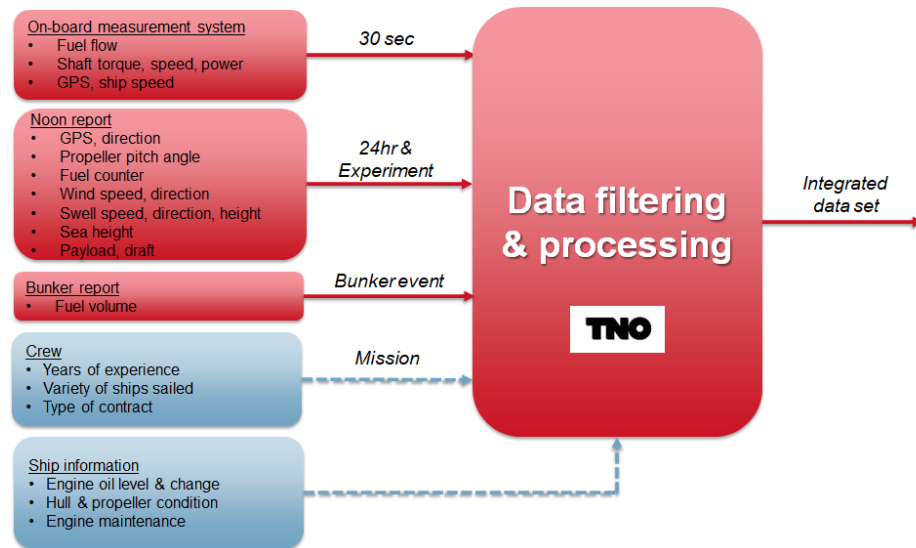


Figure 3-2: Overview of data acquisition and data processing flow.

For the fuel consumption evaluation method, TNO integrated three data sources (in red) for performance analysis: on-board measurement system, noon reports, and bunker reports. In the next sections, these data sources are discussed in more detail.

3.2.1 On-board measurement system

To monitor the real-world ship performance, both ships, PERFECT and PROGRESS are equipped with additional sensors, as shown in Figure 3-1:

- Fuel flow meters;
- Tank level gauges; and
- Shaft power meter.

The data acquisition system records sensor readings and via a GUI (Graphical User Interface) it visualises the ship performance for the ship operators. An example of the feature of the GUI is to show the average fuel consumption of the ship for the last 24 hours of sailing.

For this project, TNO has gained remote access to the stored measurement data for analysis and assessment of the ship's fuel consumption performance.

In Table 3-1 the signals that are recorded by sampling every 30 seconds without any additional filtering are listed.

Table 3-1: List of measured signals from the installed data acquisition system

Signal Name	Description	Unit
ae1out_ctr	Auxiliary Engine 1 (AE1) out fuel counter	L
ae1out_mtpd	AE1 out fuel oil consumption (foc) counter	ton/day
ae2out_ctr	AE2 out counter	L
ae2out_mtpd	AE2 out foc counter	ton/day

aein_ctr	AE1 + AE2 in counter	L
aein_mtpd	AE in foc counter	ton/day
ae_avg_24h	AE foc average (last 24 h)	ton/day
afoc_me	Allowed ME foc	ton/day
boil_avg_24h	Boiler foc average (last 24 h)	ton/day
boil_ctr	Boiler counter	L
bu_hfo_ctr_mass	Bunker flowmeter HFO counter mass	kg
bu_hfo_ctr_vol	Bunker flowmeter HFO counter volume	m3
bu_hfo_dens	Bunker flowmeter HFO density	kg/L
bu_hfo_flow_mass	Bunker flowmeter HFO massflow	kg/h
bu_hfo_flow_vol	Bunker flowmeter HFO flow vol	m3/h
bu_hfo_tmp	Bunker flowmeter HFO temperature	deg C
bu_mgo_ctr_mass	Bunker flowmeter MGO counter mass	kg
bu_mgo_ctr_vol	Bunker flowmeter MGO counter volume	m3
bu_mgo_dens	Bunker flowmeter MGO density	kg/l
bu_mgo_flow_mass	Bunker flowmeter MGO flow mass	kg/h
bu_mgo_flow_vol	Bunker flowmeter MGO flow volume	m3/h
bu_mgo_tmp	Bunker flowmeter MGO temperature	deg C
bu_rep_hfo_active	Bunker report HFO (active = 1)	boolean
bu_rep_hfo_mass	Bunker report HFO mass	kg
bu_rep_hfo_vol	Bunker report HFO mass	m3
bu_rep_mgo_active	Bunker report MGO (active = 1)	boolean
bu_rep_mgo_mass	Bunker report MGO mass	kg
bu_rep_mgo_vol	Bunker report MGO mass	m3
cubm_hfops	Tank HFO port side	m3
cubm_hfosb	Tank HFO star board	m3
cubm_mgops	Tank MGO port side	m3
cubm_mgosb	Tank MGO star board	m3
foc_ae	Actual foc AE	ton/day
foc_boil	Actual foc boiler	ton/day
foc_me	Actual foc Main Engine (ME)	ton/day
gps_course	Course	°
gps_speed	Boat speed	knot
heading	Heading	°
log_speed	Speed	knot
me_avg_24h	ME foc average (last 24 h)	ton/day
me_ctr	ME fuel counter	L
me_dens	ME fuel density	kg/L
mgo_dens	AE/boiler MGO density	kg/L
position_lat	Latitude	°
position_long	Longitude	°
sfoc_me	Specific Fuel Oil Consumption (SFOC) ME	g/kWh

sh_alr	Shaft meter alarm	boolean
sh_gen_on	Shaft generator on	boolean
sh_pwr	Shaft-power	kW
sh_rpm	Shaft-rpm	RPM
sh_tor	Shaft-torque	kNm
tlev_hfops	Tank level HFO port side	m
tlev_hfosb	Tank level HFO star board	m
tlev_mgops	Tank level MGO port side	m
tlev_mgosb	Tank level MGO star board	m

The sensors installed in the ship are the main source of monitoring data, which will be used to assess the ships' fuel consumption and performance. The fuel volume signals and the fuel flow signals from the monitoring data are also compared to the information found in noon report and bunker report for validity check.

3.2.2 Noon report

On top of the sensor signals, the ship's captain sends a noon report every 24 hours to the in-land operators. The noon report contains mission information such as destination of the ship, average fuel consumption, and weather data at the time of report. The weather data consists of information regarding wind condition and sea condition (current strength and swell height). An example of a standard noon report is shown in Figure 3-3.

```

Ship: PROGRESS - Noon (Position) - Sea passage - Ballast

date/time (UTC): 29-01-2020 07:00 (UTC)
voyage no.: 20012503
voyage from-to: Sevilla - Setubal
position: 38° 12.0' N 9° 02.6' W n/a - n/a
total miles: 221
miles to go: 14
miles last 24h: 221
ETC/ETS (LT): n/a
ETA: 29-01-2020 09:30 (LT) - 29-01-2020 09:30 (UTC)
cargo (mt): n/am³
draft: F= 2.7m, A= 3.5m, M= 3.1m
weather: wind direction 290, wind speed BFT 3, sea height 1m
v-24h: 10.4kn (OG)
v-voy: 10.44kn (OG)
pitch/rpm: 720rpm
brob/grade: HFO total 73.71 (HFO HS 73.71*, HFO LS 0*), MDO/MGO total 59.23
(MDO/MGO HS 0* MDO/MGO LS 59.23*)
brob/taken: when applicable, see attachment
consumption: ME 5.9mt RMG 380, AE mt , Boiler mt
remarks:
ET FOB 29/01/2020 09.30 lt - (e.g. NOR tendered, weight of single cargoes, type of
single cargoes)

based on StormGeo Navigator Insight data
Master Andrii Prymakov
* Obsolete variable content to be treated with care.

```

Figure 3-3: Example of a standard noon report.

At the later stage of the project, additional information such as cargo load in the ship and water ballast volume is included in an adapted version of the noon report. An example of the adapted noon report is shown in Figure 3-4.

Ship: PERFECT - TNO test 07-01-2021 07:00 (UTC) - Laden - sea passage

voyage no.: 20011601 B
voyage from-to: Dunkerque - Rouen

date/time (UTC): 07-01-2021 07:00 (UTC)
position: 49° 59.0' N 0° 09.0' W n/a - n/a

time since last report: 11:15
distance since last report (over ground / GPS): 116nm distance since last report 116nm

course (gyroheading): 180
Speed (over ground / GPS): 10.3kn
Speed (through water / speedlog): 10.3kn

wind speed: 3bft
wind direction (true): Ndeg
sea height: 0.8m
swell direction: n/adeg
swell height: n/am
current direction (true): n/adeg
current speed: n/akts
rolling period: 7sec

cargo (m³): n/am³
total on board weight: 6132
cargo on board weight:
total cargo loaded weight: 0

rpm: 700rpm
pitch: 1.1
consumption: ME 2.45mt DMA
consumption: AE mt
consumption: Boiler mt

draft: F= 5.8m, M= 6m, A= 6.1m
total ballast water on board: 20m³

remarks: n/a - (e.g. NOR tendered, weight of single cargoes, type of single cargoes)

Figure 3-4: Example of the adapted noon report, with additional information on cargo and weather conditions.

The weather information, the sea condition and the fuel consumption from the noon report, together with the experiment results, were used to analyse the ship performance. The fuel consumption information was also used to validate the fuel flowmeter sensor readings in the ships.

3.2.3 *Bunker report*

The bunker report gives information on the bunkered fuel. It includes the volume of fuel delivered (HFO or MGO) and the physical properties of the fuel such as the density, sulphur content, viscosity and flash point.

In this research, we used the total bunkered fuel volume. This data is compared with sensor readings of the bunker tank fuel flow and engine fuel flow.

3.2.4 Required operational and weather parameters

The relevant signals that were used for development of the ship's operational model are shown in Table 3-2.

Table 3-2: Signals used in ship operational model.

Ship parameters		
Draft (F/A/M)	Noon report Experiment	Every 24 hrs Every point change
Ballast	Noon report Experiment	Every 24 hrs Every point change
Operational parameters		
Propeller pitch	Noon report Experiment	Every 24 hrs Every point change
Ship speed (LOG)	Additional sensor	Every 30 seconds
Ship speed GPS	Additional sensor	Every 30 seconds
Propulsion shaft torque	Additional sensor	Every 30 seconds
Propulsion shaft speed	Additional sensor	Every 30 seconds
Propulsion shaft power	Additional sensor	Every 30 seconds
Fuel tank counter (main engine)	Additional sensor	Every 30 seconds
Fuel consumption (main engine)	Additional sensor	Every 30 seconds
Wind & sea conditions		
Wind speed	Noon report Experiment	Every 24 hours Every point change
Wind direction	Noon report Experiment	Every 24 hours Every point change
Swell speed	Noon report Experiment	Every 24 hours Every point change
Swell direction	Noon report Experiment	Every 24 hours Every point change
Swell height	Noon report Experiment	Every 24 hours Every point change
Sea height	Noon report Experiment	Every 24 hours Every point change
Current speed	Noon report Experiment	Every 24 hours Every point change
Current direction	Noon report Experiment	Every 24 hours Every point change

The ship's speed signals are measured from the LOG sensor and the GPS data. The LOG sensor is installed on the ship to measure the ship's speed relative to the water. The LOG ship's speed signal is the main signal used by the ship crews for determining the voyage speed, however, this signal is sensitive to noise as the sensor can be contaminated with dirt, sea water, and marine growth.

The GPS data is based on satellite position information and gives the ship speed relative to the fixed earth coordination system. The GPS ship speed is less sensitive to noise and is more reliable for data analysis.

4 Data processing

To obtain an integrated, high-quality data set, various data processing steps are introduced. More precisely, integration of the various data sources (Section 4.1), data post-processing (Section 4.2), including graphical interfaces and calculation of additional parameters, and checking data quality (Section 4.3) is required. This resulting data set is essential for performance analysis and model development.

4.1 Data source integration

As different signals are measured in different ways and at different sample frequencies, a post-processing routine is required to transform the information to workable data. The post-processing includes data filtering to reduce noise for data analysis, calculating new parameters such as water current magnitude and direction, and time alignment of sensor data with experiment results (which was manually recorded in the designed Excel sheet per operating point). For each data source listed in Section 3.2, a specific data-processing routine is performed. The general schematic of the data-processing flow is shown in Figure 4-1.

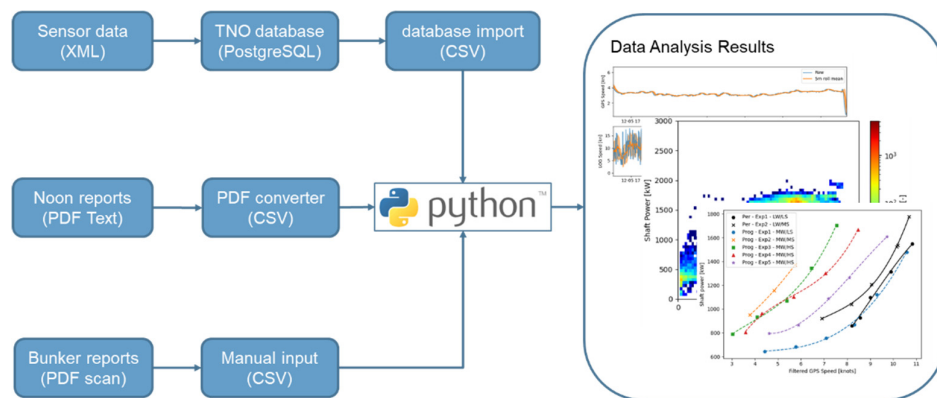


Figure 4-1: Data-processing flowchart for analysis and data quality check.

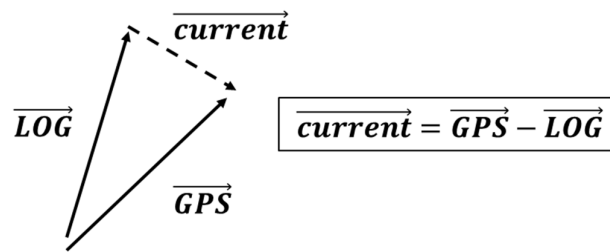
4.2 Data post-processing

4.2.1 Calculation of parameters

In the post-processing routine, additional parameters based on the sensor data are calculated for identifying factors that may affect fuel consumption. The following new variables were calculated during the post-processing routine:

Water current magnitude and direction

Using the GPS and LOG ship speed signals, the water current vector (magnitude and direction) can be estimated using vector calculation. Using the water current information, together with the available weather data, helps to analyse the effect of water current to ship's performance.



Fuel consumption

As illustrated in Figure 3-1, the ships are equipped with various fuel flow sensors. These sensors determine fuel volume flow in l/h. Fuel mass flow is calculated by multiplying the volume flow by the fuel density in kg/m³.

The fuel specifications, such as density, are only reported in the bunker report. Accurate density information would help in accurate translation between volumetric flow rate and mass flow rate, which affects the engine fuel efficiency calculation. At the moment, impact of fuel quality on ship performance analysis cannot be investigated thoroughly.

Main engine power

In order to understand the impact of operating conditions on the main engine's fuel consumption, the availability of the engine speed and torque are crucial. In this case, fuel consumption could also be validated using the engine maps from the manufacturer. However, currently, the engine maps are unavailable.

4.2.2 *Data averaging*

The sensor data provides detailed information regarding the ship operating point: geographical location of the ship during the voyage, the ship speed and the fuel consumption of the ship during a mission.

For a given ship operating point, various factors play a role:

- Ship control parameters, such as cargo load, ballast and draft settings;
- External factors: weather and sea conditions, and operating crews.

For developing the ship operational model for optimising the fuel consumption, it is useful to identify the ship operating points at steady-state operation. Steady-state operation is identified with constant ship speed and the same ship parameters. To reliably observe steady-state operation, the designed experiment instructed the ship crews to sail on a specific ship control setting (for example: a fixed pitching angle) for a fixed duration (20 to 40 minutes). The end point of this steady-state operating point is taken as an isolated operating point for the correlation analysis. An example of isolating the operating points from experiment results can be seen in Figure 4-2. The left side figures show the effect of changing pitching angle to the ship GPS speed. After 20 minutes sailing on the fixed pitching angle, the steady state operating point can be taken (shown by the circle markers) and plotted for correlation analysis, shown on the right hand subplots.

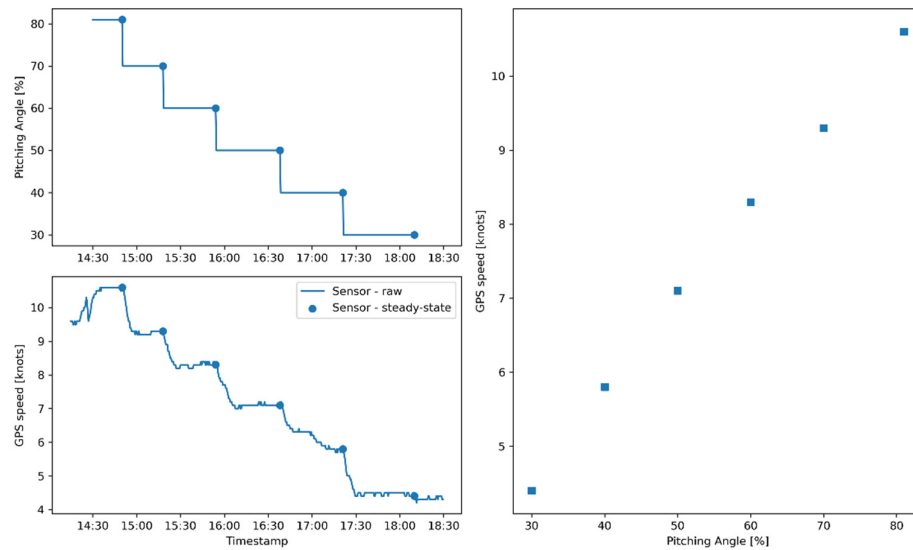


Figure 4-2: Example of isolating operating points to define steady-state operating points.

The GPS speed signal plotted in the lower left-hand plot in Figure 4-2 shows some fluctuation in the signal due to noise. As a result, taking only the end point as the steady state point might be affected by this noise. In order to have a more stable GPS speed signal, a filtering technique is applied to smoothen the signal, therefore, the end point of GPS speed signal will be more stabilised and reliable.

4.2.3 Visualisation for analysis

For data analysis, visualisation of data is important in understanding the ship performance during the voyage. To do so, various graphs are created.

Geographical-related information

In order to analyse the ship's operational conditions during the voyage, geographical visualisations are made. Figure 4-3 shows an example for a voyage from Garrucha to Southampton. For each GPS location, the main engine fuel consumption (ME), LOG, GPS speed of ship and calculated current speed are plotted. From these graphs, it is seen that the low GPS ship speed in the Gibraltar strait might be attributed to the high current speed, which is visualised in the lower left-hand plot.

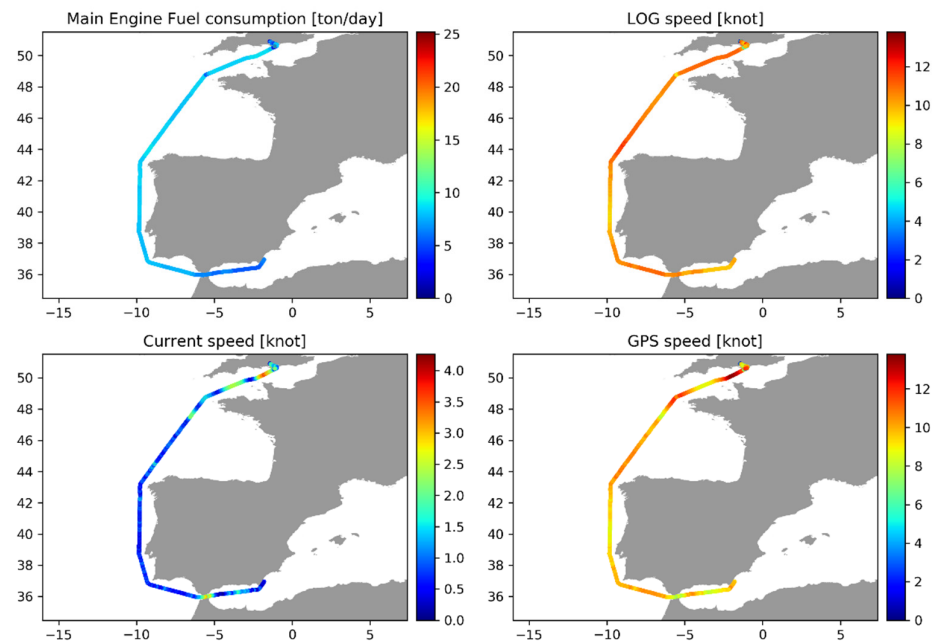


Figure 4-3: Geographical visualization of voyage from Garrucha to Southampton.

Engine operation

To understand fuel consumption, visualisation of the engine operating is very helpful. Therefore, fuel consumption is correlated to shaft power and shaft rotational speed, as shown in Figure 4-4. By comparison with the engine map, it can be checked whether the engine is frequently operated in the high fuel efficiency region.

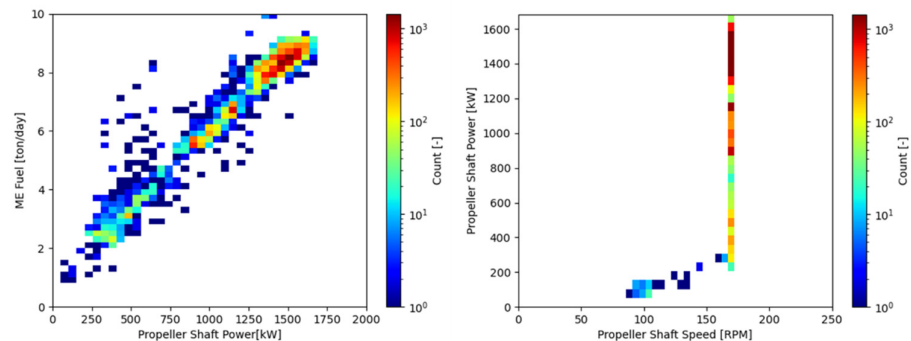


Figure 4-4: Main engine fuel consumption as a function of propeller shaft power and population heat map showing the most common propeller shaft operation.

4.3 Data quality check

As illustrated in Figure 4-5, the data quality is affected by many aspects in the measurement chain. This is ranging from external factors and operating conditions; and selected hardware (sensors, converters and data acquisition systems) towards applied post-processing methods. For data analysis and model development, it is crucial to perform a data quality check to ensure that the sensor signals are reliable and accurate.

Especially, focus is on the determination of KPI related quantities, see also Figure 5-1. More precisely, ship speed (to determine sailing time) and shaft power, sea and weather conditions and fuel consumption.

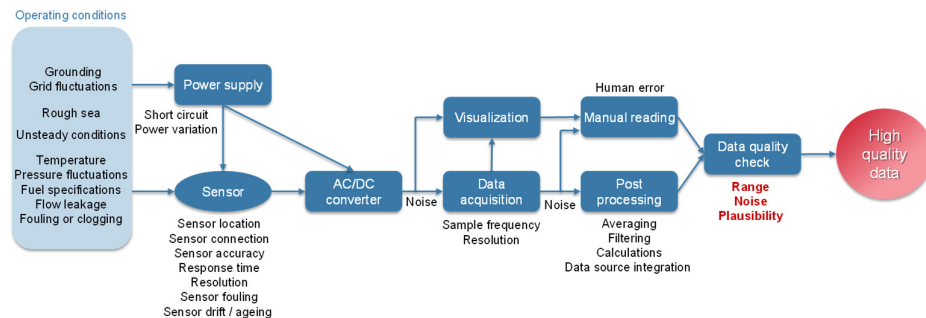


Figure 4-5: Schematic of measurement chain and of various aspects that influence data quality (in red: data quality aspects tackled in this project).

Although many aspects related to data quality have to be covered, focus in this research was on signal range, noise and plausibility, as indicated in Figure 4-5. Other topics, such as detection of abnormal operating conditions (incl. fouling) and detection of sensor drift and aging, are not taken into account for this research.

We applied methodologies for *signal anomaly detection* for the following aspects:

- Signal range: neglect abnormal spikes, neglect unrealistic large values, positive mass flows;
- Determine normal noise levels to detect incorrect sensor connection or possible fouling;
- Plausibility check: fuel mass balance, realistic acceleration/deceleration (optional pressure drops (not rise) for positive flow)

4.3.1 Recommendations

There are still issues that need to be resolved to further improve the data quality for analysis:

- One of the control variables in the ship, the pitching angle, is not available in the sensor data. The pitching angle determines the angle of the propeller blades, and observations show that the actuation of the pitching angle affects the propeller shaft torque and the ship speed. At the moment, the crews are requested to record the pitching angle manually during experiments. With the pitching angle information available, it is possible to obtain steady-state ship operation data without dedicated experiments and also obtain insight about the allowable range of pitching angle and ship speed in various weather conditions.
- The weather data (wind condition and sea condition) is still recorded every 24 hours by means of noon report. This is not ideal for correlation analysis as the weather is changing much faster than a 24-hour range. Having a hourly or half-hourly weather report would bring improvement on studying the effect of weather on ship operation, and learn how the crews adapt the ship operation to the severity of the weather.

- An anomaly was detected when comparing the fuel flow rate in the auxiliary engines, whereby negative values were measured in the sensors, while positive values are reported in the noon report. Further investigation shows that the negative values are caused by a bypassed fuel flow sensor that is installed in the intake of the auxiliary engines. For more accurate data on fuel consumption on ship level, this issue should be resolved.
- The generator power is currently not available in the sensor data. This is not crucial if we assume that the generator power is always constant. However, if the generator power is variable, the availability of such a generator power signal would help in resolving the net power output of the main engine and thus allowing to check optimal engine operation with smart operation of the generator. This would be more crucial for ship configurations that involve electric engines and batteries for buffering, which opens the path to energy optimisation.
- Detection of anomalies in the signals is currently only possible after the sensor data has been collected and post-processed. The anomaly detection algorithm should be automated on board by raising warning flags, which is essential for real-time use of data.

5 Development of a data-driven ship operational model

This chapter discusses the development of a data-driven ship operational model. First, the proposed approach is outlined in Section 5.1. Besides the introduction of model details, the experimental approach is presented in Section 5.2. More precisely, the considered variations in weather, sea and ship parameters are discussed. In Section 5.3 the experimental results are presented and discussed.

5.1 Ship operational model

To realise the fuel consumption evaluation method in Section 2.2, a proposed ship operational model has to be developed. Therefore, we aim to determine the relationship between fuel consumption and sailing time for varying weather, sea and ship parameters.

In this study, it is chosen to follow a data-driven model approach. This is mainly motivated by the complex relationship between fuel consumption and weather and sea conditions. Figure 5-1 illustrates the followed approach.

This figure clearly illustrates that, to construct the desired graph for a fixed mission, we have to combine two data-driven sub models:

- **Ship load model**, which describes the relation between the required propulsion power P_{shaft} and the ship speed v , weather conditions, sea conditions and ship parameters;
- **Main engine fuel consumption model**, which describes the relation between the required propulsion power and the fuel consumption. Note that we assume that the generator power is constant during experiments. In case the manufacturer's engine map is available, the model could be replaced by the map using (an estimation) of the generator torque and speed.

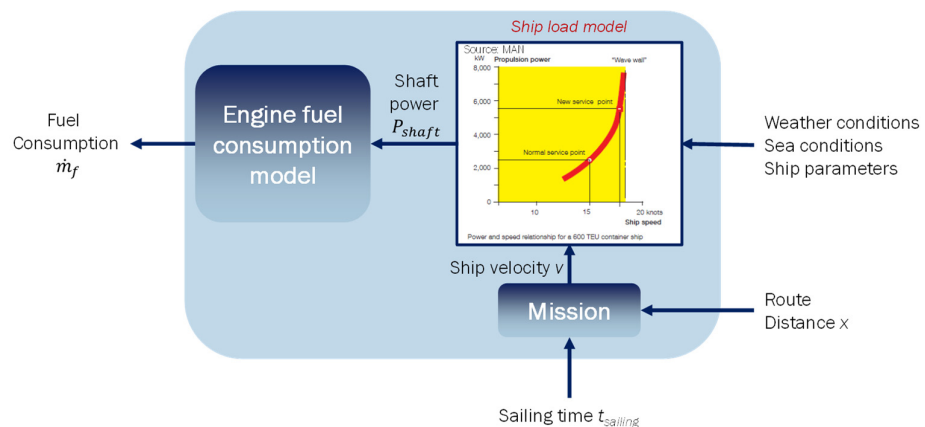


Figure 5-1: Illustration of the data-driven ship operational model.

5.1.1 Weather and sea conditions

Modelling of weather and sea conditions is not straightforward. However, to understand the impact of these conditions on ship performance, we introduced the following classification to deal with an arbitrary, but limited number of cases.

From literature, it is concluded that wind, swell and current have a considerable effect on fuel consumption. In this work, wind and swell, are grouped in four overall weather conditions; light, medium, heavy and very heavy (see Table 5-1). The current is deemed to be not exclusively dependent on the proposed weather characteristics and is therefore left out of the grouped effects. For the current, the measured or calculated magnitude will be used separately.

Table 5-1: Classification of weather effects.

	Light Weather	Moderate Weather	Heavy Weather	Very Heavy Weather
Wind speed range (Bft)	1-3	4-6	7-10	11+
Swell height range (m)	0-1.25	1.25-4	4-9	9+

Aside from the magnitude of the wind, swell and current, the ship's traveling direction is assumed to have a considerable impact on fuel performance as well. More precisely, strong winds on the bow of the ship very likely result in higher fuel consumption than strong winds on the stern. To account for the direction, the ship is arbitrarily divided in three overall segments; Bow [330°-30°], Stern [150°-210°] and Cross [30°-150° & 210°-330°], see Figure 5-2. Similar considerations hold for swell and current direction. Three classifications for these three effects results in 27 individual combinations. The correlations between wind, swell and current are neglected. The variation of the parameters involved, such as temperature, air pressure, and geophysical attributes, is too high to accurately correlate the defined weather classifications.

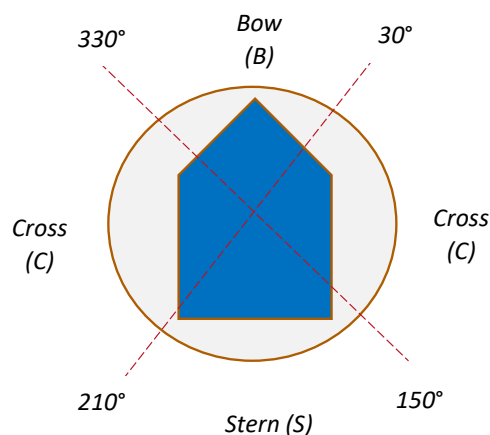


Figure 5-2: Definition of zones for the angle of attack of wind, swell and current effects.

5.1.2 *Ship parameters*

Besides the discussed weather effects, also some ship characteristics have been identified as variables that influence fuel consumption.

One of these general variables is the load of the ship; when it is sailing with ballast or with cargo and the respective tonnage. We know that the ship speed is a dominant factor in fuel consumption: reducing speed reduces fuel consumption. For the displacement, the same can be observed to a lesser extent, where decreasing draft decreases fuel consumption. The total tonnage and ballast on board is reported in both the noon-reports and the experiment reporting sheet. Another variable reported in both reporting instruments is the front, middle and aft draft of the ship. Moreover, hull fouling is not considered in this project.

Along with the main physical characteristics of the ship, the shaft generator is assumed to have effect on the main engine fuel consumption. In general, the shaft generator is reported to produce a steady 50 kW of power throughout the use. Turning the generator off would result in the need to use an auxiliary engine for onboard power systems.

5.2 **Experimental approach**

5.2.1 *Defined experiments*

Experiments were performed during the sea passage phase of a voyage to generate the required data for the proposed model. Here, conditions could be kept as constant as possible for the duration of the experiment as similarity in conditions made it easier to compare different experiments and to isolate effects in order to infer correlations. This will result in a more accurate model.

The experiments' procedures are specified in close cooperation with the project partners.

Main considerations were:

- **Minimal impact on daily ship operation;** this allows minimal adjustment to route, traveling direction and ship parameters (ballast, trim). In addition, an efficient test procedure was developed (see Section 5.2.2)
- **Safe operation;** very heavy weather conditions were not considered.

Based on these considerations, it was decided to vary the propeller pitch angle to create the desired graphs. This variation affects the shaft power and, consequently, the ship speed and has immediate effect on ME fuel consumption. Experiments were performed for various weather and sea conditions; main focus was on light and moderate weather conditions, while it was expected that heavy weather conditions might not occur in the test period. A test matrix was generated. For PROGRESS, an example is shown in Table 5-2.

Table 5-2: Test matrix for PROGRESS. Overview of results up to end of March. Colours indicate the 13 performed experiments (angle of attack: B=bow, C=cross, S=stern).

Weather	light	1-3 Bft	
Swell	B	C	S
Wind	B	C	S
Current	B	C	S
		2x	2x
Weather	moderate	4-6 Bft	
Swell	B	C	S
Wind	B	C	S
Current	B	C	S
		1x	4x
Weather	heavy	7-10 Bft	
Swell	B	C	S
Wind	B	C	S
Current	B	C	S

5.2.2 Test procedure

To gather the necessary data on fuel consumption under different scenarios and pitch angles, a stepwise experimental approach and data acquisition is proposed.

Figure 5-3 shows the three step approach to be taken by the captain and crew in order to complete one full experiment:

1. The operating crew member identifies the **weather conditions** and decides if these fulfil the experimental requirements;
2. The **weather directions are identified and reported** using the sheet shown in Figure 5-3, along with additional remarks and overall information;
3. The **experiment is carried out**, in which the pitch is changed at a 40 minute interval. Note that in an early stage some experiments have been conducted with 20 minute intervals, this however proved to be too short for the ship to reach steady-state operating conditions. The operating crew member fills in ship details in the reporting reference sheet from Figure 5-4 for each change of pitch.

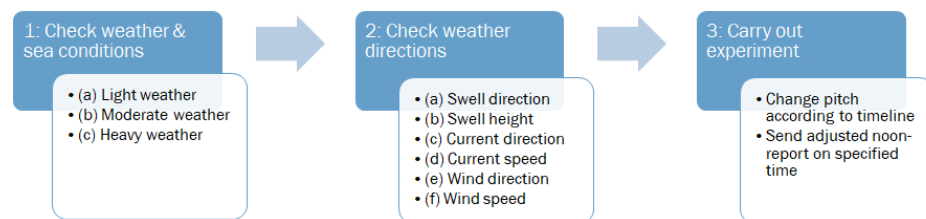


Figure 5-3: Stepwise experimental approach.

Ship							
Master							
Date							
Cargo in tons							
Total m3 ballast water							
		Experiment 1					
		Start (0 min)	Change pitch (+40 min)	Change pitch (+80 min)	Change pitch (+120 min)	Change pitch (+160 min)	Stop (+200 min)
Time (UTC)	<i>UTC</i>						
Position lat	<i>Lat</i>						
Position long	<i>Long</i>						
Pitch	<i>%</i>						
GPS speed	<i>knts</i>						
Heading	<i>°</i>						
Wind direction	<i>°</i>						
Wind speed	<i>bft</i>						
Current direction	<i>°</i>						
Current speed	<i>knts</i>						
Swell direction	<i>°</i>						
Sea height	<i>m</i>						
Rolling period	<i>s</i>						
Draft [F/M/A]	<i>m</i>						
RPM	<i>rpm</i>						
Fuel Remaining [ME counter]	<i>ton</i>						

Figure 5-4: Example of experiment reporting sheet.

At the start of the experiment, the ship sails with 80% pitch for 40 minutes and the required parameters are registered in the first (0 min) column. After 40 minutes of 80% pitch, the second stage is initiated for 40 minutes with 70% pitch. The required parameters are then documented in the second column of the reporting sheet. This repeats with 40 minute intervals for columns 3 through 6, for propeller pitch of 60%, 50%, 40% and 30%, respectively.

The variables in the reporting sheet are additional to the data acquisition systems as discussed in Section 3.2.1. The onboard reporting is necessary to provide insight in weather effects and the pitch changes, as these signals are only available in the noon report on a 24-hour basis. Time and position variables are reported in order to synchronize the reporting sheet with the sensor data. Additional variables such as fuel remaining on board and draft are added to provide a double check on some key indicators, for example the fuel consumption during the experiment and potential draft changes.

5.2.3 Determine steady-state operating points

Figure 5-5 and Figure 5-6 show examples of typical results for experiments performed in different weather conditions. The first subplot shows the change in propeller pitch angle. From top to bottom, the resulting ship speed, fuel consumption and shaft torque are shown. Note that the propeller pitching angle is not recorded digitally. As a result, the manually reported values were added to the sensor data according to the crews' recorded timestamp. For exact alignment of the pitching angle with the propeller shaft power, the recorded timestamp is shifted accordingly.

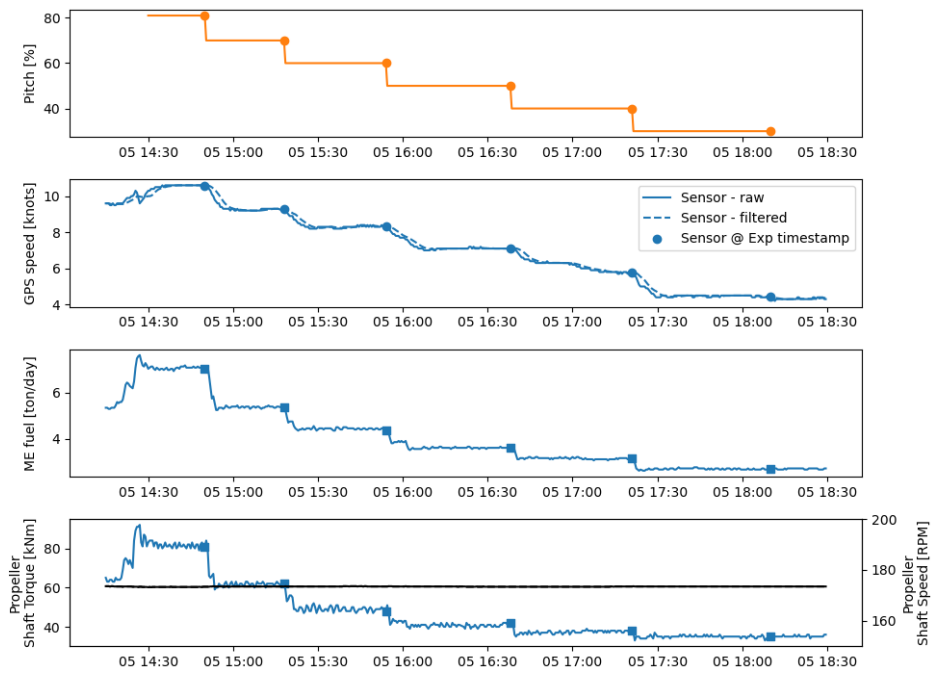


Figure 5-5: Example of experiment performed by ship PROGRESS in light weather condition on 5 January 2021.

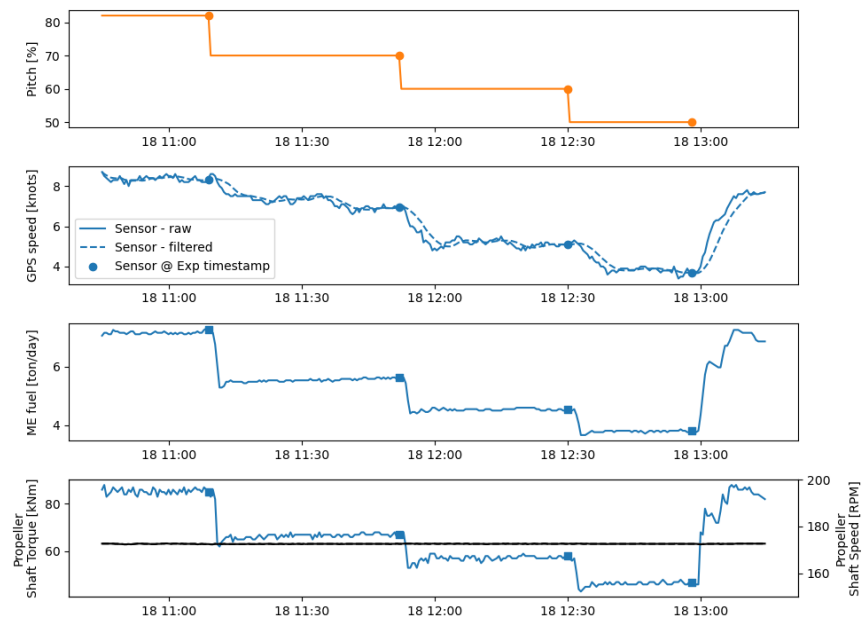


Figure 5-6: Example of experiment performed by ship PROGRESS in moderate weather condition on 18 March 2021.

For model development, we are mainly interested in stationary operating conditions. As seen from these figures, it requires some time until the ship speed is stabilised around a (nearly) constant value.

Then, stationary operating conditions are determined by taking the last sensor data point just before the change in pitching angle, which will be labelled steady-state values (noted with the blue square markers). The steady-state values were used for modelling purposes.

From the two examples, it is seen that as the weather condition worsens from light to moderate (increased wind speed and higher swell), the magnitude of the noise in the GPS speed signal becomes more significant. The data averaging method mentioned in Section 4.2.2 is applied to retrieve filtered signals. This also helps to determine stationary operating conditions.

5.3 Experimental results

5.3.1 Overview of experiment results

We performed 15 experiments during this study: 2 experiments were performed by ship PERFECT and 13 experiments were performed by ship PROGRESS. The experiments have been carried out mainly in the Mediterranean sea and the coast of Portugal, with the ship parameters and weather conditions listed in Table 5-3 and Table 5-4 and geographical locations illustrated in Figure 5-7.

Table 5-3: Overview of the ship parameters in the experiments.

Overview of ship parameters in experiment					
Ship	Test	Cargo load [ton]	Trim [F/M/A]	Ballast [m3]	Crews Code [-]
PERFECT	Per – Exp1	6250	5.9/6.3/NA	15	VB
PERFECT	Per – Exp2	6000	5.9/6.3/NA	215	PR
PROGRESS	Prog – Exp1	6000	5.8/6.1/6.4	320	DO
PROGRESS	Prog – Exp2	6140	5.4/6.0/6.6	21	DO
PROGRESS	Prog – Exp3	6140	5.4/6.0/6.6	21	DO
PROGRESS	Prog – Exp4	6140	5.4/6.0/6.6	21	DO
PROGRESS	Prog – Exp5	6140	5.4/6.0/6.6	21	DO
PROGRESS	Prog – Exp6	5500	5.5/5.8/6.1	155	KV
PROGRESS	Prog – Exp7	5500	5.5/5.8/6.1	155	KV
PROGRESS	Prog – Exp8	5500	5.5/5.8/6.1	155	KV
PROGRESS	Prog – Exp9	5500	5.5/5.8/6.1	155	KV
PROGRESS	Prog – Exp10	6105	6.0/6.0/6.1	0	KV
PROGRESS	Prog – Exp11	6105	6.0/6.0/6.1	0	KV
PROGRESS	Prog – Exp12	6105	6.0/6.0/6.1	0	KV
PROGRESS	Prog – Exp13	6105	6.0/6.0/6.1	0	KV

Table 5-4: Overview of the weather conditions during the performed experiment (mentioned directions are with respect to the map (N=0°)) (LW = Light Wind, MW = Moderate Wind, LS = Light Swell, MS = Moderate Swell, HS = Heavy Swell - see Table 5-1).

Overview of weather parameters during experiment				
Test	Wind / Swell category [-]	Wind direction [°]	Swell direction [°]	Range of current direction [°]
Per – Exp1	LW/LS	330	NA	21 – 54
Per – Exp2	LW/MS	40	330	42 – 54
Prog – Exp1	MW/LS	210	210	199 – 250
Prog – Exp2	MW/MS	330	330	73– 136
Prog – Exp3	MW/HS	360	360	54– 210
Prog – Exp4	MW/HS	270	270	105 – 168
Prog – Exp5	MW/MS	230	270	125 – 179
Prog – Exp6	MW/LS	100	110	263 – 312
Prog – Exp7	LW/LS	45	45	141 – 223
Prog – Exp8	LW/LS	90	90	134 – 293
Prog – Exp9	LW/LS	270	270	135 – 246
Prog – Exp10	LW/LS	110	270	72 – 330
Prog – Exp11	MW/LS	250	250	61 – 147
Prog – Exp12	MW/MS	270	270	242 – 292
Prog – Exp13	MW/MS	280	280	97 – 141

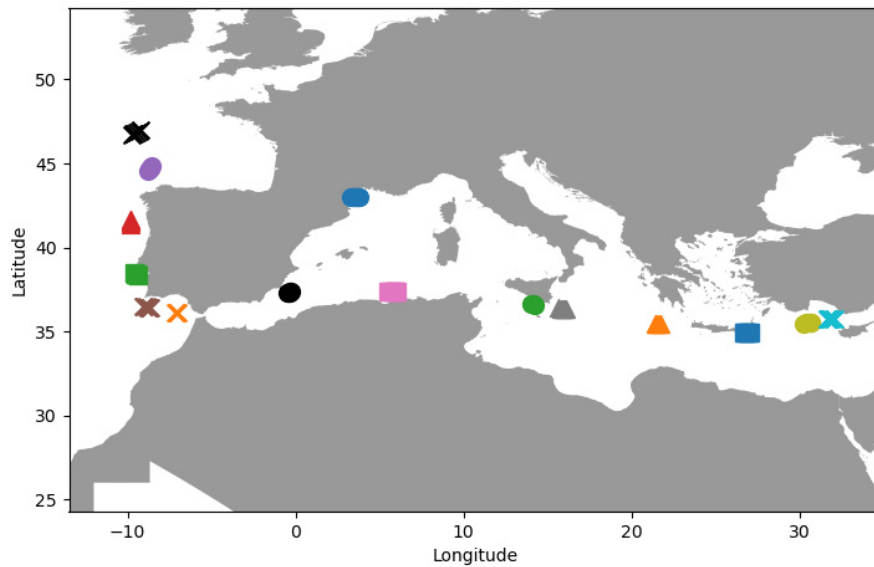


Figure 5-7: Geographical location of the 15 experiments performed by PROGRESS and PERFECT. Black markers indicate the locations of PERFECT during experiments and coloured markers indicate the locations of PROGRESS.

5.3.2 Determine correlations for sub-models

Following the approach described in Section 5.2.3, the determined steady-state operating conditions are used to generate correlation plots for each specific operating condition, as illustrated in Figure 5-8. The upper plots illustrate that the variation of pitching angle affects the speed of the ship and ME fuel consumption. In the lower plots, the corresponding ship load and engine fuel consumption models are shown.

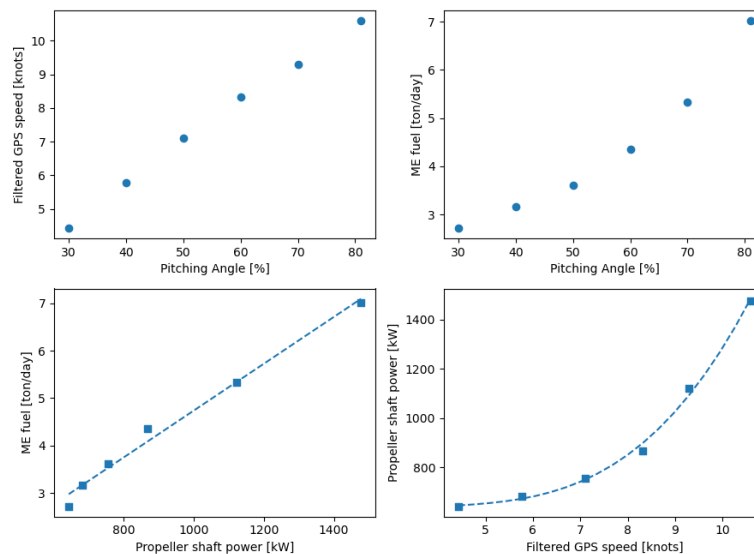


Figure 5-8: Correlation plots for PROGRESS based on the experiment illustrated in Figure 5-5, performed in January 2021.

At the moment, the model is formulated based on data in each experiment set. The coefficients of polynomials formulated are therefore only applicable to the ship parameter and environment condition during that experiment. Further investigation is needed to include the ship parameter and environment condition explicitly to design a universal model that is robust to variations of untested ship parameters and weather conditions.

5.3.3 Ship load model

Figure 5-9 illustrates the correlation plots between propeller shaft power and the GPS speed from all the performed experiments. The error bars plotted in Figure 5-9 are based on the standard deviation of the ship speed due to the weather effect. As the wind speed and the swell height increase, to the point of hindering the ship trajectory, additional propeller shaft power is needed for the ship to sail with the same speed.

Note that the chosen speed signal in the model is based on the GPS sensor. From the mission perspective, the GPS speed is more relevant since it is used to determine the total duration of the mission. Moreover, the GPS speed also represents the net result of the chosen LOG speed and the weather effect.

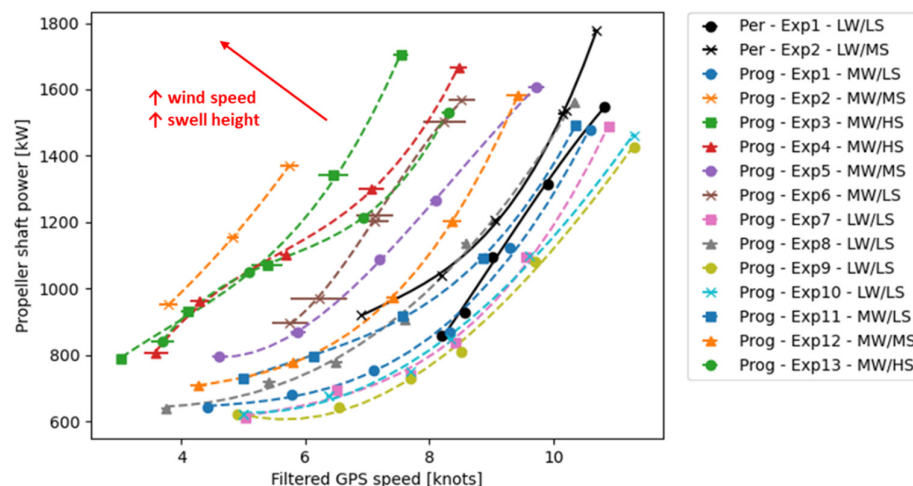


Figure 5-9: Data-driven ship load model based on 15 experiments performed by PROGRESS and PERFECT. Solid black lines are experiments performed by PERFECT and coloured dashed lines are experiments performed by PROGRESS. L*/M*/H* = Light / medium / heavy, *W/*S = wind / swell.

From the experiments carried out, a sample of datasets based on the weather condition can be selected and compared side by side, as shown in Figure 5-10. The left subplot shows that in the light weather conditions, the ship load model has some variation of correlation between propeller shaft power and the GPS speed. The variation in the light weather, however, is dwarfed by the large range of variation of the ship load model in the moderate weather condition in the right subplot.

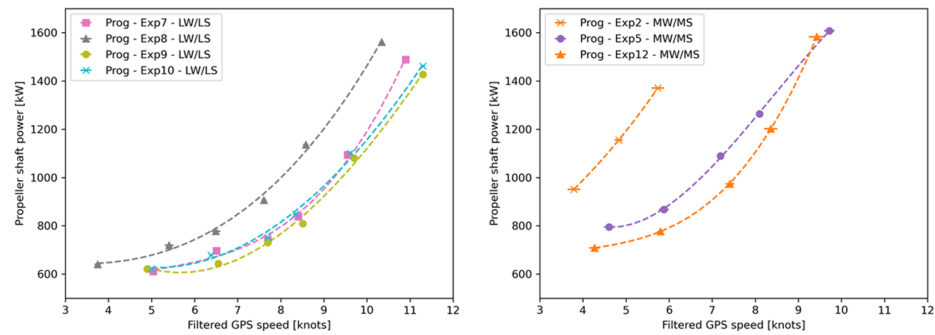


Figure 5-10: Comparison of ship load model from dataset in light weather condition (left) and moderate weather condition (right). Variation of ship load model due to light weather is smaller than the variation due to moderate weather.

This sample of datasets highlights the contribution of the external conditions to the ship performance, and consequently, the ship load model.

5.3.4 Engine fuel consumption model

Figure 5-11 shows the linear relationship between the propeller shaft power and the main engine fuel consumption. It is noted that the slope of this line is a measure for the powertrain efficiency.

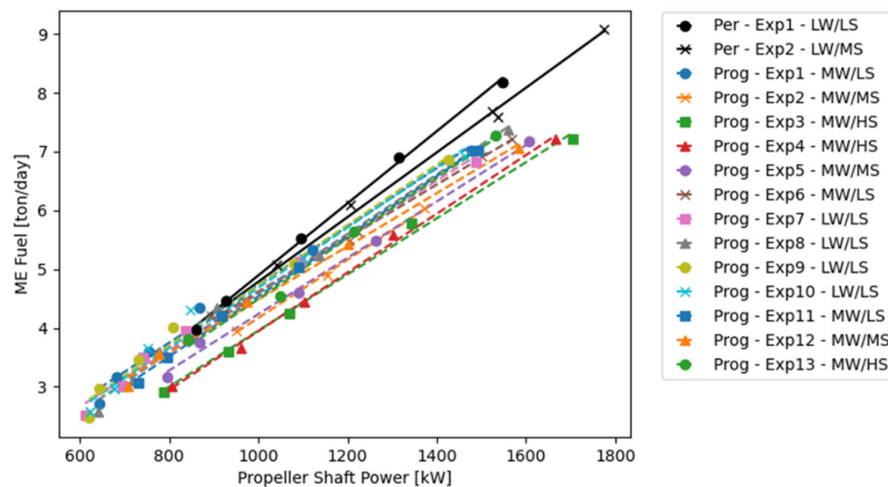


Figure 5-11: Data-driven main engine fuel consumption model based on 15 experiments, performed by PERFECT and PROGRESS. Solid black lines are experiments performed by PERFECT and coloured dashed lines are experiments performed by PROGRESS. L*/M*/H* = Light / medium / heavy, *W*/S = wind / swell

There is a spread in the linear model of the figure: to achieve the same propeller shaft power, there is variation of fuel consumption for the main engine. This variation may be caused by the variation of the fuel used to power the main engine (whether it is HFO or MGO), perhaps also due to the variation of the fuel quality or possibly because of inaccuracy of the fuel flow measurement (no information on return flow in booster tank, assumptions of flow towards main engine, ...).

To reduce the variation in the linear model, simple moving average method was applied to the fuel flow signal and the propeller shaft power, however, this method did not improve the quality of the linear model.

Another observation noted is the different trend between the fuel usage in PERFECT (marked by the solid black lines) and PROGRESS (marked by the various colourful dashed lines). All the experiments carried out by PROGRESS resulted in similar linear model of fuel consumption (gradient = 0.0049 ton/day/kW). These linear models, however, have a lower gradient than the fuel consumption of PERFECT (gradient = 0.0058 ton/day/kW), which suggests that the ship PERFECT requires higher fuel consumption to achieve the same propeller shaft power.

Further experiments with the ship PERFECT would be needed to find the root cause of this difference.

6 Definition of test cases

In order to demonstrate the potential of the developed fuel consumption evaluation method, two case studies are defined. These cases are seen as test scenario's for future real-world demonstration. The first case study illustrates that light weather conditions can already have a significant effect on the ship's fuel consumption. In the second case study, we propose alternative ship operation scenarios based on information of weather conditions.

6.1 Case study 1: Light weather effect

The first case study is based on two experiments carried out by the ship PROGRESS in the Mediterranean sea, labelled *Prog-Exp8* and *Prog-Exp9*, as shown in Figure 6-1.

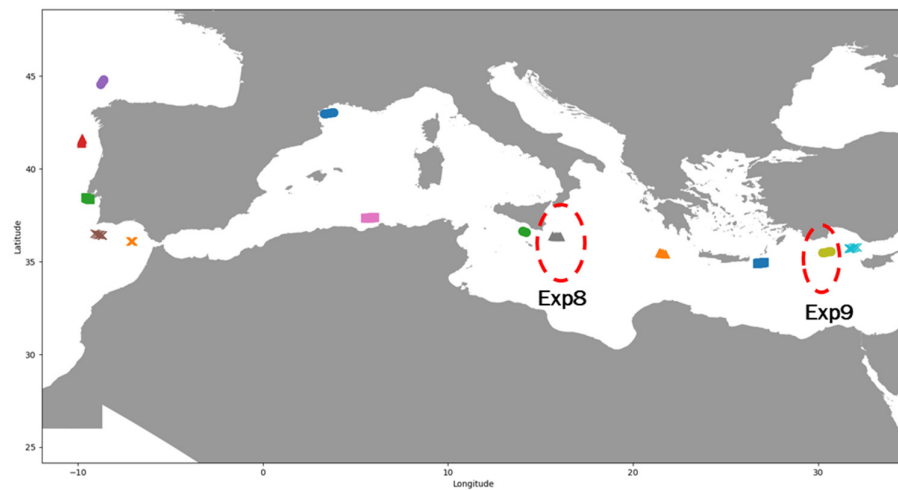


Figure 6-1: Location of experiment Prog-Exp8 and Prog-Exp9 carried out by ship PROGRESS. The ship is sailing within the same mission towards east.

The ship parameters and the weather conditions during the experiments could be found in Table 6-1 and Table 6-2. As the ship performed both experiments within the same mission, the ship parameters are almost equal. This analysis, therefore, focuses on the effect of weather and sea conditions.

Table 6-1: Parameters of Ship PROGRESS during Prog-Exp8 and Prog-Exp9.

Experiment timestamp and ship parameters					
Test	Date	Cargo load [ton]	Trim [F/M/A]	Ballast [m3]	Ship heading [°]
Prog – Exp8	01/03/2021	5500	5.5/5.8/6.05	155	96
Prog – Exp9	04/03/2021	5500	5.5/5.8/6.05	155	79

Table 6-2: Weather conditions during Prog-Exp8 and Prog-Exp9 (B=Bow, C=Cross, S=Stern).

Weather conditions during experiments				
Test	Wind Speed [bft]	Wind direction [°]	Swell Height [m]	Swell direction [°]
Prog – Exp8	3	90 (B)	0.5	90 (B)
Prog – Exp9	3	270 (S)	0.5	270 (S)

Wind direction wrt the ship			
Test	Wind direction wrt map [°]	Ship heading [°]	Wind direction ship [°]
Prog – Exp8	90	96	354
Prog – Exp9	270	79	191

As the ship is travelling with the same ship parameters and same fuel type, the correlation analysis between main engine fuel consumption and the filtered GPS speed can be directly plotted, see Figure 6-2. This figure illustrates that, depending on the weather and sea conditions, the fuel consumption profile of the ship is different.

For example, to sail with constant speed of 10 knots, the ship requires around 6.9 ton/day fuel during Prog – Exp8 but only around 5.4 ton/day during Prog – Exp 9. This results in around 22% difference in fuel consumption. On the other hand, for sailing with a constant fuel consumption of 4.3 ton/day, a ship speed of 8.9 knots is found during Prog – Exp 9, as opposed to 7.6 knots during Prog – Exp 8 (17% faster).

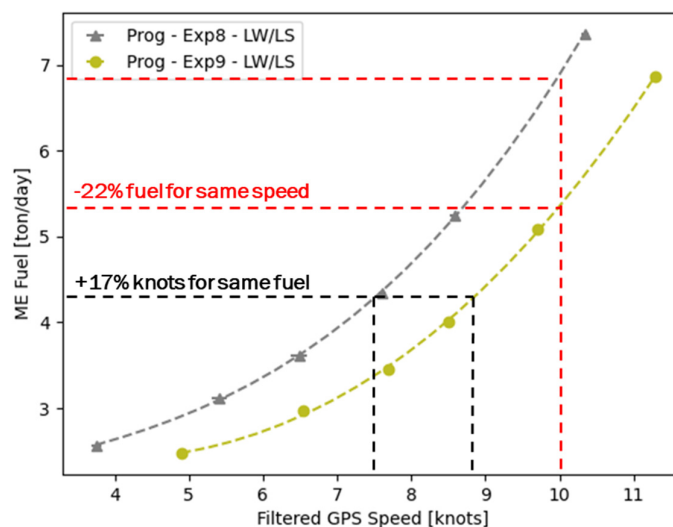


Figure 6-2: Correlation between ME fuel and ship speed from Prog-Exp8 and Prog-Exp9.

The difference in fuel consumption is attributed to the different weather conditions.

In Prog - Exp8, the direction of wind and swell is opposite to the ship's travelling direction (wind is blowing from ship's bow) while in Prog – Exp 9 the direction of wind and swell is in the same with the ship's heading (wind blowing from ship's stern). Furthermore, the magnitude of the current in each experiment could be calculated, as shown in Table 6-3. The difference in current speed, especially in higher LOG ship speed (8-11 knots) may also contribute to the change of the fuel consumption profile of the ship.

Table 6-3: Calculation of current magnitude according to Section 4.2.1 for Prog-Exp8 and Prog-Exp9.

Test	GPS speed (filtered) [knots]	LOG speed (filtered) [knots]	Current speed [knots]
Prog – Exp8	10.3	10.9	0.7
	8.6	9.4	0.8
	7.6	8.4	0.8
	6.5	6.9	0.3
	5.4	5.5	0.2
	3.8	3.7	0.1
Prog – Exp9	11.3	11.7	0.7
	9.7	10.5	0.5
	8.5	8.9	0.3
	7.7	7.9	0.1
	6.6	6.4	0.4
	4.9	4.7	0.5

This case study based on two experiments shows a clear difference in ship performance, even for light weather conditions. In this case study, the direction of the wind and swells are distinctly opposite: against the bow or against the stern and this resulted in a distinguishable difference in the ship performance. With the proposed modelling approach, these differences can be assessed and quantified. This opens the route to more accurate fuel consumption predictions for a specific voyage.

In a longer mission that spans for days, the ship will experience even more varying weather conditions and thus the trade-off between the fuel consumption and the ship speed has a wider range of variation compared to this case study. The second case study will therefore examine a mission with a longer duration and distance, with varying weather conditions.

6.2 Case study 2: Fuel- and time-optimal ship speed optimisation

The second case study is based on the results of four experiments performed by PROGRESS.

These experiments were carried out between 20 January 2021 to 24 January 2021 near the coast of Portugal, as illustrated in the left-hand graph of Figure 6-3. The ship parameters as well as the weather and sea conditions during these experiments are given in Table 6-4 and Table 6-5, respectively.

Table 6-4: Parameters of Ship PROGRESS from Prog-Exp2 to Prog-Exp5.

Experiment timestamp and ship parameters					
Test	Date	Cargo load [ton]	Trim [F/M/A]	Ballast [m3]	Ship heading [°]
Prog – Exp2	20/01/21	6140	5.40/6.02/6.65	21	284
Prog – Exp3	22/01/21	6140	5.40/6.02/6.65	21	296
Prog – Exp4	23/01/21	6140	5.40/6.02/6.65	21	354
Prog – Exp5	24/01/21	6140	5.40/6.02/6.65	21	22

Table 6-5: Weather and sea conditions from Prog-Exp2 to Prog-Exp5 (B=bow; C=cross; S=stern).

Weather conditions during experiments				
Test	Wind Speed [bft]	Wind direction [°]	Swell Height [m]	Swell direction [°]
Prog – Exp2	6	330 (C)	3	330 (C)
Prog – Exp3	6	360 (C)	5	360 (C)
Prog – Exp4	5	270 (C)	5	270 (C)
Prog – Exp5	5	230 (S)	4	270 (S)

Wind direction wrt the ship			
Test	Wind direction wrt map [°]	Ship heading [°]	Wind direction ship [°]
Prog – Exp2	330	284	46
Prog – Exp3	360	296	64
Prog – Exp4	270	354	276
Prog – Exp5	230	22	208

At the four different locations (indicated by different colours), the correlation between the main engine fuel consumption and the ship speed is determined, as illustrated in the right-hand side of Figure 6-3. These correlation curves visualise the effect of the weather and sea condition on the ship's operation profile.

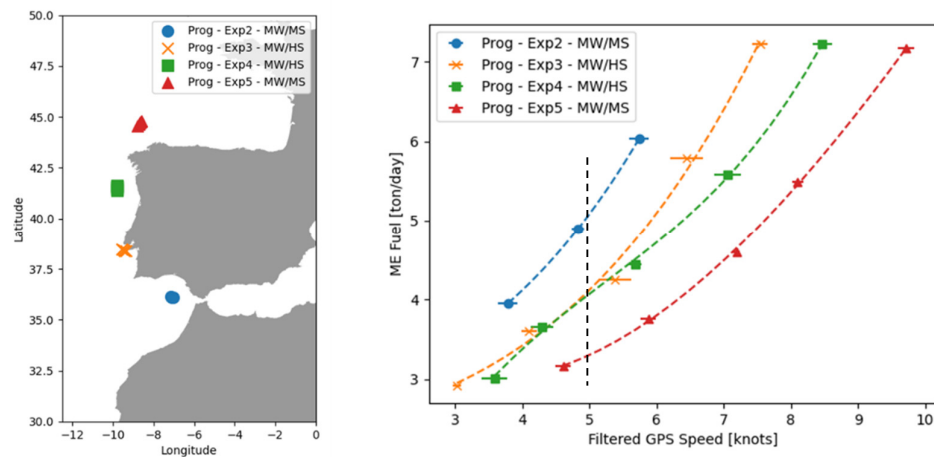


Figure 6-3: Case study: PROGRESS experiment 2 to 5 near the coast of Portugal (MW = moderate weather, MS = moderate swell; HS = heavy swell – according to Figure 5-2).

Considering a same ship speed (for example the black dashed line in Figure 6-3), exp 5 (red curve) has the lowest fuel consumption, while exp 2 (blue curve) has the highest fuel consumption. Exp 3 (yellow) and exp 4 (green) have similar fuel consumption until the ship speed is larger than 6 knots. The low consumption in exp 5 (red) can be attributed to the sea/weather condition that is not impeding the ship motion (wind and swell from stern side). The high fuel consumption in exp 2 (blue) is attributed to the bad weather that impedes the ship motion. These correlation curves are used to calculate the potential of fuel savings of the ship.

6.2.1 Simulated benchmark mission

A benchmark mission is designed by using the data after the end of each experiment. The corresponding ship operational and external conditions at the end of each experiments is assumed to be constant until the next experiment. Following this approach, we create a sailing profile consisting of four different stages. First, the timeline of the ship speed from the start of Prog-Exp2 until the end of Prog-Exp 5 is visualised in Figure 6-4. The experiments are labelled. The sailing conditions after these experiments, which are called “After Exp 2”, “After Exp 3”, “After Exp 4”, and “After Exp 5”, are assumed to represent standard ship operation and will be used to design the phases of the benchmark mission.

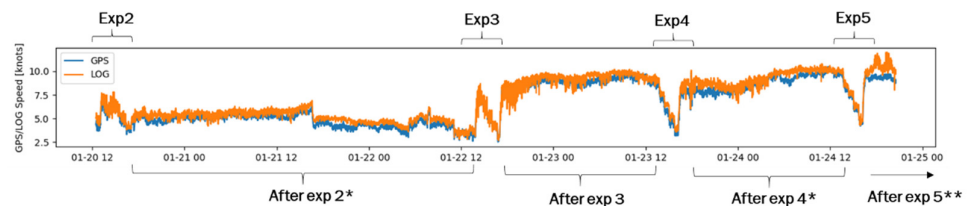


Figure 6-4: Timeline of ship speed for PROGRESS from the start of Prog-Exp2 until the end of Prog-Exp5.

Looking at the measurement data, several assumptions are made for designing the benchmark mission:

1. The benchmark mission has four distinct phases

Four distinct phases based on the four experiment results are used to design the benchmark mission. Each phase has a constant weather condition equal to the weather condition during the experiment (eg: “After Exp2” will have the same weather conditions as experiment “Prog-Exp2”).

The ship operation during each phase behaves according to the correlation curves plotted in the right-hand side graph of Figure 6-3.

2. * One constant speed in each phase

The ship speed timeline in Figure 6-4 shows that the sailing profile in “After Exp 2” and “After Exp 4” occurred at 2 different ship speed settings. However, weather conditions in these speed settings were not measured and therefore could not be defined as distinct phase.

In each defined phase of the benchmark mission, therefore, it is assumed that the ship always travel at one constant speed, with associated constant fuel consumption described in the correlation curves plotted in right side of the Figure 6-3.

3. ** Sail duration of “After Exp 5”

The sailing duration “After Exp 5” is assumed to be equal to the duration of “After Exp 3” and “After Exp 4”.

The designed benchmark mission profile is tabulated in Table 6-6 and visualised in Figure 6-5. For the benchmark mission, the total distance to be travelled is 642 nautical miles with duration of the sailing time of 94 hours with an estimated total main engine fuel consumption of 24 tons.

Table 6-6: Benchmark mission profile for Case Study 2.

Benchmark mission based on operation after end of experiment					
Test Label	GPS speed [knots]	ME fuel [ton/day]	Observed Duration [hrs]	Assumed Total Dist. [naut. mi]	Estimate Total Fuel [ton]
Prog – Exp2	4.7*	4.5*	40	188	7.5
Prog – Exp3	8.0	7.2	18	144	5.4
Prog – Exp4	8.0*	7.4*	18	144	5.6
Prog – Exp5	9.2	7.3	18**	166	5.5
Average/Total	6.8	6.1	94	642	24

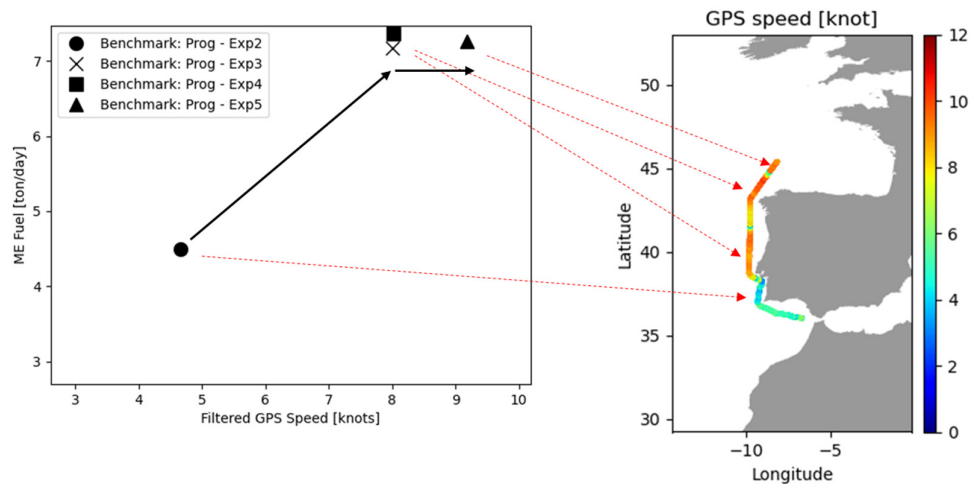


Figure 6-5: Visualisation of the ship performance in the benchmark condition per test label or per weather condition.

The benchmark mission can be described as follows: In the first part of the mission the ship encounters a bad weather condition. The captain chooses to sail at ship speed around 4.7 knots for safety reasons. When the ship has escaped the bad weather condition, the captain chooses to sail at a ship speed of 8-9 knots for the rest of the mission.

Two possible scenarios are simulated to show potential for fuel optimisation in the same mission profile, with trade-offs in sailing time.

6.2.2 Scenario 1: *Escape the bad weather as soon as possible*

The first alternative scenario assumes that it is possible to sail through the first phase (188 nmi of distance) in bad weather at maximum ship speed at 5.8 knots (highest speed measured during experiment), followed by a constant ship speed to match the benchmark total sail duration of 94 hours.

The progression of each phase in the simulation and the simulated ship parameters are shown in Figure 6-6 and Table 6-7.

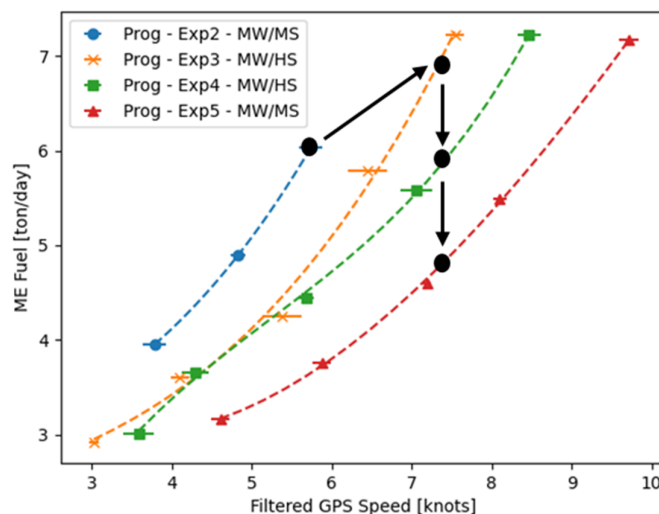


Figure 6-6: Visualisation of scenario 1: maximum allowable speed on first phase, followed by constant speed.

Table 6-7: Simulated ship parameters for Scenario 1.

Test Label	Scenario 1: Escape bad weather ASAP, new constant speed to meet time limit				
	GPS speed [knots]	ME fuel [ton/day]	Required Duration [hrs]	Fixed Total distance [naut. mi]	Estimate Total Fuel [ton]
Prog – Exp2	5.8	6.0	32.4	188	8.1
Prog – Exp3	7.4	6.8	19.5	144	5.5
Prog – Exp4	7.4	5.9	19.5	144	4.8
Prog – Exp5	7.4	4.8	22.4	166	4.5
Total			93.8	642	22.9 (- 4.6 %)
Benchmark			94	642	24

Scenario 1 shows that the simulated ship parameters resulted in 22.9 tons of main engine fuel consumption, which is a fuel consumption reduction of 4.6% compared to the benchmark situation.

6.2.3 *Scenario 2: Escape bad weather as safely as possible, followed by constant fuel consumption*

Scenario 1 is designed based on the assumption that it is possible to escape the bad weather with maximum speed. However, higher speed in the bad weather conditions may pose too high safety risks.

In scenario 2, it is assumed that the first phase is constrained with safe sailing at 4.7 knots similar to the benchmark case. For the remaining phase of the mission, the captain targets a constant fuel consumption rate of 6.8 ton/day (based on the benchmark mission average).

The progression of each phase in the simulation and the simulated ship parameters are shown in Figure 6-7 and Table 6-8.

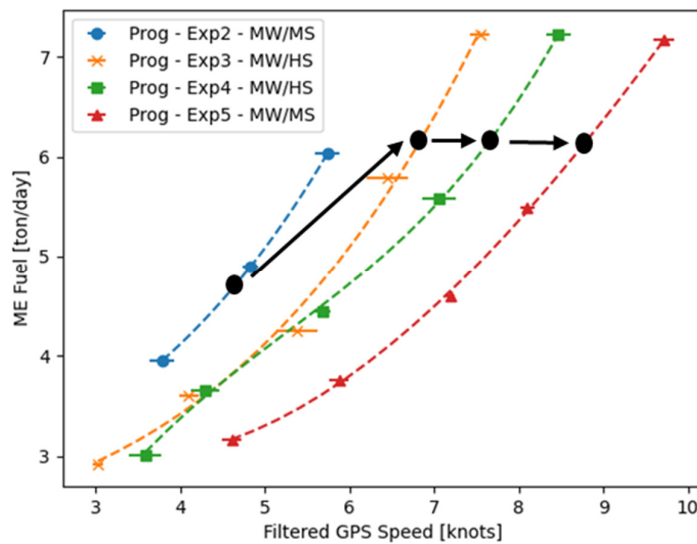


Figure 6-7: Visualization of scenario 2: safe sailing on first phase, followed by constant fuel consumption rate.

Table 6-8: Simulated ship parameters for Scenario 2.

Test Label	Scenario 2: Escaping bad weather <u>safely</u> , benchmark average fuel consumption				
	GPS speed [knots]	ME fuel [ton/day]	Required Duration [hrs]	Fixed Total distance [naut. mi]	Estimate Total Fuel [ton]
Prog – Exp2	4.7	4.5	40	188	7.5
Prog – Exp3	6.8	6.1	21.2	144	5.4
Prog – Exp4	7.6	6.1	18.9	144	4.8
Prog – Exp5	8.7	6.1	19.1	166	4.8
Total			99.2 (+5.5%)	642	22.5 (- 6.3 %)
Benchmark			94	642	24

In this scenario, the total sailing time increases up to 99.2 hours, which is 5.5% longer than the benchmark mission. At the same, the total fuel consumption is reduced down to 22.5 tons; this is a 6.3% reduction compared to the benchmark mission.

To summarise the results for case study 2, the trade-off between total fuel consumption and the mission duration is shown in Figure 6-8 for the studied scenarios. As a reference, the benchmark mission result is also shown.

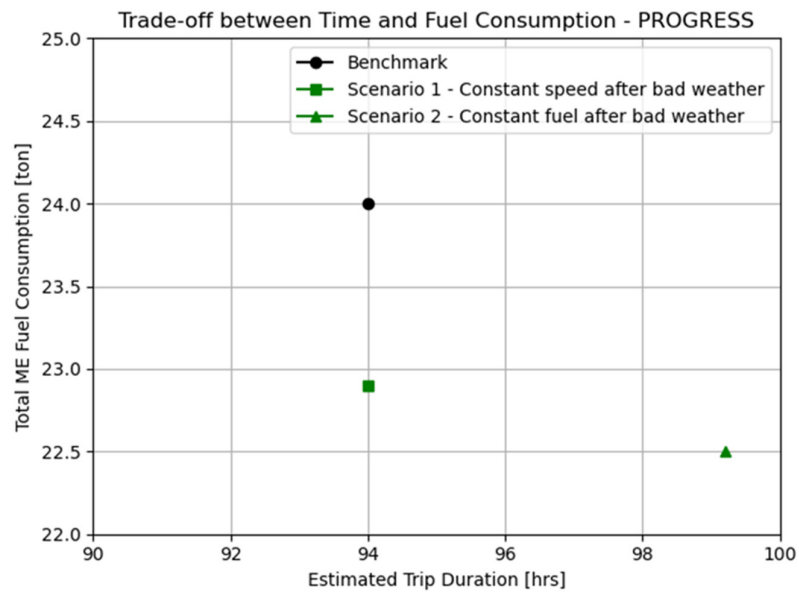


Figure 6-8: Trade-off between sailing time and fuel consumption in the benchmark mission and the scenarios in Case Study 2.

Both scenario 1 and scenario 2 show the potential for fuel consumption reduction by sailing-time optimal and fuel-optimal ship speed optimisation, respectively. This clearly illustrates that the constraint on the mission duration has to be defined clearly to fully exploit the trade-off between sailing time and fuel consumption. The shipping profile of the simulated scenarios in case study 2 is visualised in Figure 6-9.

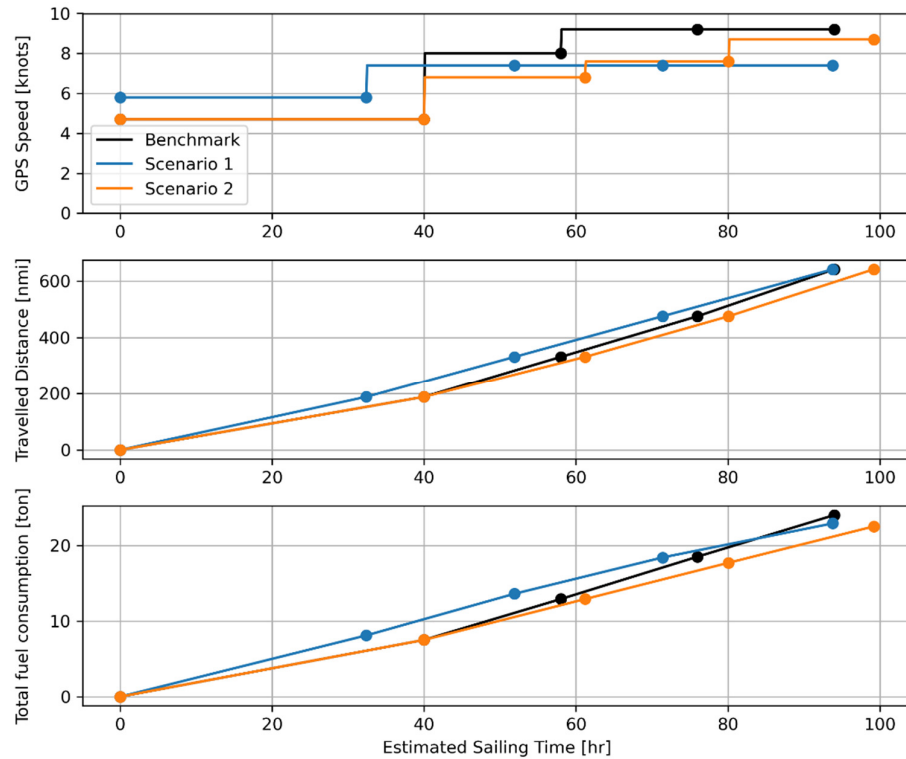


Figure 6-9: Shipping profile for case study 2: ship speed, travelled distance, and fuel consumption as function of sailing time.

The bottom subplot shows the fuel consumption profile of each scenario. For scenario 1, the fuel consumption in phase 1 is high due to high speed to escape the bad weather. For the rest of the journey, lower ship speed and thus lower fuel consumption closes the gap of fuel consumption, until it is lower than the benchmark at the end of the simulation.

For scenario 2, the fuel consumption in phase 1 is equal to the benchmark mission. However, a slower ship speed for the rest of trip results in lower total fuel consumption as the mission progresses, at the expense of total sailing time.

6.2.4 Conclusion on case studies

Case study 1 quantifies the effect of the weather and sea condition on the ship performance. Two experiments with distinct opposite directions of the wind and swell shows a huge fuel reduction with the same ship speed when the ship is sailing in the same direction of the wind and swell as opposed to against these environmental factors.

Case study 2 demonstrates the fuel saving potential by simulating different scenarios in the different weather conditions. With the collected measurement data, it is possible to quantify this potential. In real life, however, accurate simulation will require an accurate measurement of the weather conditions; not only at the current location, but also for the upcoming part of the mission.

It is therefore crucial to have good mission planning with reliable weather forecast information for optimal adaptation of ship operation.

6.2.5 Next steps

Additional experiments

During the research several experiment variations have been proposed to the standard 40 minute interval pitch changes. These variations aim to reduce uncertainty or more insight in different fuel consumption variables. One proposed variation to reduce uncertainty is to perform two experiments subsequently. When conditions remain fairly similar during this period, more can be said about the quality of data acquisition. Another option is to reverse the orientation of the experiment, instead of the proposed decline of 80% to 30% pitch, an increase from 30% to 80% pitch is suggested. This gives more insight on the relation between pitch, speed and fuel consumption. It also may result in more efficient experiments. Reducing speed is a passive process, because ships are not using active braking but rely on the current sea conditions. Since these are highly variable, a large buffer until steady state should be taken into account. Increasing the speed is an active process making the waiting time until steady-state shorter and thus experiment segments could be possibly shortened to 20-30 minutes instead of 40 minutes.

Lastly, as mentioned in Section 5.1, ship characteristics such as draft and generator have an influence on the overall fuel consumption. By varying these during normal experiment sessions, the influence of these variables on fuel consumption can be included in the model.

Adoption in operational procedures

The experiment process and data output result in an iterative process to further develop best practices and insights regarding fuel consumption, as shown in Figure 6-10. With the proposed experiments and additional variations, specific operating procedures could be established that result in minimal fuel consumption for a specific weather scenario and specific load of the ship.

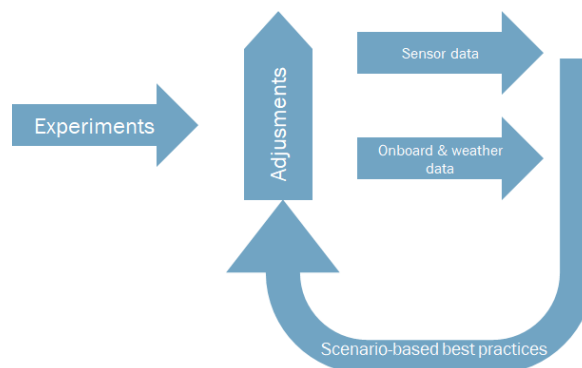


Figure 6-10: Iterative experimental process for scenario based best practices.

Calculation model accuracy

To design an accurate calculation model, more sailing data and the corresponding weather data is required. More specifically, weather data should be measured more frequently, not only during the experiment and not only during the noon reporting.

The prediction of optimal ship sailing profiles will become more accurate by designing a robust model that can handle large variations of ship parameters and weather conditions.

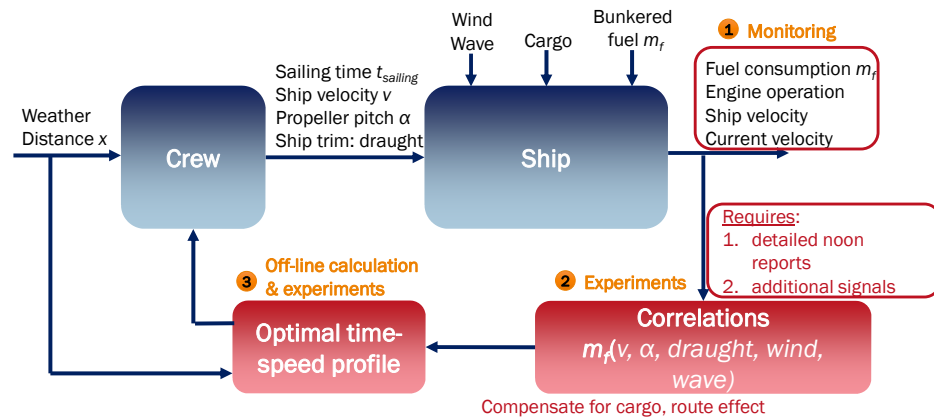


Figure 6-11: Illustration of next steps towards real-world implementation.

The current polynomial modelling is still constrained within each experiment condition, i.e., the varying weather and sea condition are not explicitly included in the formulation of the model. In the next step, the polynomial model is aimed to be able to predict the main engine fuel consumption in broader variations of weather and sea conditions. This will be crucial when the model is used by crews onboard when trying to predict the fuel consumption based on the weather forecast.

7 Conclusions and recommendations

7.1 Conclusions

The overall objective of the project is to pave the way for ship owners to perform effective monitoring of fuel consumption, assess fuel reduction measures and communicate achievements to external stakeholders.

In this project, we developed a systematic methodology that:

1. monitors the ship's actual fuel consumption; and
2. can give the and operators and crew advise on fuel-optimal sailing time.

To monitor actual ship performance, two key performance indicators (i.e. fuel consumption and sailing time) are derived and visualized. An efficient approach is introduced that integrates different data sources (i.e. ship data acquisition, noon report and bunker reports), checks data quality and derives the desired parameters based and post-processed data. For the first time, the project partners, especially ship owners and operators, got detailed insight in real-world fuel consumption and the impact of external factors for specific ships, voyages and crews. This opens opportunities to move from daily operation monitoring (with noon reports) to real-time monitoring. This data is also essential for operators to make a well-motivated trade-off between economical and technical criteria (see conclusion commercial partners).

For operator and crew advise, the developed methodology combines data with a ship operational model that is able to assesses and predict the key performance indicators (KPI's) under varying weather and sea conditions. This data-driven ship operational model was developed based on dedicated experiments performed by the crew. For mild and moderate weather and sea conditions, a qualitative categorization is introduced. The impact of ship parameters and of crew are not considered yet in the model.

The potential of the developed data-driven model is illustrated for two use cases. First desk study results are promising; up to 6% fuel consumption reduction is possible if the crew modify ship speed. To fully exploit the actual potential, this will require accurate knowledge of sea conditions and sailing time, i.e. arrival time.

7.2 Recommendations

Based on this study, the following recommendations are done:

- **Implement the operational scenarios that are proposed by the desk study.** Besides validation of the actual performance improvement and of the model prediction capabilities, it is also crucial to learn from the crew's experiences and further improve the introduced methodology;
- **Improved ship operational model** by including the effect of ship parameters, crew and fuel properties.

In addition, we strongly believe that validation of the model from separate experiments (preferably measured at other locations to prove generality) is essential to maximize the value of the developed model;

- **Automated tests to validate scenarios and further improve model.** This creates the necessary data sets for model improvement and methodology implementation with minimal effort for operation department and crew. Especially, we strongly recommend to add pitch angle and generator power to the ship's dataset;
- **Based on actual implementation results, a revision of the division of roles between charterer and ship owner (and additionally cargo owner and harbour) for more efficient sailing has to be considered.** A value chain analysis should be performed to give evidence of the possible gain (and possible necessity for policy measures and regulation) and societal consequences. The current research focused on ship level, but the added value possibly lies in fleet management;
- **Additional functionality of data usage;** examine use of real-world data to assess impact of hull fouling on real-world fuel consumption. Based on data and newly to be derived models, required maintenance can be predicted;
- **Ultimate goal is to develop a techno-economical model for cost-optimal sailing.** The current study focuses on fuel-optimal sailing time, which is a first step towards this end goal. As illustrated in Appendix A, this next step requires data and knowledge to create a journey OPEX model.

7.3 User perspectives and proposed future work

Taking the outcomes of the detailed research and case studies into considerations, the commercial partners identified a variety of conclusions, takeaways and opportunities for future research.

Before reaching a conclusion about the actual impact of this study on the day-to-day operations of operating and/or exploiting a sea going vessel, it makes sense to focus on commercial aspects first. After all, one has to observe that economic performance related aspects within a for-profit organisation often plays a more important role than ecological performance related aspects. Economic performance entails more than a focus on freight tariffs and/or fuels costs only. These aspects are all part of a broader picture with the ambition to facilitate customers/partners with competitive sustainable transport solutions. By acknowledging the importance of decarbonisation and the reduction of GHG, a transition of awareness and priority can be identified in favour of the ecological aspects of such business activities.

Taking the above transition into consideration, the economic principles of the exploitation of sea going vessels has changed. In the past, shipowners mainly focused on creating as much voyages (e.g. economic performance) per year as possible, without any direct restrains on ecological performance from stakeholders. Currently, shipowners are focusing on creating as much voyages per year, as ecological as possible.

Shipowners not operating in the upmost ecological manner are subject to increased pressure from multiple stakeholders, such as customers/partners and (semi-) governmental organisations.

From Rivermaas' or owners perspective, the outcomes of the case studies and the model developed in this research to potentially adapt the sailing time of a voyage and therefore optimise fuel consumption are clear. It can be concluded that fuel consumption during the voyage of vessels by means of adapting sailing time, using green maritime monitoring and the model presented by TNO, is indeed an opportunity that should be implemented. However, It should be emphasized that the window of opportunity to create such fuel savings is limited and restricted due to several external factors.

Two limitations that have a direct effect on the usability of the TNO model can be highlighted: (a) upfront knowledge about the characteristics about an upcoming voyage and (b) the technical characteristics of the vessel allowing it to amend its speed without negative economic effects on the operational expenditures (OPEX).

- a) Upfront knowledge about the upcoming events of a vessels turned out to be an important decisive factor whether or not a vessel can operate in a more ecological manner. After all, knowing that the vessel is on a tight schedule for the upcoming voyage is a hard limitation on whether or not the pitch of a vessel can be lowered (e.g. slow steaming). Currently, detailed information about the upcoming voyage, loading / discharging conditions and possible congestions are often unknown or not made available by external partners such as terminals and port authorities.
- b) Again, acknowledging the current focus on economic performance of a vessel, technical managers are instructed to minimise OPEX as much as possible. This means as less maintenance as possible, and therefore the crew is instructed by technical managers to operate as maintenance friendly as possible. In short this means that vessels should sail at its designed speed as much as possible at a pitch of approximately 80%. This results in the most optimum combustion and therefore minimises maintenance. Lowering the pitch of a vessel (e.g. slow steaming) can result in a less optimum combustion and an increased OPEX. This will come at the expense of the economic performance of the vessel and is therefore also an additional restriction to the model.

These restrictions are not taken into account in the model from an owners economical perspective (out of scope for this phase). In our believe, green maritime monitoring and other decarbonisation investments should create a commercial upside resulting in a strong sustainable business model for the concerned investments. Only in this way scalability can be created. After all, scalability is that unique and essential aspect of innovation that enables it to create significant impact on a complete industry.

It must be mentioned that current dominant positions and interests present within the maritime industry are respected within the boundaries of this research. The power game of the different perspectives and roles within the industry are not necessarily working together, on the contrary, several conflicts of interest are currently present within the industry at the expense of focus on ecological performance. A prime example of this is the interest of a technical manager versus the interest of commercial manager.

Both - in the case of Vertom, working within the same organisation - are working with the same assets, the vessel. As mentioned before, the technical manager mainly focuses on minimizing the OPEX. On the other hand, the commercial manager focuses on maximizing the economic performance. Both are not aligned (please also see the explanation of point b) since this implicates that a technical manager is instructed to ideally operate at its design speed (e.g. approximately 80% pitch) while to commercial manager aims to operate the vessel as fast (e.g. approximately 100% pitch) as possible and increases the number of voyages (e.g. increase the number of sailing days) as much as possible.

Aligning the interests of all parties currently active in the power game within the maritime industry would be an important subject for future research. Significant change will only be possible when the interest of dominant positions within the industry become in favour of in the ecological aspects of our business activities. Coming back to the increased scrutiny to enforce global decarbonisation by for instance the IMO and the EU, governmental organisations are currently enforcing this by means of additional rules and regulations, stimulating decarbonisation of the industry. As always, the industry will follow. Vertom has the ambition to become one of the leading shipowners within the shortsea shipping segment pushing the boundaries when it comes to providing our stakeholders with both economical and ecological transport solutions.

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9 Signature

The Hague, 5 november 2021



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A Cost optimal sailing

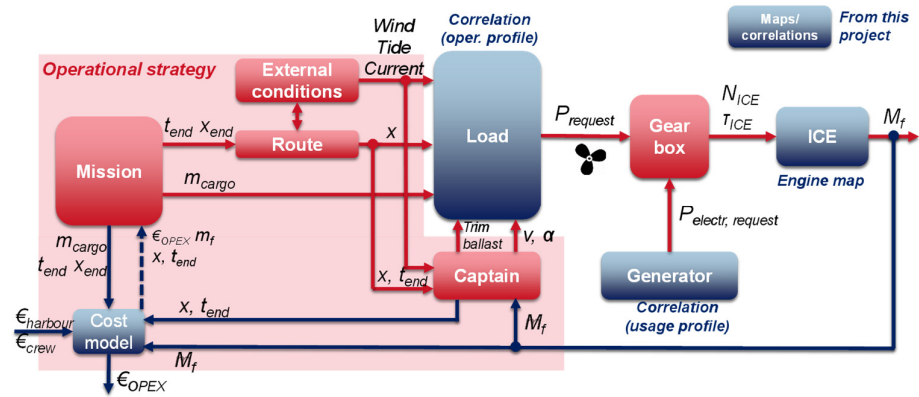


Figure A-1: Proposed model for cost-optimal sailing.