THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Improving ship energy efficiency through a systems perspective

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Gothenburg, Sweden 2013

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ISSN: 1652-9189
Technical report no 13:147

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Cover:
Artist impression of ship energy systems

Printed by Chalmers Reproservice
Gothenburg, Sweden 2013

# Abstract

The last years have been particularly challenging for the shipping industry. Fuel prices have increased to levels only seen during the oil crisis in the 70's, and environmental regulations have grown much stricter than in the past. Climate change, at a global level, is going to become a major threat to society.

Increasing energy efficiency is one of the only possibilities of reducing fuel costs and environmental impact of the shipping sector without influencing the output. However, despite the recent developments in several aspects of ship technology, little effort has been made in looking at the whole ship as an energy system.

This licentiate thesis aims at filling a gap in the existing scientific knowledge on the way energy in its different forms is generated, converted, and used on board of a vessel. This is done by applying energy and exergy analysis to ship energy system analysis. The results of this analysis allow improving the understanding of energy flows on board and identifying the main inefficiencies and waste flows.

As a further development of this work, these results are used as a basis for generation and evaluation of alternatives for improving ship energy efficiency. This is applied to the three main categories of: ship operations, retrofitting, and design. Engine-propeller interaction, waste heat recovery systems and the early stages of ship design are identified as relevant aspects and their evaluation indicates that there is a relevant potential of improvement.

# Acknowledgements

The first version of my licentiate thesis was more than 100 pages long. After discussion with my supervisors, it went down to roughly 60 pages. I will therefore take what is my only chance to be lengthy for thanking those who have had, in different ways, a role in the achievement of this key stone of my education, and of my life.

First of all, thanks to my supervisors, Karin and Cecilia. It must not have been easy, I acknowledge that, as my way of moving forward is not always structured and methodical. This is why I need to thank you twice: once for helping me, and once for standing me.

Big thanks also go to Bengt-Olof, Pär Brandholm, Mikael Karlsson, and in general all the people at Laurin Maritime who contributed to the development of my work providing me with data and support. I enjoyed very much your expertise, your professionalism, and your cordiality in my regards. Thanks also to Jon Agust, Kristinn and Stefn at Marorka. Working with you has been motivating and I learnt a lot during my visits to Iceland. All people I collaborated to, both in Laurin and Marorka, have been examples of what a company should have for being successful in its business.

Thank you Gesa, thank you very much. You deserve your own little paragraph, for all your support, ranging from work to personal life. If there is one person I can say ”I would not be here without you”, that is definitely you.

A lot of thanks to all my colleagues in the environmental group. Thanks to Selma, for making a patient smile every time I came to your door just for having a short chat. Thanks to Mathias, for your lessons on the Swedes, and for coming to the cinema with me for watching trash movies. Thanks to, Hannes for introducing me to Laurin and for the numerous confrontations on energy efficiency, and research in general. Thanks to Philip for making me feel you counted on me also outside of the working hours. Thanks to Erik, for the all the afterworks we had together that reminded me there is life out there. Thanks to Steven, Luis, Florian, Hedy, Nicole, Henrik, and all those who make me feel, every time I wake up in the morning, that I am happy to go to work because I am surrounded by wonderful people.

Thanks to my friends, for their support in the happy and the sad moments. Thanks to (in random order, I hate alphabetic rankings!) Erry, Marco, Stefano, Silvia, Ann, Alberto, Oana, Raquel, Jack, Pablo, Gabo, Bernadette,

Roberta, Ignacio, Saimir, Stella, Chiara, Dado, Karl, Josefin, Angela, Luana, Suny, Romolo, Bartolo, Loris, Marzi, Ale, Giaele, Filo, Fierro, ... I am not thanking you individually for the only reason that would require a whole thesis alone. But I cannot help giving a special thank to Maurizio, who introduced me to sailing, the new little world where I just can feel good when I need to escape from everything else.

Last, but definitely not least, thanks to Antonella and Sandro, papá e mamma. I thanked all the people who had a role in making me the researcher I am, but if I have to thank somebody for being the person I am, that is you.

# Appended papers

This thesis represents the combination of the research presented in the three following appended papers:

**Paper I** : *Baldi, F. , Gabrielii, C. & Anderssson, K. (2013) Energy and exergy analysis of a ship: the case study of a chemical tanker*, ready for submission to *Energy.*
The study focuses on the analysis of ship energy system using energy and exergy analysis. These methods are applied to a specific case-study. The results identify the main energy flows and the most important inefficiencies on board of the selected vessel.

**Paper II** : *Baldi, F. , Larsen, U. , Gabrielii, C. & Andersson, K. (2013) A validated zero-dimensional four-stroke medium speed Diesel engine model for waste heat recovery marine applications*, submitted to *Applied Energy* on the 2013-06-10.
The study focuses on the description of a model for predicting medium-speed marine Diesel engine performance and on its application to the case of engine-propeller interaction modelling for a case-study ship. Results underscore how the use of presented models can help identifying more efficient operations.

**Paper III** : *Baldi, F. , Bengtsson, S. & Andersson, K. (2013) The influence of propulsion system design on the carbon footprint of different marine fuels*, *Low Carbon Shipping Conference*, London, 9-10 September 2013.
The study focuses on proposing a method for comparing the carbon footprint of different fuels and propulsion systems. A number of possible arrangements for the case-study ship were analysed and compared in their energy performance and carbon footprint. The results show how fuel and propulsion system choice in the design phase must be tackled contemporarily and how a carbon footprint analysis can give a much more detailed understanding of the environmental performance of different propulsion systems and fuels.

*For all the appended papers, the author of this thesis contributed to the ideas presented and had a major role in planning the paper, data collection, performing the analysis, and writing the manuscript.*

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# Symbols and abbreviations

### Roman Symbols

| | |
|---|---|
| $EX$ | Exergy $[kW]$ |
| $H$ | Enthalpy $[kJ]$ |
| $I$ | Irreversibility $[kJ]$ |
| $m$ | Mass $[kg]$ |
| $MCR$ | Maximum continuous rate $[kW]$ |
| $P$ | Power $[kW]$ |
| $Q$ | Heat $[kJ]$ |
| $S$ | Entropy $[\frac{kJ}{K}]$ |
| $SFOC$ | Specific fuel oil consumption $[\frac{g}{kWh}]$ |
| $SSFC$ | Specific ship fuel consumption $[\frac{kg}{nm}]$ |
| $T$ | Temperature $[K]$ |
| $W$ | Work $[kJ]$ |

### Greek Symbols

| | |
|---|---|
| $\delta$ | Contribution to total exergy destruction |
| $\eta$ | Efficiency |
| $\lambda$ | Irreversibility ratio |

### Subscripts

| | |
|---|---|
| $0$ | Reference ambient conditions |
| $en$ | Energy |
| $ex$ | Exergy |

### Abbreviations

| | |
|---|---|
| **AE** | Auxiliary engine |
| **CAC** | Charge air cooler |
| **CO$_2$** | Carbon dioxide |
| **CPP** | Controllable pitch propeller |
| **ECA** | Emission controlled area |
| **EEDI** | Energy Efficiency Design Index |
| **EGE** | Exhaust gas economiser |
| **FPP** | Fixed pitch propeller |
| **GHG** | Greenhouse gas |
| **HFO** | Heavy fuel oil |
| **HHV** | Higher heating value |
| **HT** | High Temperature |
| **HVAC** | Heat, ventilation, and air conditioning |
| **IMO** | International Maritime Organisation |
| **JW** | Jacket wataer |
| **LHV** | Lower heating value |
| **LNG** | Liquified Natural Gas |
| **LO** | Lubricating oil |
| **LT** | Low Temperature |
| **MDO** | Marine diesel oil |
| **ME** | Main engine |
| **NO$_X$** | Nitrogen oxides |
| **PM** | Particulate matter |
| **S/G** | Shaft generator |
| **SEEMP** | Ship Energy Efficiency Management Plan |
| **SO$_X$** | Sulphur oxides |
| **WHR** | Waste heat recovery |

# SYMBOLS AND ABBREVIATIONS

# 1

# Introduction

The shipping industry is today facing very strong challenges. In a period of low freight rates, fuel prices have increased to levels only seen during the oil crisis in the 70's. Stricter environmental regulations are putting additional stress on the sector. Meanwhile, the latest IPCC report highlighted the increased confidence in the existence of an anthropic contribution to global warming. Shipping, though only contributing by an estimated 3% to global $CO_2$ emissions, is expected to increase its share in the future.

In such a context, it is not surprising that the interest in energy efficiency has exponentially grown during last years. The critical role of shipping in global economy implies that increasing the efficiency of the sector is one of the only ways to reduce its consumption without decreasing its output. There is the need of addressing energy efficiency in shipping from a number of different angles. This thesis approaches this challenge from a technical perspective[1].

This chapter provides an introduction to the subject of the thesis. In Section 1.1 a short description of the shipping sector and its current challenges is presented, leading to the identification of the problem. The aim of the thesis and the research questions are then explicitly defined in Section 1.2, while Section 1.3 draws the delimitations. Finally, the thesis outline presented in Section 1.4 helps the reader in the orientation through the different chapters and sections of this work.

## 1.1 Background

Shipping has always been intrinsically related to the history of mankind, from the Pheonicians to the Romans, the Venetians, the Hanseatic League and the journeys of Colombo, Diaz, Caboto, Zheng He. Today, shipping is one of the largest drives of world's globalised economy, as it contributes to more than 80% of global world trade by volume, and 70% by value (UNCTAD, 2012). Figure 1.1 shows the evolution of global trade in the last decades; even after the step back caused by the economic crisis in 2008, global trade has already taken back on its previous pace, and most analysts

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[1] For a more interdisciplinary perspective, *Towards understanding energy efficiency in shipping*, by Johnson *et al.* (2013), is a very informative reading.

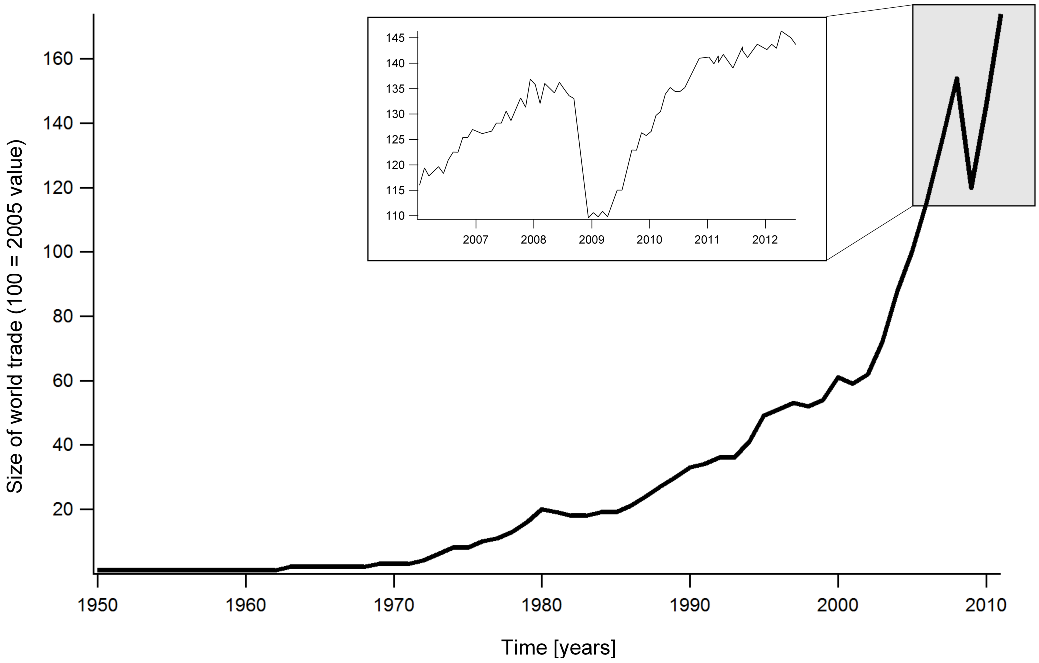

**Figure 1.1:** World trade evolution, 1950-2012; detail of the 2007-2012 period[1]

agree that this growing trend is very likely to continue in the future, fostered by the growth in non-OECD countries (UN, 2013).

As a result of this trend, merchant shipping has been growing steadily over the past years, hand in hand with world trade. In the period between 1999 and 2004 merchant shipping increased its economic turnover by a striking average of 22% per year[2]. This astonishing growth, together with the rising global economy, is explained by phenomena like containerisation, increased economy of scale, and advances in marine engineering. Under these conditions, the cost of freight is not a major concern anymore when deciding where to purchase goods and materials (Stopford, 2009).

### 1.1.1 The evolution of bunker prices

The low cost of transport by sea has also been historically connected to very low prices for marine fuels (normally referred as "bunkers"). During latest years, however, the increase in bunker prices has made fuel cost the largest element for virtually every shipping company (DNV, 2012c). If as late as in the early 70s the fuel bill accounted for around 13% of total ship costs, for the period between 2006 and 2008, fuel costs were estimated to account for between 43% and 67% of total operating costs depending on vessel type (Kalli *et al.*, 2009). Figure 1.2 presents bunker prices evolution from 1984 until 2012, showing how they have seen a sharp increase since the 80's and,

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[1] Author's elaboration, from WTO (2012).

[2] Source: Douglas-Westwood Ltd, available on (Stopford, 2009)

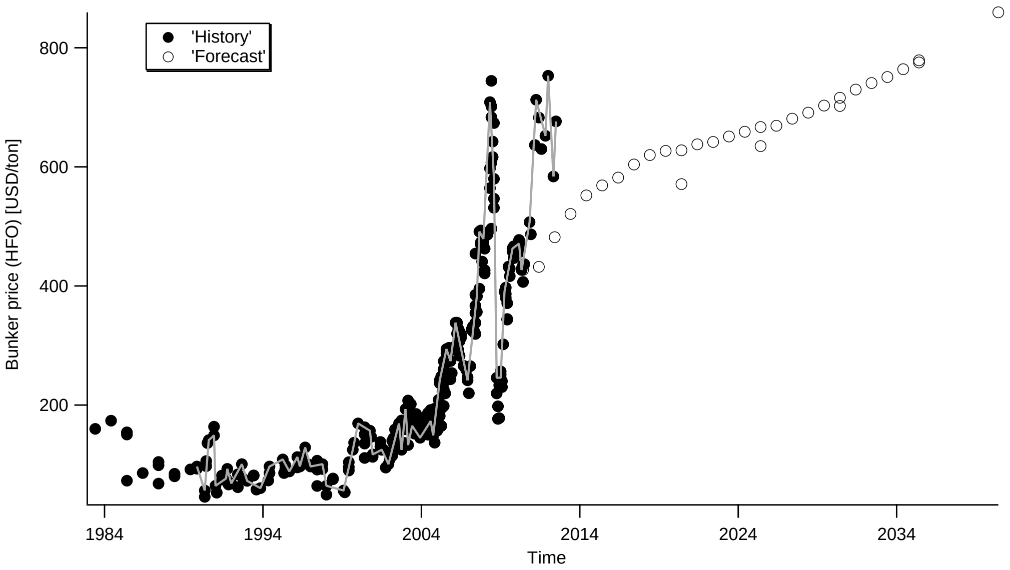

**Figure 1.2:** HFO price historical evolution (1984-2012) and forecast (2012-2035)[1]

especially, in the last ten years. As it can be observed, even if prices fell around 2009 in coincidence with the economic crisis, they have already promptly recovered. In the moment this thesis is going to print, the price for residual fuels ranged from 586 USD/ton in Rotterdam to 718 USD/ton in Sydney[3].

This is not the first period in history when oil prices (and, consequently, bunker prices) have experienced this kind of increase. During the oil crisis of the 70s fuel costs had risen to over 50% of ship operating costs (Buxton, 1985), creating the deepest recession for the maritime sector since the Great Depression (Böme, 1983). Nevertheless, in spite of the large number of studies connected to the reduction of fuel consumption that was produced (Gauthey & DeTolla, 1974; DeTolla & Fleming, 1981; Brady, 1981; Sack, 1981), most of the technical and managerial improvements discussed in those years just faded as bunker prices dropped (Johnson *et al.*, 2013). However, even if there is disagreement among experts on the forecasts, reference scenarios hypothesised by the major international agencies assume increasing prices in medium to far time horizons (EIA, 2013; DNV, 2012b). This is a crucial matter for the subject of this thesis, since fuel prices have a direct, strong impact on the uptake of new technologies for increasing energy efficiency, as well as on the implementation of existing ones (DNV, 2012c).

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[3] Source:bunkerworld.com. Prices refer to IFO380, a type of residual fuel. Last updated 2013-10-20

[1] Author's elaboration from Brett (2008), Mazraati (2011), EPA (2008), Vivid & Economics (2010), Sabinsky, SCC (2005), SSPA (2011)

### 1.1.2 The influence of environmental concerns on fuel costs

Yet, this is only the economic part of the picture. In 2013 there could be no discussion connected to the transport sector without a mention to greenhouse gases (GHG) and, in general, emissions to air. Transportation by sea requires energy for propulsion, which with today's technological standard is provided by the combustion of fossil fuels. The oxidation of carbon content in the fuel, in turn, releases carbon dioxide ($CO_2$), which stays in the atmosphere for centuries and contributes to global warming.

Shipping contribution to global $CO_2$ emissions is relatively low and hard to evaluate. Estimates relative to 2007 give an upper and lower boundary of respectively around 600 $\frac{MTCO_2}{year}$ (IEA, 2012) and around 1250 $\frac{MTCO_2}{year}$ (Buhaug *et al.*, 2009), which correspond to a share of global $CO_2$ emissions of between 2.7% and 3.6%. Taking into account the contribution to the overall emissions of GHG, shipping is estimated to account for 1.2% to 2.5% of the total.

According to Rogelj *et al.* (2011), global GHG emissions need to be reduced to approximately 43 $\frac{GTCO_{2,eq}}{year}$ by 2020 and 17 $\frac{GTCO_{2,eq}}{year}$ by 2050 in order to have a 90% likelihood of keeping the temperature from increasing more than 2°C compared to pre-industrial levels. On the other hand, shipping emissions are not expected to decrease at all. Even when the implementation of all cost efficient measures in a high carbon-tax scenario is accounted for, projections do not forecast any reduction in total emissions (Buhaug *et al.*, 2009; Eide *et al.*, 2011; Faber *et al.*, 2009). As shown in Figure 1.3, shipping might become the major contributor to global GHG emissions if present trends are not diverted.

Two main policy instruments have been issued by the International Maritime Or-

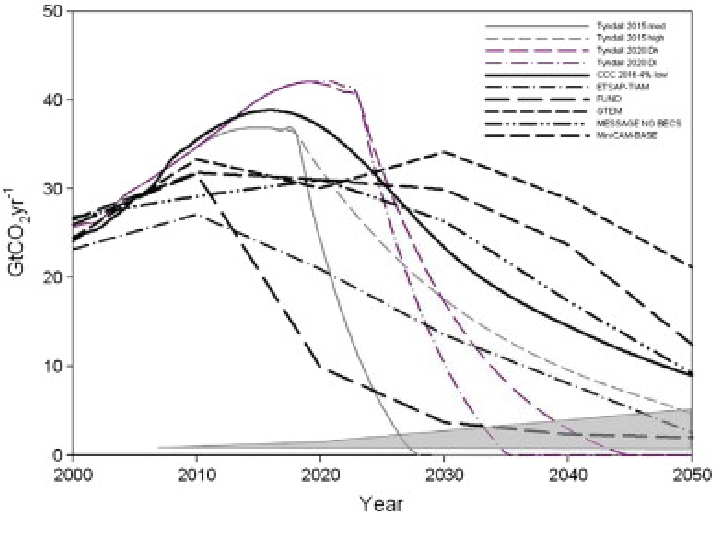

**Figure 1.3:** Forecasted shipping contribution to global $CO_2$ emissions. Lines represent different scenarios for global $CO_2$ emissions, while the gray area represents the possibility space for shipping-related $CO_2$ emissions as forecasted by Buhaug *et al.* (2009). From Gilbert & Bows (2012)

ganisation (IMO)[1] in the effort of reducing shipping impact on global warming: the *Energy Efficiency Design Index* (EEDI), which sets minimum limits on the emissions of $CO_2$ per unit of transport work from newly built vessels, and the *Ship Energy Efficiency Management Plan (SEEMP)*, which aims at improving awareness for energy efficiency on existing vessels[2]. Their effectiveness, however, has been put under question (Johnson *et al.*, 2013; Bazari & Longva, 2011; Devanney, 2011).

A part from GHG[3], sulphur oxides ($SO_X$) and nitrogen oxides ($SO_X$) are often discussed as they have an influence on fuel costs. New, stringent limits on the emissions of these two pollutants are expected to be enforced in the coming years. As reported by the European Environmental Agency (EEA), shipping contribution to the national $SO_X$ and $NO_X$ deposition is estimated to be between 10% and 30% of the total for most of the European countries having a significant portion of their borders facing the sea (EEA, 2013). Meeting the requirements imposed by new regulations on the matter (especially in Emission Control Areas (ECAs), where limits are even more stringent) will require either the installation of costly equipment on board, or the switch to cleaner and more expensive fuels[4]. In both cases, fuel-related costs are expected to increase in the near future because of the more stringent requirements on emissions to air (DNV, 2012c).

### 1.1.3 Energy efficiency and the need for a systems approach

This thesis deals with the challenge of increasing ships energy efficiency, i.e. reducing fuel consumption without decreasing the output. But if research and development have reached very high standards in the technology of engines and propellers, the same cannot be said of the design of ship energy systems. Until the recent past, low fuel prices have generated very little demand for more energy efficient ships from the industry; as a consequence, technical knowledge in this field has stagnated. There is the need of approaching the subject with systems perspective, which regards the ship as a complex system rather than focus on individual components (Lassesson & Andersson, 2009; DNV, 2012a). This thesis aims at addressing this gap in the scientific knowledge in the field.

## 1.2 Aim and research questions

The aim of this licentiate thesis is to contribute to a better understanding of the ship as an energy system and to use this acquired knowledge in order to analyse possible

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[1] The processes inside the International Maritime Organisation (IMO), the body of the UN responsible for international shipping, can be very complex. An analysis of one such example, related to sulphur dioxides emissions from shipping, can be found in Svensson (2011).

[2] EEDI and SEEMP have been adopted at MEPC 62 in July 2012 as an amendment to the Maritime Pollution (MARPOL) convention.

[3] There is still an open discussion, especially from a juridical point of view, on whether $CO_2$ should be considered a pollutant or not. For further details on the subject please refer to (Linné, 2012)

[4] There is a large debate on what will be the marine fuels in the future. A thorough environmental comparison of different marine fuels is presented in Bengtsson (2011).

improvements to its energy efficiency.

To improve the understanding of ship energy systems translates in the objective of evaluating components performances and energy flows sizes. The importance and efficiency of producers, converters and consumers from one side and the size of inputs, outputs and internal flows from the other should be evaluated. This can be translated in the following research questions:

How can *energy and exergy analysis* be used to identify:

- identify the main energy producers and consumers on board? (Paper I)
- the main waste heat flows? (Paper I)

Once the main possibilities for improvement are identified, alternatives to the current practice should be generated and evaluated. In general, three kinds of intervention are considered: ship operations, retrofitting and design. In this thesis, this challenge is addressed using a systems approach, focusing on the system as a whole rather than on its individual components. This objective can be translated in the following research questions:

How can the use of a *systems perspective* and of *mathematical modelling* assist in:

- the improvement of the energy efficiency of the propulsion system through a better engine-propeller interaction? (Paper II)
- the evaluation of the feasibility of the installation of waste heat recovery systems on ships? (Paper I, Paper II)
- the estimation and comparison of the energy consumption and the carbon footprint of alternative arrangements in the initial stage of ship design? (Paper III)

Results from the application of energy and exergy analysis are further developed in Paper I in order to evaluate WHR feasibility. In Paper II, models for the main part of ship energy systems are built in order to evaluate alternative operational modes for propulsion, also including a WHR system. Finally, in Paper III alternative fuels and propulsion system designs are evaluated in their annual energy consumption and carbon footprint.

## 1.3 Delimitations

International shipping is the largest contributor both to the benefits (trade volume) and to some of the drawbacks (GHG emissions) of shipping in general. This thesis will hence focus on the types of vessels mostly used in international shipping. This kind of ships are generally operated in stable conditions over long distances, which makes a steady-state approach the most appropriate for tackling this subject. Dynamic effects are, in most cases, of little interest and they are therefore not taken into account.

Furthermore, this thesis aims at providing tools and information on how to improve the energy efficiency of ship energy systems, by means of generating and evaluating alternatives to current setups. The results of the thesis should, as a consequence, be seen as a part of a larger picture, also including economic, environmental, and human aspects. From an energy perspective, the analysis sets its boundaries at the ship as a system, and again the results should be seen as part of a larger figure, where energy needs for fuel production and transportation, and for ship production are also taken into account.

## 1.4 Thesis outline

This thesis presents a synthesis of the research conducted over two and a half years on the subject of improving ship energy efficiency through a systems perspective. Although additional details can be found in the three appended papers, the thesis is supposed to be understandable as a stand-alone work.

This thesis is subdivided in eight chapters; after the introduction to the background, subject and scope of the thesis, Chapter 2 describes the ship as an engineering and energy system and motivates the use of a systems approach by introducing to its complexity. Chapter 3 presents the main methodological framework of the work, first describing the case study that have been used in the work, and then introducing the reader to the concepts of systems analysis, energy analysis and system modeling. Chapters 4 and 5 represent the core of the thesis, presenting the results of energy and exergy analysis of ship systems and providing relevant examples of how these can be used in order to generate and evaluate alternatives for the improvement of ship energy efficiency. Results and methodology are then discussed in Chapter 6, while Chapters 7 and 8 respectively present suggestions for further research and recommendations to the industry, and draws conclusions from the work and.

## 2

# The ship as complex energy system

Concepts such as "energy system" or "systems approach" have already been mentioned many times in this work. In particular, the aim of the thesis lies in the utilisation of a systems approach in order to identify possible improvements of ship energy efficiency. This is justified by the fact that in complex systems "*a major contributory factor* [to erroneous predictions of systems behavior] *has been the unwitting adoption of piecemeal thinking, which sees only parts and neglects to deal with the whole* "Flood & Carson (1993, p. 14). Inefficient design is often connected to erroneous predictions of system behavior, which are normally originated by counter-intuitive behavior. However, referring again to Flood & Carson (1993, p. 14),

> *this* [counter-intuitive behavior] *is not an intrinsic property of phenomena; rather, it is largely caused by our neglect of, or lack or respect being paid to, the nature and complexity that we are trying to represent. That is one reason why we need systems thinking, methodologies, and models. We argue that without this formal thinking we see only parts, the extremes, the simple explanations or solutions.*

This thesis addresses the subject of ship energy efficiency using a systems perspective. This kind of approach is most suitable, if not required, when a complex system is to be understood and improved without risking sub-optimisation. Section 2.1 introduces the subject of complexity and identifies what features of the ship make it identifiable as a complex system. This leads to a description of the ship as an engineering system, and in particular of the features related to its energy efficiency, presented in Section 2.2.

## 2.1 An introduction to complexity

Scientific literature can propose several examples which refer to the ship as a complex system from the point of view of control theory, social sciences, environmental sciences, and other more (Dupuis & Neilson, 1997). The interest of this work, however, lies specifically in looking at the ship as an *energy system*, and components and sub-systems are considered under the light of their influence on the energy balance of the ship. Components which are extremely relevant from other perspectives, as for example navigation equipment, can be considered as a mere fixed, small contribution to the overall energy balance of the ship.

The complexity of a system can be broken down to a number of attributes (Yates, 1978; Flood & Carson, 1993; Checkland, 1999):

- Large number of parts and significant interactions
- Non-linearity
- Emergence

Ship energy systems have a number of significantly interacting parts that is large enough not allow intuitive prediction of all input-output relations, but small enough to enable a clear identification of all components and of their interactions.

A system is non linear when "*at least one element in the system relates to and varies in a non-linear way with another* " (Flood & Carson, 1993, p. 28). Linearity allows very simple intuitive estimations. A ship is made of several complex components, few of which can be described with a linear behavior. These components also give rise to asymmetrical relationships.

*Emergence* refers to the property of the system to be more than the sum of its parts. The ability of a ship to fulfil its mission depends on the coexistence of a number of interacting components. A ship is more than the sum of an engine, and propeller, a hull, and many other subsystems; it is the unique combination of all these components that makes the system to be able to deliver its final function.

The ship, and in particular its energy systems, can therefore be said to be a complex system which can take a benefit from the application of a systems approach. Before proceeding further with the description of the work the led to the results of this thesis, the most relevant features of a ship are introduced, with a special focus on those that are most closely connected to the thematic of energy efficiency.

## 2.2 The ship

A ship is a floating, autonomously propelled platform which is designed for performing a specific mission. As this generally implies moving the ship through water, propulsion is often one of the major sources of energy consumption. The propulsion system fulfils this function on board of the ship. On the other hand, a ship has additional functional requirements, such as providing accommodation to the crew, supplying cooling and lubrication, etc. These functions require additional power, in the form of electric, mechanical, and thermal energy. A short overview of the most relevant auxiliary consumers and of the most common technologies for the generation of auxiliary power and heat is then presented. A visual representation of ship energy systems is provided in Figures 2.1 and 2.2[1].

### 2.2.1 The propulsion system

A detailed description of ship resistance would be out of the scope of this work; however, for giving an estimation of how the system is influenced by external parameters, it is often assumed that the power required for ship propulsion can be approximated as shown in equation 2.1 (Woud & Stapersma, 2008, p. 52).

$$P = y \cdot c_0(v)v^3 \tag{2.1}$$

The factor $y$ accounts for the influence of non-design conditions, such as hull fouling, displacement, sea state, and water depth. The coefficient $c_0$, representing the characteristic behavior of a specific ship, is normally increasing with speed, meaning that the final dependance of ship propulsion power requirement with speed is not exactly a third power curve (Woud & Stapersma, 2008, p. 52). The function of the propulsion system is to provide the ship with the ability to move. Even if the propulsion arrangement can vary substantially from vessel to vessel, the most common configuration can be described by one or more prime movers, coupled to one or more propellers. This is the typical arrangement for most of today's commercial vessels.

#### Propellers

The propeller is the most widespread solution among for converting of the rotating mechanical power from the engine shaft into a thrust force. Thrust bearings connect the shaft to the ship, thus allowing to convert thrust force into ship motion.

Fixed pitch propellers (FPP) are characterized by having blades whose angle relative to the axis of the shaft (pitch) is fixed. FPPs are generally directly connected to low-speed two-stroke engines, therefore building a very solid, reliable, and efficient propulsion train. However, this system suffers low flexibility and scarce manoeuvrability (Molland, 2008). FPPs are the most widespread solution for ship propulsion, and are particularly common among container ships, tankers, and bulk carriers (Carlton, 2007).

Controllable pitch propellers (CPP) allow the variation of the pitch. This ability provides the CPP with an extra degree of freedom in addition to its rotational speed. As a consequence, CPPs are installed for increasing ship manoeuvrability, for improving the ability of adapting load to drive characteristic, and for giving the possibility to generate constant-frequency electric power with a generator coupled to the main engines (Woud & Stapersma, 2008). As a consequence of the system being more complex, CPPs are more expensive and delicate than FPPs. CPPs are most favoured in passenger ships, ferries, general cargo ships, tugs, and fishing vessels (Carlton, 2007).

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[1] Please note that the arrangement represented in these figure is only intended to give a feeling of what are the main components positioned on board of the case study vessel. Their location in the actual arrangement might differ substantially.

### Prime movers

Diesel[1] engines are the most widespread solution for the generation of mechanical power from chemical energy. Firs installed on a ship in 1903, Diesel engine finally substituted steam turbines in the 60s, and today constitute 96% of installed power on board of merchant vessels larger than 100 gross tons (Eyring *et al.*, 2010). Marine Diesel engines, in fact, can achieve efficiencies up to 50%, allow operations to very low load (down to 10% of maximum continuous rating, MCR (Laerke, 2012)), and are designed to burn both residual fuels (heavy fuel oil, HFO, and intermediate fuel oil, IFO), and distillates (marine diesel oil, MDO, and marine gas oil, MGO) (Woud & Stapersma, 2008, p. 132). Recent developments also made dual-fuel engines available on the market, which can run both on liquid fuels and on natural gas (Aesoy *et al.*, 2011). The most relevant features of Diesel engines are summarised in Table 2.1[2].

| **Diesel Engines** | | | |
|---|---|---|---|
| | Low-speed | Medium-speed | High-speed |
| Process | 2-stroke | 4-stroke | 4-stroke |
| Construction | Crosshead | Trunk piston | Trunk piston |
| Output power range [kW] | 8000 - 80000 | 500 - 35000 | 500 - 9000 |
| Output speed range [rpm] | 80 - 300 | 300 - 1000 | 1000 - 3500 |
| Fuel type | HFO/MDO | HFO/MDO | MDO |
| SFOC [g/kWh] | 160 - 180 | 170 - 210 | 200 - 220 |
| Specific mass [kg/kW] | 60 - 17 | 20 - 5 | 6 - 2.3 |

**Table 2.1:** Performance parameters of Diesel engines, state of art 2001 (Woud & Stapersma, 2008, p. 136)

Gas turbines are today the only alternative to Diesel engines for ship propulsion. Despite being less efficient (efficiency for gas turbines ranges between 30% and 40%), and less flexible with load and fuel quality (Woud & Stapersma, 2008, p. 138) than Diesel engines, their main advantage lies in their higher power density. This makes them suitable for applications where high power and low weight are required, as in the case of fast ferries or naval vessels.

## 2.2.2 Auxiliaries

Ship auxiliary systems are a vital part of the ship. They are generally connected with energy demands that can, depending on ship type, represent a significant portion of

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[1] As Diesel is the surname of the inventor of this type of engine, Rudolf Diesel, I will refer to Diesel engines with capital letter.

[2] For a detailed description of the different principles the reader is invited to refer to the extensive literature on the subject, such as (Stone, 1999; Heywood, 1988; Kuiken, 2008).

overall ship energy use. As a ship at sea cannot use an external source of energy for its auxiliary needs, these must be provided by on board machinery. This can be divided as a function of the purpose (consumers, producers) or of the type of energy processed (thermal, electrical).

### Auxiliary consumers

A number of components on board require electric or mechanical power. Pumps are often a major consumer in this category, and they can be found in fuel and lubrication systems. Compressors are installed on board for air conditioning (HVAC, especially when additional accommodation is required for passengers), refrigeration and compressed air systems. Fans, both in the engine room and in cargo spaces, cargo handling, in the form of pumps or cranes, lighting, especially for passenger vessels, and all navigation equipment can also be a relevant source of electric power consumption. Ballast water pumps also constitute large auxiliary consumers, as most ships need to load water into specifically allocated tanks in order to maintain stability, especially when sailing with empty holds[1]. Most ships are also equipped with bow thrusters, propulsors located in the fore of the ship, that provide additional manoeuvrability in port.

Cooling demand is met by using sea water as a cooling flow and is also associated to relevant power demand, especially for pumps. The main cooling demand is represented by the main engines, which is subdivided into cooling of the cylinder walls (normally referred as jacket cooling, JW), of the charge air flow (charge air cooler, CAC), and of the lubricating oil (lubricating oil cooler, LO). In general, a high temperature (HT) and a low temperature (LT) circuits are used not to provoke too high thermal stress in the components. Additional systems are installed when refrigeration or air conditioning are required. The first is often needed by fishing vessels and reefers, while the second is connected to accommodation facilities and is a major consumer in cruise ships and ferries. Cooling demand generally translates in additional auxiliary power requirement for the operation of cooling pumps and refrigeration systems.

Heat consumers can also be relevant to the overall energy balance of the ship, especially for some specific vessel types, such as tankers and cruise ships. A large heat demand is often connected to accommodation, both for heating and fresh water generation. As HFO has very high viscosity at ambient temperature, fuel heating is also often a major figure in this category. Finally, some vessel types (e.g. tankers) can have specific mission-related heat demands, such as cargo heating.

### Auxiliary producers

Electric power is often generated using auxiliary Diesel engines (AEs, also referred to as auxiliary generators), coupled to electric generators and, in turn, to a main switchboard. This solution is the most common when a 2-stroke engine is used for propulsion. When a larger amount of auxiliary power is needed, a generator (in this case normally referred

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[1] A ship is said to be "sailing ballast" when it is navigating with empty cargo holds for picking a new cargo.

to as "shaft generator", S/G) can be coupled to the main engine shaft. This increases the efficiency of auxiliary power generation since the main engines are generally more efficient than the auxiliary engines. This solution requires however either a constant engine speed (and, thus, a CPP), or the installation of power electronics for frequency conversion, since the frequency of the current generated by the S/G directly depends on the speed of the main engine (Woud & Stapersma, 2008).

Auxiliary heat is generated in different ways depending on the required quality (temperature) and quantity. Heat exchangers recovering energy from the exhaust gas (also referred to as exhaust gas economisers, EGE) are often employed when a relatively small amount of process heat is required (i.e. only for fuel heating and accommodation, which is the most usual case on merchant ships). A separate boiler is necessary for higher heat demand, such as in the case of tankers and cruise ships. Heat is normally distributed to different consumers either using steam or thermal oil. The freshwater generator is a special case, as it can use low-grade heat and is therefore often located on the high temperature cooling water systems.

### Waste heat recovery systems

WHR systems refer to technical devices designed to make use of thermal energy that would otherwise be wasted to the environment, a solution which is widely used in various industrial sectors. The possibility of recovering waste heat from the main engines exhaust gas to meet auxiliary heat demand has already been mentioned in the previous section, and conceptually falls in this category. However the acronym WHR will be used, in the continuation of this thesis, to identify *systems whose main purpose is to generate mechanical and/or electric power from a flow of waste heat.* This distinction is used since the technology required for the conversion of waste heat into mechanical/electric power are conceptually different from what needed for the heat-to-heat conversion.

Some different technologies exist for the conversion from thermal to mechanical energy (Shu *et al.*, 2013). However, this work focuses on the utilisation of systems based on Rankine cycles. This technology has been particularly successful because of its simplicity, safety, and relatively high efficiency (Tchanche *et al.*, 2011). A Rankine cycle is based on the generation of high-pressure steam and its subsequent expansion in a turbine, which generates mechanical power. Organic Rankine cycles (ORC) are often used when only low-temperature waste heat is available; their working process is analogous to that of a standard Rankine cycle, but they make use of different working fluids which allow additional freedom in the choice of the evaporating temperature.

On a ship, the main engines are the principal source of waste heat on board of most of vessels, in particular through the exhaust gas and the cooling water flows. Despite the application of WHR systems is still quite rare in shipping, they are considered to have a high likelihood to be retrofitted on existent ships in the future (DNV, 2012c).

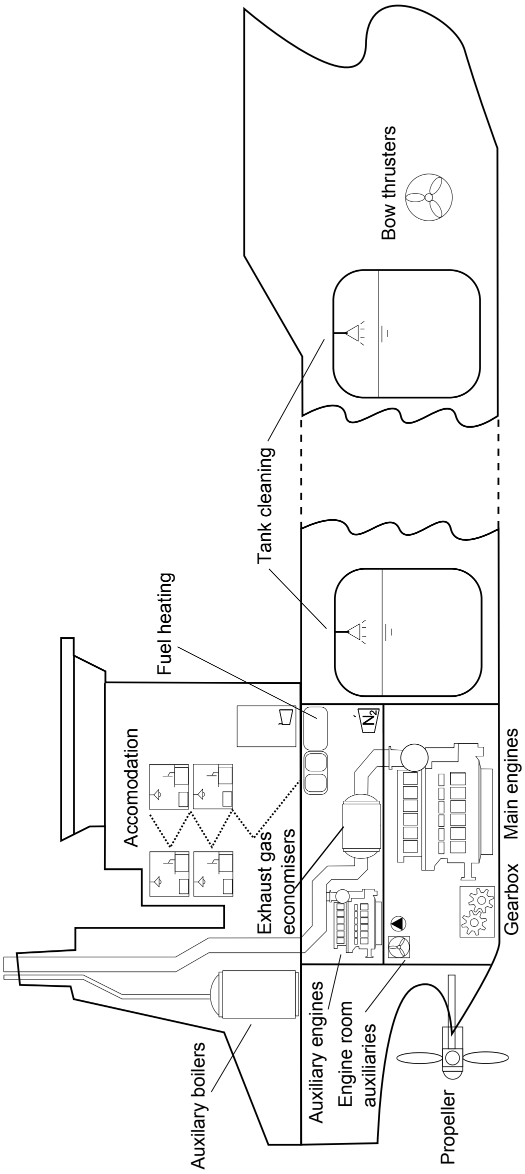

**Figure 2.1:** Schematic representation of ship energy system

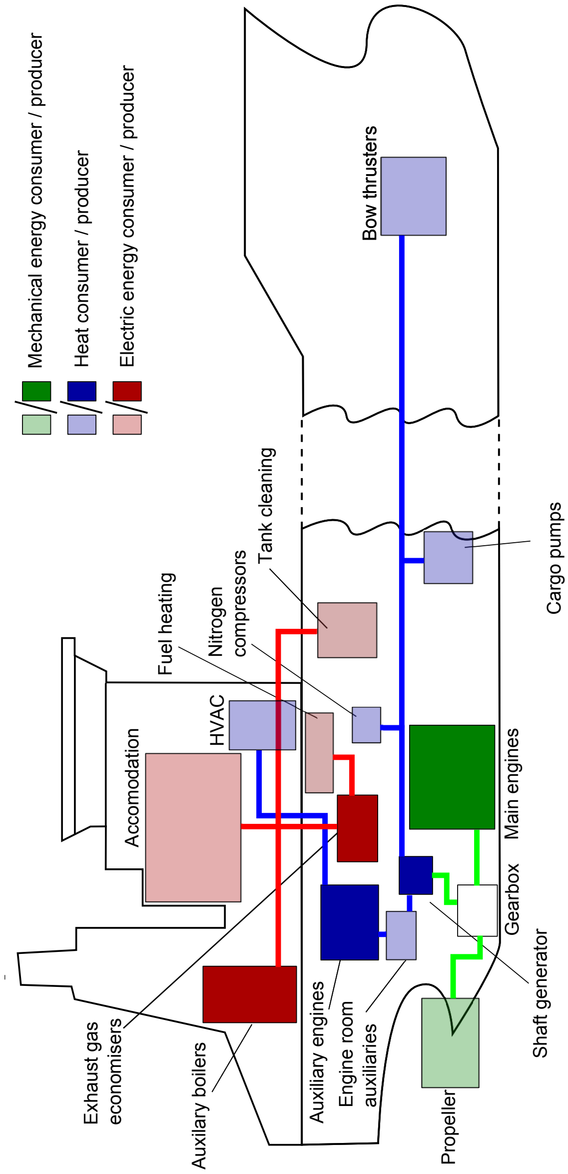

**Figure 2.2:** Schmeatic representation of ship energy flows

# 3

# The study of ship energy systems with a systems approach

In Chapter 2 ship energy systems have been described, and they have been shortly analysed from a systems science perspective. Having assessed the complexity of ship energy systems, it is necessary to employ a systems perspective rather than a component-wise optimisation. *Systems analysis* is a methodology suggested when dealing with problem-solving in complex systems (Flood & Carson, 1993, p. 100).

The community of systems scientists only partially agrees on the specific procedures to be applied in systems analysis (Checkland, 1999, p. 139), and it is common to adapt the methodology to the specific need of the situation. In the case of this thesis, the task of problem solving has to coexist with the more scientific need of improving the understanding of a system.

The analysis of the problem constitutes the first part of a systems analysis. The focus can be summarised in the question *What are the limitations of the present system?* (Flood & Carson, 1993). Valuable information for answering to this question can be provided by the results of energy and exergy analysis. A description of these methods, together with some required thermodynamic background to the concept of exergy and with an investigation of the existing literature, are provided in section 3.2.

The results from the energy and exergy analysis provide the basis for the following steps of systems analysis: the generation and evaluation of alternative solutions. This process requires an additional premise; in fact, *during specific and in-depth studies, conceptual or mental models are often not sufficient to cope with the type of complexity involved.* [...] *It is, therefore, necessary to seek more formal structured approaches to modeling* (Flood & Carson, 1993). The second part of this thesis, hence, focuses on the application of models to the evaluation of alternative solutions for improving the system. This process is subdivided in its application to ship operations, retrofitting, and design. More details on systems modeling and its application to ships in existing literature are provided in Section 3.3.

The main interest of this study is to argue for the application of a systems perspective to ship energy systems. However, the presentation of such a method without any

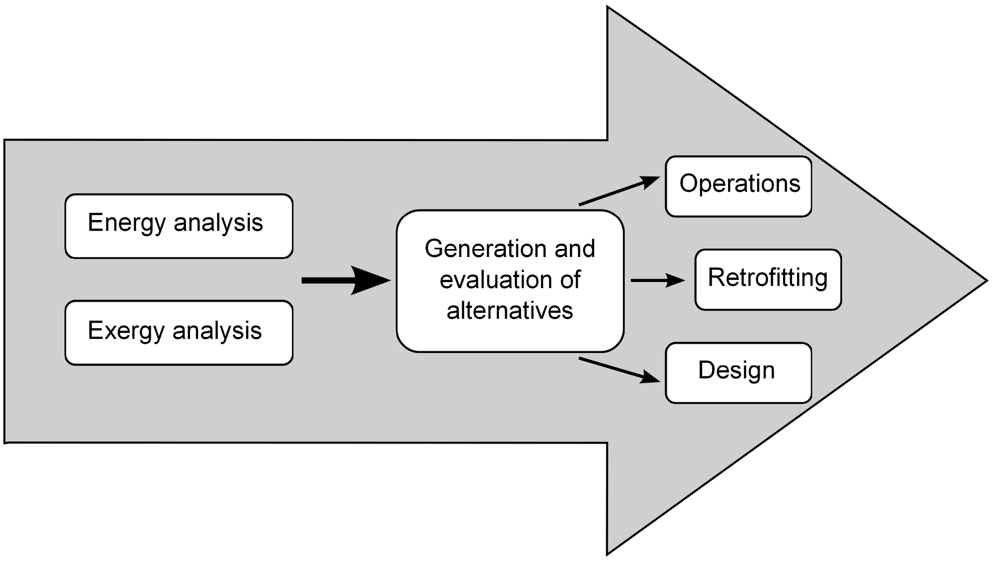

**Figure 3.1:** Graphical representation of thesis methodology

reference to real cases would fall short both in explanatory power and persuasion. As observed in most literature in the field, in the present work the proposed methods are applied to a case study. The technical details of the selected case study ship and more information about the data sources used in this study are here presented.

## 3.1 The case study of a chemical tanker

The case study represents an existing vessel, for which the company owning the vessel (named the "partner company") provided extensive operational measurements and technical information.

### 3.1.1 Description of the ship

The case study ship is a chemical/product tanker of 45 000 tons of deadweight which largely operates in international waters and, often, in ECA areas. The propulsion system is composed of two equally sized medium speed 4-stroke engines for a total installed power of 7 680 kW. Both engines are connected to a common gearbox, which in turn is connected to the propeller shaft, which provides the required thrust for propulsion.

The ship is equipped with a S/G (rated 3200 kW), connected to the main gearbox, which can provide auxiliary power. When operating in this configuration ("generator mode") both the main engines and the propeller need to be run at constant speed, while acting on the pitch of the CPP enables setting the speed. Alternatively, the ship can run in "combinator mode"; this operational mode allows for variable propeller speed, and consequently requires the use of at least on the two auxiliary engines (rated

682 kW each) for power generation. The ship is, however, operated in generator mode during most of its operations.

When the main engines are running, the auxiliary heat is supplied by two EGEs, capable of generating 700 kg/h of steam at 10 bar each, while two large auxiliary boilers, rated 14 000 kg/h of steam at 14 bar, are used for peak demands and when the main engines are not in operation.

For both electric power and heat, most auxiliary consumers are the same that can typically be found on most merchant ships. Special functions connected to the ship mission are the following:

**Inert gas production and compression:** Nitrogen needs to be produced on board and pumped into cargo tanks when inflammable liquids are transported. Nitrogen compressors have a high power demand, but are only operated intermittently.

**Cargo pumping:** When unloading the vessel, cargo pumps are required (high pressure in the shore-based tanks is normally sufficient for cargo loading). They can require a large amount of power when operated simultaneously.

**Tank cleaning:** After one cargo has been unloaded, tank cleaning is generally necessary in order to prepare the cargo tanks for the following shipment. This operation is performed either directly in port or during ballast trips, and requires the use of the auxiliary boilers.

**Cargo heating:** Some specific liquids are characterized by very high viscosity at ambient temperature, which makes them unsuitable for handling. For this reason, cargo heating can be ensured by means of process steam. This operation is, however, very seldom required.

The energy system of the case study ship is schematically represented in Figure 3.2.

### 3.1.2 Input data

Measured data and technical information for the case study ship were provided by the partner company. The different sources of quantitative and qualitative information are hereafter described.

#### Continuous monitoring

The case study ship is equipped with an energy monitoring system which logs on board measurements on a dedicated server with a frequency of acquisition ranging between 1 and 15 seconds. Data are automatically processed by the systems in order to produce 15 minutes averages, to check data reliability, and to filter output values. The list of the measurements available on the energy monitoring system is presented in Table 3.1.

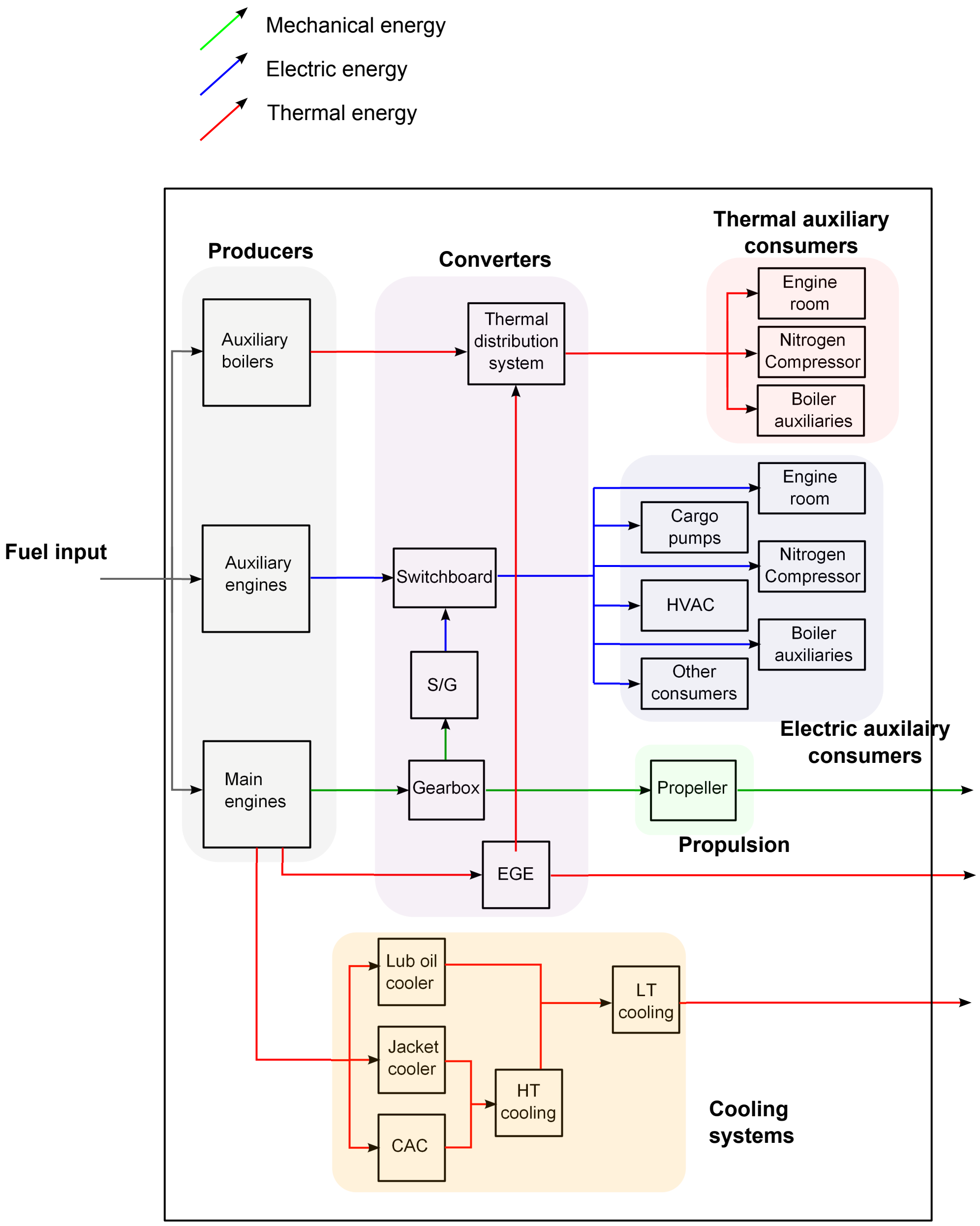

**Figure 3.2:** Conceptual representation of ship energy systems and flows

| **Measured variable** | **Unit** |
|---|---|
| Ambient air | |
| Dew point temperature | °C |
| Relative humidity | % |
| Auxiliary engines | |
| Fuel consumption | $\frac{ton}{15mins}$ |
| Power output | kW |
| Shaft generator power output | kW |
| Propeller | |
| Power | kW |
| Speed | rpm |
| Torque | kNm |
| Main engines fuel consumption | $\frac{ton}{15mins}$ |
| Fuel temperature | °C |
| Seawater temperature | °C |

**Table 3.1:** Available measurements from on board energy management system

### Technical documentation

When direct measurements of ship and components performance are not available, they can be calculated starting from available knowledge of the system. In this sense quite extensive technical documentation was made available by the partner company for the different components installed on board.

**Main engines project guide** contains information directly provided by the engine manufacturer and publicly available online (MaK). Data here provided comply with ISO 3046/1 and 15550 standards. Information connected to engine performance, inlet and outlet flows, and thermal losses to the environment are used in the study.

**Main engine shop test** contains experimental data provided by the manufacturer and measured under well-defined conditions. Information on engine performance for different load, including efficiency and exhaust temperature, is available from this type of technical document.

**Ship sea trials** are performed when the construction of the ship is completed in order to verify that the actual vessel performance conforms to the initial requirements set by the customer. Ship sea trials were available for the case study ship and for all its sister ships[1]. On board sensors are generally used in this phase, but a

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[1] In shipping jargon, "sister ships" are vessels built according to the same design

reasonable level of accuracy is guaranteed.

**Propeller curves** are represented as a diagram provided by the propeller manufacturer and generated through numerical codes. They provide information on propeller performance for different values of propeller pitch, speed and power and for different ship speeds.

**Combinator diagram** maps the characteristics of the control system installed on board for engine-propeller interaction. The combinator diagram is used when the ship is run in combinator mode, and is needed for engine protection versus too high torque at low speed, which would result in excessive thermal loading for the engine.

**Ship electric balance** is provided by the shipyard and summarises the expected power consumption of different auxiliary components depending on ship operational mode.

**Ship heat balance** is supplied by the shipyard and provides details on the different parameters used in the calculations such as heat exchange areas and heat transfer coefficients.

Other technical documents provide design information to be used for the estimation of the efficiency of the auxiliary engines, the shaft generator, and of other ship components.

### Noon reports and other data sources

On the case study ship, as on most vessels, information and measurements related to on board fuel consumption and machinery relevant parameters is manually collected daily by the crew and logged in paper and electronic format. Although the accuracy and reliability of these data is often questioned (Aldous *et al.*, 2013), they constitute a broad source of knowledge and are used in this thesis when none of the previously mentioned sources could provide the required information.

## 3.2 The analysis of ship energy systems

In this thesis, as energy efficiency is the main focus, the analysis of ship energy systems is performed as first step of the systems analysis methodology. The analysis of ship energy systems is subdivided in two main parts, *energy* and *exergy analysis*. While the former is quite known in various fields of science and in the industry, exergy is only seldom used, and will hence require some additional background.

The analysis of energy systems is often also divided between two main approaches A *top-down approach* mostly relies on the analysis of extensive measurements carried out in existing facilities (see, for example, Basurko *et al.* (2013)). On the other hand, a *bottom-up* approach uses mechanistic knowledge of the system in order to simulate its behavior and draw conclusions based on simulation results (see, for example, Nguyen *et al.* (2013)). The choice of the type of analysis strongly depends on the availability of input data and other information about the system.

### 3.2.1 Energy analysis

Energy analysis is defined as *the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service*(IFIAS, 1974), and refers to the application of the first law of thermodynamics, which states the principle of energy conservation (Clausius, 1850).

Energy analysis provides a quantitative insight of the relevance of different energy flows. It can help to identify, for example, the largest consumers in a system, on which efforts should be focused in order to improve the overall efficiency[1].

Studies reporting the analysis of the whole ship energy system are not common in literature. The work of Thomas *et al.* (2010) and Basurko *et al.* (2013), related to fishing vessels, propose an estimation of ship energy consumption and its repartition among different consumers, followed by the generation of a number of different alternative solutions for decreasing fuel consumption and their evaluation.

### 3.2.2 Exergy analysis

Energy analysis becomes incomplete and can be misleading when thermal energy flows are compared to electric and mechanical flows; the first law of thermodynamics, in fact, does not include any consideration about energy *quality* (Dincer & Rosen, 2013). The concept of *exergy* can be of particular use in this case, as the exergy content of a flow depends both on the quantity and on the quality of its energy content.

#### Heat and disorder

The need of introducing a new concept lies in the discrepancies between different energy types and, especially, in the conversion from one to another. Electric energy can be easily transformed into mechanical power and vice verse (electric motors have efficiencies of more than 90%, and the same holds for electric generators). Both these forms of energy can also be easily converted into thermal energy (respectively, for instance, through a fan and a resistance), with efficiencies close to 100%. The same cannot be said of the opposite: in practical applications the conversion from thermal to mechanical energy reaches maximum values of roughly 60% in advanced combined cycles. There is always a part of the thermal energy input which cannot be converted into work. This asymmetry is expressed by the *second law of thermodynamics*, which states that it is not possible to have a cycle whose only result is to convert a given amount of heat into work.

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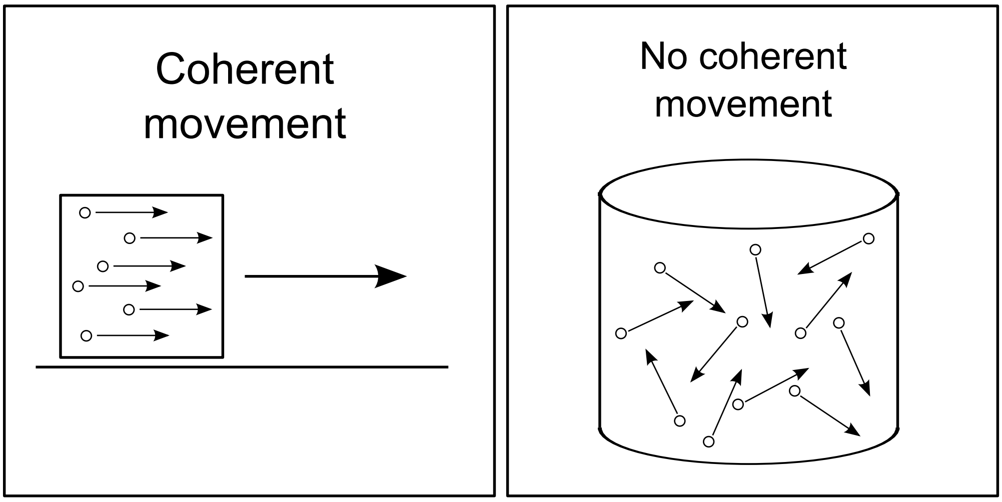
[1] Using high efficiency led lamps can be a very good idea for an office building, where large amounts of energy is required for lighting. On a container-ship, on the other hand, the same measure would lead to much less rewarding improvements as overall consumption for lighting is almost negligible in comparison to other needs.



(a) Mechanical energy (b) Thermal energy

**Figure 3.3:** Conceptual representation of the coherency of mechanical and thermal energy

Explaining the reasons of this asymmetry requires to look into matter at microscopic level. With reference to Figure 3.3, it is easy to observe that mechanical energy is characterised by a coherent motion of particles, for which it is possible to identify a principal direction. On the other hand, thermal energy is characterised by a completely random motion, for which it is not possible to identify any main pattern. A cost is associated to the passage from chaos to order, and the second law of thermodynamics qualitatively describes this cost (Atkins, 1984).

A quantification of this cost would allow to compare thermal flows among each other and versus more coherent forms of energy. Sadi Carnot provided the tools for this quantification: the *Carnot efficiency* is defined as the maximum efficiency that could be achieved by an ideal engine in generating mechanical power when receiving heat from a thermal source at a temperature $T_h$ and rejecting the waste heat to a thermal sink at a temperature $T_c$, lower than $T_h$:

$$\eta_{ex} = 1 - \frac{T_c}{T_h} \tag{3.1}$$

### Exergy

The concept of exergy derives from a generalisation of the Carnot efficiency. As conceptually represented in Figure 3.4, exergy represents the fraction of a given energy flow that could be converted into work using an ideal, Carnot engine. In fact, for a given amount of matter, its thermal exergy content is defined as showed in Equation 3.2. The remaining fraction of the initial energy flow represents the part that cannot

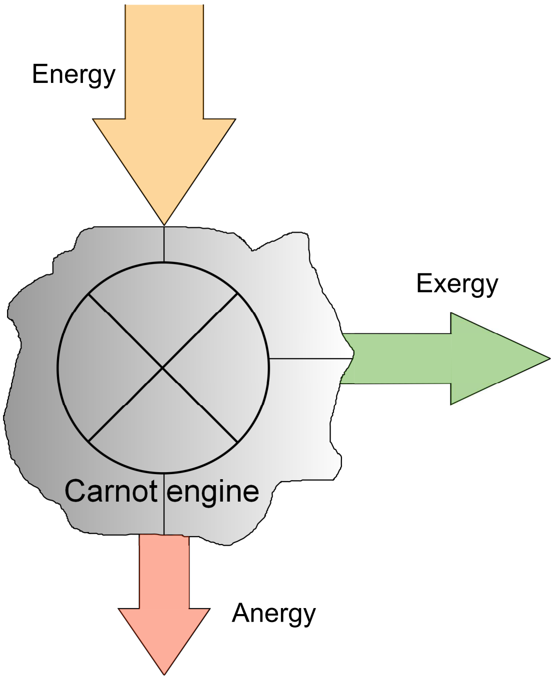


**Figure 3.4:** Conceptual representation of the property of exergy

be converted into work, even in ideal conditions, and is called anergy.

$$EX = m[(h - h_0) + T_0(s - s_0)] \tag{3.2}$$

where $EX$, $h$, $T$ and $s$ respectively represent exergy, specific enthalpy, temperature and specific entropy, while the subscript 0 represents reference conditions. It is possible to demonstrate that, under certain assumptions, Equation 3.2 can be derived from Equation 3.1.

For energy in a coherent form, such as in the case of mechanical, chemical, and electric, energy and exergy flows coincide[1]. Exergy and energy flows are instead remarkably different in the case of thermal energy. As it appears from Equation 3.1, the higher the temperature of a flow, the higher the fraction of that flow that can be converted to work.

Equation 3.2 shows how the exergy content of a flow of thermal energy also depends on the ambient temperature, which in general represents the cold sink of the hypothetical Carnot cycle. A flow of steam at 500°C could not be converted into work if its environment was at the same temperature[2].

---

[1] In this thesis, differently from common practice in exergy analysis, the lower heating value (LHV) is used instead of the higher heating value (HHV) for the quantification of chemical exergy. The reason for this choice lies in the fact that as conditions of exhaust gas condensation are never reached in ship energy systems, the use of HHV does not add any additional accuracy to the analysis.

[2] Despite this argument, there is still debate on whether a fixed reference temperature should be

### Exergy flows and efficiencies

According to Dincer & Rosen (2013) exergy flows calculated according to equation 3.2 can be divided in three main categories:

**Input** ($\dot{EX}_{in}$) : the flow of exergy entering the component.

**Output** ($\dot{EX}_{out}$) : the flow of exergy leaving the component.

**Irreversibility** ($\dot{I}$) : the amount of exergy lost in the component operation (also known as exergy distruction). This part represents energy quality deterioration and is defined as $\dot{I} = T_0 \dot{S}_{gen}$, where $\dot{S}_{gen}$ represents the rate of entropy generation in the component. In practical terms, however, exergy destruction is normally calculated as the difference between input and output exergy flows.

There are several different figures of merit that are commonly used in exergy analysis. In this thesis, four different quantities are used:

**Exergy efficiency** $\eta_{ex}$ is defined for this study as $\eta_{ex} = \frac{\dot{EX}_p}{\dot{EX}_{in}}$, where the subscripts $p$ and $in$ respectively refer to products and inputs. This definition of exergy efficiency gives an estimation of how efficient the component is in the generation of useful products. In the case of heat exchangers, as there is not a clear distinction between inputs and products, the alternative definition of $\eta_{ex} = \frac{\Delta \dot{EX}_c}{\Delta \dot{EX}_h}$ is used, where subscripts $c$ and $h$ respectively refer to the cold and the hot fluid. The definition of the $\Delta EX$ are adapted depending whether the component is meant for cooling or heating.

**Irreversibility ratio** $\lambda$ is used according to the definition proposed by Kotas (1980), i.e. $\lambda = \frac{\dot{I}}{\dot{EX}_{in}}$. The irreversibility ratio gives an estimation of how much energy quality is lost in the component.

**Irreversibility share** $\delta$ is defined as the ratio between the exergy destroyed in the component and the total rate of exergy destruction in the whole system, i.e. $\delta = \frac{\dot{I}_i}{\dot{I}_{tot}}$.

**Task efficiency** $\eta_{task}$ is used in this thesis in a modified form from what proposed in Dincer & Rosen (2013), and is defined as the ratio between the irreversibility in an ideal exchange at constant temperature difference (here arbitrarily fixed to 10°C ) and the irreversibility in the actual process, i.e. $\eta_{task} = \frac{\dot{I}_{id}}{\dot{I}}$. The task efficiency gives an estimation of how close the component behavior is to an ideal process.

Exergy analysis allows overcoming many of the shortcomings related to energy analysis. The most typical and clear example is that of a heat exchanger: from a first-law analysis, the component can be assumed to have a 100% efficiency, if the small

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used instead for the evaluation of exergy flows (Pons, 2009).

heat losses to the environment are neglected, regardless the temperatures of inlet and outlet flows. If a second-law analysis is performed instead, the exergy losses connected to inefficient thermal exchanges (those, for instance, in which a low-temperature fluid is heated using a very high-temperature fluid, as generally happens in households boilers) can be identified. Exergy analysis provides, in general, an insight when both thermal and mechanical/electrical energy flows are present in the systems (Dincer & Rosen, 2013).

Exergy analysis, however, is not widely used in shipping. Only few examples of the application of this method to ships can be found in literature, and only focus on individual components (Matuszak, 2008; Leo *et al.*, 2010) or subsystems (Lijun *et al.*, 1996; Choi & Kim, 2012). In the only example of the application of exergy analysis to the whole ship, Dimopoulos *et al.* (2012) presented the utilisation of exergy analysis for the optimisation of a marine WHR system.

### 3.2.3 Procedure

In the application of the analysis of energy systems to the case study presented in this thesis, a top-down approach is used, as extensive measurements are available. Input data from the continuous monitoring system for propeller power demand, MEs and AEs fuel consumption, S/G and AEs power output are used. The whole analysis of energy and exergy flows represents an aggregation over one year of operation of the case study ship.

Mechanistic knowledge of the system is used to break down the analysis of the energy flows among different components. Data from the different sources presented in Section 3.1.2 are used to identify thermal flows in the exhaust gas, cooling systems, and in the heat consumers. Data from the electric balance is elaborated to subdivide the overall auxiliary power consumption among different users. Records from noon reports are used to calculate the fuel input to auxiliary boilers. Heat exchange areas and coefficients from the heat balance are used to estimate auxiliary heat consumption. Available measurements of external seawater temperature are used as reference temperature for the calculation of exergy flows.

## 3.3 The improvement of ship energy performance

As introduced in the beginning of this chapter, the results provided by the application of energy and exergy analysis to ship energy systems should be used for the subsequent process of proposing and evaluating possible improvements to the system under study. This thesis focuses on the application of such process to the three main types of intervention in systems improvement: operational, retrofitting, and design.

In Section 2.1 the ship has been identified as a complex energy system. As suggested by Flood & Carson (1993, p. 151) *during specific and in-depth studies, conceptual or mental models are often not sufficient to cope with the type of complexity involved.[...] It is, therefore, necessary to seek more formal structured approaches to modeling.* The subject of system modeling is therefore hereafter introduced.

### 3.3.1 Systems modeling

Structured, mathematical modeling allows predicting the response of a system to different inputs without the need of experimentation or prototyping (Blanchard & Fabrycky, 2006, p. 164). Depending on the problem to solve, different modeling approaches can be used; a basic description of different criteria used when making decisions on approaches and assumptions to be used in models is here provided, adapted from Grimmelius *et al.* (2007) and Flood & Carson (1993, p.155):

**Physical requirements:** The model must be able to produce the outputs required by its utilisation and must to reproduce the required physics. This for instance might include the decision of whether the model should be dynamic or stationary, or of which variables it is required to predict.

**Accuracy requirements:** Higher accuracy means better results. However, as resources are limited, a target for model accuracy should be set in order to optimise computational effort and final result. Accuracy requirements for a specific model are normally related to the accuracy of other models in the same systems (in order to avoid the "bottleneck effect"), and to the accuracy of model inputs.

**Data availability:** A model should be constructed in accordance with the available information on the system, both in terms of system parameters and system inputs. Some parameters can be assumed based on previous work (physical constants, empirical correlations), while in presence of experimental data it is also possible to let some of the parameters vary in a calibration process, as long as enough experimental points are available for performing both the calibration and the validation of the model.

The main choice connected to the modeling approach refers to the use of *mechanistic* (often referred to also as *white-box*, *bottom-up*, or *deterministic*) models, as opposed to *empirical* (also referred to as *black-box* or *top-down*) models. Mechanistic models attempt to describe the physical phenomena that characterise a system, thereby assuming a deterministic approach; they typically make use of physical laws or empirical correlations in order to model and predict the behavior of a system. In contrast, empirical models treat the system to model as a black-box, and have no interest in the description of the underlying physical phenomena; starting from input-output databases, the empirical modeller employes regression techniques in order to generate a model able to predict system's output. The difference between the two approaches is conceptually visualised in Figure 3.5, while their characteristics are compared in Table 3.2.0

Finally, *hybrid* models (also known as *gray-box* or *semi-empirical* models) attempt to mix the positive properties of both white- and black-box models.

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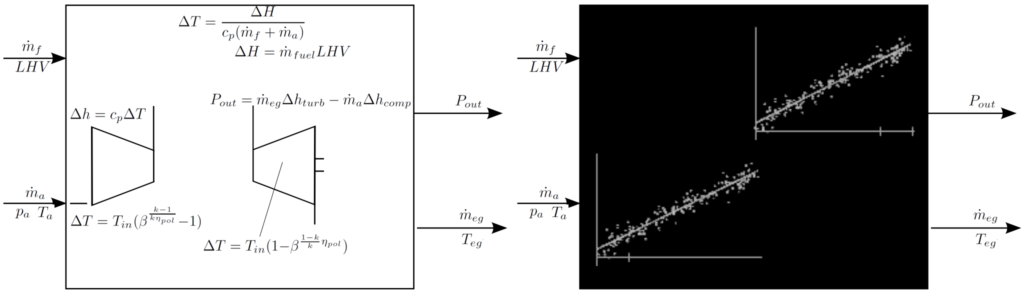
[1] The information summarised in this table is taken from (Duarte *et al.*, 2004; Bieler *et al.*, 2003, 2004; Braake *et al.*, 1998; Groscurth *et al.*, 1995; Bontempi *et al.*, 2004; Grimmelius *et al.*, 2007; Oliveira, 2004), which the reader is also referred to for further reading on various types of system modeling



**(a)** White box **(b)** Black box

**Figure 3.5:** Conceptual representation of white and black box modeling

| | **Mechanistic models** | **Empirical models** |
|---|---|---|
| System knowledge required | High | Low |
| Validity of extrapolation | High | Low |
| Applicability in design phase | High | Low |
| Accuracy | Low | High |
| Improvement of system knowledge | High | Low |
| Amount of input data required | Low | High |

**Table 3.2:** Comparison of mechanistic and empirical models[1]

### 3.3.2 Ship systems modeling

Application of energy system analysis in shipping dates as back as 1979 (Fake & Pundyk, 1979). More recently, Shi *et al.* proposed models for predicting ship fuel consumption in design and off-design conditions, both aiming at ships in general (Shi *et al.*, 2009, 2010) and in the specific case of dredgers[1] (Shi & Grimmelius, 2010; Shi, 2013). The work of Shi (2013) focuses on the dynamic modeling of dredger energy systems with the aim predicting energy consumption starting from the knowledge of a limited number of external variables.

More focus on energy and fuel consumption while considering the ship as a system was introduced by Dimopoulos *et al.*, whose work first focused on LNG carriers (Dimopoulos & Frangopoulos, 2008a,b) and then more generally on marine energy systems (Dimopoulos & Kakalis, 2010). In Dimopoulos *et al.* (2011) the use of optimisation algorithms in order to optimise the design of marine energy systems, with a particular focus on the implementation of WHR solutions and to the optimisation of related design parameters is proposed. The same authors also introduced exergy analysis applied to ship energy systems (Dimopoulos *et al.*, 2012).

#### Propulsion system modeling

The largest quantity of work in the field of ship systems modeling with an energy perspective has been devoted to the propulsion system, as it constitutes the largest share of ship energy consumption. Attempts in this sense started from the works of DeTolla & Fleming (1981) in the US Navy during the oil crisis, and went to the tool presented by Dupuis & Neilson (1997) and the modeling analysis described by Neilson & Tarbet (1997).

Work by Benvenuto *et al.* (2005); Benvenuto & Figari (2011); Campora & Figari (2003); Figari & Altosole (2007) focused on the propulsion system, proposing different alternatives for the modeling of Diesel engines and gas turbines, ship dynamics, and different control systems. Similar work was presented by Theotokatos (2007, 2008), while Schulten (2005) focused on the interaction between the engines, the propeller and the hull, with a particular focus of the dynamic events occurring during manoeuvring. Grimmelius (2003); Grimmelius *et al.* (2007) also relates to modeling of ship propulsion system, with a specific focus on the main engines. Tian *et al.* (2012) proposed and validated a model for the prediction of the behavior of the propulsion system of a RoRo vessel.

Some examples exist of the application of pure black-box models to ship propulsion systems modeling. Among them, work from Leifsson *et al.* (2008) and Shi & Grimmelius (2010) showed the comparison of the application of white-, grey-,and black-box models to the prediction of ship performance. The results, in accordance to the theory, show that black-box models provide the most effective prediction, but only when applied inside the initial data range and when a large amount of input data is available. Other

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[1] A dredger is a vessel whose purpose is to excavate and remove material from the bottom of a body of water.

attempts of predicting the influence of different control variables (speed, trim, etc.) are mostly related to navigation, as proposed for instance by (Petersen *et al.*, 2012). In relation to the objectives of this thesis, however, black-box models fail to provide additional insight on flows and phenomena in the energy system; furthermore, black-box models are not suitable for the evaluation of alternative solutions, as they provide only little possibility for extrapolation.

#### Auxiliary modeling

Studies related to ship auxiliaries are not common, as auxiliary power and heat demand often constitute a negligible part of ship energy consumption. Some of the studies mentioned in previous sections also include some part of the auxiliaries, such as in Shi (2013) for the case of dredger pumps.

Among the few examples of auxiliary system modeling in literature, Balaji & Yaakob (2012) analysed ship heat availability for use in ballast water thermal treatment technologies; others studied very specific types of auxiliary power consumption, such as Fitzgerald *et al.* (2011) who focused on the consumption of refrigerated containers, where Tilke *et al.* (2010) directed their interest on ship unloaders from bulk carriers. Hulskotte & Denier van der Gon (2010) specifically studied ship consumption when at berth, which is of particular relevance for the high impact of ship emissions when released in densely populated areas (Winnes, 2010). Bidini *et al.* (2005) proposed instead an analysis of the combined heat and power energy consumption of a small ferry operating in lakes.

Work has been published on the design and optimisation of WHR applications to ships already starting from the 70's (Tarkir, 1979). Some studies, such as Tien *et al.* (2007); Larsen *et al.* (2013), focused on a theoretical investigation of the WHR cycle, while Ma *et al.* (2012); Grimmelius *et al.* (2010); Theotokatos & Livanos (2013); Dimopoulos *et al.* (2011) proposed and evaluated different designs for the installation of WHR systems on ships.

### 3.3.3 Ship operations

The first possibility for reducing ship energy consumption relates to the improvement of ship operations. This alternative is of particular interest as it does not require any installation of new equipment and, therefore, only limited investment. Ships are normally optimised for one specific design point, while energy efficiency deteriorates in off-design conditions. The design power for the case study ship refers to the condition of sailing at a speed of approximately 15 kn in calm sea. Figures 3.6 and 3.7 show the frequency distribution for ship speed, propulsion system load, and individual engines load over one year of operations.

The figures show that the condition at design load (85% MCR) is far from being the most frequent condition for ship operations, a consequence of the fact that the ship is very seldom sailing at its design speed. In fact, it appears that the engines are mostly operating between 40% and 70% load and that the ship mostly sails in the of range 8-12

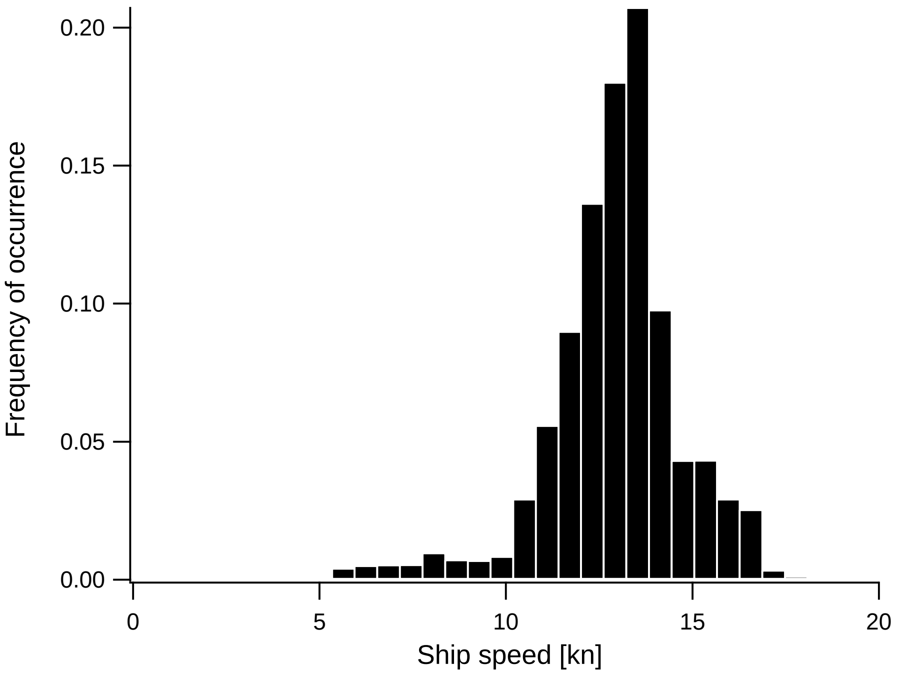


**Figure 3.6:** Ship speed distribution over one year of operations for the case study ship

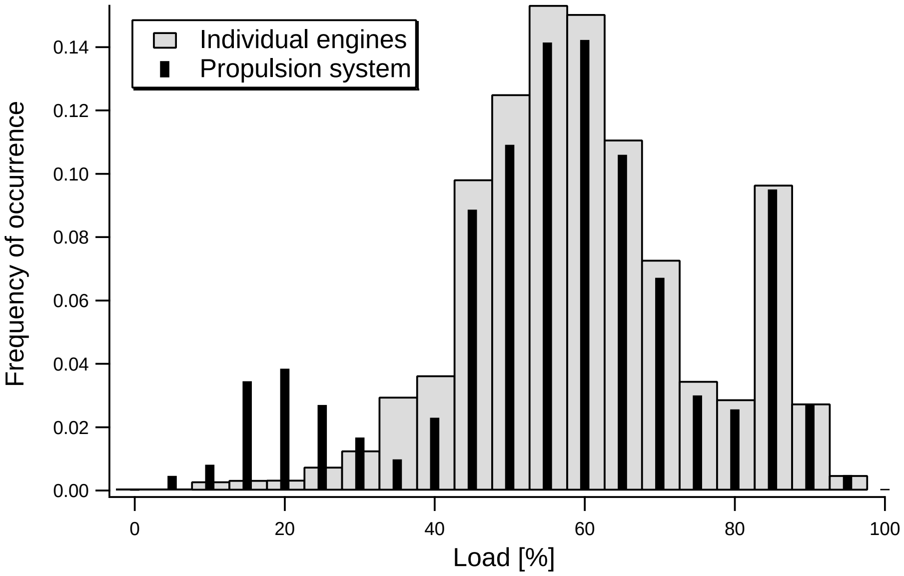


**Figure 3.7:** Propulsion system and individual engines load distribution over one year of operations for the case study ship

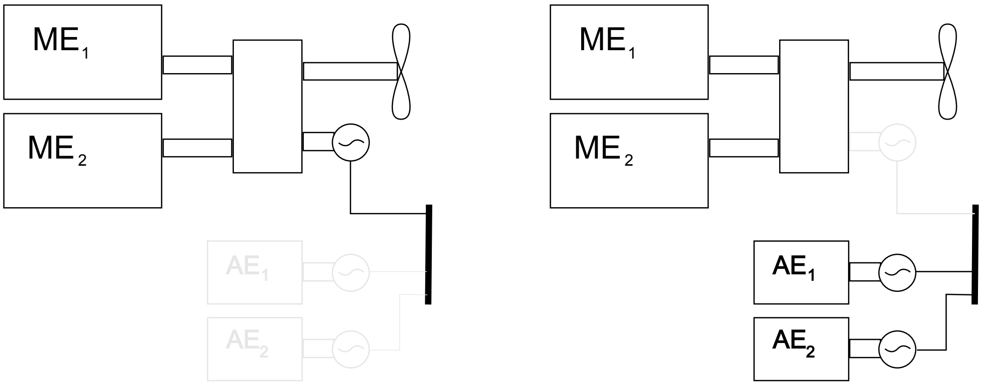
knots. Ship energy performance at low loads becomes therefore of primary importance. This consideration, here deducted from the analysis of the case study ship, has also been proved to apply to many other vessels operated today (Banks *et al.*, 2013).

Propulsion is the main source of energy consumption on board of the ship and should be addressed first. The systems approach suggests to look at interactions between components rather than at components themselves, which in the specific case is corroborated by discussions with the partner company. The issue of engine-propeller coupling, especially when the presence of a shaft generator requires to operate at constant propeller speed, has also already been treated in literature (Woud & Stapersma, 2008; Van Beek & Van Der Steenhoven, 2005).

In this case, two alternative arrangements for ship propulsion are evaluated and compared (see Figure 3.8):

**Case 1** Fixed engine speed, auxiliary power provided by the shaft generator. This arrangement corresponds to the standard operations in today's settings.

**Case 2** Variable engine speed, auxiliary power provided by the auxiliary engines. The advantage in this case is the possibility of modifying propeller speed in order to adapt to the conditions of best efficiency for different ship speeds. This case represents the proposed alternative to be evaluated.



**(a)** Case 1 **(b)** Case 2

**Figure 3.8:** Schematic representation of the two operational modes compared in the study

As mentioned in the introduction to this section, the use of models rather than prototypes or intuitive estimation is used to evaluate the different proposed alternatives. In the case of the propeller, curves produced by the manufacturer displaying propeller power as a function of ship speed, propeller pitch, and engine speed are available and used in this study. In the case of the engine, however, more modeling effort is required. In fact, all available information is related to engine operation at constant speed, which does not reflect the operating conditions for Case 2. For this reason, an in-house engine model is built in the Matlab© environment[1]. The modeling of auxiliary engines and

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[1] A detailed description of the model is provided in Paper II.

of the shaft generator is based on simpler numerical regressions, widely used in this field of engineering. All the different models are finally coupled and the behavior of the system for the two different alternatives at different ship speed is evaluated.

### 3.3.4 Retrofitting

Retrofitting, i.e. the modification of an already existing vessel, is also considered as a possible alternative for the improvement of ship energy performance.

Despite their high efficiency, Diesel engines reject to the environment a considerable amount of energy, especially in the form of exhaust gas and cooling water. The implementation of WHR technologies is not new in shipping, even if still not common. The utilisation of a systems perspective in the analysis of the feasibility of such systems is hence employed. In particular, this thesis focuses on evaluating the recovery potential compared to the actual need of auxiliary power, based on measurements relative to one year of operations of the case study ship[1]. A criteria was set for the evaluation of the possible installation of such systems, as compared to standard operations: if installed, it should provide the totality of ship auxiliary power need for a minimum of 80% of the time spent sailing. The exergy efficiency of the WHR system required to achieve this goal is then calculated for a number of different possible sources of waste heat.

The availability of waste heat is also influenced by engine load, and therefore by ship operations. For this reason, in the second part of the study the focus is shifted to the evaluation of the WHR potential as a function of ship speed. The same modeling approach as proposed for ship operations is used, where the potential for WHR is evaluated using model output on exhaust gas temperature and mass flow. The arrangement here proposed consists of positioning a WHR system on the exhaust gas flows of the main engines (Case 3, see Figure 3.9). Case 3 is compared to both the previously proposed Case 1 and Case 2.

In both parts of this study, the concept of exergy efficiency was used in order to give an estimation of the technical complexity of the recovery system. This approach, though only partially corresponding to real conditions, represents an improvement from the use of energy efficiency, which does not allow to account for differences in energy quality.

### 3.3.5 Design

As possible improvements both in operations and retrofitting are identified, the question can be further moved to investigating how it is possible to improve the ship directly from the design stage. Compared to common practice, the work presented in this thesis aims at proposing a more holistic perspective, thus taking into account aspects such as fuel selection, engine selection, WHR installation, energy performance and environmental

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[1] It should be noted that, as reviewed by Shu *et al.* (2013), several alternatives to power generation exist for the exploitation of ship waste heat. However, given the ship needs of auxiliary heat are already fulfilled by heat recovery and no additional requirement of, for instance, refrigeration was measured, auxiliary power generation was the only possible utilisation of waste heat taken into account.

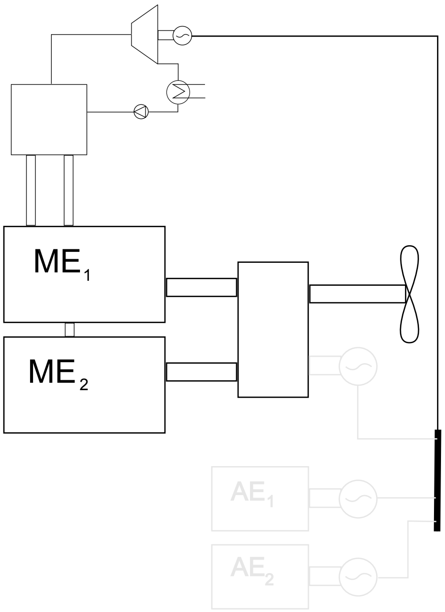

**Figure 3.9:** Schematic representation of the propulsion arrangement with WHR system installed: Case 3

performance in the same study. In addition, the influence of the utilisation of a real operational profile instead of a single design point, as suggested by Motley *et al.* (2012), is evaluated.

The study is carried out by comparing a total of 11 different arrangements, as showed in Table 3.3, which are generated assuming that the system should comply with future emission limits in ECAs for $SO_X$ and $NO_X$. The arrangements are generated combining different alternatives of fuel type (HFO, MGO, or LNG), type of engine (2-stroke and 4-stroke) and the utilisation of a WHR system[1]. The performance of a database of engines collected from technical documentation is evaluated using numerical regressions. For each of the 11 proposed arrangements, the best performing engine was selected. This allowed to compare "best practice to best practice". The analysis is then completed by looking at how the picture changed when including a carbon footprint analysis, thus including focusing on GHG emissions and employing an LCA approach.

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[1] The case of two-stroke engine with WHR using HFO as a fuel was not taken into account. This case would require too complex arrangements in order to fulfil future ECA emission limits and therefore was excluded from the study.

| **Case** | **Fuel** | **Engine** | **WHR** |
|---|---|---|---|
| 1 | HFO | 2-st | N |
| 2 | HFO | 4-st | N |
| 3 | HFO | 4-st | Y |
| 4 | MDO | 2-st | N |
| 5 | MDO | 2-st | Y |
| 6 | MDO | 4-st | N |
| 7 | MDO | 4-st | Y |
| 8 | LNG | 2-st | N |
| 9 | LNG | 2-st | Y |
| 10 | LNG | 4-st | N |
| 11 | LNG | 4-st | Y |

**Table 3.3:** Alternative arrangements evaluated in ship design. 2-st and 4-st respectively stand for two-stroke and four-stroke engines

# 4

# Ship energy system analysis

The analysis of ship energy systems is applied to the case study ship. The objective is to show the typical results of this application and the kind of information that it is possible to extract. Energy and exergy analysis are applied to the case study ship.

## 4.1 Energy analysis

The results of the application of energy analysis to the case study ship are shown in Figure 4.1 and in Table 4.1.

The first observable result is that consumption related to propulsion is the largest figure, as expected, accounting for 70% of the overall energy consumption. This also translates in the main engines consuming the largest share of the overall energy input of the system, representing around 89% of the total.

However, the contribution from the auxiliaries cannot be neglected, particularly because the ship spends a significant part of time waiting in port, when the only energy demand comes from ship auxiliaries. Both auxiliary engines and boilers (respectively representing 8.0% and 2.6% of ship energy input) on one side, and auxiliary power and heat consumers (16% and 14% of ship energy output) on the other, should be given significant attention. Boiler auxiliaries should be added to these considerations, as they also represent a significant share of the total output (2.7%). Auxiliary boilers are also run at low load most of the time, leading to low efficiency. Fuel heating also represents a surprisingly high share of the overall ship energy consumption (7.8%).

Finally, a large amount of energy is wasted to the environment through the exhaust gas (41% of main engines power output), the CAC (20%), JW cooler (22%) and the LO cooler (24%). This suggests that there is a potential for the utilisation of these waste flows for the generation of additional useful power.

## 4.2 Exergy analysis

Results of the application of exergy analysis to the case study ship are presented in Figure 4.2 and in Table 4.2.

The exergy analysis provides a different type of information on the system under study. The irreversibility ratio ($\lambda$) quantifies the tendency of a component to deteriorate energy quality in its internal processes. High values of $\lambda$ correspond to high losses in energy quality. It can be seen, for example, that according to this definition, boilers ($\lambda = 64\%$) are much less efficient than both main (37%) and auxiliary engines (38%). In the case of heat exchangers, the utilisation of the irreversibility ratio as a figure of merit can be misleading: a heat exchanger located on a large exergy flow (e.g. on the exhaust gas) could have very high $\lambda$ only because of its low heat exchange area. This is the case, for example, of the EGE, which has a very low rate of exergy destruction compared to the total exergy input ($\lambda = 6.5\%$) and therefore appears to be a very efficient component. If task efficiency ($\eta_{task}$) is used instead, it appears that the EGE and all heat consumers are very badly designed exchangers, from an exergy perspective, as they could achieve the same task with a much lower exergy destruction. On the other hand the LT/SW exchanger, which is responsible of the highest rate of exergy destruction among heat exchangers ($\delta = 5.3\%$), shows that this is connected to its particular function; its task efficiency is not, in fact, particularly low ($\eta_{task} = 32\%$)

Figure 4.2 can be helpful in the evaluation of different waste flows with respect to both energy quantity and quality. It is here shown that the exhaust gas is a much larger source of potentially recoverable heat than the cooling systems, contrarily to what could be deducted from Figure 4.1. When looking at the results of the exergy analysis, exergy flow in the exhaust gas represent 54% of the total recoverable energy, compared to 38% in energy analysis. The absolute estimation of the recoverable energy is also redimensioned: the energy flow in the exhaust is estimated to be 41% of the main engine output, while this value is decreased to 18% from an exergy perspective. This reduction is even more pronounced when looking at the cooling systems. In this case, it should also be noted that every step of heat exchange brings a decrease in the recovery potential; as an example, the exergy flow entering the jacket cooling alone is almost the same size as that flowing into the LT/SW heat exchanger. These results show how exergy gives a much more realistic estimation of the actual power that could be generated through a WHR system.

Even if smaller in size than that of the exhaust gas, the energy flow in the cooling systems should not be discarded as it still constitute a relevant source of potentially recoverable energy. Looking at task efficiencies leads to the identification of which components could be improved in order to perform the same task while reducing exergy destruction. This is particularly true for the charge air cooler ($\eta_{task} = 27.5\%$).

From the point of view of energy use, the very low efficiency of all auxiliary heat consumers (tank cleaning, hotelling, and fuel heating respectively have task efficiencies of 4.7%, 7.2% and 9.1%) indicates that it would be possible, by using a different heat transfer fluid (or, in alternative, steam at a lower pressure), to generate the same heat requirements while using much lower heat-grade sources. It is noted, for instance, that fuel handling and hotelling only require temperatures as low as 70-80 °C (a part from fuel heaters before the engine, which warm HFO up to around 100°C ), which could be provided at much lower temperature than by 9 bar steam.

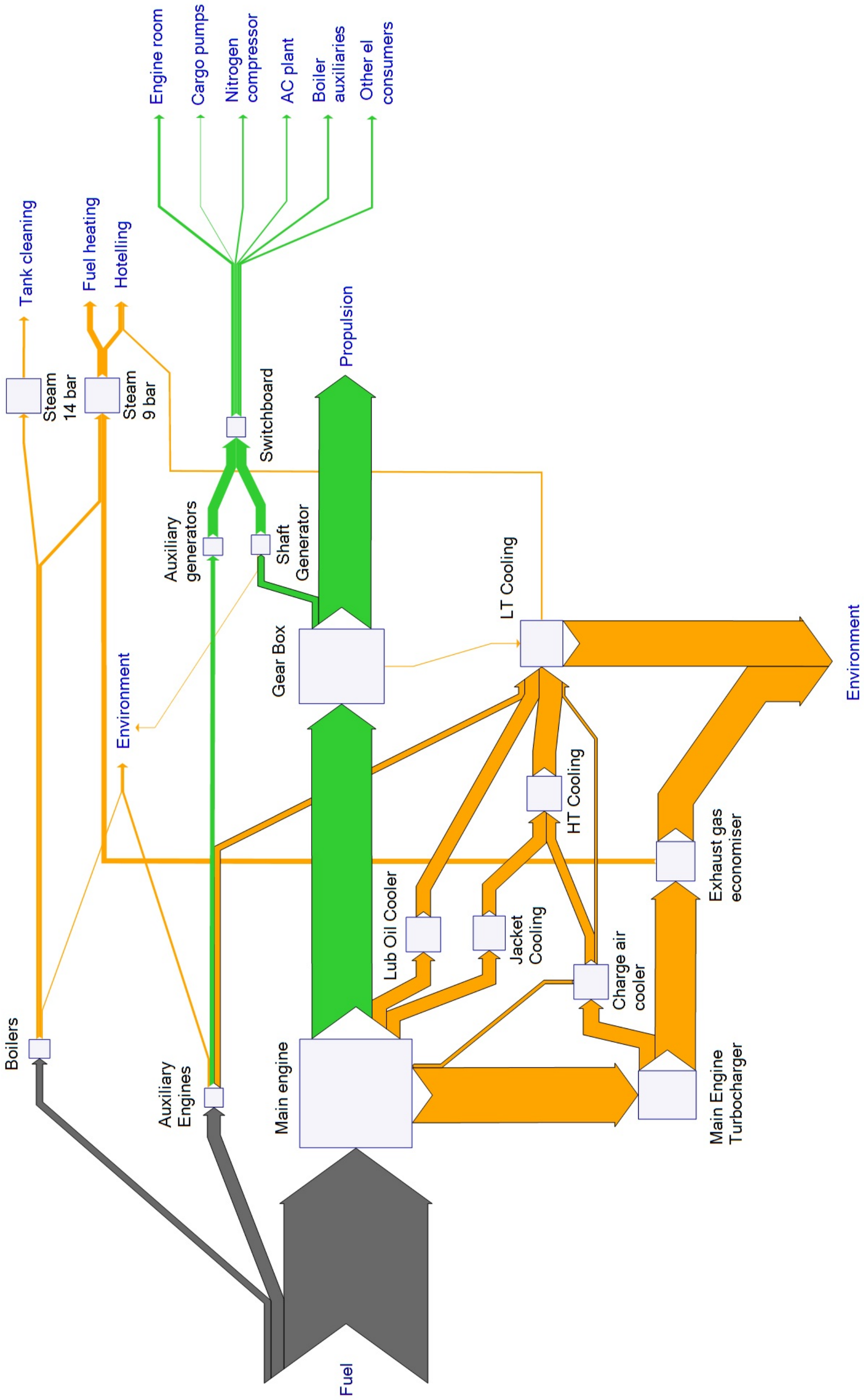

**Figure 4.1:** Sankey diagram for the case study ship

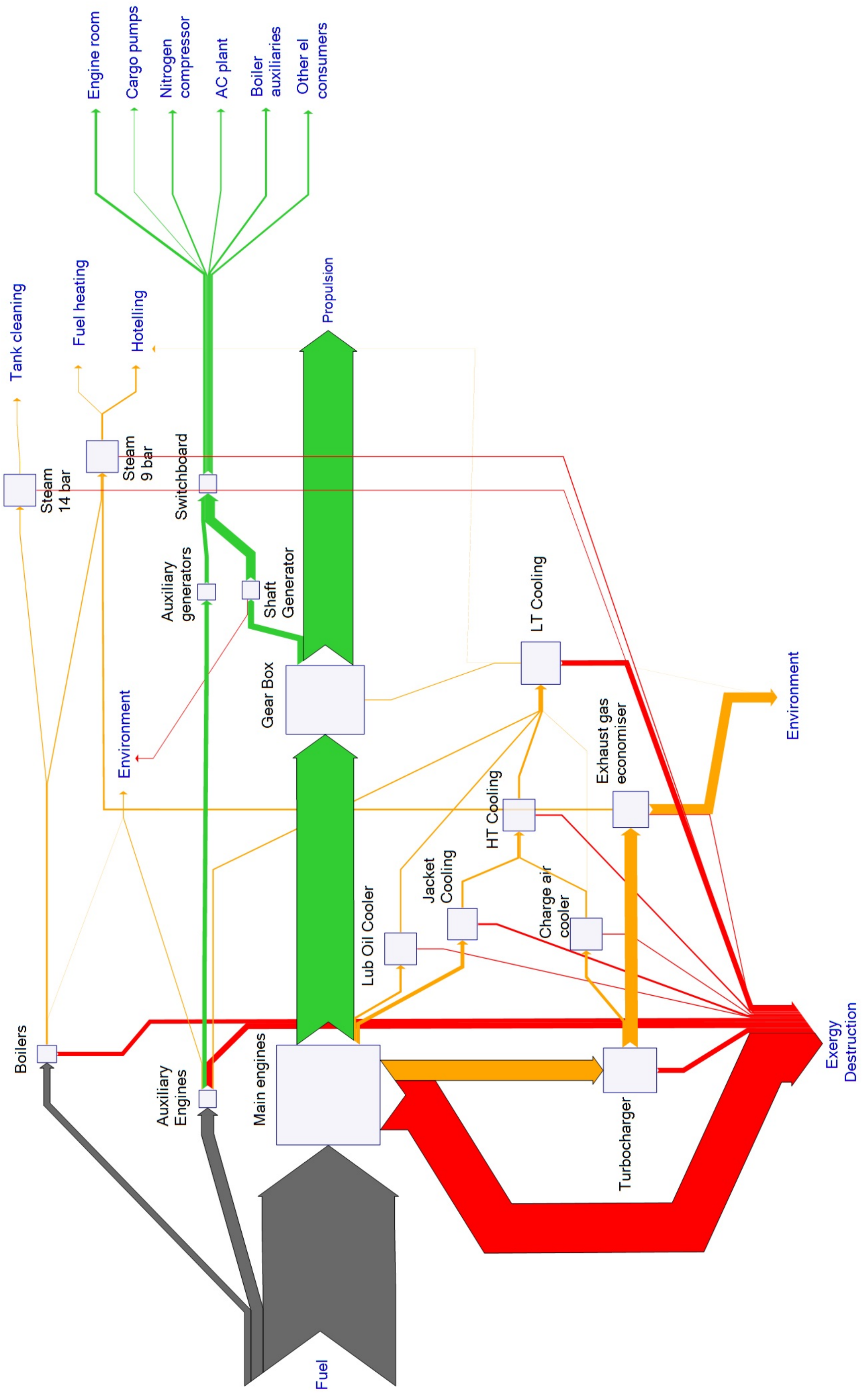

**Figure 4.2:** Grassmann diagram for the case study ship

| **Energy analysis** | | | |
|---|---|---|---|
| | $\%_{inp}$ | $\%_{out}$ | $\eta_{en}$ |
| *Producers* | | | |
| Main engines | 88.4 | | 42 |
| Auxiliary engines | 8.0 | | 36 |
| Boilers | 2.6 | | 81 |
| *Consumers* | | | |
| Propeller | | 70.0 | |
| Nitrogen compressors | | 2.1 | |
| Cargo pumps | | 0.8 | |
| Boiler auxiliaries | | 2.7 | |
| Engine room | | 3.5 | |
| HVAC | | 1.8 | |
| Miscellaneous | | 2.6 | |
| Tank cleaning | | 3.1 | |
| Hotelling | | 5.5 | |
| Fuel heating | | 7.8 | |
| *Internal flows* | | | |
| Gearbox | 37.0 | | 99 |
| Shaft generator | 4.0 | | 91 |
| Turbocharger | 34.1 | | 26 |
| EGE | 3.2 | | |
| Exhaust (after EGE) | 22.0 | | |
| Charge air cooler | 7.6 | | |
| Lub oil cooler | 9.0 | | |
| Jacket water cooler | 8.4 | | |
| HT/LT heat exchanger | 14.0 | | |
| LT/SW heat exchanger | 28.0 | | |

**Table 4.1:** Energy flows and efficiencies for system components

| Exergy analysis | | | | |
|---|---|---|---|---|
| | $\eta_{ex}$ | $\lambda$ | $\delta$ | $\eta_{task}$ |
| **Main engines** | | | | |
| Engine | 42.9% | 37.2 % | 64.2 % | - |
| Turbocharger | 35.9% | 24.4% | 6.4% | - |
| Exhaust gas economiser | 67.0% | 6.5% | 1.1% | 4.8% |
| Charge air cooler | 66.4% | 6.8% | 1.1% | 27.5% |
| Lubricating oil cooler | 59.3% | 20.1% | 1.1% | 38.8% |
| Jacket water cooler | 50.1% | 15.9% | 2.5% | 49.5% |
| HT/LT heat exchanger | 59.5% | 11.6% | 1.8% | 38.5% |
| LT/SW heat exchanger | 2.1% | 85.3% | 5.3% | 31.5% |
| **Auxiliary power** | | | | |
| Auxiliary engines | 61.7% | 38.3% | 5.3% | - |
| **Auxiliary heat** | | | | |
| Boilers | 29.7% | 63.7% | 5.4% | - |
| Tank cleaning | 25.3% | 61.1% | 0.8% | 4.7% |
| Hotelling | 37.8% | 46.7% | 0.6% | 7.2% |
| Fuel heating | 26.2% | 62.1% | 1.8% | 9.1% |

**Table 4.2:** Exergy flows and efficiencies for system components

| | **Energy** | | **Exergy** | |
|---|---|---|---|---|
| | $\%_{rec}$ | $\%_{ME,out}$ | $\%_{rec}$ | $\%_{ME,out}$ |
| Exhaust gas | 38 | 41 | 54 | 17.7 |
| Charge air cooler | 19 | 20 | 14 | 4.6 |
| Jacket water cooler | 21 | 22 | 20 | 6.7 |
| Lubricating oil cooler | 22 | 24 | 12 | 3.8 |

**Table 4.3:** Energy and exergy analysis of waste heat flows

# 5

# Ship energy performance improvement

Departing from the results of the first part of the thesis, the newly acquired knowledge of the system can be used in order to improve its performance from an energy perspective. Measures of intervention are generally subdivided in the categories of operational, retrofitting, and design, which are presented in Sections 5.1 to 5.3.

## 5.1 Ship operations

Figure 5.1 presents the result of the comparison of Case 1 and Case 2 operational modes. The specific ship fuel consumption (SSFC), defined as the amount of fuel consumed by the both the main and the auxiliary engines over one nautical mile distance (see Paper II, equations 15 and 16), is plotted versus ship speed. The dashed and the solid lines respectively represent the SSFC of the Case 1 and Case 2 arrangements.

The results indicate that a large reduction in SSFC can be obtained by modifying the operating mode from fixed to variable propeller speed. The reason lies in the very different efficiency of the propeller, at given ship speed, depending on propeller speed, as shown in Figure 5.2. The propeller is designed for a ship speed of 15 knots, where its best efficiency point corresponds to a rotational speed of 105 rpm. At lower ship speeds, efficient propeller operations would require a slower rotation. Operations in combinator mode do not allow reducing engine speed when only running on one, high-loaded engine. As soon as operating on two engines is permitted, the reduction of propeller speed brings an improvement of ship energy efficiency, as can be seen in Figure 5.1 in the range between 11 and 13 kn. This advantage peaks at around 12 kn and then diminishes when increasing ship speed. At around 14 knots, close to design conditions, the performance of Case 1 becomes again more efficient than that of Case 2, as expected. With reference to Figure 5.1, it is possible to observe the moment when the second main engine is clutched in, which in both cases corresponds to a sharp increase in SSFC.

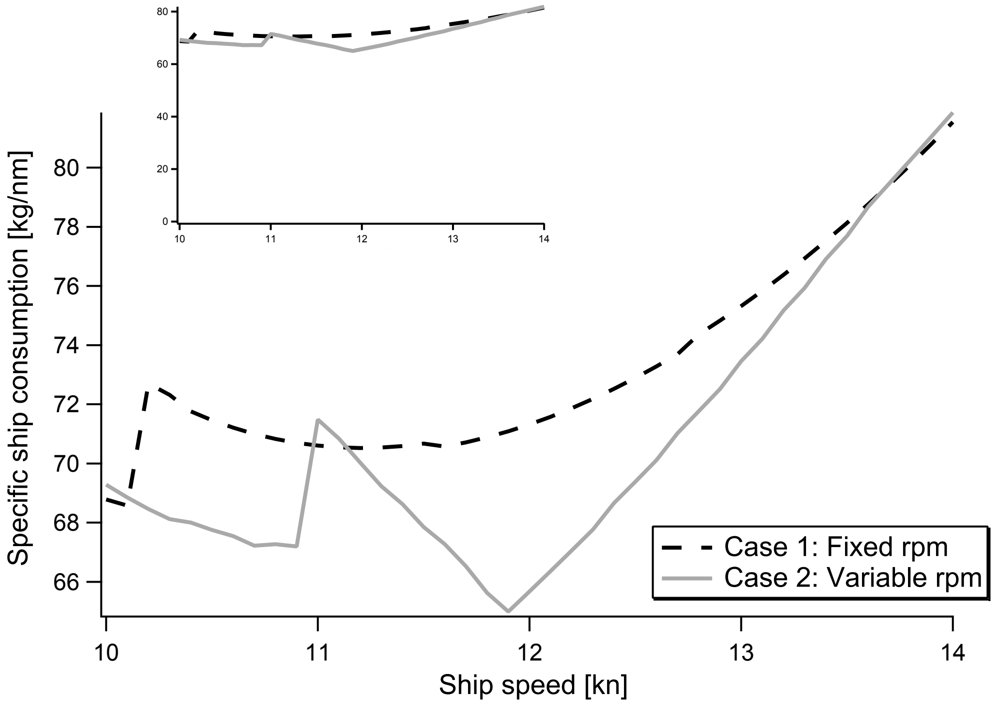

**Figure 5.1:** Comparison of case study ship specific fuel consumption, fixed-speed versus variable-speed setup

## 5.2 Retrofitting and waste heat recovery

The results of the first part of the analysis of WHR potential for the case study ship are presented in Figure 5.3; for each value of WHR cycle exergy efficiency (X-axis), the correspondent generated power is compared to the actual ship demand in auxiliary power. The percentage of time during which the WHR system is able to generate the required amount of auxiliary power is calculated (Y-axis). This process is repeated for different choices on which waste heat flow is used as an energy source for the WHR system. For each of these possibilities, the exergy efficiency of the WHR system required for meeting auxiliary power demand for at least 80% of the time is shown.

When recovering on the exhaust gas alone the required efficiency amounts to approximately 58% if the WHR system is installed before the EGE (continuous line, circular marks), while this value increases up to around 62% if the easier retrofitting arrangement of installing the WHR after the EGE was employed (dashed line, triangular marks). The required efficiency of the recovery cycle can be drastically reduced by taking the cooling systems into account: either for the generation of auxiliary heat (chained line, square marks) where 50% efficiency is required, and where all the energy in the exhaust gas is available for WHR purposes; or for the WHR system itself (dashed line, plus marks, and dotted line, rhombus marks) where 48% efficiency is required. It should be noted however that these solutions would imply a shift in system complexity,

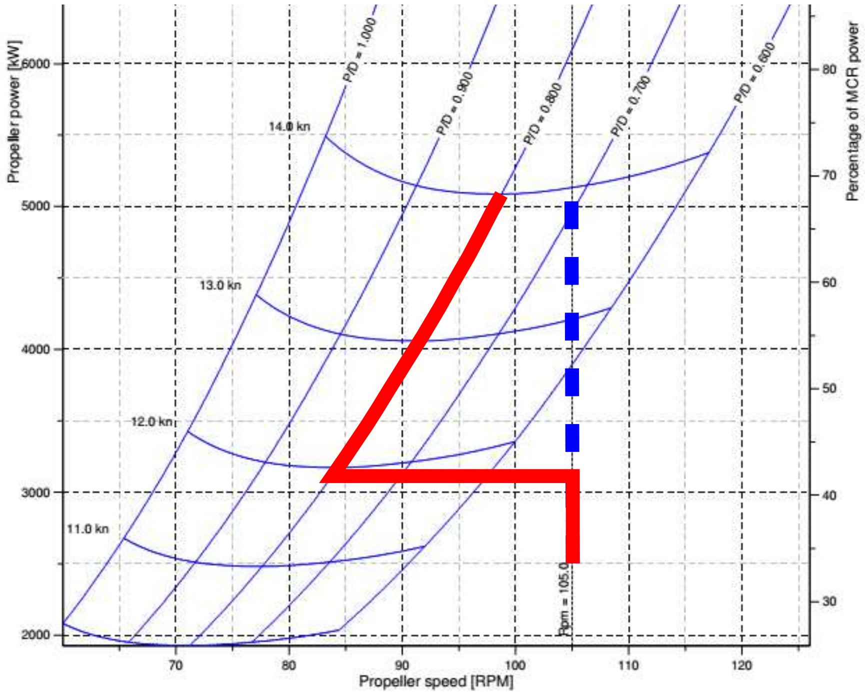

**Figure 5.2:** Propeller power versus propeller speed, for different values of ship speed and propeller pitch; kindly provided by the partner company

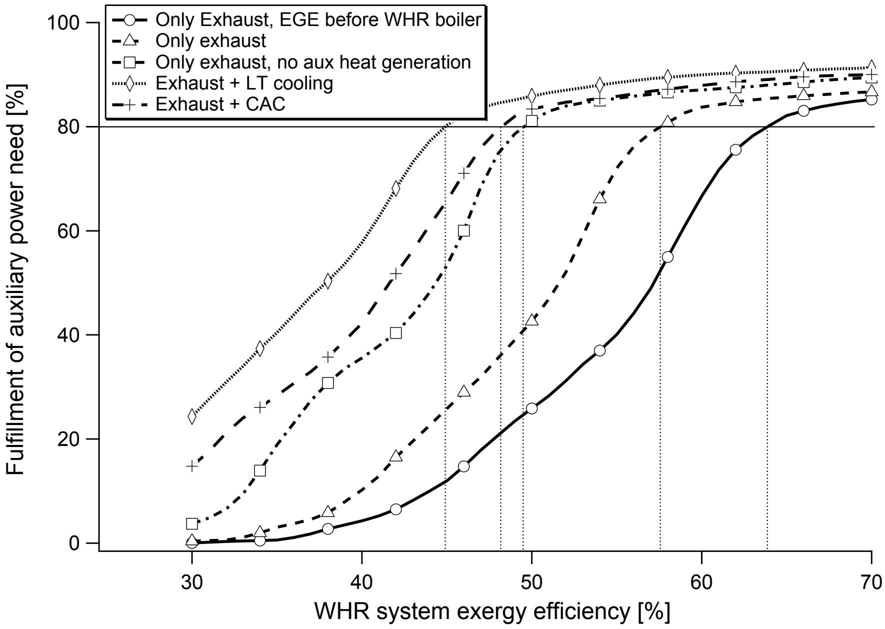

**Figure 5.3:** Fractional coverage of the auxiliary need for different recovery arrangements versus cycle exergy efficiency

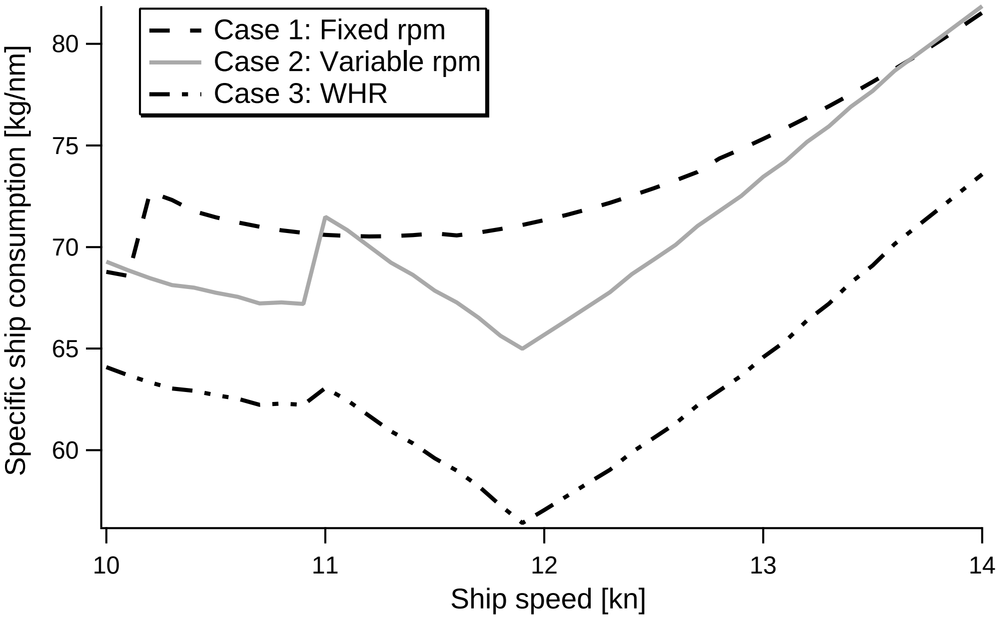

**Figure 5.4:** Comparison of case study ship specific consumption, standard setup versus WHR retrofitting

from the efficiency of the WHR cycle to the equipment required for recovering waste heat from the cooling systems.

The possibility of adapting ship operations towards the optimisation of the efficiency of the whole system (including WHR) was also explored. The results indicate that the installation of a WHR system on the case study ship becomes easier if both engines are operated simultaneously. In this case, in fact, the advantages of permitting low-propeller speed operations and having additional exhaust flow neutralise the disadvantage of operating at low load. This is graphically shown in Figure 5.4, where the SSFC of the propulsion system with WHR (Case 3) is compared to operations in the current arrangement of the case study ship (Case 1 and Case 2, see Section 5.1). For operating speeds high enough to allow the utilisation of two engines (around 11 kn), the calculated minimum exergy efficiency required in order to provide auxiliary power (364 kW) on board was estimated at 39% (auxiliary needs are lower or equal to 364 kW for 80% of the sailing time). The utilisation of a WHR system for auxiliary power production also allows operating the engine in combinator mode, as presented in the previous section, hence contributing to the large improvement displayed in figure 5.4.

## 5.3 Ship design

The results related to the application of a method for the comparison of different propulsion arrangements, presented in Section 3.3.5, are shown in Figure 5.5. Different fuels perform in dissimilar manners depending on the selected propulsion system arrangement, and vice verse. This distinction is particularly strong when WHR is taken into account. It is therefore considered important to include the choice of both the propulsion system and the fuel in the early phases of ship design.

Additionally, the study aims at evaluating the possible advantages of selecting the propulsion system based on the whole operational cycle rather than on the design point. The results show that there is no difference in the two approaches for 2-stroke engines, which means that employing an engine selected based on its high efficiency at design point also leads to the most efficient solution when the whole operational cycle is taken into account. For 4-stroke engines instead a small improvement is computed when using the "operational-cycle approach", evaluated in a decrease in fuel consumption of 0.56% for the cases of HFO and MGO and 1.7% in the case of LNG. This latter result is of particular interest and is connected to the fact that 4-stroke LNG-powered engines operate according to a Otto cycle, which is known to have worse performance at low-load than a comparable Diesel cycle-based engine. The use of the "operational-cycle approach" is therefore particularly advised when the choice of LNG as a fuel is associated to a propulsion arrangement where 4-stroke engines are the prime mover, which is becoming quite a common choice for ferries operated in ECAs (Aesoy *et al.*, 2011).

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[2] Note that in the LNG case pilot fuel injection is also taken into account

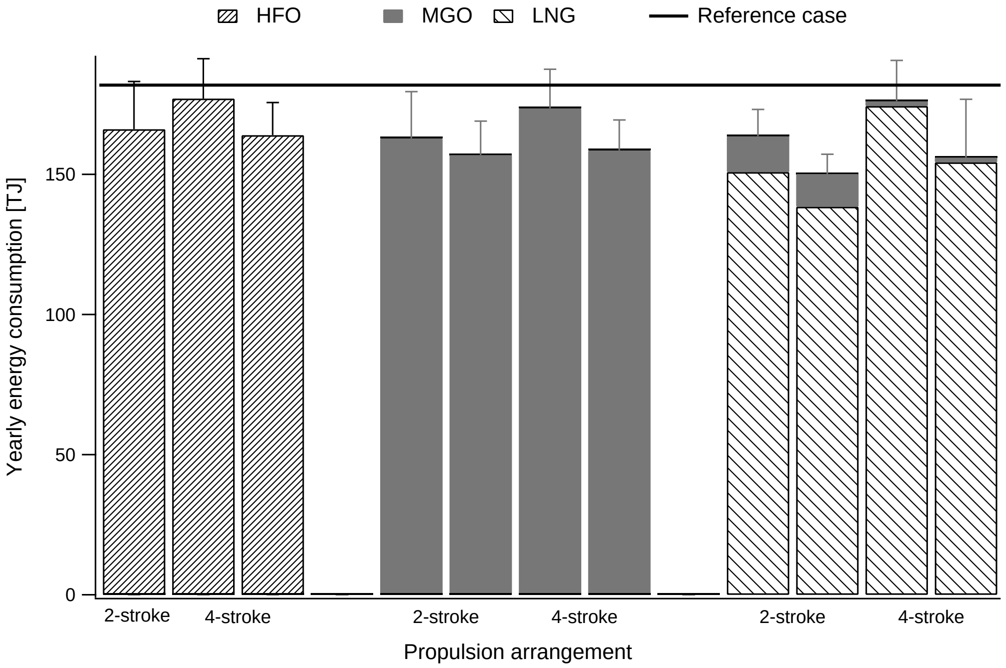

**Figure 5.5:** Cumulative fossil energy consumption over one year of operation for the alternative design cases. *Each group of bars represents the main fuel (HFO, MGO, LNG*$^2$*). In each group of bars, the first two represent the performance of a two-stroke engine arrangement, while the last two that of a four-stroke engine arrangement. Finally, for each pair, the first bar represent the yearly consumption of the vessel without WHR, while the second also accounts for such system to be installed. The horizontal line gives the calculated consumption of the existing ship arrangement. Finally, the error bars represent the extent of the range of results for all the evaluated arrangements for each specific case. As the main bars represent the most efficient engine choice for each arrangement, error bars only stretch above the main level*

# 6

# Discussion

In Chapter 6 the implications connected to the results of this thesis are discussed, together with the validity and generality of the conclusions that can be deducted (Sections6.1 and 6.2). A discussion related to the methodology employed in the study is proposed in Section 6.3, referring to the validity of the thesis and to the quality of the data.

## 6.1 Energy and exergy analysis

The application of energy and exergy analysis to the case study ship shows how these methods can be used in order to improve the understanding of ship energy flows. These methods can guide in the identification of main energy flows, therefore getting an understanding of where intervention should be prioritised, and main inefficiencies, which in turn can foster the ability of understanding where the potential for improvement is located.

In this thesis, energy analysis led to results conceptually similar to what presented in energy audits available in literature, such as Thomas *et al.* (2010) and Basurko *et al.* (2013), which also include the identification of energy flows. The energy analysis proposed by the author, however, brings further detail in the analysis of internal energy flows in systems such as the turbocharger, the cooling systems, the heat distribution systems and auxiliary power generators. This level of detail, to the best of my knowledge, has never been presented in literature before and provides an improved understanding of the relative and absolute sizes of different flows of different energy types on board the ship.

The analysis of energy consumption led to the unexpected result of showing that thermal (14% of total energy use) and electric (16%) users make up a large part of the total ship consumption. Even if this result underscores the fact that the propulsion line should be the first priority when approaching the issue of reducing ship fuel consumption, it also shows that optimising ship energy systems performance based on the propulsion power demand alone is not justified.

One additional contribution from this work is give by the introduction of exergy analysis to the whole ship, which provided the basis for approaching the possibility of implementing WHR systems on the ship as a way of reducing fuel consumption need for auxiliary power generation. The estimation of the different energy flows including considerations on energy quality allowed to select which flows could be of major interest for energy recovery way that would not be allowed by energy analysis.

Additionally, exergy analysis allowed the identification of those components which could be targeted in order to improve the overall potential for WHR. However, from a technical point of view, improving the task efficiency of a heat exchanger is achieved by reducing the temperature difference across the component. This reflects into an increase in the exchange area required for maintaining the same amount of heat exchange, which *de facto* translates into additional space and weight requirements. Furthermore, improvements in the design of the network of heat exchangers could only be beneficial if additional use of waste heat is planned. In the current arrangement all heat needs, when the main engines are running, are met by the EGE and there is no need for an optimisation.

## 6.2 Energy performance improvement

The results from the application of energy and exergy analysis to ship systems can be used as the basis to ship energy performance improvement. The attention focused on engine-propeller interaction, WHR systems, and whole propulsion system design.

It should be noted that the results presented in Chapter 5 only attempt to see the matter from an *energy* perspective. Details regarding other aspects, such as the economic (balance between savings and additional costs for installation, training, contingent increased maintenance), human (increased workload in the engine room, lack of expertise, safety), structural (additional space/weight requirements), and environmental (use of dangerous chemicals) were either not included, or considered qualitatively. The results presented in this thesis should be seen as information to be put in a larger context by the interested stakeholders when a decision is to be taken on how to operate, retrofit, or build a ship.

The investigation of engine-propeller interaction led to the identification of possibilities for improvement in this area for the case study ship. The results obtained through the application of mathematical models to the interaction between engine and propeller in the case study ship suggested that a reduction in ship fuel consumption of 5.8% can be achieved while increasing ship speed from 10 to 12 kn if the ship is run in variable propeller speed. Even though the outcome could vary for different ship types, the results suggest that this analysis can lead to the identification of possible improvements of ship energy efficiency. Furthermore, although in this thesis the interaction between engine and propeller was studied from an operational perspective, efforts can also be directed to the retrofitting of existing ships and to the design of new vessels.

WHR systems are often suggested as one possible solution for decreasing ship energy consumption, but the actual feasibility is seldom analysed in all its complexity. In this sense, the main limitation in the approach proposed by the cited authors lies in the accounting of the operational mode of the selected ship. Ma *et al.* (2012) assume that the system is operated at design conditions for 280 days a year, an assumption that rarely reflects real operational conditions (Banks *et al.*, 2013). Grimmelius *et al.* (2010) and Theotokatos & Livanos (2013) both take into account a typical voyage and quantitatively use this assumption for the calculation of expected system performance. The "typical voyage" approach represents a widely accepted approximation, but is only partially able to account for the impact of real operations on fluctuations in ship operational pattern (typical of ships operating on the spot market) and in boundary conditions (increased resistance due to weather and waves). In the work presented by Dimopoulos *et al.* (2011) ship operations are divided in 4 well-defined categories with an assumption for the time spent during each operation, which additionally increases the detail, but is more suitable for the operational pattern typical of container ships.

The main contribution of this thesis to the subject consists in the evaluation of the WHR potential over one year of real ship operations. The results indicate a profitable application of WHR to the case study ship would require a rather complex recovery system, either from the point of view of the recovery cycle (efficiencies of around 60% are required, which could only be met by advanced Organic Rankine Cycles (ORC) with high-performance fluids (Larsen *et al.*, 2013)), or from that of the type and amount of waste heat to be recovered (by making use of the waste heat in the cooling system the required efficiency can be reduced to 48%[1]).

The possibility of adapting ship operations in order to maximise the energy efficiency of the propulsion system including WHR was also explored. The results suggest that by adapting operations for running the ship on two engines, even at low load, the advantages from improved propeller and WHR performance would outweigh the loss in engine efficiency, while requiring a relatively simple recovery system (16% reduction of fuel consumption with a required $\eta_{ex}$ of 39% recovering waste heat on the exhaust gas alone). This result indicates that the installation of WHR systems should be evaluated taking also operational aspects into account. This results is considered to be of particular relevance as it underscores the importance of addressing ship energy systems with a systems approach. For the case study ship, both the improved engine-propeller interaction and the installation of WHR systems, if taken alone, would provide much smaller benefits than the two applied together. Looking at ship energy systems as a whole allowed the identification of this synergy, something that would not have been possible otherwise.

A similar consideration can be done on possible energy savings on auxiliary power consumers. Small reductions in auxiliary electric demand can make the difference on the feasibility of a WHR system. The availability of measured data on auxiliary consumption would allow further research in this direction.

Finally, the possibility of influencing the system from the design stage was explored. Even if results in the initial phases of the design are only partly representative of

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[1] It should be noted that the use of cooling systems as a source of waste heat is not technically easy. Cooling is vital to engine operations, and introducing an additional system could generate issues in safety and control.

what the real systems will look like, the methods proposed in this thesis show very promising results. Different engines, arrangements, and fuels can be compared and the resulting estimated yearly consumption can be used as one of the basis for the decision of which propulsive arrangement should be installed. The importance of including several different parameters in the early design phase is demonstrated by the large variance in the results depending on the chosen arrangement. Finally, the influence of including the operational cycle in the evaluation proved rather limited, and only relevant in the case of four-stroke dual fuel engines based on an Otto-cycle.

## 6.3 Methodology

As part of the analysis of the scientific value of this thesis, the quality of the work should be critically discussed. Validity is often referred to as a measure of the quality of a scientific work. It is often subdivided in *internal validity*, which refers to the extent to which the results represent the real problem to be studied, and *external validity*, which concerns instead the generalisability of the results to a larger sample than what specifically addressed in the work. Finally, the quality of the data also has a very important influence on the value of the results.

### 6.3.1 External validity and case studies

External validity deals with the extent to which the results and the methods presented in a scientific study can be extended outside of the specific application presented in the work (Mitchell & Jolley, 2001). In the case of this thesis, external validity is a subject of major importance, as the use of case studies is often connected to a loss generalisability.

The methods proposed in this thesis are potentially applicable to all ship types. The main restriction to the external validity of the methods here presented is the assumption of steady-state behavior, as all models and analysis are conceived for steady state operation. This requirement implies that vessel types characterised by a very dynamic behavior, such as tugs and inland ferries, would not be suitable for the application of the proposed methods. Other possible differences, such as a different engine type (two-stroke Diesel engine, gas turbine), different propeller type (FPP, water jet), and propulsion arrangement would just require an additional effort in the modeling of a different component.

On the other hand, the external validity of the numerical results is more limited. For what concerns the analysis of ship energy systems, it has been observed that time spent in different operational modes tends to remain approximately constant over different years (Banks *et al.*, 2013). The possibility of extending the results of this thesis to future operations of the case study, is correlated to vessel speed distribution, as it has a strong influence on fuel consumption for propulsion, and can be subject to large variations over the years (Banks *et al.*, 2013). When it comes to the extension to other ship types, the possibility of extending the results presented in this thesis is limited by:

**Engine type:** Two-stroke engines have lower exhaust temperatures (Theotokatos & Livanos, 2013), therefore revolting all conclusion drawn in connection to the evaluation of WHR potential.

**Propeller type:** FPPs behave substantially differently from CPPs, and therefore all results related to engine-propeller interaction would differ if a FPP is used instead.

**Auxiliary power generation arrangement:** Results related to engine-propeller interaction are connected to the use of a shaft generator.

**Ship type:** All results, especially those connected to the evaluation of WHR potential, are strictly related to the balance between ship requirement of propulsion power, auxiliary heat, and auxiliary power. Different ship types might differ sensibly in this matter.

These restrictions, should not lead the reader to think that the arrangement featured by the case study ship is a special one. Four-stroke engines represent a significant portion of the market (27.7% in terms of number of installed engines and 10.5% in terms of installed power for engines with MCR $>$ 2 MW (Haight, 2012)). Similarly, CPPs have reached a stable market share of around 35% of the total number of propellers installed; this is particularly true for some specific ship types, such as general cargo vessels (80%), ferries (63%), tugs and offshore vessels (78%), and fishing vessels (89%)[1].

The utilisation of case studies is very widespread among applied researchers, especially when methods are proposed rather than specific designs. This is the case for almost all work mentioned or referred to in this thesis: (Dimopoulos *et al.*, 2011, 2012) refer to a specific containership with well defined loads and operational pattens; Theotokatos & Livanos (2013) study one specific application to a bulk carrier, while Thomas *et al.* (2010) present their method for energy audit applied to a fishing vessel. Therefore, even if in applied science there is not such thing as a well defined scientific method, as is instead the case in basic science (Niiniluoto, 1993), the thesis reflects common practice in the field.

As an additional motivation to the choice of working on a case study, it should be noticed that the close interaction with the company allowed to get a much better insight of how the academic work here presented could be used in the "real world". It is sometimes observed in academic researchers to become too much theoretical and forgetting the challenges that arise when theories and models need to be applied in practice. As highlighted by Cross *et al.* (1981), "knowing how" is often as important as "knowing that", where the first refers to explicit, procedural knowledge and the second to the knowledge that, despite its evident existence, is not structured.

### 6.3.2 Internal validity

Internal validity refers to the extent to which it is possible to identify a causal connection between a study and its results (Brewer, 2000). Verification and validation are two of

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[1] Data referring to the 2000 to 2004 period, (Carlton, 2007, p. 21)

the main methods employed in the evaluation of internal validity (Oberkampf *et al.*, 2002).

*Verification* refers to "*the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model* "(DoD). Verification is very important in those cases, such as system design, when no data for validation is available.

*Validation* refers to "*the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model* "(AIAA, 1998). The validation of a model is performed by comparing model outputs versus experimental measurements. Different levels of validation can be achieved depending on the thoroughness of this process (Oberkampf *et al.*, 2002).

As described in the dedicated methodology section, energy and exergy analysis involve both a top-down and a bottom-up approach. The two parts are connected to different issues when it comes to internal validity. From a top-down perspective, the analysis simply relates to the observation of existing measurements, which allows no validation. From a bottom-up perspective, instead, the individual models used to simulate different components could, and should, be validated. In particular, the absence of data for model validation when the propulsion system is operating at variable speed can cast some doubts on the applicability of the model to such cases. Furthermore, no information was available for the validation of individual components either.

The main uncertainty is related to the main engine model; even though a validation of the model is proposed (see Paper II), it only refers to operations at fixed speed, as no information is available on variable speed operations. However, the absence of the related data was also a major justification for employing a larger mechanistic content in the modelling: in fact, white-box models provide much larger safety when extrapolating them out of the initial boundaries. This explains why not only pure black-box, but also hybrid models that employ a lower grade of mechanistic content (such as mean-value models) were excluded. If extensive data were available on off-load engine speed, the task of modeling would have been approached in a different way, giving larger room to the black-box part of the model. It should be noted, additionally, that despite the modifications proposed in Paper II, the modeling approach used in this thesis is not dissimilar to what can be found in literature (e.g. Scappin *et al.* (2012); Payri *et al.* (2011); Benvenuto *et al.* (1998)) and therefore represents an application of common practice. The validation of the overall results is discussed with the partner company, and tests are being carried out for the purpose. Unfortunately, to the moment the thesis is going to print, this kind of validation data has not been provided yet.

A verification process, comparing findings versus existing literature, was performed instead. As studies available from scientific literature normally only include sailing operations, the results from the energy analysis used in this thesis were recalculated for only accounting for the time spent by the ship at sea. From the energy analysis perspective, results presented by Thomas *et al.* (2010) and Basurko *et al.* (2013) can be used as a confirmation of the orders of magnitude. Figures for total propulsion need, for example, are quite in accordance in identifying propulsion as the main consumer on board (75.7% in the author's work, 76% in Thomas *et al.* (2010) and 84.3%, 87.3%, and 87.8% in Basurko *et al.* (2013)).

The results of the exergy analysis here proposed could be partially compared to what was obtained by Dimopoulos *et al.* (2012). The paper confirms the fact that most of system irreversibilities are connected to main engine operations (79% in this thesis compared to 82% in literature[1]), while relevant losses are also connected to turbocharger operations (respectively 7.5% and 3.9%). As the exergy analysis proposed by Dimopoulos *et al.* (2012) refers to a system equipped with a WHR system it is not possible to compare the results connected to other components, as the resulting arrangement is much different for the two case-studies.

Results related to the evaluation of WHR systems are rather consistent with what expressed in similar studies. The results presented by Dimopoulos *et al.* (2011) relate to a similar ratio of propulsive over auxiliary power and show how auxiliary power demand can be completely met by a recovery system only for high loads. In this case, full power production using WHR system is guaranteed for only 17% of the time, but this is mostly connected to the higher auxiliary power need compared to propulsion (for normal speed transit the auxiliary power need represents 11.4% of total demand, while on the case study ship this value is normally lower then 10%) and to the use of two-stroke engines, known for their lower availability of waste heat (Theotokatos & Livanos, 2013). Similar results are also obtained by Theotokatos & Livanos (2013), who present the analysis of a simpler recovery cycle (around 34% exergy efficiency[2]) which leads to a higher need for the operation of auxiliary engines in order to generate the required electric power. It should be noted that even in this case, in sea-going mode, the WHR system is able to provide around 72% of the power requirement.

### 6.3.3 Data quality

The availability and quality of the available information used in a scientific study are of vital importance for the quality of the work itself. A perfectly built model can still give misleading results if data are not handled correctly. A model can only be as accurate as the data it is used to process.

Data quality is often defined as "fitness for use", i.e. can only be evaluated in light of the purpose data are used for (Haug *et al.*, 2001). According to Wang (1996) the data qualities most found in reviewed scientific literature are:

**Intrinsic:** The extent to which data values conform to the actual variable to be measured.

**Contextual:** The extent to which data are useful to the purpose.

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[1] Note that the value referred to the result presented in this thesis refers to the aggregation of losses in the main engine and in the cooling systems.

[2] It was not possible, unfortunately, to evaluate the exergy efficiency of the WHR system proposed by Dimopoulos *et al.* (2011) based on the information provided in the article. The estimation of complexity is based on a purely qualitative evaluation of system design, ad described by the authors of the two studies

**Representational:** The extent to which data are presented in a clear and unambiguous manner.

**Accessibility:** The extent to which data are easy to obtain.

As already mentioned in section 3.1.2, it has not been possible to perform extensive, own measurements. Data were made available from one shipping company, who collaborated with the author, for one of their ships.

The strong collaborative framework with a ship operator in the related industrial sector (in this case a shipping company) have both positive and negative sides. On the one hand, in fact, it has not been possible to run own experiments, as the ship was sailing in very different locations under hardly predictable schedules; moreover, the company manifested the interest in sharing large amount of available information with the author, but did not back up any experimental campaign. This translates in inconsistencies in data quality: continuous monitoring, for instance, provides higher data quality than noon reports, which is reflected in the accuracy of the results (Aldous *et al.*, 2013). Referring to the categories of data quality presented before, *intrinsic quality* was very variable depending on the specific measurement; *contextual quality* was limited, as extensive data were available on variables of little interest to the scope of the thesis and lacked for other, more important variables. Additionally, data *consistency* was rather poor, as very different sources had to be used to be able to perform the analysis. No issue can instead be reported on data *representational* and *accessibility quality.*

On the other hand, the process showed that the proposed methodology is very resilient to different data quality (this is often referred to as *ecological validity* (Shadish *et al.*, 2002)). The analyses was conducted using data from the real world, meaning that the presented methods do not belong to a restricted community of researchers but can be used in virtually any real life situation. The alternative of tailoring the method on measurements performed in a proper scientific way would have improved the accuracy of the results, but would have made the model of limited use outside the specific proposed application.

# 7

# Future work and recommendations

Suggestions on how to proceed from the results of this thesis are here presented. These are divided into proposals to the scientific community (Section 7.1) and recommendations to the industry (Section 7.2).

## 7.1 Proposals to the scientific community

- The application of energy and exergy analysis to ship energy systems should be expanded to include *different ship types*. This would bring a larger literature on which to base further studies like the one presented in this thesis.

- This thesis focuses on large vessels, operating on mostly international routes, for which it is legitimate to assume a steady-state behavior. Some specific applications do not allow this kind of assumption, such as small inland ferries and fishing vessels. *The influence of transient phenomena* can become relevant in particular when phenomena characterised by different inertiae are coupled. This is for example the case of WHR systems, where fast mechanical transients are coupled to slower thermal ones.

- *Engine-propeller interaction* showed large margins of improvements in arrangements were the propulsion system is operated at constant speed for using a shaft generator, especially at low propeller load. The findings presented in this thesis should be extended to other types of propulsion systems, including slow-speed engines and fixed pitch propellers.

- Additional focus should be put on the *environmental impact* from the initial stage of ship design. Future work should be focused on including not only GHGs but also other relevant pollutant emissions, such as $NO_X$, $SO_X$, and PM to the analysis. Issues related to different pollutants are, in fact, strongly interconnected and should not be addressed separately.

- Even if extensive work on Diesel engine models has been performed to date, very little has been done on their modeling for implementation into energy systems modeling, especially when it comes to the cooling systems. As showed in paper I there are large amounts of energy available through different flows from engine cooling, and a more detailed *modeling of thermal losses and cooling systems* should be available for the optimisation of WHR systems for using the highest possible amount of available waste heat.

## 7.2 Recommendations to the industry

- *"Know what you do, know what to do"*. The application of energy and exergy analysis to the case study ship has been facilitated by the existence of a large, reliable dataset based on a continuous monitoring system. The availability of such large and complete databases is still not common in shipping. Resources should be invested on reliable sensors and online data storage, since this would expand the information available for a correct planning actions to improve energy efficiency.
- *WHR systems* are a promising solution for improving ship energy efficiency. It is recommended to consider this possibility for both retrofitting and new buildings. However, as showed in this thesis, the profitability of this technology strongly depends on ship operational mode, engine type and auxiliary demands. For this reason, it is recommended to increase the expertise in such systems and in the evaluation of waste heat availability and quality.
- As suggested by the results of this thesis and by existing literature, *engine-propeller interaction* can have a strong influence on ship energy efficiency. This aspect should be kept under strong focus, both in the operation, retrofitting, and design of marine vessels. The impact of this interaction on propulsion systems based on FPPs and two-stroke engines, as well as the influence of sea state and hull fouling, should be investigated.
- The *initial design phase* of a vessel should be emphasised more. New knowledge in the field of systems optimisation and environmental studies should not be relegated to the last phases of the design, where most of the choices are already taken, but rather be included in the initial phases of ship design.
- Sampling data is not enough. The *analysis* of these data is crucial. In this sense, I would personally like to further emphasise the importance of *academic collaboration*. We, as researchers, have an interest in improving our understanding of systems and reality; you, running a business, have an interest in having access to knowledge and expertise that might be missing in your human resources. It is a win-win situation that should happen more often!

# 8

# Conclusions

The main findings of this work can here be summarised:

- Energy and exergy analysis applied to ship energy systems provide a useful tool for the identification of main energy flows and of inefficiencies. For the case study ship, auxiliary heat and power consumption was found to account together for 30% of the total ship energy consumption. The evaluation of the waste flows allowed to estimate that a large potential for WHR exists on the case study ship, particularly in the exhaust gas.

- Engine-propeller interaction can have a strong impact on ship energy efficiency. In the case study ship, the application of such models suggests that specific ship fuel consumption can be reduced by 5.8% while increasing the speed from 10 to 12 knots by operating engine and propeller at variable speed instead of at constant speed. The benefit of an increased energy efficiency of the propulsion train outweighs the disadvantage of using the auxiliary engines instead of the shaft generator for meeting on board auxiliary power demand.

- The profitable application of WHR systems is subjected to an analysis of the availability of waste energy in comparison of auxiliary power demand. For the case study ship, results suggest that a rather effective system ($\eta_{ex}$ of 58%) is required if only heat in the exhaust gas is recovered. The situation can be improved either by increasing the number of sources of waste heat (the required $\eta_{ex}$ when including cooling water goes down to 48%) or by adapting ship operations in order to always run on two engines ($\eta_{ex} = 39\%$.)

- Ship design can be improved, with both economic and environmental benefits, if parameters such as engine type and fuel choice are taken into account from the initial stages of the design. Results from the application of mathematical models to the evaluation of alternative arrangements suggested that both fuel consumption and carbon footprint are strongly influenced by these choices.

All the results and findings presented in this thesis were obtained by addressing the challenge of improving ship energy efficiency with a systems perspective. This translated in the application of energy and exergy analysis to ship energy systems, as well in the use of mathematical models for the simulation of these systems without the need to resort to time consuming sea trials. This approach proved to be particularly beneficial, and systems thinking is expected to become more and more important in the challenge of making shipping a cleaner and more energy efficient mean of transportation.

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