Systems modelling for energy-efficient shipping

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Summary

There is a wide selection of methods and models that can be used to predict and monitor energy utilisation in ships. There is, however, no single model/method that can be applied generally to a vessel to increase its energy efficiency. The shipping industry faces the challenge of reducing fuel consumption and air emissions. There is a need to understand how much energy is needed and used by the entire energy system of a ship but with a resolution that can analyse this usage at a subsystem or component level. This report presents a state-of-the-art investigation of published models and methods within the research area of ship energy efficiency. Emphasis is placed on the existing models and methods for energy systems modelling (prediction, monitoring and improvements) and their applicability, strengths and weaknesses. The report also presents a review of green ship energy concepts such as wind power as auxiliary propulsion in ships, together with ship routing optimisation. The outcome of the study highlights two important issues. First, there is a need to develop a generic holistic model that would be applicable for ship energy efficiency analysis and simulations. The current state-of-the-art shows that parts of such a model exist, but they need to be combined to interact on a common basis. Second, the potential of wind power to act as auxiliary propulsion and ship routing optimisation can significantly reduce energy consumption and improve the energy efficiency of ships. Several technical concepts have been evaluated and tested, and wingsails are a solution that, together with ship routing algorithms, can significantly lower fuel consumption.

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1. Introduction

More than 90% of the total transport of goods in the world currently uses vessels, which are unfortunately a significant source of emissions. These emissions account together for approximately 3% of global CO_2 emissions, 1-3% of SO_x and more than 10% of NO_x. The emissions are expected to increase further by between 150 and 200% before 2050 due to increased transport volumes. The European Commission's strategic document "A strategy to reduce atmospheric emissions from seagoing ships" underlines the importance of reducing emissions from ships to improve human health and the environment. Additionally, the EU and the Swedish national climate goals have the following objectives for the transport sector in 2020:

- a 20 percent improvement in energy efficiency,
- a 40 percent reduction in greenhouse gas emissions, and
- the use of at least 10% renewable energy.

To achieve these goals, sustainable sea transport with minimal environmental impact is required. At the same time, because of the rapid increase in the price of oil, the fuel for certain types of ships represents approximately 70% of the total transport cost. An increased awareness of the environmental impact, the global economic crisis and high oil prices are the driving forces for the development of more energy-efficient maritime transport with lower fuel consumption. This has been particularly evident over the last decade, as several national and international industrial and research projects have targeted energy-efficient shipping. These projects have studied, analysed and evaluated conceptual solutions and proposals for measures that could lead to more energy-efficient maritime transportation. A common denominator for the projects is that they are often focused on and sub-optimise a solution or an area of the ship, hereafter referred to as subsystems, without considering the fact that each subsystem must interact with the ship and its resulting total energy system as a whole. This sub-optimisation makes it difficult to apply results of these projects to other ship types and operating conditions than those used in the original research projects. However, shipping needs general methods and models to implement the right measures that can actually lead to credible energy saving measures. Consequently, there is a lack of a holistic overview, methodology and generic model.

The increased research interest in "green shipping" in the maritime industry is also reflected in the form of innovative ship design, operation optimisation, and smarter fuel-efficient engines. Additionally, various green concepts using wind have been investigated within the Swedish shipping industry, such as wingsails, kite-sails, Flettner rotors and wind turbines. A few years ago, Marinvest AB and the Department of Shipping and Marine Technology at the Chalmers University of Technology investigated the possibility of using wingsails. They found that, as for other concepts, a major obstacle to the practical implementation was the lack of an integrated system for optimisation and accurate estimation of energy savings and impact on the ship (e.g., stability conditions, fatigue). The lack of such a system entails high risk in both the economic investment and the ship's structural safety. Systems perspective along with reliability-based analysis and optimisations can be performed in a better way.

This report summarises the results from a state-of-the-art investigation of the application of and research into ship energy efficiency, focusing on models and methods for energy systems modelling and wind on ships as an alternative green concept. It also includes methods for ship route planning and route optimisation as part of energy efficiency. The report is divided into several chapters. Chapter 2 presents a general description of a ship as a system model, how it can be divided into subsystems or components, and where the connection points are between subsystems and challenges that follow from that. In Chapter 3, the results from a literature review and state-of-the-art monitoring of energy consumption/ship performance monitoring are presented. Different approaches are identified, and their advantages and limitations are discussed. Groups primarily working in Europe on this topic have been identified and are presented in connection to each approach. Chapter 4 continues to present and discuss existing tools and numerical models for energy efficiency prediction. As part of this chapter, in-house developed codes and commercial software packages are presented. Chapters 5 to 6 emphasise different solutions and techniques for wind propulsion. In addition to technical solutions for wind propulsion, routing tools and models that can maximise the benefit of using sails are presented and discussed. Some examples of ship routing commercial software are presented. Finally, in Chapter 7, concluding remarks from the study are outlined.

2. General description of a ship as a system model

Systems modelling is a technique that is used to visualise, analyse and potentially optimise complex systems in a broad range of applications. Energy system models are widely used to analyse the energy consumption and efficiency of energy systems in buildings or entire countries. These models can provide deep insight into the processes and interactions between different parts of a system or subsystems. The main difficulty with systems modelling is finding the right level of abstraction to be able to capture the nature of the system while also describing it by means of mathematical equations.

A system is a combination of equipment, machinery, external influences and processes that together fulfil a mission, and can be decomposed in specific functions. A subsystem is a complex group of machinery, equipment or processes that are used together to fulfil one certain function of the full system. Merchant ships at sea can be considered such energy systems, with the general mission to transport goods. This overall mission can be decomposed into specific functions (Mermeris et al. 2011):

- platform functions (carrying cargo, safety),
- hotel functions (HVAC, accommodation),
- general support functions (cooling, fresh water supply, fuel supply), and
- mission specific functions (cargo handling).

In Grimmelius (2003), system models of physical systems are categorised using four dimensions:

- model level, i.e., the level of detail in the description of the process,
- model time domain, i.e., the time domain in which the model is developed,
- application time domain, i.e., the time domain in which the model is applied, and
- model data, i.e., the amount and character of required data to produce useful output.

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In the first dimension, model level, three approaches can be identified: black box, grey box and white box models (Grimmelius 2003). Though the last is fully based on physical principles and might result in complex differential equations and slower models in terms of computational time, a black box model describes a pure input/output relationship. A grey box model is a combination of transfer functions similar to the black box and white box methods. A considerably deeper understanding of the natural process is required if a white box model is to be applied, but the simulation will at the same time deliver more valuable results and a deeper insight into the process (Grimmelius 2003).

Model time domains can be divided into steady-state and time-dependent domains, and the latter can be further divided into time domain behaviour or frequency domain behaviour. Steady state models are the least expensive in terms of computational effort but are unable to represent dynamic processes where a time dependent model is needed. Of great importance for the required performance of the model is the application time. If real-time use is required, the computational effort must be minimised and well specified. If real-time use is not required, only practical limitations should be kept in mind. For example, if the model should be used for a huge number of simulations within an optimisation loop, the computational time should not exceed a specified maximum for practical reasons. Finally, the available or required input to the model is of importance for model development. In Grimmelius (2003), four categories are specified:

- models requiring limited measurements,
- models requiring limited system parameters,
- models requiring mainly parameters, and
- models requiring mainly extensive system parameters.

When applied to a ship's energy system model, several approaches must be considered. A simulation model of an engine or engine component might require a time-based simulation, whereas a prediction of the ship's propulsive power requirement can be performed with a steady state simulation if only one operational point is of interest. For the model input, the requirements are different for each subsystem. An engine simulation for example requires a considerable amount of system parameters but can be completed with only a few measurements, whereas the propulsive power prediction requires much more measurements of the ship's condition and the weather. Altogether, a holistic ship energy model will fall into several categories and thus be much more complex than a subsystem model. The complete system must therefore be divided into its components to define the structure of the entire system model.

2.1 Division into components

A general energy system can be divided into three main components (Baldi 2013, Osses et al. 2014): supply, conversion and consumption/demand. Additionally, a component for waste can be inserted, which becomes useful, particularly with the focus of a ship's waste heat recovery and cooling systems. An overview of a generic ship energy system is given in Figure 1.

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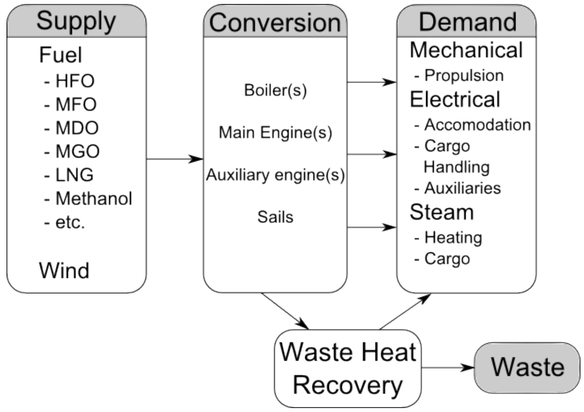

Figure 1: Overview of a ship energy system.

On the supply side, usually wind is not part of the efficiency evaluation because it is difficult to measure how much of the available wind energy is actually used by sails. Additionally, the energy available from wind is considered available without costs other than those for the sails and equipment. Thus, the efficiency can be evaluated using the difference between the theoretical energy available in the fuel on board and the energy that was produced from this fuel. In shipping, efficiency is often considered the quotient of used energy (fuel) and transported cargo, which makes the ship's light weight part of the energy system. Using this formula, a lighter ship with the same cargo capacity will certainly have a better efficiency, assuming that the hull form and ship systems are of the same quality.

The components demanding electrical power or steam are rather easy to capture because they physically exist in the engine, cargo or accommodation compartments of the ship. For an existing ship, the energy consumption of these components can be measured, and those measurements can be used for model development. A generic model of these components, conversely, requires many system parameters and assumptions or special models for environmental parameters.

The total demand for propulsion is also measured rather easily for an existing ship because the propeller shaft power can be measured by means of revolutions and torque. Simulating and predicting the propulsion power demand is, however, complicated. In fact, the propulsion of a ship is a complete and complex subsystem. A ship's calm water resistance can be divided into viscous form, frictional and wave making components. Additionally, added resistance in waves, due to wind, due to steering and due to added roughness will appear under service conditions, according to Kristensen and Lützen (2012).

Figure 2 provides an overview of the components of a ship as an energy system, including the links to the environment. The energy input and output is illustrated for each component. Of course, not all of the components exist in every ship's energy system.

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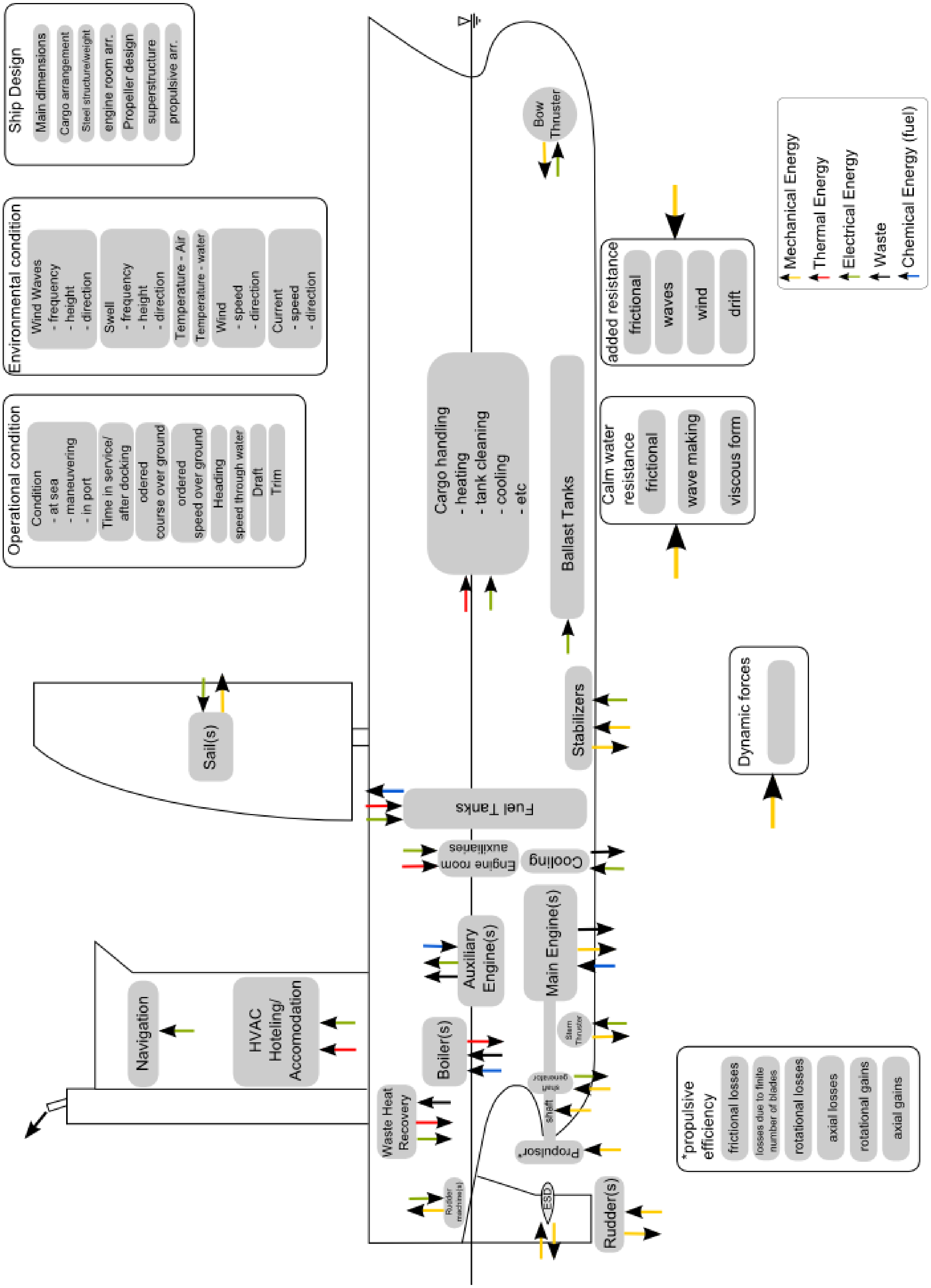

Figure 2: Overview of system components and influences to the energy system.

2.2 Connection points and challenges

In a ship as an energy system, three main connection points can be identified: the propeller-hull interaction, the propeller-main engine interaction and the response of the ship in environmental conditions. The latter can be further divided into the response of the different components. The resistance of the ship is primarily dependent on the wind, waves and water temperature. Further components such as the HVAC system or the cargo handling (in particular heating and cooling) are dependent on the air temperature and wind chill effects. Additional, secondary connections can be identified, such as the response of the generators (especially in connection with shaft generators), waste heat recovery systems and boilers on the main engine load.

The propeller-hull interaction is often referred to as the propulsive efficiency (Kristensen and Lützen 2012). It is defined as the difference between the effective power (resistance times speed) and the power that can be measured at the propeller shaft. For single propeller ships, the propulsive efficiency is approximately 0.6-0.7, and twin skeg ships can have a propulsive efficiency up to 0.85. To understand the reason for these losses, the total efficiency can be divided into six components (Dyne 1995) as shown in Figure 2 and listed below:

- axial losses,
- rotational losses,
- axial gains,
- rotational gains,
- losses due to infinite number of blades of the propeller, and
- frictional losses.

To define these components, one must analyse the wake pattern of the hull with a working propeller just before and behind the propeller (Dyne 1995). Axial and rotational gains appear if the propeller fills in a wake or recovers a rotation that exists in front of the propeller. Axial and rotational losses occur when rotations or axial velocities that are higher than the ship's speed appear in the slipstream of the propeller. Theoretically, a ship can have a propulsive efficiency higher than one, assuming that the propeller can fill the entire wake and recover the existing rotation to be zero in the slipstream. In practice, however, this is not the case. Energy-saving devices (ESDs) often work by creating a rotation in front of the propeller or by neutralising the rotation in the slipstream to increase rotational gain or decrease rotational loss. Wake equalising ducts aim to decrease the axial losses (accelerating ducts) or increase the axial gains (decelerating ducts); see Dyne (1995). ESDs or specially designed hull forms that should increase the wake in the propeller plane cause a higher propeller load and might lead to higher rotational losses. Unfortunately, the wake pattern of a hull with a working propeller is not easy to predict. To run a full analysis using the above theory, full viscous CFD computations with a working propeller have to be performed.

In model tests or theoretic predictions, the propulsive efficiency is determined by using either approximations (in theoretic predictions) or tests without a working propeller to determine the resistance of the hull. Later, tests with a working propeller can be used to measure propeller power. According to this method, the propulsive efficiency is divided into the propeller open water efficiency, the relative rotational efficiency (the difference between the open water efficiency and the efficiency in behind conditions) and the hull efficiency (ITTC 1999). A clear

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explanation of which losses and gains are captured for efficiency in this method can unfortunately not be given. Because the latter method is used in model test predictions, many statistical data are available. Thus, this method is often used for theoretical predictions.

In conclusion, the propeller-hull interaction is challenging because the propulsive efficiency depends not only on the hull form and propeller design but also on the operational condition, i.e., the propeller load. The propeller load is often defined using the advance ratio $J = v_a/nD$, where v_a is the advance speed of the propeller, D is the diameter and n is the revolution (rpm). For a fixed pitch propeller (FPP), the torque and thrust are directly coupled to the rpm. Additionally, the velocity of advance is not equal to the ship speed due to hull form, propeller design and propeller load specific efficient wake (w_e) of the hull.

For calm water conditions and clean hull and propeller (FPP), the advance ratio of the propeller is almost constant over a wide speed range. Due to added resistance caused by wind, waves or fouling, the advance ratio can be considerably reduced because the speed of advance is close to constant but the revolutions of the propeller must be increased due to the higher demand of thrust and torque. Additionally, propeller fouling causes higher torque values at the same rpm and similar thrust. These points together lead not only to a higher propeller load but also to difficulties concerning the engine-propeller relation because the engine has upper limits for deliverable torque at a certain rpm and for the rpm itself. Thus, an involuntary speed reduction caused by one of these effects must be accounted for when modelling the energy system. In conclusion, finding the equilibrium of the propulsion system of the ship, which consists of resistance, propulsive efficiency, propeller and engine characteristics, is a major challenge.

3. Monitoring of energy consumption/ship performance monitoring

Ship performance monitoring describes the process of measuring the ship's actual energy consumption and predicting the theoretical consumption considering the environmental conditions. Tools, equipment and methods for monitoring the performance of ships have existed for a long time, as reported by Crane (1982) and Tosi et al. (1982). However, the wide application of such systems was first driven by the rising fuel costs and the declining market situation during the past decade. The purpose of such analysis and measurements is monitoring of the vessel condition, particularly hull and propeller fouling. It is also important for the control of the ship's operational state, which offers the opportunity of operational optimisation, especially with regard to speed and draft/trim (Hansen 2011). In addition to performance monitoring with regard to the ship's resistance and propulsion performance, monitoring the ship's energy system, especially the main engine, is possible and was developed for steam plants in the 1980s (Crane 1982).

Monitoring of the energy consumption of the ship can be performed using mass flow meters measuring the fuel consumption of the main and auxiliary engines. Due to earlier discussed environmental influences on the ship's hydrodynamic resistance and power consumption, such measurements will not give any indication on how well the ship is operated or the conditions under which the systems, the hull and the propeller exist. To analyse the performance of the ship, a power prediction model must be used, as discussed and presented by Hansen (2011) and Andersen et al. (2005). For this approach, multiple measurements are needed, including the ship speed, the fuel consumption, the loading condition of the ship (draft and trim) and environmental

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conditions regarding wind and waves. Using the measured environmental data and loading conditions, a prediction of the fuel consumption can be performed using the theoretical model. The predicted consumption can then be compared with the actual consumption, and the performance of the ship can be evaluated (Hansen 2011).

Difficulties can be identified at two points (Hansen 2011). The first point is data logging and acquisition, and the second is the prediction of added resistance due to waves and loading conditions. In Hansen (2011), manual data sampling proved to introduce many uncertainties and possible errors, and Caprino et al. (1993) discussed the automatic logging of available parameters. Automatic data logging can often be performed using the ship's existing systems (Hansen 2011) and customised time steps. The latter provides the opportunity to adjust the amount of data by determining which of the measured parameters are actually time-dependent. These time-dependent parameters can then be sampled with shorter intervals. However, only data that can be measured on board can be collected using the ship's systems. One main problem thus remains, which is the measuring of wave height and frequency. In general, five options are available:

1. Manual estimation of the wave height by deck officers. This is most likely the most uncertain option.
2. Estimation of the wave height using the wind speed, geographical position and statistical wave data. This option requires detailed analysis of the geographical position and weather in close areas and might only work well for a certain amount of time.
3. Estimation of the wave height and period using on board measurements of the motions of the ship. This option was used in Hansen (2011).
4. Measurement of the wave height using on board wave radars. This option will certainly give adequate results but requires additional equipment on board the ships.
5. Measurement of the wave height using radar pictures from the ship's radar system. A 3D Fourier analysis of the picture from a conventional radar systems was developed by Young et al. (1985), but an application of such a system could not be found.

Once the data are collected, the second problem is the prediction of the added resistance or the prediction of the baseline performance of the new hull in the present condition. The resistance of a ship in service can be divided by the calm water resistance at a certain loading condition for which resistance data can be obtained from model tests. A theoretical prediction or computation is available, and numerous added resistances due to the ship's condition and the environment are listed below (ISO 2002):

- calm water resistance at even keel and known loading condition,
- additional resistance due to trim and loading condition,
- additional resistance due to salinity, density and water temperature,
- additional resistance due to steering,
- additional resistance due to wind,
- additional resistance due to waves, and
- additional resistance due to shallow water.

Additionally, effects from current and drift must be considered if the ship's speed is not measured as pure longitudinal speed through the water. In the ISO guidelines (ISO 2002) and the ITTC

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proceedings (ITTC 2002), the necessary measurement data and methods to evaluate the above-listed effects are presented. Most of the effects are captured by analytical formulas, except for the additional resistance due to the loading condition and trim as well as the additional resistance due to waves.

The additional resistance due to draft and trim is highly dependent on the hull form, particularly the bow region, and does not have linear relationship with draft or trim. Especially for ships with a large bulbous bow, the residual (wave making) resistance is influenced by the draft at the forward perpendicular, as shown in Larsen et al. (2012), where a variation of the propulsive efficiency was found in addition to the variation in resistance over draft and trim of a large cargo vessel. The non-linear behaviour of the power variation was shown in Liu et al. (2011). It has been suggested that viscous CFD computations or model tests should be performed to capture these effects.

Added resistance due to waves and ship motion is difficult to evaluate with a high level of accuracy. Early strip theory methods were developed in the 1970s (Boese 1970) and can primarily be used for early design evaluation when quick responses are needed. In Journée (1992), it was found that the results were satisfactory for conventional, slender mono hull ships. However, due to the nature of the strip theory, the results would not be satisfactory for ships with large bulbous bows, very full block ships or if the wave encounter frequency is very high (Pérez 2006). More satisfactory results can be obtained using 3-dimensional, non-linear methods, as discussed by Fang et al. (2006), including Maruo's far field method, as shown by Liu et al. (2011) and proposed in ISO (2002). The implementation and validation of a nonlinear boundary element method for ship motions is discussed by Kjellberg (2013). The method presented by Liu et al. (2011) was able to provide a satisfactory evaluation of the added resistance for different wave lengths for both, slender and full ships. Additionally, the reported computational time was very short, which offers the opportunity to use such a method to compute a large number of cases. This would be necessary if applied for the performance evaluation of ships in seaway.

Aside from computational methods, model tests in regular waves will still give the most reliable results and are widely used to validate the computational methods. However, extensive model test results, including trim variation tests, were available for the study undertaken by Hansen (2011). The resulting performance indices or estimated roughness of the hull showed a considerable large spread over time. This might be due to the rather simple approach that was used to estimate the added resistance due to waves, which is an empirical formula based on the wave height, ship's breadth, water line length and the block coefficient (ITTC 2005, Hansen 2011). Thus, no influence of the hull form, especially of the forebody form, was analysed. This spread shows the very high importance of an accurate estimation of the added resistance due to seaway.

The result of performance analyses is often shown as a "slip", a "performance index" or the theoretical roughness of the hull at a certain time (Hansen 2011). The slip or the performance index is the difference in predicted power and measured power, whereas the hull roughness is obtained by assuming that the difference in the predicted and measured power is caused purely by added frictional resistance.

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4. Tools and models for energy efficiency prediction

Numerous tools and methods for energy and performance prediction of ships are available both commercially and academically. These will be divided into two groups, i.e., holistic and subsystem models, and discussed in the following chapters. Commercially available tools and software will be mentioned in Chapter 4.3.

4.1 Holistic models

As of today, no commercial tools are available for the holistic prediction of the energy consumption of a ship. Holistic means that all parts, including the propulsion, resistance, engine, hoteling, cargo handling and environmental influences, are taken into account. The mandatory components of such a holistic model were discussed above and can be found in Figure 2. Furthermore, there have been two holistic models reported from different universities:

- the entire ship model and ship impact model reported from University College London (Calleya 2014, Calleya et al. 2014), and
- the dynamic energy model from University of Strathclyde (Mermeris et al. 2011).

The first model from University College London is based on a method to apply rather small changes to the baseline ship from which the energy systems and behaviour is known. The method is divided into two levels of detail: the ship impact model and the whole ship model (Calleya et al. 2014). Whereas the ship impact model provides a high level view of the ship and its impact on the fleet, the whole ship model provides a more detailed view on the changes of the single ship itself. The model is built using Paramarine and Matlab (Calleya et al. 2014). The hydrodynamic properties of the models ships are obtained using the Holtrop-Mennen method (Holtrop et al. 1982). Due to the nature of this method, the ship model cannot give any information about the engine load, propeller-engine or propeller-hull interaction. Thus, this model is more suitable in an early stage of the design process when the level of details is low compared with other holistic or subsystem models.

The dynamic energy model from the University of Strathclyde is assembled from numerous sub system models using Matlab/Simulink (Mermeris et al. 2011). As the name indicates, this model is time dependent and can thus provide information regarding changing energy consumption over time. It is not clearly described by Mermeris et al. (2011) whether the model is reversible, i.e., if the user can, at the same time, provide the ship's speed as input to the propulsion system and the next time the main engine power. Mermeris et al. (2011) also mentioned that the resistance and propeller-hull interaction were not yet integrated. According to Marzi (2014) the integration of the hydrodynamic components is done by means of CFD computation and response surface technologies for the hull resistance and an artificial neural network (ANN) for propeller properties. One drawback of using Simulink for such models can be attributed to the fact that Simulink models information flow and not a real physical model. Thus, the model becomes more complicated and more difficult to work with. Overall, this model seems more flexible and detailed than the first mentioned model, but it is not clear how it can be used when limited information is available, such as with early ship design.

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4.2 Subsystem models

A subsystem model is a model of only one part of the entire ship. This could be the main engine, the hull resistance or a combination of some parts. The different types of subsystem models existing are discussed in the following items.

Models for resistance and propulsion

One can classify most performance analysis and monitoring tools and models as subsystems for resistance and propulsion. This is true if the main engine parameters are not taken into account, with the exception of the main engine power. Most of the common commercial tools are models of this type. These tools are discussed in Chapter 4.3. In addition, numerous power prediction methods are available that can be considered models for resistance and propulsion. Methods for the calm water resistance are described by Kristensen et al. (2012) and Holtrop et al. (1982). A simple method for the added resistance in seaway is described in ITTC (2005), but both should be classified as more theoretical/empirical methods than as energy models.

Main engine models

There are numerous main engine models found in the literature, and most of them use slightly different approaches and are more or less flexible. Most of the more detailed models are focused on either 2- or 4-stroke engines. An example for a theoretical engine model is reported by Osses et al. (2014). In such a model, the shaft load is simply set by an assumption and no hydrodynamic properties or loads from shaft generators are taken into account. A different approach of using CFD to model the diesel engine is reported by Jin et al. (2013). Such a model can give accurate results for certain operational points but may be too time-consuming to be included in a holistic energy model.

Main engine and propulsion models

These models capture the main engine performance coupled to the hydrodynamic properties of the hull and are therefore very well suited for more advanced performance analysis, as discussed and presented by Hansen (2011). In Schulten (2005), a coupled main engine and propulsion model is used to predict the power consumption and engine behaviour of a ship during manoeuvring. The models used at the University of Athens (Papalambrou et al. 2012) and Newcastle University (Tian et al. 2012) follow the same strategy of considering only the main engine and the hydrodynamics. The approach to leave out all other on-board systems apart from the main engine seems suitable if the main interest is the performance of the ship in terms of speed or manoeuvring but lacks information if the total fuel consumption or emission is of interest.

On board energy systems models

The models in this category focus on all on board energy systems, such as main and auxiliary engines, boilers, hydraulics, tank heating, HVAC, fans and pumps, but neglect the hydrodynamics of the ship's hull. Normally, the propeller load is set as constant or roughly estimated using approximation methods such as in Holtrop et al. (1982). Such a model is discussed by Baldi (2013) and is available in some commercial tools as discussed in Chapter 4.3.

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4.3 Commercial tools and software

Numerous commercial systems are available for performance monitoring and analysis, as summarised in Table 1. Although the input and the results of such systems are rather similar (except for the Kongsberg system, which is more engine focused), the methods are rather different. In general, there are some black box systems such as the Marorka system, and some white/grey box systems such as the Marin system. All of these are only focused on parts of the whole, complex energy system "ship", and most of them on the hull resistance and main engine performance.
From the literature, the most holistic system for the on-board energy systems seems to be the DNV Cossmos (DNV 2012), but it does not include the ship's hydrodynamics.

Table 1: Examples of companies selling commercial software for performance monitoring.

Company name	Website
NAPA	www.napa.fi
Marorka	www.marorka.com
Marin	www.marin.nl
Kongsberg	www.kongsberg.com
Insatech	www.insatechmarine.com
Seaweb	www.sea-web.com
Amarcon	www.amarcon.com
Weather Routing Inc.	www.wriwx.com
Kyma	www.kyma.no

5. Energy-saving measures and wind power as auxiliary propulsion

In current shipping market, the bunker price has increased more than 6 times since 2000. It is likely to further increase to 1000 USD/ton over the service life of today's newly built ships. Improving energy efficiency to reduce fuel consumption is becoming one of the most important topics. In addition to the increasing pressure on high bunker prices, its main driving forces also result from stricter regulations on energy performance and air emissions from ships, and ambitious goals to strength market positions, trade flexibly, branding and attract external stakeholders, who put more weight on energy efficiency to make their investment decisions. It is known that shipping is a substantial emitter, accounting for approximately 3% of the total global CO_2, 1-3% of SO_x and more than 10% of NO_x (Buhaug et al. 2009). Emissions from shipping are expected to increase 150-200% by 2050 due to the growth of the maritime transport sector (EC 2011). The effect of air emissions of NOx and SOx from shipping on environmental and health impacts has also been realised to a large extent (Corbett et al. 2007, Eyring et al. 2010). The International Maritime Organization (IMO) has established regulations to reduce fuel consumption and air emission (EEDI, EEOI, SEEMP, ECA); see IMO (2012, 2013a, 2013b). The inclusion of emission tax in fuel price is also likely to be established in future shipping market (DNV 2011). According to the future fuel cost scenarios by Eide et al. (2011) and DNV GL (2014) for the reduction of CO_2 and SO_x emissions, the added premiums may push the price to 2000 USD/ton by 2040.

The increased awareness of environmental impact, global economic crisis and high oil price acts as the catalyst to stricter regulation requirements (DNV GL 2014) to push shipping toward more

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energy-efficient transport. Currently, research interests have been focused on the maritime industry to seek energy-efficient measures in terms of innovative ship design, optimal operation, smarter propulsion, and efficient machinery. In the following Chapter 5.1, general pros/cons of those realised measures are addressed, as are the barriers that hinder their practical implementations. In particular, this report focuses on the status of green shipping concepts of utilising wind power as extra propulsion, as summarised in Chapter 5.2. Furthermore, Chapter 5.3 narrows down shipping concepts, research progress and technical matureness with respect to the implementation of energy saving devices to provide wind assist propulsion for ships.

5.1 Measures and their barriers to improve energy efficiency in shipping

Different stakeholders and policy makers in the maritime industry have identified a vast range of measures, which aim at reducing the fuel consumption and air emissions in shipping. A summary of these measures and their potential savings are listed in Table 2. These are based on extensive investigation of various industry projects and research activities, e.g., ABS (2013), Buhaug et al. (2009), DNV GL (2014), Faber et al. (2011) and Wärtsilä (2010). It should be noted that the percentages of potential energy savings by implementing these measures can differ significantly depending on the analysis source. The colours in the table are to give a basic reference and relative savings potential in comparison with different measures.

In Table 2, the ability to implement each measure is categorised into new building and existing vessels. Due to significant differences in the specific characteristics of each ship type, some measures may be limited to certain groups of ships. For example, the utilisation of lightweight material for ship construction may be only beneficial to ships with larger superstructures but have limited application for conventional ships such as bulk carriers and tankers (Faber et al. 2009). Furthermore, some measures are mutually exclusive. A simple summation of all measures will greatly overestimate the energy-efficiency improvement potentials of employing multiple measures for a given ship, as noted by Johnson et al. (2014), Kesicki and Strachan (2011), and Kesicki and Ekin (2012).

As shown in Table 2, a large energy savings potential is available through the implementation of a combination of different measures for both newly built and existing ships, according to the extensive market survey carried out by DNV GL (2014). Shipping companies tend to apply well-known and mature measures that require little investment and have easily accessed benefits such as slow-steaming, weather routing and optimised voyage planning. The biggest incentive of implementing energy efficient measures is to be in compliance with regulation requirements rather than market-focused goals, such as strengthening their market position and economic profits. Most such measures rely on service providers' or manufacturers' data and analysis, in which there is often a lack of transparency leading to significant uncertainties of possible energy savings. One of the most significant challenges in undertaking these tasks is the lack of data. To develop robust and accurate models, detailed ship cost effectiveness data and technical/operational data are needed.

In addition to non-transparent data and models for energy-efficient assessment, other barriers hinder the implementation of energy-saving measures in the shipping market. These were categorised by Jafarzadeh et al. (2014) and were discovered based on an extensive market survey in Norway and international research activities by Cagno et al. (2013), Faber et al. (2009, 2011)

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and Fleiter et al. (2011). In general, these barriers can be grouped into five levels: information barriers, economic barriers, (intra and inter) organisational barriers, technical barriers and policy barriers.

Table 2: Available energy-saving measures and concepts with potential savings and main barriers for their practical implementation.

Concept categorizes		Detailed measures	Fuel saving Potentials *	Barries
New building vessels	Hull form optimisation and propeller configuration	Main dimensions optimisation, e.g. slender and larger ships, and less ballast water volumn	10%	Policy and regulation
		Ship energy system optimisation based on actural planned operaitonal profiles, fuel price, trade routes, loading conditions etc.	5%	Information and organiation
		Optimisation of stern bigle , rudder and propeller for inflow considerations (e.g. better skeg design, better propeller balde design)	5%	Information, economic, organizational and technical
		Optimisation of hull shape and bulbous bow	2%	Information and technical
		Better design with consideration of added resistance due to wind and waves in open sea	2%	Technical and economic
		Influence from IMO EEDI on ship design	≥20%	Policy and organization
	light weight construction	High strength steel	2%	Technical
		Composite material	5%	Technical and economic
Existing vessels	Machineary system	Waste heat recovery system	10%	Economic, organisation and information
		Alternative fuel for power	2%	
		Hybrid auxiliary power generation	2%	
		Optimum heating and cooling systems	2%	
		Adaptive pump and power management systems	5%	
	Energy saving devices	Propulsion improving devices	5%	Technical and information
		Skin friction reduction	5%	Technical and economic
		Wind power and other renewable devices for auxiliary propulsion	10%	Technical, economic and organization
	Ship operation manamgement and optimisation	Ship speed reduction	≥20%	Organisation
		Optimised ship maintenance schedule, hull and propeller cleaning	5%	Information and economic
		Autopilot adjustment	2%	Technical
		Intelligent engine adjustment according to weather and loading conditions	5%	Technical and economic
		Trim, ballast and rudder control optimisation, air lubriation etc.	5%	Technical and information
		Weather routing and voyage optimisation	10%	Information and technical

* The potentials of energy savings can differ significantly from individual ships, even by implementing the same measure. The percentages here, rather, give an average savings potential indication based on general ship types. The potentials are divided into the following four levels:

Fuel saving up to	2%	5%	10%	≥20%
Marker	(light green)	(green)	(dark green)	(dark blue)

For most newly built vessels, current ship designs provided by shipyards have already been optimised to have the best operation performance. New changes and arrangements to a specific ship are often negotiated with shipyards possible with a high construction cost. However, the energy savings due to the installation of these measures on new building ships will eventually benefit most ship chartering companies, which are not responsible for the payment of the extra installations. There obviously exist some conflicts of interest between different stakeholders of the shipping industry. This is referred to as inter-organisational barriers for the implementation of energy efficient measures. Even within the same company, upper management may have different motivations from technical advisors to update their conventional designs to more

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energy-efficient ship concepts. This is often associated with risk of the actual energy gains through the new implementations. In some cases, the organisational barriers are also combined or due to the technical maturity of certain measures and methodologies. For example, it is well recognised that a ship's optimisation design should be carried out for its actual operational conditions and future service weather environments, whereas construction contracts between shipyards and ship owners normally refer to calm water conditions with a specific service speed. All of the subsystems are therefore arranged and optimised based on requirements for the ship operated in calm waters, whereas ships rarely sail under such conditions. The reason behind this is that the mature information and technology for such conditions are not available to judge the success of the ship construction project. Another more obvious example is the utilisation of high tensile steel (HTS) for ship construction. This could help to reduce a ship's plate thickness, thus leading to a significant total weight deduction. However, the technical problems associated with the use of HTS such as fatigue and welding issues also limit its wide usage in ship construction. The same problem is also faced for the use of composite materials, which are also strongly limited due to cost and technical immaturity.

For currently existing ships, many measures are available in the market aimed at increasing energy efficiency and reducing air emissions. The implementation of these measures can be categorised into machinery systems, energy-saving devices and ship operation management and optimisations, as shown in Table 2. The services of implementing these measures within machinery systems are often provided by marine engine companies. The main barriers for such implementations are often related to economic concerns from the ship owners' perspective. Organisational barriers occur when the shipping company has different priorities than the measures' implementation. Information barriers are essential for the application of such measures because the data and analysis provided by engine companies often lack transparency. The consequence is that larger percentages of energy savings are claims but not actually observed in the market. These information barriers can also be found in retrofitting energy saving devices, such as installing a duct to harmonise and stabilise the flow distribution entering into the propeller to increase propulsion efficiency or the re-configuration of propellers. The lack of information can also be induced by the lack of technical solutions to prove the efficiency of energy saving devices. Most often, these energy saving devices need large amounts of investments for their implementations. The technical maturity of these measures should be further developed to ensure the confidence to estimate their investment and payback time. One example is the utilisation of wind assist propulsion for ships. Although large potentials can be expected from such measures, their arrangement on board ships, installations, maintenance and impacts on a ship's overall safety, manoeuvrability, and optimum utilisation of wind forces actually require a complex system with different levels of models and technologies to support the entire concept. In addition to retrofitting or updating subsystems in the existing ships, optimal ship operation management, such as slow steaming and optimisation voyage plans, are cheaper, straightforward, efficient and highly implemented in the shipping industry. Due to the advancement of information and communication technology, the increased reliability of weather forecast provided by metrological institutes and large established database on long-term marine weather environments, higher energy savings from an optimal ship operation can be realised through the integration of an voyage optimisation system with some energy saving measures, such as wind assist devices and propulsion retrofitting etc.

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5.2 Wind power as auxiliary propulsion in ships

The EU Commission's Communication on a "Strategy to reduce atmospheric emissions from seagoing ships" indicated the importance of reducing these emissions from ships for the improvement of human health and environment. The EU and Swedish national climate goal in the transport sector includes 20% improvement in energy efficiency, 40% reduction of greenhouse gas emissions and a minimum of 10% renewable energy by the year 2020. It also requires sustainable maritime transport with minimal environmental impact. Further motivated by the high bunker fuel cost, many research activities have focused on the concepts of wind energy utilisation as auxiliary propulsion in ships, which was extensively investigated in the 1980s due to the 1979 oil crisis (Letcher 1982, Schenzle 1985). In Figure 3, some of the most commonly discussed wind assist ship concepts are presented. Different refinements of these concepts and their combinations were also proposed. The state-of-the-art research and feasibility of these wind assistance ship concepts during 1980s (1979-1985) were extensively reviewed by, e.g., Bergeson and Greenwald (1985) and Nance (1985).

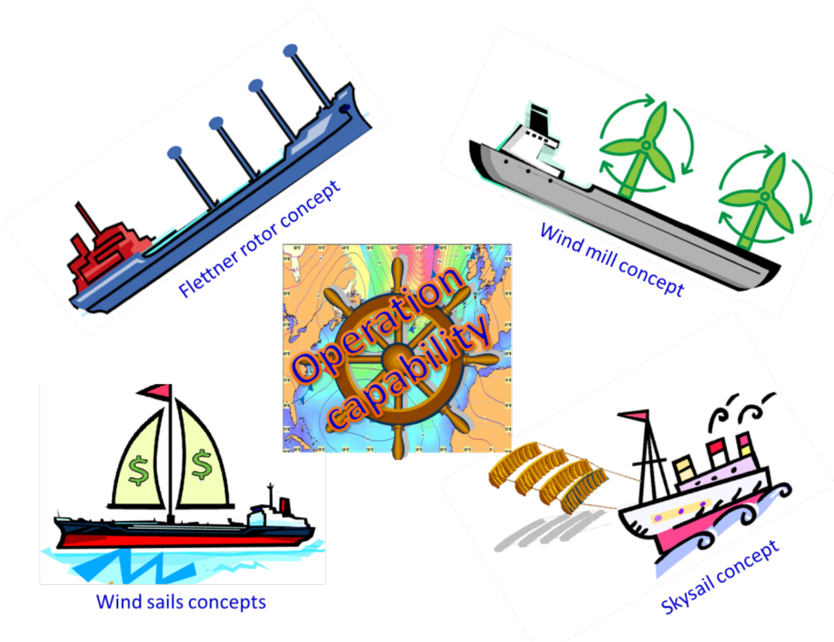

Figure 3: Different green shipping concepts using wind power as auxiliary propulsion.

The Flettner rotor ship concept uses the Magnus effect (Magnus 1853) to generate a propulsive force from the airflow around rotating cylinders. As shown in Figure 4, it is assumed that a ship is heading to the west and that the wind is blowing to the north. To generate propulsion force to push the ship toward the west, the cylinder must be rotated clockwise. The rotating cylinder will cause a fractional drag force on the surrounding airflows, causing the speed of the airflow in front of the cylinder to be greater than that behind. Based on the Bernoulli equation, this can cause lower air pressure in front of the cylinder and generate a lift force on the cylinder to push the ship forward.

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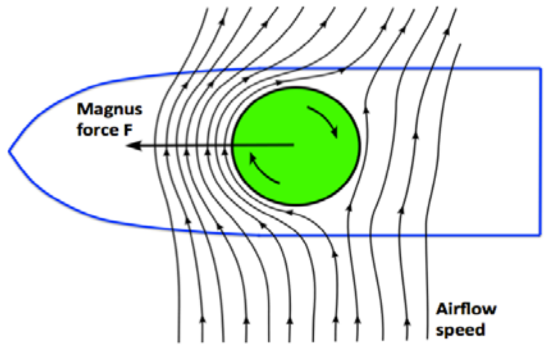

Figure 4: A sketch of the Magnus effect for a Flettner rotor ship with a vertical rotating cylinder.

The first system to prove that the Magnus effect concept could provide auxiliary propulsion to ships was designed by the German engineer Anton Flettner (Flettner 1925). The demonstration project was conducted on a schooner (the Buckau) that was outfitted with cylindrically shaped, rotating masts that were 15 meters tall and 3 meters in diameter. It crossed the Baltic Sea and North Sea from Gdansk to Scotland in February 1925. Over the past century, the Flettner rotor ship concept never took hold in the commercial shipping market due to its non-competitive capabilities in comparison with steam and diesel engines as ship propulsions. However, the concepts were briefly revisited in the 1980s by maritime academia and research institutions driven by the concerns of the oil crisis (Nance 1985, Bergeson and Greenwald 1985). Flettner's cylindrical rotors were further revised by Thom (1934) with discs distributed along the cylinder. The performance of cylinder rotors with and without discs for ship auxiliary propulsion was experimentally studied by Clayton (1985). However, the distributed disc cylinder concept was abandoned by the inventor Thom because the power required to spin the rotor with large discs became too expensive.

Currently, due to high bunker prices and correspondingly increased market pressure toward a more energy efficient merchant shipping industry and environmental concerns through the international and national regulations, Flettner's concept is now under the spotlight of the entire maritime community as an important alternative to using wind power as auxiliary propulsion to ships. The research activities on Flettner's concepts mainly focus on the computation of lift and drag forces generated from the cylinder rotor because a high Reynolds numbers airflow makes the reliable computation a bit challenging (e.g., Aoki and Ito 2001, Karabelas et al. 2012, Craft et al. 2014). In the industry market, dozens of patents have been granted to support and utilise Flettner rotor concept related technologies and subsystems during the past few years.

Due to the large weight and high central gravity of the rotors, a ship's structural integrity and the vessel's hydrostatic and seakeeping capability should be carefully planned and analysed to ensure its safety. After 10 years of technical development, the first modern vessel, i.e., the 10,000 dwt cargo vessel E-Ship 1 (ENERCON 2013), was completed and launched in 2010. It was equipped with four Flettner rotors that were 27 m height and 4 m in diameter, demonstrating the design feasibility of the technology. As shown in Figure 4, Flettner rotors are controlled through a single parameter, i.e., the rotational speed.

The concept of utilising wind force from towing kites to provide propulsion forces to ships has been systematically developed since the 1980s (Duckworth 1985, Wellicome and Wilkinson

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1984). Similar to other wind assist ship concepts, the incentive for the development of towing kite propulsions is originated from financial reasons and environmental concerns of bunker fuel consumption in shipping. Schlaak et al. (2009) investigated the worldwide shipping market for the implementation of wind towing kites as auxiliary ship propulsions. Based on similar results from field trials with a kite into a study, they concluded that kite systems could be retrofitted to approximately 60,000 of a total of 90,000 ships. Significant fuel saving potential has been presented for a multi-purpose freighter, estimated between 1% and 21% for a ship speed of 15 knots and between 4% and 36% for a ship speed of 13 knots.

Before the practical installation of kite systems in ships, two technical problems must be solved. The first is a reliable prediction of mechanical performance of auxiliary wind propulsion using kites. The second is the kite control/operation system, as well as the effect of ship structure and stability due to installation and optimum ship route plan system, which is required for all wind assist propulsion concepts. Mechanical models for kite performance prediction have been researched and developed by e.g., Argatov et al. (2009), Lloyd (1980), Naaijen et al. (2006), Wellicome and Wilkinson (1984), and Williams (2006). The proposed zero mass theory (Wellicome and Wilkinson 1984) has even been validated by published experimental data. The theory is based on the assumption that the aerodynamic forces are larger than the kite mass, allowing for acceleration effects to be neglected. Therefore, the entire kite system can be considered to be in an equilibrium flight state. Dadd et al. (2010) also used the zero mass kite manoeuvring theory to predict kite line tension and other parameters connected with a kite's performance. Good agreement has been found between the computed results and a real test dataset recorded using a purpose-specific kite dynamometer. In addition, the kite operation system for auxiliary ship propulsion has been investigated. For example, Grosan and Dinu (2010) studied the influence of a ship's stability and manoeuvrability with zero forward speed under certain wind conditions, Wrage (2007) patented his technical achievement for the kite launch and recovery systems, and Erhard and Struch (2012) presented their research efforts on an autopilot kite control. These technical developments have enabled kite systems to be installed commercially for trans-oceanic voyages. These have become the most popular wind assist ship propulsion concept in the current shipping market due to its technical maturity. The industry partner SkySails GmbH (Skysail 2014) is the market and technology leader in the field of marine towing kite systems. SkySails kites are key technology for capturing the vast potential of high-altitude winds, and SkySails is the first company in the world that has succeeded in developing towing-kite technology into an industrial application. Figure 5 presents a prototype of the SkySails towing kite implemented in an oceangoing commercial vessel. The latest product generation developed by the company can replace up to 2 MW of the main engine's propulsion power. Another successful market player on the kite assist ship propulsion uses a system of different size and shape of kites developed by KiteShip (Kiteship 2014), which has a successful track record of using kites to provide propulsion force to yachts. The company has also built the world's largest sailing kite in 1997 and recently applied their systems to power ocean going tankers with auxiliary energy.

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Figure 5: (Left) A SkySails towing kite implemented in oceangoing commercial vessel, and (right) another kite propulsion concept developed by Kiteship.

Another more challenging concept is to install one or several windmills on board a ship. This concept can use not only provide propulsion forces but also the electrical power generated by windmills. Windmill propulsion generally provides high propulsive force only when the ship speed is less than approximately half the wind speed (Blackford 1985). This finding implies that wind turbine propulsion is more preferable for slow steaming ships or sailing in high wind conditions. However, high wind conditions may induce extra challenges to a ship's structural safety and its stability in open sea operations. Ship motions, when operated in the open sea, can significantly decrease the efficiency of the power generation from on board windmills. Furthermore, to use the electrical power generated by the retrofitted windmills, a large investment must be made to revise the marine engine system in ships. Maintenance costs may become too expensive during the operating period of windmills due to their working conditions under moist and salty sea environments. Hence, no merchant ships have been equipped with windmills to provide auxiliary ship propulsions (Bøckmann and Steen 2011).

One century of the history of the maritime industry included merchant ships using hybrid propulsions between steam engine and traditional sails. Eventually, by the early 1900s, shipping companies migrated their ships to steam ships. Gradually, every transoceanic sailing-ship company went out of business because of the high energy efficiency of a marine engine combined with a modern propeller design and the low cost of energy resources. Furthermore, merchant ships with a steam/marine engine were capable of sailing across oceans faster than the wind. They could also be operated in a more regular and flexible manner. Currently, due to the high bunker price and environmental concerns related to bunker burning, hybrid ships using sails as auxiliary propulsions have attracted much attention among different stakeholders in the maritime transport sector. Sails on masts are often categorised as traditional soft sails and wingsails, which are airfoil-like structures similar to airplane wings.

Traditional soft sails are still used for primary propulsion to many commercial fishing crafts in developing countries. These sails are also used on larger trading vessels in trade areas, including along South Pacific routes, with a long distance and high fuel costs, as noted by Bose (2008), Teeter and Cleary (2014). Soft sails are often designed as fore-and-aft sails or square sails, as described by Angvik (2009), Nance (1985), and Silvanius (2009). The largest advantage of using soft sails on merchant ships is their relatively low cost installation and maintenance. A major drawback is the lack of auto operation/control of the soft sails. These sails must either rely on extra crew members to pilot sails or use very complex and expensive automated system for the launch, recovery and operation of the sails. Furthermore, the fuel savings using soft sails are usually marginal, and handling is difficult (Schenzle 1985). The technical requirements for the practical applications of soft sails for auxiliary ship propulsion have been discussed at several conferences (e.g., ICSACFV 1983, WASP 1985, and WINDTECH 1985).

Due to the growing theoretical understanding of aerodynamics and advancements in wingsail design and construction in the aircraft industry, Abbott and von Doenhoff (1959), rigid airfoil-like sails (wingsails) have become more attractive alternatives for providing wind propulsions to ships. The appearance of wingsails looks similar, whereas the details can differ (Atkins 1994):

- plain aerofoil section,
- aerofoil with plain flap,
- aerofoil with single slotted flap,
- aerofoil with double-slotted flap, and
- aerofoil with variable "nose" camber.

These details can increase the wingsails' maximum lift coefficient and lift-to-drag ratio. In addition, different materials for wingsail construction, size and arrangement of wingsails on the ship, and the pilot/control/operation method can be quite different from those wingsail systems. Figure 6 lists a few wingsail design proposals from the early 1980s; see Nance (1985). The most successfully implemented concept is the folding wingsail developed by the Japanese company NKK and fitted first to the Shin-Aitoku-Maru, a 1400 DWT tanker (Fujiwara et al. 2003, Watanabe et al. 1982). After the successful installation of the system on board the Shin-Aitoku-Maru tanker, it was also retrofitted to approximately 10 ships of different sizes, ranging from 600 to 31,000 tons, built in six different shipyards, and operated by six different companies in Japan. This system has been demonstrated to possess a potential fuel savings of up to 20-30%.

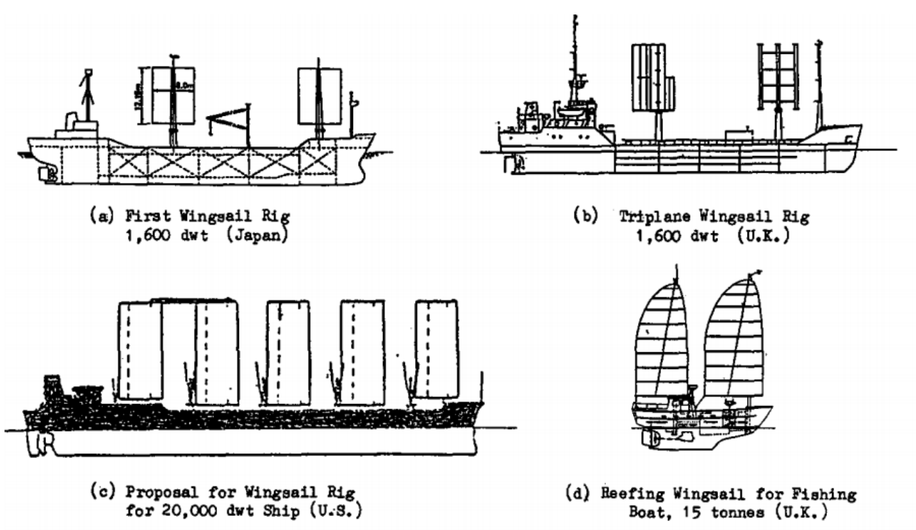

Figure 6: Typical wingsail proposals developed in the early 1980s (Nance 1985).

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According to Cooke Associates (2014), the Walker Wingsail (Walker 1985) was a more aerodynamically efficient wingsail that was developed and applied to the M.V. Ashington recreational vessel during the period between 1986 and 1988. Another wingsail proposal, the Boatek wingsail, is believed to have an even higher efficiency and larger lift coefficient. The Walker wingsail has been compared with the Boatek wingsail through a numerical simulation of two-dimensional section aerodynamic characteristics. According to the analysis by Cooke Associate (2014), the Boatek design exhibits better aerodynamic characteristics, most likely due to the use of cambered, as opposed to symmetrical, wing elements. Cambered designs, however, must be rotated each time the boat changes tack. Figure 7 presents two examples of the Walker and Boatek wingsails. Although the economic benefits and technical development of the two wingsail proposals are not proven by their practical installation on merchant vessels, these designs are applied extensively on recreational vessels. For their application on merchant ships, robust and advanced sail-assist/operation systems are usually required to avoid the need for extra crew sources to handle the wingsails on board. Both the development of sail-assist systems and optimisation of wingsails requires good understanding of the mechanical behaviour/response of wingsails under windy conditions. Insight can be gleaned from the aircraft industry for both numerical analysis and experimental tests; see Atkins (1994), Bergeson and Greenwald (1985), Fujiwara et al. (2003), Marie and Courteille (2014), Satchwell (1985), Scherer (1974), and Sheldahl and Klimas (1981). However, the special characteristics of wingsail applications on ships, such as the mechanical interaction between aerodynamic on wingsails and hydrodynamic response under a ship's open sea operation, and the low and irregular wind speed encountered by wingsails also bring further challenges to sail assist ships; see Firestein (1985), Prandtl and Tietjens (1957), and Spaans (1985). It is well known that today's computational capability enables advanced CFD computations of fluid dynamics for understanding the physical phenomena of wind assist ship performances. However, the complete coupling of aerodynamic and hydrodynamic analysis still requires too much computational effort. In particular, wind assist operation systems often need robust models to describe such a ship's aerodynamic and hydrodynamic performance via a fast and efficient approach. More challenges in addition to the technical development of these concepts are described in the following chapter.

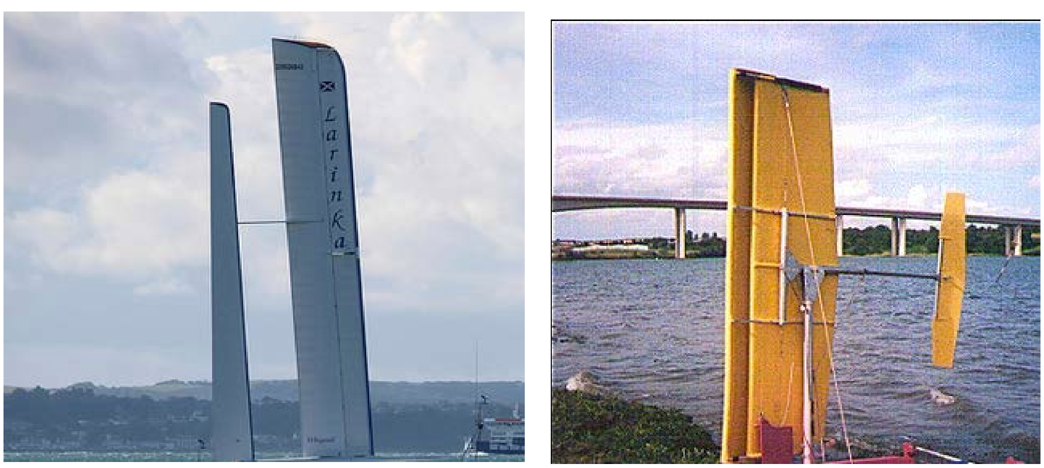

Figure 7: Modern aerodynamically efficient wingsail designs:
(left) Walker wingsail and (right) Boatek wingsail.

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5.3 Feasibility study for wind assist propulsions

In the previous chapter, potential barriers that hinder the practical applications of different measures for energy efficient shipping were briefly presented. Although the maritime industry has accumulated long periods of sailing experiences using wind power as the main propulsion, its application on today's ships to provide auxiliary propulsions is facing new challenges with respect to economic investment, design and operation of the devices, as well as operational viabilities. Based on a literature review of the technical development of different wind assist ship concepts, Table 3 summarises the feasibilities of implementing these concepts to identify further research and development efforts to enable practical applications. All of these economic and technical barriers can be overcome by engineering intelligently before marketing.

Table 3: Feasibility study with respect to the potential application of wind assist devices

Application feasibility		Flettner Rotor	Skykite	Wind mill	Soft sail	Wingsail
Economic viability	Expensive installation cost	X		X		X
	Maintenances			X	X	X
	Uncertain energy gains	X	X	X	X	X
Design and installation	Reliable performance prediction	X	X	X	X	
	Devices efficiency (weight, performance)	X	X	X	X	X
	Maneuverability		X	X	X	X
	Structural safety	X		X	X	X
	Interference with Cargo handing	X		X	X	X
Operation viability	Automated device control system		X	X	X	X
	Serviceability in arbitrary conditions	X	X			
	Bridge view blocked			X	X	X
	Integrated with routing system	X	X	X	X	X

Viability of economic investment

In general, to generate a large wind force to provide auxiliary propulsion to merchant ships, wind assist devices should also be appropriately large. Thus, the investment required to design, construct and install is usually not a small cost. In particular, these devices should be designed separately for individual ships to achieve a higher efficiency and energy gains in comparison with its investment for real installations. Furthermore, due to severe working environments (high moisture and salinity) of these wind assist devices in the open sea, one also needs to account for long-term maintenance costs during their operation. For ship owners, the preferred payback time of their investment is 5 to 10 years. However, usually the current payback time is often longer than that. For example, according to O'Rourke (2006), to install the wind device of a skysail, the cost of retrofitting a cargo ship with a row of masts and strengthening the ship to dissipate stress due to the sail was estimated to be more than 10 million USD. This would take approximately 15 years to recoup their costs through fuel savings. In addition, a high level of maintenance costs is usually associated with the initial installation investments of such expensive devices. The maintenance sometimes can double the payback time. It should be noted that the fuel savings cost is also strong related to future market oil price and future fuel cost scenarios for reduction of shipping emissions Eide et al. (2011) and Faber et al. (2011). This may shorten payback time and make the wind assist concepts more attractive to the shipping market.

Furthermore, large uncertainties are included in the estimation of fuel savings by implementing these devices. One important source leading to this uncertainty is a lack of reliable methods/models for predicting the performance (aerodynamic and hydrodynamic coupling analysis) of these devices under real operating conditions, e.g., WASP (1985) and WINDTECH

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(1985). Another reason is that the estimation of fuel savings should rely on the encountered sea environments (e.g., trade routes, wind, wave) of a ship's future sailing service. Fortunately, large data sources are freely available to provide the long-term statistics of sea environments along specific ship routes. For example, Clauss et al. (2007) and Traut et al. (2014) used weather data from the European Centre for Medium-Range Weather Forecast (ECMWF) and the UK Met office's Unified Model to access wind statistics to estimate potential energy savings of different wind assist devices along trade routes.

Moreover, the fuel savings by implementing these devices could be further maximised through the optimised planning of ship routes for each individual ship voyage. Currently, most ocean-crossing vessels are instrumented with a routing plan system, where a routing optimisation tool is used to assist ship operation in a more optimal way based on weather forecast information. The routing tool has the potential to save up to 5% of fuel cost and reduce structural fatigue damage by 50%, Mao et al. (2012). The routing optimisation system is also one of the key factors in maximising the use of wind propulsion in practical shipping. Spaans (1985) investigated different optimisation algorithms for the utilisation of wind assist devices to reduce the energy cost of shipping. However, there is no routing tool that can account for lift and drag wind forces for routing optimisation.

Design and installation challenges

The work efficiency of the wind assist devices is of greatest concern for their practical installation and practical applications. The aerodynamic performances of these devices were extensively studied via wind tunnel tests (see Argatov 2006, Bergeson and Greenwald 1985, Blackford 1985, Clayton 1985, Craft et al. 2012, Flettner 1925, and Satchwell 1985) and CFD analysis. This was possible due to the rapid increase in computational capability (see Atkins 1994, Cooke Association 2014, Craft et al. 2010, and Johnson 2011). However, the reliability of those established models to describe the operational performances of these devices obviously requires further development. Furthermore, some devices have a high weight and centre of gravity, which may affect a ship's seakeeping behaviour in addition to its high building cost. Wind devices are often installed on ships through large masts. In unfavourable winds, large masts can only create drag force, which causes ships to heel, sometimes dangerously. Masts and their pivoting sails take up valuable cargo space on the deck. Loading and unloading is more expensive because the cranes must work around the masts, Bose (2008). Tall masts or wingsails exceeding 100 meters in height must often use collapsible equipment to avoid operation problems when meeting waters with bridges. These collapsible masts will significantly increase the building cost.

Furthermore, due to the large forces generated by wind devices, the ships' structural components should be strengthened to enhance ship structural safety. For example, following the success of wingsail implementation on the tanker Shin-Aitoku-Maru, another vessel installed a similar wingsail on board that failed during high wind in a Japanese harbour. The high forces, partly from the wingsail, broke the moorings of the vessel, which was blown across the harbour. The parts seriously damaged other vessels in the harbour as well as the harbour itself. The accident discredited wingsail safety and indicates a need for further technical development of the wind assist device applications.

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Operational challenges leading to energy efficiency (fuel saving)
In addition to the design and construction of wind assist devices, both the operation of a ship fitted with these devices and the device handling/control requires robust performance prediction models to describe the ship and wind devices' response in real ship operations. Numerically modelling complex ship motions in real sea environments has always been one of the greatest challenges for hydrodynamic analysis in the maritime industry. The development of wind assist ship performance models requires even more sophisticated aerodynamics and hydromechanics coupling analysis.

A sailing ship sails with a constant heel and leeway angle to make use of wind propulsions to power the ship, whereas current merchant ships are mainly powered by marine engines connected with well-designed propellers. The installation of auxiliary wind propulsion devices will add at least two extra wind forces to ships, depending on the number and arrangements of the devices. Wind forces, which should be sufficiently large to ensure the device working efficiency (note that large wind assist devices may block a ship's operation view on the bridge, which is quite essential in particular in port operations) will significantly affect a ship's response behaviour. This includes effects on the ship's resistance, propeller efficiency, ship manoeuvrability and ship motions. Furthermore, the drag and lift forces generated from wind assist devices have to interact with the thrust force provided by a ship's propellers. The ship's sailing course might also be affected by such interactions. To achieve the highest work efficiency of these devices, an optimisation procedure should be developed to guide the operation of the ship, referred to as routing optimisation (optimum voyage plan) systems. In this case, routing optimisation is a key factor in helping captains to operate their ships and maximise the utilisation of wind propulsion through the iterative consideration of wind device performance and the ship's main power management. This helps achieve the expected time of arrival with minimum fuel cost. In the following chapter, the characteristics of routing systems available in the current shipping market will be summarised to give a state-of-the-art description of such services. Further development requirements and directions to account for the wind assist device in future routing systems will also be discussed.

6. Ship routing systems for energy-efficient shipping

Ship routing systems, also known as weather routing or optimisation voyage plans depending on their functionalities, are the discipline of producing the most favourable route with respect to expected time of arrival (ETA), passing waypoints, ship speed, heading and engine power profiles for a given voyage trade based on encountered weather forecast information and a ship's operational performance. The primary use for these systems is ocean crossing transits, but they are also used for coastal navigation. In the current routing system market, the most interesting objective of ship routing systems is to provide a service to minimise fuel costs during sailing while arriving on time, considering the safety of crew, ship, and cargo, as well as air emissions in certain control areas.

To further the understanding of the structure of a ship routing system, it can be broken down into comprehendible categories and sub-components. Figure 8 is intended to provide a general overview of this structure. The basic idea of ship routing is to provide/suggest a ship route (including ship course, speed, heading and engine power), as illustrated in a digital chart with plotted forecasted weather information. At its early stage, a system should be able to account for

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the expected time of arrival and safety issues, which can be a ship's motions/stability in the open sea, structural safety under extreme sea conditions, cargo safety and crew/passenger comfort.

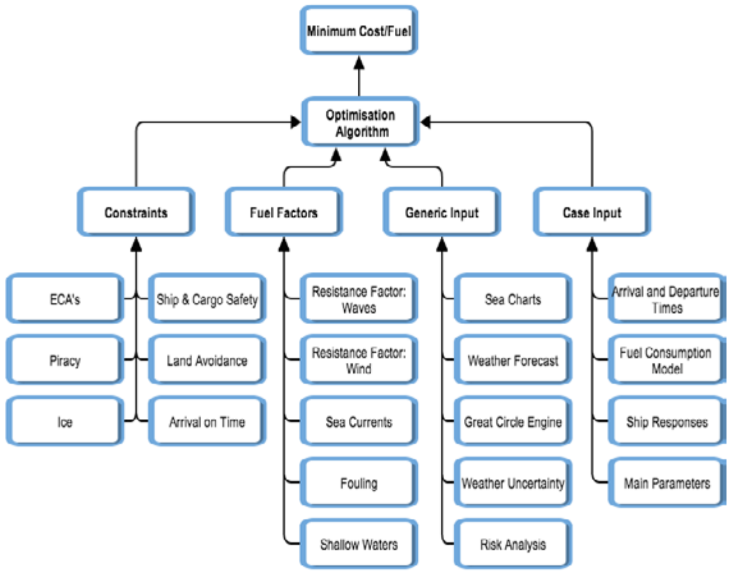

Figure 8: Overall structure of a weather routing system.

6.1 Basic capabilities of current routing systems

A ship routing system is designed to provide the service of optimising and planning a ship's sailing course/route with respect to the earliest possible time of safe arrival or expected time of safe arrival (ETA) based on weather forecast information and hindcast statistics such as air pressure, waves, wind, and current. The safety factors considered in the service include a ship's stability, seakeeping, structural integrity, cargo protection, and passenger comfort. The functionalities of these systems are summarised as follows, based on 6 companies providing routing services in the worldwide market as shown in Table 4.

Table 4: Typical routing systems in the worldwide shipping market.

Company		**No. of vessels installed**	**Website**
Voyage planning	WN weathernews	4000	http://weathernews.com
BonVoyage	AWT The Fleet Optimization Experts	3500+	http://www.appliedweather.com
SPOS	MeteoGroup	2500+	http://www.meteogroup-maritime.com
Seaware	seaWARE	unknown	http://www.seaware.se
OCTOPUS	AMARCON A MEMBER OF THE ABB GROUP	unknown	http://www.amarcon.com
SeaRoutes	danaos SeaRoutes	unknown	http://www.searoutes.gr

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To optimise a ship's sailing route to minimise fuel cost in operation and enhance safety, the basis of a routing system is the access to reliable weather forecast information. There exists a wide range scatter of weather forecasting provided by different institutes; hence, some systems also use satellite and hindcast weather statistics to calibrate their accepted weather forecast information from metrological institutes. Normally, a routing system receives updated weather forecast information from meteorological institutes to ships every 6 to 24 hours. Depending on the trade regions, weather information can be chosen with different resolutions. The weather information is primarily used to plan an optimised ship route for a sailing voyage. In addition, it can be plotted in a sea chart for captains to visualise the weather change, which may help them adjust their planned routing schedule. In the planning process of a routing schedule, the information contained in the sea chart such as water depth and surrounding marine traffic is also necessary. In general, the most important weather forecast information received from metrological institutes for routing plan can include the following:

- pressure contours,
- surface wind,
- temperature and moisture,
- wave and swell, and
- current and tides.

Furthermore, some routing systems also provide wave and wind statistics based on historical data for the locations along the planned course. The primary target of a routing service is to provide ships with a reliable ship sailing schedule to achieve the ETA. The expected time of arrival can be to plan a ship's route with respect to the earliest possible time of safe arrivals or required time of safe arrival, depending on the transport contract. It will not be distinguished in this report and will be denoted as ETA hereafter. To have a good plan for the ship with an expected time of arrival, routing systems can implement the following information for optimisation:

- requirements from ship operation company or ship owners,
- departure and arrival port database, and
- interface with other transportation.

Though ship safety issues have been casually dismissed by the current maritime field because the technical issues seemed to be advanced for many years, the routing systems can implement technical solutions to provide ships with safety-related services. These would include, for example, ship structural ultimate strength in large storms (wave/wind loads), structural fatigue damage, risks of collision and ground along the route, and ship stability problem. The stability may also be related to seakeeping properties, i.e., ship motions and accelerations of roll/pitch/heave for different loading and weather conditions. These technical issues should be considered separately for each individual ship. However, some routing systems may focus on more general problems connected with the weather forecast information and just set a threshold value of the weather (wind/wave) with respect to the ship safety resistance.

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The analysis of ship safety can be carried out via different approaches:

- Performance models based on experimental tests and numerical simulations.
- Development of robust models to describe a ship's motions and wave-induced loads applied on the ship's hull to gain a quick understanding of the ship's seakeeping behaviour and structural integrity response for different operational conditions during practical sailings.
- Hull monitoring system.
- Installing sensors along the hull to measure the six degrees of motions of the ship. The strain signal is also occasionally recorded to investigate/check ship structural integrity.
- Post-voyage analysis.
- Analysing a ship's response characteristics after the planned voyage is complete. This will help the engineer/inspector understand more about the ship's safety status. The insight gained from the post-analysis can also help further optimise the ship's future routes.

The most popular topic in the current maritime market is, most likely, energy-efficient shipping, which can help the industry reduce fuel consumption and air emissions. In addition, the shipping performance and efficiency may include the following criteria:

- minimum fuel consumption,
- best cargo protection,
- less ship speed loss, and
- passenger comfort such as avoiding large motions and whipping phenomena.

6.2 Optimisation algorithm in routing systems

The core element in the development of a routing system is to choose a powerful optimisation algorithm, which has a crucial effect on the computation time, solution and quality of routing plans. In the maritime community, the most common algorithms are Dynamic Programming, Dijkstra Algorithm, and the genetic-evolutionary algorithm. In a study by Larsson and Simonsen (2014), the so-called DIRECT (DIviding RECTangles) algorithm (Finkel 2003), which was developed based on Lipschitz optimisation (Jones et al. 1993), was also implemented in a routing system. The DIRECT algorithm illustrates how the algorithm moves toward an optimum. It is simple in nature and requires only adjustment of few settings. The algorithm searches locally and globally simultaneously, and intensification of a local search is not restrictive for the global, which is contrary to many other algorithms. A state-of-the-art analysis of selected algorithms is presented as follows.

3D Dynamic Programming

The Bellman principle of optimality forms the basis of dynamic programming, stating that "an optimal scheme has the built in feature, that no matter what the initial circumstance and selections are, the remaining decisions must comprise an optimal scheme regarding that circumstance". The more conventional 2D Dynamic Programming method (Chen et al. 1998) may be used to compute an optimum route by determining headings. However, it is restricted to determining the route using constant speed or power for the entirety of the route. The 3D Dynamic Programming model (3DDP), as noted by Avgouleas (2008), Wei and Zhou (2012), allows for the optimisation of the sailing profile through speed and power control.

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Shao et al. (2006) described the development of a forward dynamic programming method for weather routing. The method provides a route based on both course and power to allow for the ship to slow down or speed up relative to its average speed throughout the journey. The 3DDP method, (3D Dynamic Programming) shows significant fuel savings compared with the more common 2D Dynamic Programming method. The method presented does not account for the uncertainty of weather but only handles weather forecast data directly. The method was measured against three different Genetic Algorithms (GAs) by Shao et al. (2006). The 3DDP method showed improved performance compared with all three GA methods. The 3DDP method is dependent on a pre-processed grid.

Pros & Cons: Because the method relies on a predefined grid, impassable areas may be easily handled by skipping grid points. The pre-processed grid may be created relatively simply by spreading grid points out perpendicularly at intervals following the great circle route. A secondary advantage of the method lies in a by-product resulting from the nature of the solution space, which produces optimal routes for different arrival times, thus allowing the user an active selection. Though this method shows the advantage of easily handling impassable areas, finding the shortest route around or between islands requires significant grid resolution. This makes the accuracy of the result highly dependent on the grid resolution, which directly couples to the required computation time.

Dijkstra

The algorithm works based on two principles. The first principle forms the basis for dynamic programming (Sniedovich 2006): "A sub-route of a shortest route is itself a shortest route". The second principle is that "With a given shortest distance, x, between points ***A*** and ***C***, a path going from point ***A*** to ***C*** through a third point ***B*** will always be of a distance greater than or equal to ***x***".

From the starting point, all connecting lines to neighbouring points are simulated and assigned cost values. This value may be distance or fuel consumption or a weighted combination. From the line with the lowest end point value, possible lines to the next neighbouring points are simulated and assigned costs. When a line reaches a point that has already been tested, the second principle stated above is used. If the end point cost for the newly tested route is smaller than the original, the new cost is assigned to that point, and the original route dismissed as part of an optimum solution. Following this routine, routes will evolve toward the end point, and one optimum route remains. An example of such a route optimisation can be observed in Figure 9. The bold lines mark the routes with the smallest values, and the one stretching from point "Start" to point "Destination" is the optimum route.

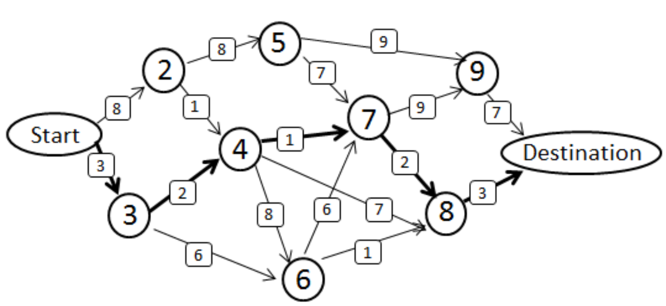

Figure 9: Illustration of the Dijkstra algorithm.

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Mannarini et al. (2013) described the development of a conceptual model relying on a modification of the Dijkstra algorithm (Dijkstra 1959). The method only accounts for wave height and direction, along with safety restrictions based on these parameters. The described method does not handle voluntary speed reductions. Padhy et al. (2008) presented another modification to the Dijkstra algorithm with the capability of handling voluntary speed reduction. The method uses weather conditions as influences on the obtained speed and may handle impassable areas through assigned weight of edges.

Pros & Cons: The Dijkstra algorithm will always find the most optimal route from the given grid. For cases of constant speed and handling of ship motions through reduction curves only, the algorithm is very fast. However, possible routes are restricted to move along nodes of the grid and are thus highly grid-dependent. In particular, for the 3DDP method, this method will have high grid dependency. Modifying the algorithm for handling dynamic weather, which is essential for varying speed, may be complex. Arrival time and minimum fuel consumption must be handled simultaneously, as shown by Zeszyty (2012).

Genetic Algorithm

The genetic algorithm replicates nature's evolution with principles of survival of the fittest. It does so through an initial population of solutions created through random sampling routes with advantages in fuel consumption, ETA, safety, or a combination of these. The routes are evaluated and given a fitness value based on fuel consumption, ETA, safety or predetermined combinations. A selection operator determines the routes containing the best fitness values, which may then be crossed over, mutated or handled through specialised operators to form a new solution population.

Often cited is the work of Hinnenthal (2008), who provided an elaborate suggestion of the use of a multi-objective genetic algorithm. Ship responses and constraints are modelled using ship response operators. In this proposed method, the objectives of the optimisation are both fuel consumption and arrival time, optimising both route and velocity profiles.

Pros & Cons: GAs are generally implemented fairly easily, requiring minimum tuning and modification from the base form. The algorithm may be stopped at any time and an optimal solution produced based on a Pareto front and ranking. Through mutation, crossover and other specialised operators, the algorithm is not likely to become stuck in local minima given proper tuning. From the Pareto fronts, the operator has the possibility, through ranking parameters, of selecting a most suitable solution with regard to ETA, fuel consumption, and safety. Conversely, when using this algorithm, arrival time and minimum fuel consumption must be handled simultaneously. The algorithm does not ensure an optimum solution but will instead give an approximation for it, which improves with the number of iterations. The GA is not very fast and is highly dependent on the population size of the initial generation of solutions. The selection of first generations may be very influential on the solution because these couple directly to the degree of mutations and crossovers. The parameters must be tuned and are likely to be case-specific for optimal computing.

The conclusion is that the less advanced algorithms leaning toward brute force are phased out in favour of more advanced algorithms such as versions of 3D Dynamic Programming and Genetic Algorithms. These algorithms perform better when the optimisations are multi-objective and

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when computation time is limited. Algorithms with the capability of handling black box problems are favoured because the aspects of the computations and totality of the modelling are too complex to be based on derivatives. Both the dimensionality of the solutions and dynamics of the solution space limit the number of applicable algorithms. Increased insight into system models and handling of the routing as a total voyage system are likely to lead the way to even more advanced algorithms being implemented.

6.3 Future routing concepts

The state-of-the-art and future development concepts of routing systems are summarised in Figure 10 based on three main activities. The first activity was mapping of the market leaders within weather routing software. Based on the literature, the selected software providers were contacted and were asked to fill out a questionnaire. The results of the study are presented. The second activity was a study of current and previous research to map the evolution of weather routing. The third activity was participation in network groups and workshops on weather routing to gain insight into the practical use of weather routing and its most current research and development. The general findings are illustrated in Figure 10. Features and functions are divided into three main categories depending on whether the functionality is mature and included in current software, less mature and in the process of implementation or are only present in research and possibly part of future implementation. The top weather routing software has the possibility of routing with varying speed or power profiles, enabling ships to speed up or slow down to avoid constraining weather. To prevent involuntary increases to resistance, many components are considered when routing with the leading software, including: wind, waves, currents, fouling, and engine maintenance. Basic capabilities of a routing system were described in previous chapters. The following text focuses on upcoming and future concepts, which may be included in routing systems.

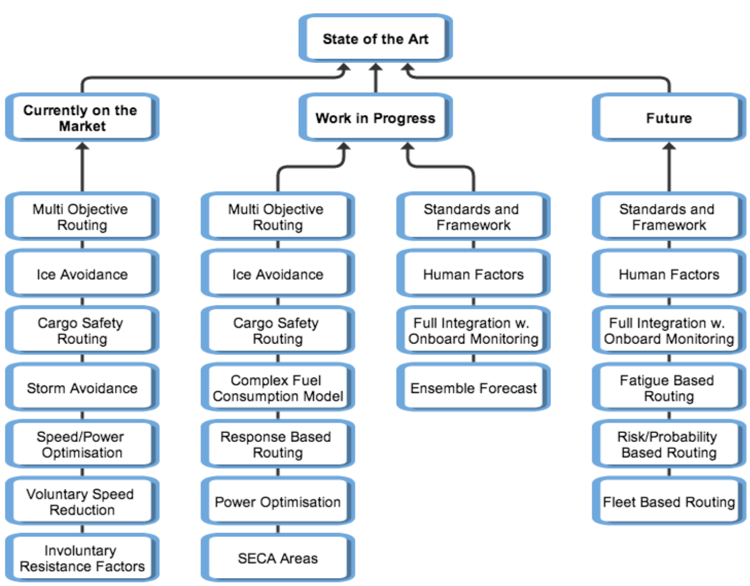

Figure 10: General overview of state-of-the-art and future routing concepts.

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In the current maritime community, the main driving force is to minimise fuel consumption for shipping. Constantly increasing computing power enables response based routing, which in turn will increase safety for ships, cargo and on board personnel. Response-based routing will most likely be coupled with on board monitoring systems to achieve even more precise models. The added resistance in seaway is of great interest to ship routing services. Speed reductions are handled in Shao et al. (2006) through the reduction equations presented by Kwon (2008). The equations are a simplification that leads to reduction percentages. The most advanced response-based routing system will be able to use models established based on model test data, on-board hull monitoring data and numerical simulations, which can achieve the highest level of precision to accurately describe a ship’s response under random sea way. Furthermore, it is possible to integrate the ship response model with other energy-efficient measures, such as wind assist devices, through the coupling of aerodynamic and hydrodynamic considerations. Using a reliable optimisation algorithm, the routing optimisation system could serve as a platform for implementations and make the best use of these energy-efficient measures to reduce fuel consumption and air emission in a more systematic way.

Another important development area is connected to the uncertainty and spread of weather forecasts. There is a possibility of risk-based routing. The difference between the paths of routes is another possible constraint. A route ahead of a storm would often be considered a higher risk route than a route behind the same storm. Weather uncertainty handling is one of the areas of research that have the greatest potential for improved routing. An obvious element is the discussed timespan of forecasts. Further, accounting for the uncertainties related to the forecasted weather may lead to very different routes. A discussed solution is weighing in probable forecasted weather from ensemble and super ensemble forecasts. Few software or research projects have yet to use this possibility. Some examples of the use of ensemble forecasts are presented by Hinnenthal (2008) and Skoglund et al. (2012).

Other focus areas in the routing domain are related to the new SECA regulations and piracy protection, which are pressing matters for ship owners and operators. As of January 1, 2015, SECA areas (Sulphur Emission Controlled Areas) came into force. These areas result in higher operational costs for larger ships operating in these areas. Current weather routing providers handle the SECA areas differently. Some providers only display the areas without considering their effects into the optimisation, others account for the effects of possibly switching fuel or requiring scrubbers, and still others add them as no-go areas. The providers that are approached but have not yet implemented the SECA areas are to implement the areas in coming releases. Piracy is a current and highly prioritised issue within shipping. Piracy services are seldom directly included in routing software but are often provided as a separate or add-on service. Piracy is also connected to risk-based routing, which is further discussed below. Fatigue routing is a discussed topic. Research has shown that container vessels in the North Atlantic trade may increase their fatigue life by 50% by implementing fatigue routing (Mao et al. 2012). Fatigue routing does not present a direct coupling to immediate costs and has therefore not been implemented yet. The inclusion of fatigue into multi-objective routing is at present a means of taking routing one step further.

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7. Concluding remarks

The current report summarises the outcome of the project "Examination of concepts, available models and methods useful for prediction, monitoring and improvement of ship energy efficiency", funded by the Swedish Energy Agency, Contract No. 39422-1. The purpose was to deliver a state-of-the-art study that compiles and examines the models and methods available for the prediction and monitoring of the vessel's energy use, with the aim of working toward improved energy efficiency. It also includes an inventory of green concepts that utilise wind power and a special section on wingsails on ships and the route planning investigated.

The outcome of the study highlights at least two important issues. First, there is a need to develop a generic holistic model that is applicable for the energy efficiency analysis and simulations for ships. Current state-of-the-art technology shows that parts of such a model exist, but they need to be combined to interact. Second, using wind power as auxiliary propulsion and ship routing optimisation can significantly reduce energy consumption and improve the energy efficiency of ships. Several technical concepts have been evaluated and tested, and wingsails are a solution that, together with ship routing algorithms, can lower fuel consumption significantly. In addition to these issues, a discussion on the scopes of different models, methods and software is presented; their limitations, strengths, weaknesses and flexibility to be applied or extended to the new extended use are also discussed. It is the authors' opinion that the means for future energy efficient shipping is to build a generic holistic energy systems model of a vessel that can be applied to demonstrate and develop concepts in a virtual but yet "realistic" environment. This model can be used efficiently to enhance the performance characteristics of existing vessels by using the model together with the results from ship monitoring and performance measurements.

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