THESIS FOR THE DEGREE OF DOCTOR OF ENGINEERING

Modelling, analysis and optimisation of ship energy systems

FRANCESCO BALDI

Department of Shipping and Marine Technology

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FRANCESCO BALDI
Francesco.baldi@chalmers.se
+46 (0)31 77 22 615

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Department of Shipping and Marine Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Abstract

Shipping is the backbone of today's economy, as 90% of global trade volumes is transported by sea. Much of our lifestyle today is only made possible by the existence of shipping as a cheap and reliable mean of transportation across the globe.

However, the shipping industry has been challenged in the latest years by, among others, fluctuating fuel prices and stricter environmental regulations. Its contribution to global warming, although today relatively small, has been set under scrutiny: for shipping to be part of a sustainable economy, it will need to reduce its emissions of greenhouse gases.

Increasing ship energy efficiency allows reducing fuel consumption and, hence, carbon dioxide emissions. The latest years have witnessed a multiplication of the efforts in research and development for increasing ship energy efficiency, ranging from improvements of existing components to the development of new solutions. This has also contributed to ship energy systems to become more complex. The optimisation of the design and operation of complex systems is a challenging process and the risks for sub-optimisation are high.

This thesis aims at contributing to the broader field of energy efficiency in shipping by adopting a systems perspective, which puts a special focus on system requirements and on interactions within the system. In this thesis, the energy systems of two case study ships were analysed using energy and exergy analysis to identify energy flows and inefficiencies. Then, solutions for improving the energy efficiency of the existing systems were proposed and evaluated accounting for the ship's observed operating range and for how added elements influenced the existing systems and their performance.

The results of this thesis show the importance of modelling the interactions between different parts of the energy systems. This allows not only a more accurate estimation of the benefits from the installation of new technologies, but also the identification of potential for additional energy savings. This is particularly important when the broad range of ship operations is included in the analysis, rather than focusing on the performance of the system in design conditions. In addition, the results of this thesis also show that there is potential for further improving ship energy efficiency by putting additional focus on heat losses from the engines and on how to efficiently recover them.

List of publications

Appended papers

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

Paper I : Baldi F. , Johnson H. , Gabrielii C. , & Anderssson, K. (2015). Energy and exergy analysis of ship energy systems: the case study of a chemical tanker. *International Journal of Thermodynamics*, **18**(2), 82-93.
The author of this thesis is the main contributor to ideas, planning, data collection, calculations, and writing.

Paper II : Baldi F. , Ahlgren F. , Nguyen T.V. , Gabrielii C. & Anderssson K. (2015). Energy and exergy analysis of a cruise ship. *Proceedings of the 28th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS)* June 2015 Pau, France.
The author of this thesis is the main contributor to ideas, planning, calculations, and writing.

Paper III : Baldi F. , Theotokatos G. & Anderssson K. (2015) Development of a combined mean value-zero dimensional model and application for a large marine four-stroke Diesel engine simulation. *Applied Energy* **154**, 402-415.
The author of this thesis participated to ideas, planning, data collection, calculations, and writing.

Paper IV : Baldi F. & Gabrielii, C. (2015). A feasibility analysis of waste heat recovery systems for marine applications. *Energy* **80**, 654-665.
The author of this thesis is the main contributor to ideas, planning, data collection, calculations, and writing.

Paper V : Baldi F. , Larsen U. & Gabrielii C. (2015). Comparison of different procedures for the optimisation of a combined Diesel engine and organic Rankine cycle system based on ship operational profile. *Ocean Engineering* **110**, 85-93.
The author of this thesis is the main contributor to ideas, planning,

data collection, and writing, while Ulrik Larsen performed the main part of the simulations and optimisation process.

Paper VI : Baldi F. , Ahlgren F. , Melino F. , Gabrielii C. & Anderssson, K. (2016). Optimal load allocation of complex ship power plants. Submitted to *Energy Conversion and Management on 2016-03-30.* *The author of this thesis is the main contributor to ideas, planning, calculations, and writing.*

Other publications

Baldi F. , Gabrielii C. , Anderssson K. & Petersen B.-O. (2012). From Energy Flows to Monetary Flows-An Innovative Way of Assessing Ship Performances Through Thermo-Economic Analysis. *Proceedings of the International Association of Maritime Economists Conference (IAME)* June 2012 Taipei, Taiwan.

Baldi F. , Bengtsson S. & Anderssson K. (2013). The influence of propulsion system design on the carbon footprint of different marine fuels. *Proceedings of the Low Carbon Shipping Conference* September 2013 London, United Kingdom.

Baldi F. , Larsen U. , Gabrielii C. & Anderssson K. (2015). Analysis of the influence of the engine, propeller and auxiliary generation interaction on the energy efficiency of controllable pitch propeller ships. *Proceedings of the International Conference of Maritime Technology* July 2014 Glasgow, United Kingdom.

Larsen U. , Pierobon L. , Baldi F. , Haglind F. & Ivarsson A. (2015). Development of a model for the prediction of the fuel consumption and nitrogen oxides emission trade-off for large ships. *Energy* **80** 545-555.

Baldi F. , Gabrielii C. , Melino F. , & Bianchi M. (2015). A preliminary study on the application of thermal storage to merchant ships. *Proceedings of the 7th International Conference on Applied Energy* March 2015 Abu Dhabi, United Arab Emirates.

Coraddu A. , Oneto L. , Baldi F. & Anguita D. (2015). Ship efficiency forecast based on sensors data collection: Improving numerical models through data analytics. *Proceedings of the OCEANS 2015* May 2015 Genoa, Italy.

Baldi F. , Lacour S. , Danel Q. , & Larsen U. (2015). Dynamic modelling and analysis of the potential for waste heat recovery on Diesel engine driven applications with a cyclical operational profile. *Proceedings of the 28th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS)* June 2015 Pau, France.

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Symbols and abbreviations

Roman Symbols

B	Exergy $[kW]$
g	Gravitation acceleration on earth $[\frac{m}{s^2}]$
H	Enthalpy $[kJ]$
I	Irreversibility $[kJ]$
J	Advance ratio
K_Q	Adimentional propeller torque
K_T	Adimentional propeller thrust
m	Mass $[kg]$
P	Power $[kW]$
P/D	Propeller pitch over diameter ratio
Q	Heat $[kJ]$
S	Entropy $[\frac{kJ}{K}]$
T	Temperature $[K]$
v	Speed $[kn]$
W	Work $[kJ]$
z	Altitude above the sea level $[m]$

Greek Symbols

δ	Efficiency loss ratio
ϵ_t	Total exergy efficiency
ϵ_u	Task (exergy) efficiency
η	Energy efficiency
γ	Relative irreversibility
λ	Load
ω	Speed $[rpm]$

Subscripts

0	Reference ambient conditions
en	Energy
ex	Exergy
in	Inlet
out	Outlet
ph	Physical

Abbreviations

0DEM	Zero-dimensional
AE	Auxiliary engine
BSFC	Brake specific fuel consumption $[\frac{g}{kWh}]$
CAC	Charge air cooler
CO_2	Carbon dioxide
CPP	Controllable pitch propeller
DLS	Data logging system
EC	European Commission
ECA	Emission controlled area
EEDI	Energy Efficiency Design Index
EU	European Union
FC	Frequency Converter
FPP	Fixed pitch propeller
GB	Gearbox
GHG	Greenhouse gas
HFO	Heavy fuel oil
HHV	Higher heating value
HRSG	Heat recovery steam generator
HT	High temperature
HVAC	Heat, ventilation, and air conditioning
IFO	Intermediate fuel oil
IMO	International Maritime Organisation
JW	Jacket water
LHV	Lower heating value

SYMBOLS AND ABBREVIATIONS

LNG Liquified Natural Gas

LO Lubricating oil

LT Low temperature

MCR Maximum continuous rate [kW]

MDO Marine diesel oil

ME Main engine

MGO Marine gas oil

MVEM Mean value engine model

NO$_X$ Nitrogen oxides

ORC Organic Rankine cycle

PM Particulate matter

S/G Shaft generator

SCR Selective catalytic reactor

SEEMP Ship Energy Efficiency Management Plan

SO$_X$ Sulphur oxides

USD United States dollars

VGT Variable geometry turbine

WHR Waste heat recovery

Chapter 1

Introduction

Low freight rates, fluctuating fuel prices, stricter environmental regulations, and expectations to reduce greenhouse gas (GHG) emissions make the current situation particularly challenging for the shipping industry. In this context, the interest in solutions for reducing ship fuel consumption has increased in the latest years, together with the technological improvements in ship energy efficiency. This thesis aims at contributing to the knowledge required for the reduction of fuel consumption from shipping. This is done by focusing on the potential for improvement coming from the application of energy systems engineering to ship on board energy systems.

1.1 Rationale

The rationale behind this thesis is related to both environmental and economic aspects.

From an **environmental perspective**, the main connection between energy efficiency and the environment relates to GHG emissions, which are today the main responsible of global warming today (IPCC, 2014). In spite of the fact that in 2012 carbon dioxide (CO_2) emissions from shipping amounted to only 2.5% of the total global anthropogenic emissions, they are expected to increase in the future by between 50% and 250% as a consequence of growing trade volumes (Smith *et al.*, 2014).

From an **economical perspective**, despite today's low fuel prices, there are reasons to advocate for improved fuel efficiency in shipping. Fuel prices have shown to be volatile in history, and there is no guarantee that they will not rise again in the future. In addition, environmental regulations are becoming stricter all over the world, and compliance often relates to higher fuel expenses. This is particularly true in the aforementioned case of CO_2, as market based measures are being discussed at different levels for incentivising a faster transition to low-carbon shipping.

The improvement of energy efficiency in shipping constitutes a relatively broad field of studies, from logistics and social studies to engineering. Narrowing the perspective to the latter, the latest research and development efforts have resulted in a large number of potential solutions, ranging from improvements of existing components (e.g. propellers and Diesel engines), applications of land-based technologies to shipping (e.g. waste heat recovery, fuel cells, batteries) to completely new solutions (e.g. hull air lubrication, Flettner rotors).

These technical innovations make ship energy systems to become increasingly complex, being composed of a large number of components interacting with each other. Solely focusing on individual parts of the system, thereby neglecting or over-simplifying the interactions between the components, can lead to misleading results and sub-optimisation. In spite of this observation, research in the application of systems science and engineering, that focuses expressively on complex systems, is limited to a handful of examples. This constitutes the main rationale of this thesis, which focuses on **looking at ship energy systems from a systems perspective**.

1.2 Aim and research questions

The aim of this thesis is to analyse the benefits of employing an energy systems engineering approach in the quest for improving energy efficiency in shipping.

This analysis is structured in two main objectives, each of them further represented by a number of research questions.

The first objective is to apply a systematic procedure for **analysing the performance** of ship on board energy systems. This can be related to two main research questions:

RQ 1.1 What type of information about the performance of the ship on board energy systems can be gathered based on the data/documentation typically available from on board monitoring systems?

RQ 1.2 What useful insight of the system can be gained by applying energy and exergy analysis to ship on board energy systems?

The improved understanding that results from an in-depth analysis of the system leads to the identification of opportunities for its improvement. Hence, the second objective of this thesis is the **synthesis of potential solutions for improving the performance** of ship on board energy systems towards a reduction of its fuel consumption. This is done according to principles of systems engineering, hence leading to the following additional research questions:

RQ 2.1 What can be gained by looking at interactions within the system rather than focusing on the performance of individual components?

RQ 2.2 What can be gained by looking at a broader range of expected ship operations rather than at one specific design point?

RQ 2.3 Based on the above principles, what is the potential for reducing fuel consumption by improving ship on board energy systems?

1.3 Delimitations

Energy focus : While the discipline of systems engineering is interdisciplinary in its original definition, this thesis focuses on the ship as an energy system and on the minimisation of the energy input for a given energy output. Economical aspects are briefly touched upon, but do not constitute the main focus of this thesis. Environmental, human factors, and other technical aspects (such as maintenance) lie outside of the main scope of this work.

System boundaries : In this thesis, the ship power plant constitutes the main system of interest. This includes the main components on board that are involved in the process of energy conversion to its final use. The different final energy users, such as the propeller, the heating systems and electric components, are not part of the main system of interest.

Case studies : Although the methods and principles presented and discussed in this thesis are general in their purpose, they are here applied specifically to two case study vessels.

Commercial vessels : This thesis focuses on large commercial vessels. Smaller ship types, such as inland ferries and leisure crafts are not directly covered by the results of this study.

Mathematical modelling : The work presented in this thesis focuses on the use of computational models for the analysis and evaluation of ship on board energy systems. This excludes, for instance, direct experimentation and the realisation of prototypes.

1.4 Thesis outline

Chapter 2 provides a brief introduction to the shipping sector (Sec. 2.1) and to the main drivers for research in the field of energy efficiency (Sec. 2.2). The main features of ship energy systems are described in Sec. 2.3, while a review of some of the most promising technical measures for energy efficiency is presented in Sec. 2.4.

Energy systems engineering represents the methodological basis of this thesis. Chapter 3 provides the reader with an introduction to its main principles (Sec. 3.1), and a description of the tools used in this study: energy and exergy analysis (Sec. 3.2) and mathematical models (3.3).

Chapter 4 describes how energy systems engineering principles were applied in this thesis. This includes an introduction to the general methodological approach (Sec. 4.1) and a description of the two case studies (Sec. 4.2) and of the data available for each of them (Sec. 4.3). The chapter also summarises the main assumptions employed in each of the studies that build up this thesis (Sec. 4.4).

Chapter 5 reports the main results of this thesis, subdivided between systems analysis (Sec. 5.1, related to Papers I and II) and synthesis (Sec. 5.2, related to Papers III to VI).

Chapter 6 then discusses how these results provide evidence of the benefits of an energy systems engineering approach, both in the analysis (Sec. 6.1) and in the synthesis process (Sec. 6.2). The chapter further develops by discussing how the findings presented in this thesis can be used to advocate for an increased focus on solutions for more efficient on board energy systems (Sec. 6.3). As this thesis focuses on the analysis of two case studies, the generalisability of the findings is also discussed (Sec. 6.4).

Proposals for future research in the field and suggestions to stakeholders are presented in Sec 7.1 and 7.2, while the conclusions are finally summarised in the last chapter (Chapter 8).

Chapter 2

Background

Shipping and energy efficiency

Chapter 2 represents an introduction to the domain of shipping. In Section 2.1 the main characteristics of shipping with particular focus on energy efficiency matters are presented; Section 2.2 describes the details of the rationale for working on energy efficiency, summarised into the economic and environmental standpoints. The ship as an energy system is described from a technical perspective in Section 2.3. Section 2.4 finally provides a survey of the current efforts for improving ship energy efficiency for the two technologies that are mostly dealt with in this thesis: waste heat recovery systems and hybrid propulsion systems.

2.1 An introduction to shipping

Throughout the course of the history of mankind, the development of society has gone hand in hand with trade. In spite of the importance of local and international land trade routes, shipping has always been the main mean of transportation for goods and people over long distances.

Merchant shipping has been growing continuously over the past years, hand in hand with global trade. The volume of world seaborne trade increased from 2.6 to 9.8 billion tons of cargo from 1970 to 2014, and today anything from iron ore, coal, oil and gas to cars, grains and containerized cargo is transported by sea, making shipping the backbone of global economy (UNCTAD, 2015). Today, shipping contributes to an estimated 80-90% of the global trade[1] (Maritime Knowledge Centre, 2012; UNCTAD, 2015).

As any other sector, shipping has some business-specific features, some of which influence the processes of designing and operating ships for reduced fuel consumption[2]:

[1]in ton km, i.e. based on the amounts of goods transported and the distance covered

[2]For a broader picture concerning energy efficiency in shipping from an organisational perspective,

- The fact that the owner of the cargo, the owner of the ship and the operator of the ship are often different actors generates **split incentives**. In particular, as the shipowner does not pay for the fuel, he/she does not have any incentive in building or buying a more energy efficient ship. On the other hand, when not even the ship operator pays for the fuel either (the cargo owner can pay for it, depending on the charter party), he/she does not have any incentive for saving fuel on an operative basis, for instance by sailing at a lower speed. This situation often hinders efforts in efficient ship operations and slows down the uptake of energy efficient technologies (Faber *et al.*, 2011; Jafarzadeh & Utne, 2014; Agnolucci *et al.*, 2014).

- Differently from e.g. planes and cars, ships are built on **individual or small-series basis**, which discourages research and development as they become too expensive if performed on an individual ship basis. This is not true for most ship components, such as engines and propellers, which partly explains why most technical developments for energy efficiency are seen in component development more than in ship design. In addition, when order books are full, shipyards tend to only accept orders for very "standard" designs which require little effort and allow maximizing the revenues (Devanney, 2011; Faber *et al.*, 2011).

- The **operational life** of a vessel can range from 15 to more than 30 years (Stopford, 2009). Ships built according to non-optimal standards for energy efficiency will therefore have an impact for a long time.

- Ships are sometimes used as **mere assets** by investors, who look more at the value of the sales and purchase market rather than at the energy efficiency of the vessels. As a consequence, efficient vessels are not always associated to a higher value on the second-hand ship market (Jafarzadeh & Utne, 2014).

2.2 The need for energy efficiency in shipping

2.2.1 The environmental standpoint: cutting GHG emissions

The question of reducing fuel consumption from shipping is related to one of the most important challenges of today's society: global warming.

CO_2 **emissions** are known to be the main cause of the anthropogenic contribution to global warming. While shipping-related emissions contribute today to 2.5% of the total of anthropogenic emissions[1] (Smith *et al.*, 2014), these emissions are expected to increase in the future by up to 250% as a consequence of growing trade volumes (see Figure 2.1), at the same time as emissions from other sectors are expected to decrease[2]

the reader is suggested to check the Hannes Johnson (2016) PhD thesis.

[1] Note that this number refers to CO_2 emissions, while the contribution to the total GHG emissions is lower.

[2] The predictions from IMO 3^{rd} GHG study propose 16 alternative scenarios, of which only one predicts lower emissions in 2050 compared to 2012 levels (Smith *et al.*, 2014).

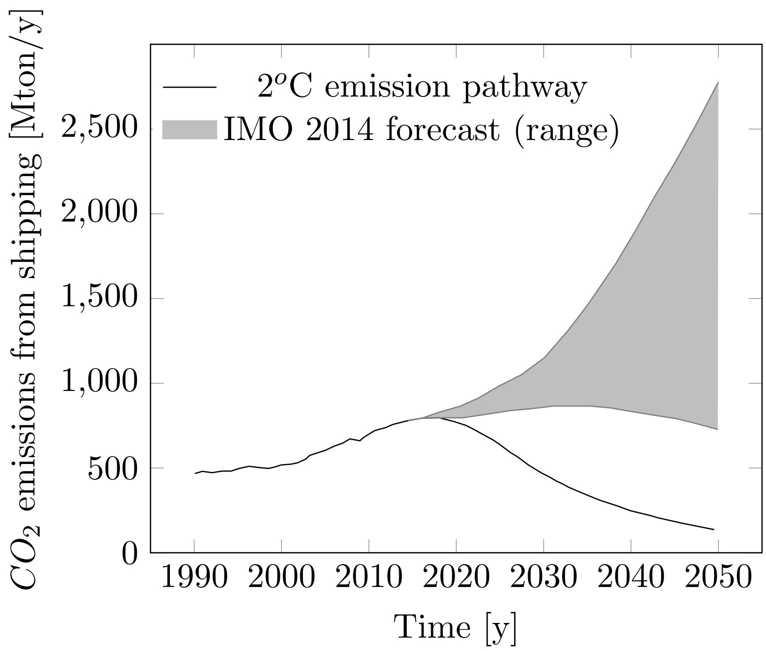


Figure 2.1: Comparison between forecast GHG emissions from shipping and viable pathways for achieving the 2 degrees climate goal. Adapted from (Anderson & Bows, 2012)

(Smith *et al.*, 2014).

However, even in the most optimistic scenario presented by IMO reports, emissions from shipping will reach much higher levels compared to what required for keeping global climate from warming beyond acceptable limits (see Figure 2.1). When more pessimistic scenarios are taken into account the picture becomes even gloomier Anderson & Bows (2012).

In 2013 the International Maritime Organisation (IMO) issued two main regulations connected to the reduction of shipping contribution to global CO_2 emissions (MEPC, 2011):

Energy Efficiency Design Index (EEDI) : A technical indicator of the ship's design energy efficiency. It is measured in tons of CO_2 emitted per ton of cargo transported and per km travelled. The EEDI is calculated based on the ship's performance when it is delivered and compared to a baseline value.

Ship Energy Efficiency Management Plan (SEEMP) : A document that has to be kept on board of every vessel where the ship operator must show that he/she has addressed the improvement of ship energy efficiency and that there is a plan for action for the future.

Although these measures represent a step forward for a reduction of CO_2 emissions from shipping, their effectiveness has been put under question for being inaccurate and not sufficiently ambitious (Johnson *et al.*, 2012; Bazari & Longva, 2011; Smith *et al.*, 2014).

2.2.2 The economic standpoint: much more than fuel prices

Shipping is primarily a business, and regardless all environmental concerns its main purpose is to generate a profit.

The most direct economic incentive to reduce fuel consumption is related to **fuel costs**. Research have shown that there is a large number of measures that could increase energy efficiency at a negative cost (Eide *et al.*, 2011). These considerations, however, heavily depend on the current fuel price.

Box 2.1: Marine fuels

As a consequence of the generally low requirements from an environmental standpoint and of the flexibility of marine engines, the shipping industry has been able to choose among a wide variety of different fuels:

Residual fuels : residual oils are mainly made of the heavy fraction remaining after the oil refinement process. Because of the high viscosity, these fuels need to be heated to up to 150^{o}C to achieve proper atomisation properties before injection. Normally, residual fuels have a relatively high sulphur content (up to 3.5% is today allowed), although low-sulphur residual fuels are available on the market. The two main variants of residual fuels are **heavy fuel oil** (HFO), made almost entirely of residual oils, and **intermediate fuel oil** (IFO), where HFO is partly blended with distillate fuels.

Distillate fuels : distillate fuels are made of lighter fractions of the oil refining process. The "lightest" of the distillate fuels is **Marine gas oil** (MGO), which is equivalent to Diesel fuels used in the automotive sector, while **Marine Diesel oil** (MDO) is a light blend of MGO and residual oil.

Other fuels : Mostly as a consequence of stricter environmental regulations, new fuels are being tested for use in the marine sector. This includes, among others, natural gas (generally in its liquefied form, LNG), ehtanol, and methanol.

In fact, fuel prices today are far from the peak achieved in 2012 (see Figure 2.2). According to observations of the past years, HFO prices tend to oscillate between 71% and 76% of the crude oil price (Ship&Bunker, 2015). Today's forecasts for crude oil prices suggest that they will range between 30 and 100 USD per barrel until 2020, which would suggest bunker fuel prices ranging between 226 and 753 USD per metric ton, while most likely remaining somewhere around 400 USD/ton (Ship&Bunker, 2015).

However, looking at the forecasts for bunker fuel prices issued in 2010, before the recent drop in crude oil prices (Figure 2.2), it appears that the reliability of these

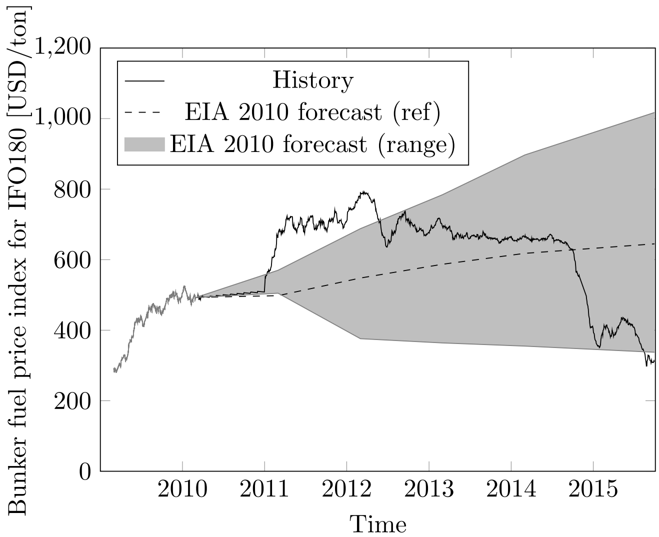


Figure 2.2: Historical IFO180 bunker prices evolution since 2009 and comparison with 2010 EIA forecast

forecasts can be questioned[1]. Although fuel prices are low today, they might rise again in the future.

2.2.3 Shipping and the environment: an economic matter

Fuel prices are not the only element influencing fuel-related costs. In recent years environmental concerns have become significantly stricter, adding to various types of operational costs on board and, particularly, on fuel related costs.

Sulphur oxides (SO_X) are emitted as a consequence of the sulphur in the fuel, which entirely oxides to SO_2 and SO_3 during combustion. SO_X emissions cause several harmful effects on the environment, such as acid rain and ocean acidification, and are precursors to the formation of particulate matter (PM) which is also harmful both to the environment and to human health. Today's global limit for the sulphur content is 3.5% on a weight basis, to be reduced to 0.5% in 2020[2] (IMO, 2013), while the global average was estimated to lie around 2.8% in 2012 (Mestl *et al.*, 2013). In emission controlled areas (ECAs), the limit was reduced to 0.1% since 2015.[3] Low-sulphur

[1]Dan Sten Olsson, manager at Stena Lines, recently declared in an interview *"When we designed the HSS-ships in 1992 oil prices were around 20 USD per barrel and further sank down to 12 USD/barrel. The ships were designed to be able to withstand a fuel price increase of up to 60%, although we never really considered an increase of more than 50% to be possible. To be able to be competitive up to 40, 100 USD/barrel was simply unthinkable" (Davidsson, 2015)*

[2]This decision will be subject to a review in relation to the availability of distillate fuels and systems for compliance, and might be postponed to 2025

[3]In spite of the recent reductions, these limits are still much higher compared to those valid for land-based transportation: fuel for trucks and Diesel trains can contain a maximum of 0.001% sulphur, 100 times less than what allowed for shipping in ports and ECAs today (EEA, 2013).

fuels are more expensive (the premium for distillate fuels normally ranges between 200 and 300 USD/ton), while scrubbers are costly to install and require energy during operations. Therefore, stricter regulations of SO_X emissions will provoke an increase of fuel costs.

Nitrogen oxides (NO_X) are emitted as a consequence of the high temperatures in the Diesel engines during combustion, which causes nitrogen and oxygen in the combustion air to react. Nitrogen oxides contribute to the processes of water eutrophication and acidification, are precursors to toxic chemicals (ground level ozone, secondary particulate matter) and can damage plant growth (Magnusson, 2014). Today NO_X emissions are regulated from the perspective of engine design (IMO, 2013). The global limit (Tier II) can be met by using today's engine technology stand-alone. Tier III limits (today valid only in US coastal waters, but under discussion in other areas of the world), on the other hand, can only be met via the installation of a selective catalytic reactor (SCR) or the use of alternative fuels (such as LNG and methanol).

Carbon dioxide (CO_2) is, as previously mentioned, the main driving force, from an environmental perspective, for improving ship energy efficiency This is generating political efforts to push shipping companies towards energy efficiency. Apart from the aforementioned IMO measures (EEDI and SEEMP), the European Union (EU) has recently decided to actively address the matter of including emissions from shipping in its GHG reduction policies (EC, 2013a), that will include, as a first step, the implementation of a monitoring, reporting and verification scheme for ships from 2018 (EC, 2013b). This will be followed by the definition of reduction targets and by the application of market based measures (EC, 2013a). Although the reduction targets for shipping have not been set yet, they are expected to be in the range of 40% to 50% by 2050, compared to 2009 levels inside the EU (EC, 2013a). Compared to current expectations of future development of CO_2 emissions from shipping (Smith *et al.*, 2014), this is an ambitious objective that will require a strong commitment.

2.3 The ship as an energy system

A ship needs fuel for operations. In the most general case, fuel is converted on board to energy in the form required for its final use: mechanical power for propulsion, electric power for on board auxiliaries and thermal power for heating purposes.

2.3.1 Energy demand

A ship is built and operated for a specific reason, normally referred to as mission, that varies from ship to ship (e.g. transporting cargo, transporting passengers, bringing fighting power at sea, etc.). In order to achieve this mission, a ship needs to be able to perform a certain amount of functions in addition to propulsion. These may range from providing a safe support for on board activities to ensuring hotel facilities for the

Box 2.2: Ship energy systems: definitions

In this thesis, different terms are used to refer to the ensemble of component and subsystems that are installed on board and that contribute to the behaviour of the ship from an energy perspective

Ship energy systems : the entirety of the ship systems that can be considered to be relevant from an energy perspective. Therefore, also hull and propeller are included.

Ship on board energy systems : the part of the ship energy systems located inside the hull. From an energy perspective, the propeller shaft constitute the main boundary of the system.

Ship power plant : the part of the on board ship energy system that is responsible for energy conversion. It therefore includes engines, generators and boilers, but not users (e.g. pumps, compressors, heaters, etc.). The ship's power plant is the main focus of this thesis.

Propulsion system : the part of the ship energy system devoted to propulsion. It generally includes the main engine(s) and the propeller(s).

crew[1].

On board energy demand is generally subdivided in three main categories (see also Fig. 2.3) (Woud & Stapersma, 2003):

Propulsion power : Ship movement generates a resistance from the water and, to a minor extent, from the air. This resistance depends primarily on a ship's speed and on the specifics of the hull (e.g., the shape, state, and wetted surface)[2]. External factors, such as the growth of various marine organisms on the hull and adverse weather conditions, also have an influence on the demand for propulsion power (Woud & Stapersma, 2003).

Auxiliary electric power : Many components on board require electric power during ship operations. Some of them are present on all ships and are related to basic support functions, such as the navigation equipment, cooling and lubricating pumps, compressors in air conditioning (HVAC) system, fans, ballast water pumps, and lights[3]. Specific ship types might require the operation of energy in-

[1] The focus of this thesis lies on the energy aspect of the ship systems. The analysis therefore focuses on the parts of the ship that have a significant influence on the ship's fuel consumption. As an example, the radar is a crucial part of the ship's navigational system, but it is not particularly interesting from an energy perspective since it requires little power to be operated.

[2] The following equation is broadly accepted as a simple approximation of the dependence of ship resistance on speed: $R_{ship} = Cv_{ship}^2$

[3] This base load can be roughly estimated as a function of the installed engine power: $P_{el}[kW] =$

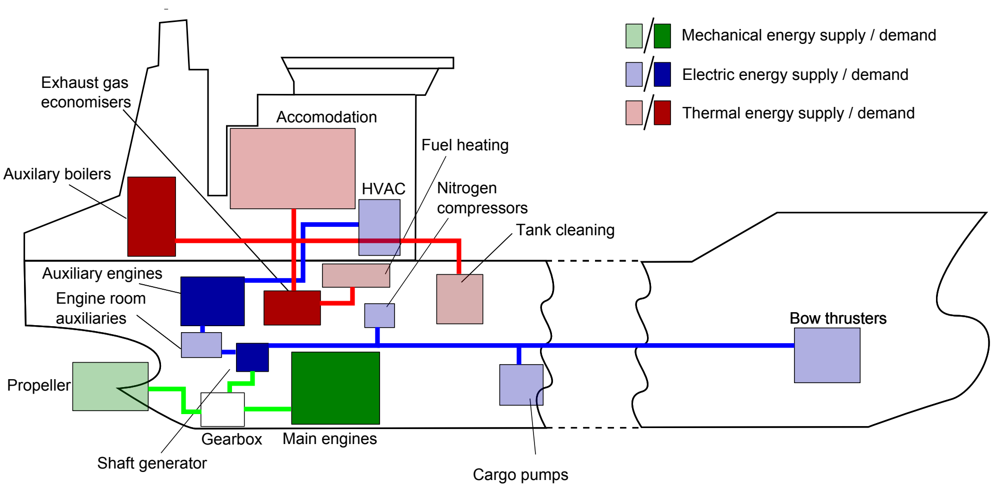


Figure 2.3: Schematic representation of the ship energy systems of a chemical tanker

tensive mission-related equipment, such as inert gas compressors and cargo pumps on tankers, refrigerated containers on containerships, etc.

Auxiliary thermal power : Heating is generally required for three main uses on board: accommodation, fuel heating, and fresh water generation. Similarly to auxiliary electric power demand, special ship types have additional requirements for heating, such as in the case of product tankers (for heating low-viscous cargo) and cruise ships (for accommodation)

2.3.2 Prime movers and energy converters

In order to provide energy in the required form to the different demands, the energy system of a ship is equipped with a number of devices for energy conversion.

Propulsors

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

Fixed pitch propellers (FPP) represent the most common and basic propeller type and are characterized by having blades whose angle relative to the axis of the shaft (pitch) is fixed. FPPs are the most widespread solution for ship propulsion, and are particularly common among container ships, tankers, and bulk carriers (Carlton, 2012).

Controllable pitch propellers (CPP) allow the variation of the propeller 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,

$100 + 0.55(MCR_{ME})^{0.7}$ (Woud & Stapersma, 2003).

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, 2003). CPPs are generally more expensive and delicate than FPPs. They are most favoured on passenger ships, ferries, general cargo ships, tugs, and fishing vessels (Carlton, 2012), and represent today roughly 35% of the propeller market.

Other types of propulsors are used only in very specific applications. Waterjets are generally installed when propellers cannot be used, particularly for very high speed vessels; cycloidal propellers (Kirsten-Boeing and Voith-Schneider) are generally employed when very high manoeuvrability or station-keeping are required (Molland *et al.*, 2011).

Internal combustion engines

Diesel engines are the most widespread solution for the conversion of chemical to mechanical energy, representing 96% of installed power on board of merchant vessels larger than 100 gross tons (Eyring *et al.*, 2010). The main marine Diesel engines features are (see also Table 2.1)[1]:

Efficiency : Diesel engines can reach up to more than 50% brake efficiency (Woud & Stapersma, 2003).

Load flexibility : Diesel engines allow low-load operations (down to 10% of the maximum continuous rating (MCR) (Laerke, 2012)) with a rather flat efficiency curve.

Fuel flexibility : Low and medium speed Diesel engines allow operations on both residual (HFO and IFO) and distillate fuels (MDO and MGO)) (Woud & Stapersma, 2003). Recent efforts from the main engine manufacturers also allowed operations on alternative fuels, such as natural gas and methanol (Aesoy *et al.*, 2011).

Maintenance : Compared to other prime movers, such as gas turbines, Diesel engines offer more possibilities to be repaired by the crew on board.

Diesel engines can be used both for providing propulsion (in which case they are normally referred to as main engines, ME) and auxiliary power (auxiliary engines, AE). Two stroke engines are generally used only for propulsion, while other engine types are used for different scopes depending on the application.

Gas turbines are today the only alternative to Diesel engines for ship power plants. Despite being less efficient (30-40%), and less flexible with load and fuel quality compared to Diesel engines (Woud & Stapersma, 2003), 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.

[1]For a more detailed description the reader is invited to refer to the extensive literature on the subject, such as the writings of Heywood (1988); Stone (1999); Woud & Stapersma (2003)

Table 2.1: Performance parameters of Diesel engines, state of art 2001 (Woud & Stapersma, 2003)

	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

2.4 Selected technologies for energy efficiency in shipping

The potential for improving ship energy efficiency in shipping based on technologies available today was estimated to lie between 25% and 75% (Buhaug *et al.*, 2009), even when only cost-effective measures are considered (Eide *et al.*, 2011; Faber *et al.*, 2011).

Reviews such as those presented by Buhaug *et al.* (2009) and Faber *et al.* (2011) generally refer to all type of measures that can potentially reduce fuel consumption: from logistics to improved hull and propeller design. While a complete review of these technologies would be out of the scope of this thesis, the following section focuses on research related to two specific solutions that will be further investigated in this thesis: waste heat recovery (WHR) systems, and hybrid propulsion systems.

2.4.1 Waste heat recovery systems

Waste heat recovery (WHR) systems refer to technical devices designed to make use of the thermal energy that would otherwise be wasted to the environment, a solution which is widely used in various industrial sectors.

A Diesel engine presents four main sources of waste heat (see Table 2.2). The **exhaust gas** are simply released to the atmosphere through the funnel, while waste heat from the **lubricating oil**, **charge air** and **engine walls** needs to be cooled on board.

On most ships, two cooling systems are installed: the **high-temperature** (HT) cooling system, with temperatures ranging between 70 and 90^{o}C, is responsible for cooling the cylinder walls (jacket water cooler, JWC) and part of the charge air flow (charge air cooler (CAC), HT section); the **low-temperature** (LT) cooling system, with temperatures normally ranging between 30 and 50^{o}C, is responsible for cooling the lubricating oil (lubricating oil cooler, LOC) and the remaining part of the charge air flow. LT cooling systems are also responsible for cooling the remaining systems on

Table 2.2: Waste heat from Diesel engines

Source	Temperature [^oC]	Energy share [%]
Exhaust gas	380	25.2
Jacket water cooling	85[a]	5.2
Charge air cooling	210 (85[a], 40[b])	13.7
Lubricating oil cooling	80(40[b])	6.3

Values refer to a four-stroke engine (Wärtsilä, 2007) at 100% load. The share changes at lower load, particularly in the case of the charge air cooling heat losses that decrease more with decreasing load then the rest.

[a] Available temperature at the HT cooling systems

[b] Available temperature at the LT cooling systems

board, such as the gearbox, propeller bearings, etc (Grimmelius *et al.*, 2010).

Heat-to-heat recovery

The recovery of waste heat from the main engines for fulfilling on board heat demand is today common practice. This is generally done by making use of the thermal energy content of the exhaust gas from the main engines, using an **heat recovery steam generator** (HRSG)[1] to generate steam which is then distributed to different users on board, such as HVAC and fuel heating (McCarthy *et al.*, 1990; Bidini *et al.*, 2005). The use of heat as means for ballast water treatment has also been proposed (Balaji *et al.*, 2015).

Heat from the engine cooling water is also often used for fulfilling on board energy demand. On many ships, this is used for freshwater generation using low-pressure evaporators (McCarthy *et al.*, 1990; Marty, 2014). When heat demand is higher, such as in the case of cruise ships, waste heat from the cooling systems can also be used for HVAC systems (Baldi *et al.*, 2015).

Heat-to-power recovery

The amount of waste heat available from the prime movers often exceeds the on board demand for heat, thereby driving engineers and researchers to investigate further opportunities for WHR[2].

[1] HRSG is a term most used in the land-based industry. In shipping it is often frequent to refer to these heat exchangers as exhaust gas economisers, or exhaust gas boilers.

[2] In principle, the expression "waste heat recovery" and the acronym WHR refer to any type of technology used for recovering waste heat. In current scientific literature, however, it is common to use this term to refer particularly to heat-to-power systems. This convention is also applied in this thesis.

One of the most interesting solutions concerns the conversion of waste heat to mechanical power. Although different technologies are available (Shu *et al.*, 2013), **Rankine cycles** have been particularly successful because of their well-known technology, safety, and relatively high efficiency (Tchanche *et al.*, 2011; DNV, 2012). Standard Rankine cycles are based on the generation of high-pressure steam and its subsequent expansion in a turbine, which generates mechanical power.

Steam-based Rankine cycles have been proposed for the application to many ship types: containerships (Dimopoulos *et al.*, 2011, 2012; Yang Min-Hsiung, 2014), ferries (Livanos *et al.*, 2014) and bulk carriers (Theotokatos & Livanos, 2013), referring to the use of both simple and dual-pressure cycles. Single-pressure steam-based Rankine cycles are installed, for instance, on E-class and on Triple-E class Maersk vessels (Maersk, 2014), and ready technical solutions are offered by several engine manufacturers (Mest *et al.*, 2013). The estimated fuel savings vary between different ship types and WHR technologies, ranging between 1% (Theotokatos & Livanos, 2013) and 10% (Dimopoulos *et al.*, 2012).

In some cases the use of steam as a working medium for Rankine cycles is not the most convenient choice. This is mainly due to the fact that:

- At low temperatures of the heat source it is not possible to maintain a sufficiently high evaporating pressure while ensuring the required minimum level of superheating (Invernizzi, 2013).

- The expansion turbine for a steam cycle is normally too expensive for low-power applications. This is due to the high enthalpy drop and low volumetric flow, which makes the design of the turbine particularly challenging (Invernizzi, 2013).

Organic Rankine cycles (ORC) are often used when only low-temperature waste heat (i.e. approximately below 250^{o}C) is available (Invernizzi, 2013), which makes the more suitable in the case of two-stroke engine; their working process is analogous to that of a steam-driven Rankine cycle, but they make use of different working fluids with more suitable thermodynamic properties.

The need of choosing the working fluid among many potential candidates implies an additional degree of freedom and, therefore, higher expected performance but also a more challenging optimisation process. This made ORCs to become the subject of many studies in scientific literature, with applications to containerships (Larsen *et al.*, 2013; Choi & Kim, 2013), LNG carriers (Soffiato *et al.*, 2014), handy-size tankers (Burel *et al.*, 2013) and passenger vessels (Ahlgren *et al.*, 2015). Grljušić *et al.* (2015) also proposed the application to oil tankers by attempting to integrate the ORC system with on board heat requirements.

The fuel savings related to the installation of ORCs are slightly higher then what estimated for steam-based WHR cycles, especially in the case of two-stroke engines where the temperatures of the available heat sources are lower. For instance, Larsen *et al.* (2015) showed that 10% fuel savings can be achieved on a marine two-stroke engine if an ORC is installed, at design load.

Rankine cycles are not the only way proposed for recovering waste heat on board. Power turbines, driven by the exhaust gas at high engine load, are efficient and have low capital investment, although they are generally connected to lower fuel savings (Dimopoulos *et al.*, 2011; Matsui *et al.*, 2010).

Other WHR technologies

Absorption refrigeration allows the use of heat for chilling purposes (Shu *et al.*, 2013). Although not common, it is sometimes employed on cruise vessels (R718.com, 2012). Finally, thermoelectric generation refers to processes based on the Seedback effect for the direct generation of electricity from a temperature difference without the need of any thermodynamic cycle (Shu *et al.*, 2013; Georgopoulou *et al.*, 2016).

2.4.2 Hybrid propulsion

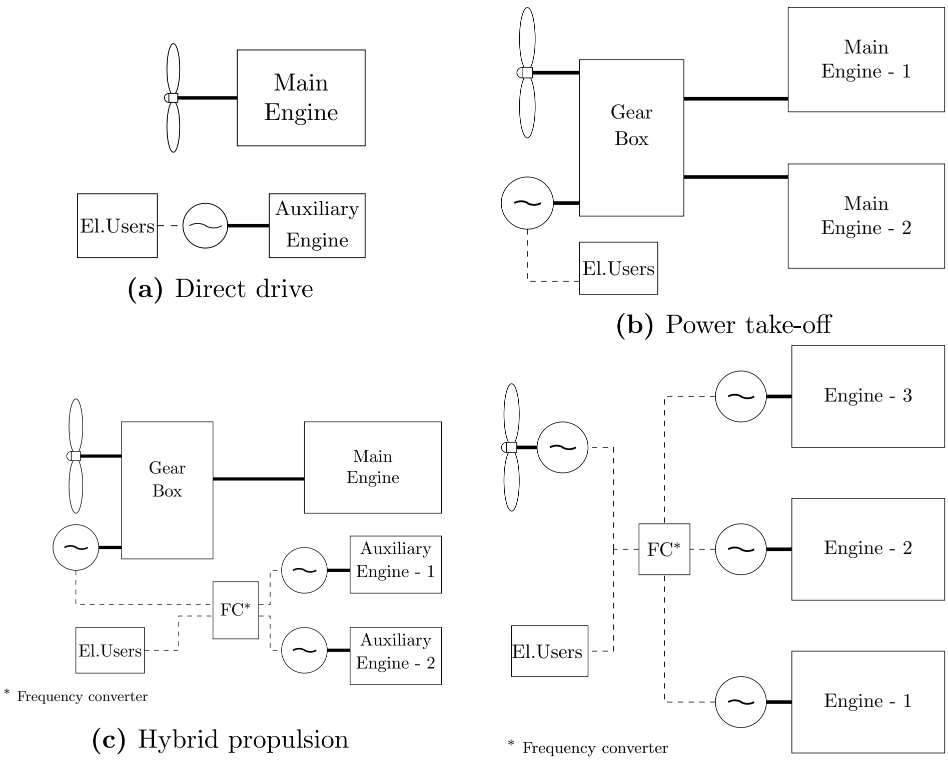
Although propulsion arrangements based on a hybridisation of mechanical and electric propulsion have been historically commonly installed on some specific ship types, such as naval ships and supply vessels (Woud & Stapersma, 2003), these systems are today also being studied for other vessel types.

The main engines are generally designed for the large propulsion power demand of sailing conditions at design speed. When sailing at low speed or manoeuvring, however, the demand for propulsion power decreases. In a conventional, direct-drive propulsion system (see Figure 2.4a) engines are operated at low load and, consequently, low efficiency.

Hybrid propulsion systems (Figure 2.4c) can be a solution to this issue. By allowing the main engines to be used to generate auxiliary power and the auxiliary engines to contribute to propulsion,s they allow additional flexibility in how the system deals with the generation of both propulsion and auxiliary power and proved to allow savings of 1-2% (Sciberras *et al.*, 2013).

Diesel-Electric systems (Figure 2.4d) can be even more attractive when higher flexibility is required. In Diesel-Electric systems there are no main and auxiliary engines: all the power generated by the prime movers is converted to electricity and further redirected to the different users, including the electrical motors driving the propeller shafts. These systems require however additional effort both in the design phase (Solem *et al.*, 2015) and in the definition of the control strategy (Vučetić *et al.*, 2011; Kanellos *et al.*, 2012).

Finally, the installation of batteries for energy storage has also gained ground as a consequence of the recent improvements in battery technology, showing a potential for savings of up to 28% (Grimmelius & de Vos, 2011; Dedes *et al.*, 2012; Sciberras *et al.*, 2013; Zahedi *et al.*, 2014).



(a) Direct drive

(b) Power take-off

(c) Hybrid propulsion

(d) Diesel-electric

Figure 2.4: Schematic representation of alternative power system configurations

Chapter 3

Theory

Energy systems engineering

Chapter 3 introduces the main principles and tools of energy systems engineering. First, the fundamentals of systems engineering are described (Sec. 3.1). Then, the main tools for energy systems analysis are presented: energy and exergy analysis (Sec. 3.2), and energy systems modelling (Sec. 3.3).

3.1 The energy systems engineering approach

The central focus of this thesis lies on the premise that ships' design and operation, with regards to energy efficiency, can be improved if the subject is approached by considering the ship as a system rather than by concentrating on its individual components.

This type of approach, normally referred to as systems approach, requires however additional effort and resources, while often reducing the focus on each individual part of the system. Its use should therefore be motivated: a systems approach is all about dealing with complexity (Flood & Carson, 1993).

3.1.1 Complexity in ship energy systems

According to Yates (1978), complexity arises when one or more of the following attributes are found:

Significant interactions : The different parts of the entity under study influence each other's behaviour.

High number of parts : The higher number of parts, the more possibilities for the different parts of the system to interact.

Non-linearity : The behaviour of the parts and their interactions cannot be represented by linear mathematical relationships. The influence of non-linearity can be seen intuitively, but is particularly relevant when dealing with models and, in particular, with optimisation (Chang, 2010).

Emergence : The interactions within the different parts are directed towards a common goal; simpler entities exhibit properties and capabilities that the simple entities themselves are not capable of. *Instead of being merely an aggregation of shaped materials, an airplane can fly. Instead of being a blob of cells, we can walk and talk.* (Flood & Carson, 1993).

Asymmetry : The interactions among the parts are not symmetrical.

Nonholonomic constraints : Some of the parts can go, temporarily, outside central control, generating localised, transient anarchy.

It is easy to observe that the energy system of a ship shows at least four of the six features mentioned above. As presented in Chapter 2, a ship is made of a large number of parts interacting with each other (hull, propeller, main engine(s), auxiliary engine(s), auxiliary electric equipment, boilers, etc.); these parts show a non-linear behaviour (e.g. the efficiency of the engine as a function of its power requirement) and operate towards a common goal. Although the degree of complexity varies between ship types, ship energy systems can be classified as complex according to the definition above.

When complexity arises "*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). Inefficient design is often connected to erroneous predictions of system behaviour, which are normally originated by counter-intuitive behaviour. However, referring again to (Flood & Carson, 1993),

> *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.*

3.1.2 From systems to systems engineering

The discipline approaching the engineering design process from a system perspective is normally referred to as systems engineering. Four main traits can be found and are emphasised in most of the available definitions (Blanchard & Fabrycky, 2006):

- The use of a an approach that views the **system as a whole** and that focuses on **interactions** within the system rather than on its individual components.

- A long-sighted approach that puts significant emphasis on **systems operations** and not only on the design.

- A detailed description of the **requirements** from the system.
- An **interdisciplinary** approach.

In this thesis, only the first three aspects of systems engineering are retained. The focus being on the energy part of the system, the approach employed in this work can be referred to as **energy systems engineering** (Vanek *et al.*, 2012).

3.1.3 Ship energy efficiency from a systems perspective

This work aims at contributing to the field of energy efficiency in shipping by applying a systems perspective. Although not as widely as in other fields, and often not explicitely in relation to systems engineering, other authors have published on this subject in the past. This is particularly true for ship energy and exergy analysis, and for studies that broadened the perspective of ship design by enlarging the boundaries of the system of interest and by taking a broader range of operational conditions into account.

Ship energy analysis

As introduced in Section 3.2, the work published to date concerning ship energy and exergy analysis can be broadly divided in two main category: studies based on a data-driven approach, and employing a model-based one.

The former approach is employed in two main studies: Thomas *et al.* (2010) and Basurko *et al.* (2013), both proposing the energy audit of fishing vessels. The results suggest that, for the selected case studies, propulsion represents a major part of the total on board energy consumption (76% in the case analysed by Thomas *et al.* (2010), 84% to 88% in the cases presented by Basurko *et al.* (2013)). In the case presented by Thomas *et al.* (2010), however, fishing equipment (14%) and lighting (6%) also showed to be relevant for the overall energy budget. None of the two aforementioned studies, however, touches the subject of thermal energy demand.

Marty *et al.* (2012); Marty (2014) proposed instead the application of model-based energy and exergy analysis. The results of his work confirmed that cruise ships a more varied energy demand compared to other ship types. Although the energy demand shares depend on each individual case, Marty (2014) estimated a share of approximately 40%-30%-30% for propulsion, auxiliary electric power and auxiliary heat for a cruise ship during sailing.

Interactions within the system

Although not common, more than one author accounted for interactions between different part of the systems in their analysis. The most notable examples come from two fields: WHR systems and hybrid propulsion.

In the case of WHR, the characteristics of the prime mover can be subject to modifications aiming at improving the performance of the whole system. Modifications to the turbocharger can influence the efficiency of the full power plant (in the case proposed by Dimopoulos *et al.* (2012) this allowed reducing the estimated payback time from 8 to 4 years). Similarly, the fine-tuning of engine injection and valve timing to optimise the efficiency of the combined engine-WHR system showed that up to 1.0% improvements in the overall efficiency can be achieved compared to optimising the components individually Larsen *et al.* (2015).

More in general, the larger the boundaries of the system of interest, the higher the expected improvement. This is mostly true for particularly complex systems, such as combined cycles (Dimopoulos & Frangopoulos, 2008) and Diesel-electric propulsion systems (Solem *et al.*, 2015; Zahedi *et al.*, 2014; Dedes *et al.*, 2012).

An appropriate understanding of system interactions is of utmost importance when the field of control systems is involved. In the case of hybrid and Diesel-electric propulsion systems, the issue of system control is not trivial and requires an additional effort in understanding how to operate all components for optimal efficiency (Grimmelius & de Vos, 2011; Dedes *et al.*, 2012; Sciberras *et al.*, 2013; Zahedi *et al.*, 2014; Vučetić *et al.*, 2011; Kanellos *et al.*, 2012).

Design for operational conditions

When a new solution for energy efficiency is proposed or optimised, a reference case is generally proposed as an example of the behaviour of the specific application, or to showcase the proposed method. Many times, however, the system under study is only evaluated at one operational condition, which most often only partly represents ship operations.

Some authors have taken into account a reference voyage, rather than a single operational point (Dedes *et al.*, 2012; Choi & Kim, 2013). Although constituting an improvement with respect to design-point evaluations, this approach misses to take into account the variability of the voyage pattern of a vessel in terms of speed, draft, weather encountered, time spent in port, etc. More in general, a correct evaluation of a proposed design should be performed on an operational profile representative of real ship operations (Ahlgren *et al.*, 2015), as these are generally substantially different from design conditions (Coraddu *et al.*, 2014).

In a design process, a correct accounting of the expected range and distribution of system operations can make the difference between a success and a failure (Gaspar *et al.*, 2010; Motley *et al.*, 2012). Kalikatzarakis & Frangopoulos (2014) showed that depending on the assumed operational profile, the net present value of the proposed WHR system after 20 years could vary by as much as 50%.

3.2 Energy and exergy analysis

The correct understanding of the requirements of a system constitutes one of the main building blocks of the systems engineering approach. In the case of energy systems, this demands for a detailed, systematic analysis of the system's energy performance. Apart from standard data analysis tools that can be used for dealing with typical marine engineering variables of interest, two additional tools used in this thess is: energy and exergy analysis.

3.2.1 Energy analysis

Energy analysis is based on the 1^{st} law of thermodynamics, which can be read as *Energy cannot be created nor destroyed.* The energy balance of a given component can be written as follows:

$$\frac{dU}{dt} = \dot{Q} - \dot{W} + \sum_i \dot{m}_{in,i} \left(h_{in,i} + \frac{1}{2} v_{in,i}^2 + g z_{in,i} \right) - \sum_j \dot{m}_{out,j} \left(h_{out,j} + \frac{1}{2} v_{out,j}^2 + g z_{out,j} \right) \tag{3.1}$$

where U, Q, W, m, h, v, g and z represent internal energy, heat, work, mass, specific enthalpy, fluid velocity, gravitational acceleration and altitude, respectively.

From an energy analysis perspective, the *energy efficiency* of a component is broadly defined as (Patterson, 1996):

$$\eta = \frac{\Delta H_{out}}{\Delta H_{in}} \tag{3.2}$$

where ΔH_{out} and ΔH_{in} represent the totality of the **useful** energy output and of the energy input to the system, respectively. Examples of the useful output of a system are the mechanical power (in the case of a Diesel engine) or the enthalpy content of a steam flow (for a boiler).

Energy analysis is generally done on either a data-driven or a model-based approach. According to a **data-driven** approach, the performance of a system is evaluated starting from measurements of relevant quantities on board. On the other hand, in **model-based** the majority of the data required in the energy analysis is generated using mathematical models of the investigated system.

3.2.2 Exergy analysis

Exergy is a thermodynamic quantity which allows combining considerations of energy quantity and quality, and is defined as "*the maximum shaft work that can be done by the composite of the system and a specified reference environment* " (Dincer & Rosen, 2013). For this reason exergy analysis is often integrated with energy analysis to get a better understanding of the system, and in particular for (Dincer & Rosen, 2013):

- Combining and applying the conservation of mass and energy and the second law of thermodynamics.

- Revealing whether or not and by how much it is possible to design more efficient systems by reducing the inefficiencies in existing systems.

Box 3.1: The quality of thermal energy

Energy analysis is based on the assessment of energy quantities, where all forms of energy are treated at the same level. This assumption is valid for most of energy forms. Given a certain amount of electric energy, this can be converted with almost 100% efficiency to any other form: using an electric motor (conversion to mechanical energy), or a resistance (to thermal energy), etc.
Thermal energy is different from other energy forms. This is a consequence of the fact that, in contrast to mechanical and electrical energy, thermal energy results from a disorganised motion of particles (Atkins, 1994).
The conversion from disorganised to organised movement does not happen "for free". As stated in the 2^{nd} law of thermodynamics, a given amount of thermal energy cannot be converted to an equal amount of mechanical energy. The efficiency of the conversion depends on several variables, where the temperature at which the thermal engine receives the heat, and that at which the heat is rejected, are the most important.
These observations have a number of practical consequences:

- Waste heat cannot be entirely converted into work. In fact, only a relatively small portion of the heat released by an engine to the environment can be converted to mechanical or electric power, even when assuming ideal conversion machines.

- Not all sources of waste heat on board of a ship are of equal importance. The energy in the exhaust gas, which (depending on the engine type) is released at between 200 and 400^{o}C is of higher quality than that contained in the cylinder cooling water (90^{o}C) or in the charge air (up to 200^{o}C at full engine load).

- The recovery of waste heat on board can be a particularly challenging process if the objective is to harvest it in the most efficient way. Using high-temperature exhaust gas to generate 8 bar steam corresponds to an inefficient use of the original energy flow and to a loss of energy quality, as the same result could have been achieved with a heat source at lower temperature. The same process occurs when 8 bar steam is used to heat fuel oil to 70^{o}C in the storage tanks.

- Analysing ship energy efficiency based solely on energy quantity can be misleading. A ship might recover all of its waste energy for heating purposes, which would appear efficient from an energy perspective. However, full recovering all available waste heat does not necessarily imply that this is done efficiently. This is the domain where exergy analysis demonstrates the greatest potential for identifying the inefficiencies of thermomechanical systems.

Electric, kinetic and potential exergy quantities coincide with their energy counterparts. The **physical exergy** content of a flow instead can be calculated as follows:

$$\dot{B}_{ph} = \dot{m}[(h - h_0) + T_0(s - s_0)] \tag{3.3}$$

where $\dot{B}$, h, and s respectively stand for exergy flow, specific enthalpy, and specific entropy, while the subscript 0 refers to the conditions of the reference environment.

Similarly, the exergy counterpart of a heat flow at a given temperature can be calculated as:

$$\dot{B}_{heat} = \dot{Q}[1 - \frac{T_0}{T}] \tag{3.4}$$

where T represents the temperature at which the heat is transferred.

Differently from energy, exergy is not conserved. Any non-reversible process involves a loss of exergy. This contribution to the exergy balance, generally known as **irreversibility rate**, is calculated as:

$$\dot{I} = T_0 \dot{S}_{gen} \tag{3.5}$$

where $\dot{S}_{gen}$ stands for the entropy generation rate in the component.

The fact that exergy is not conserved leads to the fact that a large amount of alternative performance indicators can be defined, and to date there is not a complete agreement in the scientific community concerning which ones should be used when performing an exergy analysis (Lior & Zhang, 2007). A list of the performance indicators used in this thesis is provided in Table 3.1[1].

Table 3.1: Summary of the exergy-based performance indicators employed in this work

Name	Defining equation	Function
Total exergy efficiency (ϵ_t)	$\frac{\sum \dot{B}_{out,i}}{\sum \dot{B}_{in,i}}$	Measures what fraction of the exergy input to the component is not destroyed
Task efficiency (ϵ_u)	$\frac{\sum \dot{W}_{u,i} - \sum \dot{W}_{p,i} + \sum \dot{B}_{h,u,i} + \sum \dot{B}_{c,u,i}}{\sum \dot{B}_{h,p,i} + \sum \dot{B}_{c,p,i} + \sum \dot{B}_{ch,p,i}}$	Measures the ability of the component to generate useful output
Efficiency loss ratio (δ)	$\frac{\dot{I}}{\sum \dot{B}_{in,i}}$	Measures what fraction of the exergy input to the component is destroyed
Relative irreversibility (γ)	$\frac{\dot{I}}{\sum \dot{I}_j}$	Measures the contribution of the component to the total exergy destruction of the system

[1] A detailed review of exergy-based performance indicators can be found in dedicated literature (Kotas, 1980; Lior & Zhang, 2007).

3.3 Energy systems modelling

When applying the principles of systems engineering, tools are required for being able to correctly estimate how the engineering system will perform given different operational conditions, and on how these conditions will influence the internal processes. The process of modelling refers to the act of constructing a tool for reproducing or imitating the behaviour of a real system, which is easier to study than the system itself (Kramer & de Smit, 1977).

3.3.1 Introduction to mathematical modelling

The act of modelling can refer to many different types of actions, from verbal modelling (describing the behaviour of a system in words) to physical modelling (building a physical reproduction of the system, generally in smaller scale, to perform tests). This work focuses on **mathematical models**, where the relationships between entities in the model are represented in mathematical terms (Kramer & de Smit, 1977), and in particular on models with a **predictive** purpose, i.e. that are meant to be able to simulate the behaviour of the system under varying conditions (Flood & Carson, 1993).

Mathematical models can be further subdivided in different categories depending on their defining aspects[1].

Mechanistic (often referred to also as **white-box**) models attempt to describe the physical phenomena that characterise a system by making use of physical laws (e.g. conservation of mass and energy) or semi-empirical equations (e.g. heat transfer correlations) (Duarte *et al.*, 2004). In contrast, **empirical** (also known as **black-box**) models are trained on observed data to predict the output of a system given the input (Duarte *et al.*, 2004).

Empirical models do not require any knowledge of the underlying system's physics, and are often more accurate compared to mechanistic models. However, not only they require large datasets for model training, but they also generally perform poorly when extrapolating outside of the training dataset (Duarte *et al.*, 2004).

An additional categorisation is based on how the model treats time as an internal variable. Depending on whether the time domain is included among the modelling independent variables or not, a model is called **steady-state** or **dynamic**. Steady-state models are generally easier to solve and are preferred when there is no interest in the dynamic component of the system.

Finally, a model that, given a certain input, generates one and only one possible output is called **deterministic**. **Stochastic** models instead can deal with uncertainty and are normally used in processes, such as robust optimisation, where the focus lies not only in finding one optimal solution, but also in limiting the effect of uncontrollable variations to the system's inputs and its behaviour (Sahinidis, 2004).

[1] This categorisation is a personal adaptation based on Grimmelius (2003)

3.3.2 Energy systems modelling in shipping

Computational models are extensively used for application to ship energy systems, and propulsion systems in particular, as already exemplified in early work in the field (DeTolla & Fleming, 1984; Neilson & Tarbet, 1997; Depuis & Neilson, 1997)[1].

Models of ship energy systems are generally used for three main purpose: for the control of existing systems, for the evaluation of new designs or retrofitting options, and for optimisation. Although each model is different depending on the individual study, models used in the framework to which this thesis aims to contribute are generally **mechanistic** and **deterministic**.

System control

Models used for **control** purposes are subjected by the intrinsic requirement of being dynamic. Most models proposed in academic literature in this field relate to the control of relatively complex systems, where the task of optimising the control strategy is more challenging. This is the case for instance of Diesel-electric power plants, where the total electric load needs to be allocated to different prime movers (Kanellos *et al.*, 2012), and to systems equipped with batteries (Grimmelius & de Vos, 2011; Han *et al.*, 2014), where the optimal strategy for battery charge and discharge needs to be defined. Finally, Grimmelius & Stapersma (2001) also provide an example of the use of computational models for determining the impact of the control of the propulsion plant on the thermal loading of the engine.

Prediction for system design

Mathematical models have been extensively applied to the prediction of the performance of a given design (or retrofitting) and, therefore, to its evaluation.

Many of the proposed are used to predict the performance of the system in terms of energy efficiency and fuel consumption. In these regards, it is often assumed that for many ship types the influence of ship dynamics on fuel consumption is marginal and, therefore, focus on the steady-state performance of the system[2].

Some authors presented different modelling strategies without focusing on specific uses. While Shi & Grimmelius (2010) and Theotokatos & Tzelepis (2015) focused on the ship's propulsion system, other authors leaned towards a more holistic perspective. Calleya *et al.* (2015), Cichowicz *et al.* (2015) and Tillig *et al.* (2015) proposed general, holistic modelling framework for the simulation of the performance of the ship in different operational conditions and for evaluation of different energy saving technologies; these models focused on the hydrodynamic part of the ship, while Zou *et al.* (2013)

[1] For other examples of reviews in the literature of energy systems modelling the reader is referred to the works of Tillig *et al.* (2015); Ginnetti (2014).

[2] It should be noted that, although the models presented in these papers are mostly used for predicting the performance of the system in steady-state conditions, they are often dynamic models. Most models are based on intrinsically dynamic modelling platforms, such as Simulink, Simscape and Modelica.

and Lepistö *et al.* (2016) put the emphasis on thermal energy flows on board. Pedersen & Pedersen (2012) proposed the use of bond-graph modelling for ship energy systems, and particularly for the application to Diesel-electric systems.

Other authors proposed the use of mathematical models for the evaluation of specific design solutions. Viola *et al.* (2015) focused on the design of wind-assisted propulsion; Zahedi *et al.* (2014) proposed the use of DC hybrid power systems for Diesel-electric ships, and evaluated their performance against more standard AC systems; Livanos *et al.* (2014) evaluated various propulsion systems for LNG-powered ferries, also included WHR systems in the picture, while Burel *et al.* (2013) focused on handymax tankers; Dedes *et al.* (2012) and Sciberras *et al.* (2013) attempted to asses the potential for fuel savings of hybrid propulsion systems.

Dealing with the propulsion system, dynamic models are often used for the prediction of ship performance during manoeuvring or, in general, to simulate the behaviour of the ship systems during transients (acceleration, crush-stop, turns) (Campora & Figari, 2003; Benvenuto & Figari, 2011; Theotokatos, 2008; Schulten, 2012).

Box 3.2: Black-box and stochastic modelling in shipping

Although the focus of this thesis lies on mechanistic and deterministic models, examples of the use of alternative modelling strategies can be found in academic literature.
In the latest years, the use of **black-box models** has been increasing as a consequence of the growing availability of measured data from ship operations. In particular, artificial neural networks (Petersen *et al.*, 2012a; Shi & Grimmelius, 2010), Gaussian processes (Petersen *et al.*, 2012b), regularised least squares, Lasso regression, and random forest methods (Coraddu *et al.*, 2015) have been tested, and compared to white box models. In presence of sufficiently extensive measurements of ship operations, black-box models are more reliable than white-box models in the accuracy of the predictions (Leifsson *et al.*, 2008).
The use of hybrid (gray-box) models allows achieving an accuracy comparable to that of a black-box model while requiring a lower amount of measurements and improving the performance of the model for extrapolation (Coraddu *et al.*, 2015; Leifsson *et al.*, 2008).
Although most models presented so far are deterministic, there are few examples of including **uncertainty** in the discussion. Kalikatzarakis & Frangopoulos (2014); Coraddu *et al.* (2014), for instance, proposed a sensitivity analysis, where the influence of varying operational parameter on the efficiency of the design was evaluated. Vrijdag *et al.* (2007) proposed instead an uncertainty analysis, mostly accounting for the uncertainty in model parameters and inputs. Stochastic optimisation in ship design has only been introduced in relation to ship hydrodynamics, and in particular on the choice of the ship's main dimensions Hannapel & Vlahopoulos (2010); Diez & Peri (2010).

Optimisation

The models presented in the previous section are used for aiding the designer in evaluating a pre-determined design. Models can however also be used at a even higher level of the design process: in the field of design optimisation, parts of the design choices are delegated to an optimisation procedure that helps the designer in the identification of the set of parameters or system configuration that, according to the output of the model, shows the most optimal performance.

Optimisation in ship design has been applied extensively to the choice of the ship main dimensions (among others, Ölçer (2008)), to the configuration of the power plant (Dimopoulos & Frangopoulos, 2008; Dimopoulos *et al.*, 2008; Solem *et al.*, 2015) and to the design of retrofitting options, particularly for WHR systems (Dimopoulos *et al.*, 2011; Larsen *et al.*, 2013).

Optimisation generally requires the system to be simulated a large number of times, which leads to models used for this purpose being less computational intensive. Models used for system optimisation are steady-state; the use of linear models, although not common, has also been proposed (Solem *et al.*, 2015).

3.3.3 Modelling of individual components

The choice of the modelling detail goes hand in hand with considerations related to modelling accuracy and computational time based on the requirements of the problem to be solved. In this section, the available choices for modelling the main parts of the ship energy systems are reviewed.

Propellers

Mechanistic modelling of propeller performance can be performed in three, main ways (Molland *et al.*, 2011):

Performance maps : Performance maps are generally provided by the propeller manufacturer and provide a graphical relation between the main variables of the propeller (e.g. adimensional thrust and torque, and efficiency), valid for one specific propeller model.

Standard series : Propeller series have been systematically analysed in order to derive relatively simple models for the prediction of propeller performance. The Wageningen series propellers are largely the most known and employed in scientific literature (Oosterveld & Van Oossanen, 1975), although models of several other series have been developed (Molland *et al.*, 2011).

Theory-based models : Different theories have been developed over the years for modelling propellers and their interaction with the water flow. These types of models are generally rather computationally expensive and rarely used in energy systems models.

When available, performance maps are preferred as they are easy to use and provide accurate predictions. When a performance map is not available, standard series, and in particular the Wageningen series, are by far the most employed in academic literature about modelling of ship propulsion systems (see Table 3.2).

Diesel engines

Modelling the Diesel engine can require different effort depending on the specific problem under investigation:

Empirical models represent the relationship between engine main operative variables (typical outputs are efficiency, exhaust temperature and mass flow, waste heat to cooling systems) using empirical input-output relations. In the simplest case, these are defined as polynomial functions of the engine load alone (e.g. in Kanellos *et al.* (2012); Calleya *et al.* (2015)) or of load and speed (Marty, 2014). These functions can be based on the engine's technical documentation or on experimental data. Performance maps, such as those described in the case of propellers, can also be provided by engine manufacturers. More complex models, such as those based on artificial neural networks, have also been employed (Grimmelius *et al.*, 2007).

Mean value engine models (MVEM) are based on the assumption that engine processes can be approximated as a continuous flow through the engine, and hence average engine performance over the whole operating cycle (Theotokatos, 2008; Dimopoulos *et al.*, 2011).

Zero-dimensional engine models (0DEM) models operate per crank-angle basis by solving the mass and energy conservation equations, along with the gas state equation, in their differential form. Combustion is modelled by using phenomenological models of either one or multi zones, where the latter are favoured when a more detailed representation of the combustion process and the prediction of exhaust gas emissions are needed (Scappin *et al.*, 2012).

CFD engine models are based on principles of fluid dynamics and feature the inherent ability of providing detailed geometric information on in-cylinder mass and energy flows by solving the governing flow equations.

As shown in Table 3.2, different authors have employed different types of models for simulating engine behaviour in ship energy system models. Empirical models, MVEMs and 0DEMs are all employed, while CFD models are more common for research in specific combustion-related topics and when accurate predictions of pollutant emissions (particularly NO_x and PM) are required.

Electric machinery

The modelling choices related to the electric machinery on board varies depending on the type of energy system analysed and on the scope of the work.

Table 3.2: A review of the modelling choices in scientific literature on ship propulsion systems modelling

	Type	Propeller (K_T, K_Q)	Main engines ($\dot{m}_{fuel}$)
Benvenuto & Figari (2011)	Dyn	Map ($J, P/D$)	0DEM
Campora & Figari (2003)	Dyn	Map ($J, P/D$)	0DEM
Pedersen & Pedersen (2012)	Dyn	StSe	EM ($\dot{W}_{ME}$)
Schulten (2012)	Dyn	Map ($J, P/D$)	MVEM
Theotokatos (2008)	Dyn	StSe	MVEM
Grimmelius *et al.* (2010)	Con	StSe	EM ($\dot{W}_{ME}$)
Larroudé *et al.* (2013)	Con	$P_2(J)$	EM ($\dot{W}_{ME}$)
Kanellos *et al.* (2012)	Con	-	EM ($\dot{W}_{ME}$)
Shi & Grimmelius (2010)	Mod	StSe	EM ($\dot{W}_{ME}, \omega_{ME}$)
Theotokatos & Tzelepis (2015)	Mod	StSe	MVEM
Cichowicz *et al.* (2015)	Mod	StSe	MVEM
Coraddu *et al.* (2014)	Mod	TB	EM ($\dot{W}_{ME}, \omega_{ME}$)
Calleya *et al.* (2015)	Des	StSe	EM ($\dot{W}_{ME}$)
Liu & Fan (2010)	Opt	StSe	EM ($\dot{W}_{ME}$)

Abbreviation	Model type
Dyn	Dynamic
Con	Control
Mod	General models
Des	Design evaluation
Opt	Optimisation
Map	Performance map
StSe	Standard series (e.g. Wageningen)
TB	Theory-based methods
EM	Empirical model
0DEM	Zero-dimensional model
MVEM	Mean value engine model

When dealing with "traditional" propulsion systems, where power demand for propulsion and for electric auxiliaries are provided by different systems, auxiliary generators are often neglected (Theotokatos & Livanos, 2013).

The modelling of hybrid or Diesel electric systems does not allow neglecting the influence of electric machinery, as this would lead to overestimating the performance of the system. In order to take this aspect into account it can be sufficient to model the electric components with **constant efficiencies**, as done, among others, by Dedes *et al.* (2012). Although electric machines generally have flat efficiency curves, their efficiency drops at very low load; this can be taken into account using **empirical correlations** (see McCarthy *et al.* (1990)).

Many authors, however, favour a more detailed modelling of the electric machinery, both for including the influence of these components in terms of system control (Kanellos *et al.*, 2012) and for improving the accuracy of the prediction of energy losses (Zahedi *et al.*, 2014). The use of the standard d-q (direct and quadrature axes) equations (Sciberras *et al.*, 2013) is a typical example of a more advanced modelling of on board electric machinery.

Waste heat recovery systems

As most of the work published in the literature related to the application of waste heat recovery systems (and, particularly, of Rankine cycles) to ships is focused on the estimation of the performance of the system in different conditions and on its optimisation, WHR systems are always modelled based on a component-by-component principle.

Some of the presented work, in fact, focuses on the **working cycle** without a specific modelling of the individual components. In these cases the standard principle lies in fixing a value for the pressure of the working fluid and of the minimum temperature difference in the heat exchangers (pinch point), which define the main features of the thermodynamic cycle (Larsen *et al.*, 2013; Livanos *et al.*, 2014). Once the thermodynamic cycle has been identified, the features of the heat exchangers (UA value) can be determined, while the performance of the expansion turbine and of the pump are normally determined using their isoentropic (Choi & Kim, 2013) or politropic (Larsen *et al.*, 2013) efficiencies.

The requirements in terms of model assumptions become more complex once the design parameters are identified, and the off-design performance of the system is to be evaluated. Larsen *et al.* (2015) and Dimopoulos & Kakalis (2010) provide some examples of how to determine the part-load performance of heat exchangers and expanders[1].

[1]It should be noted that the available literature on WHR systems based on Rankine cycles is significantly wider than what published in the field of shipping. For the interested reader, the work of Quoilin (2011) provides very good guidance in these regards.

Chapter 4

Methodology

Case studies, data collection, and modelling choices

Chapter 4 presents the methodology employed in this work. It includes a summary of the methodological approach (Sec. 4.1), a description of the case studies (Sec. 4.2) and information on the availability and quality of the data that could be gathered for the two case study vessels (Sec. 4.3). Finally, the main assumptions employed in each of the studies that build up this thesis are summarised (Sec. 4.4).

4.1 Methodological approach

The central focus of this thesis is to **apply principles of energy systems engineering to the analysis and improvement of ship on board energy systems**. This general aim is subdivided into two, main objectives:

- To systematically **analyse** the performance of on board ship energy systems.
- To propose the **synthesis** of solutions for improving ship energy efficiency and to evaluate their potential energy savings.

In this thesis, the proposed themes were addressed by focusing on two case studies. In both cases, operational measurements and technical documentation were used to analyse the performance of the system. Based on the results of this initial analysis, potential improvements to the systems were proposed and evaluated. In both phases, computational models were used to improve the understanding of the system and to predict its behaviour.

4.1.1 Analysis

The first objective of this thesis relates to the analysis of the existing systems.

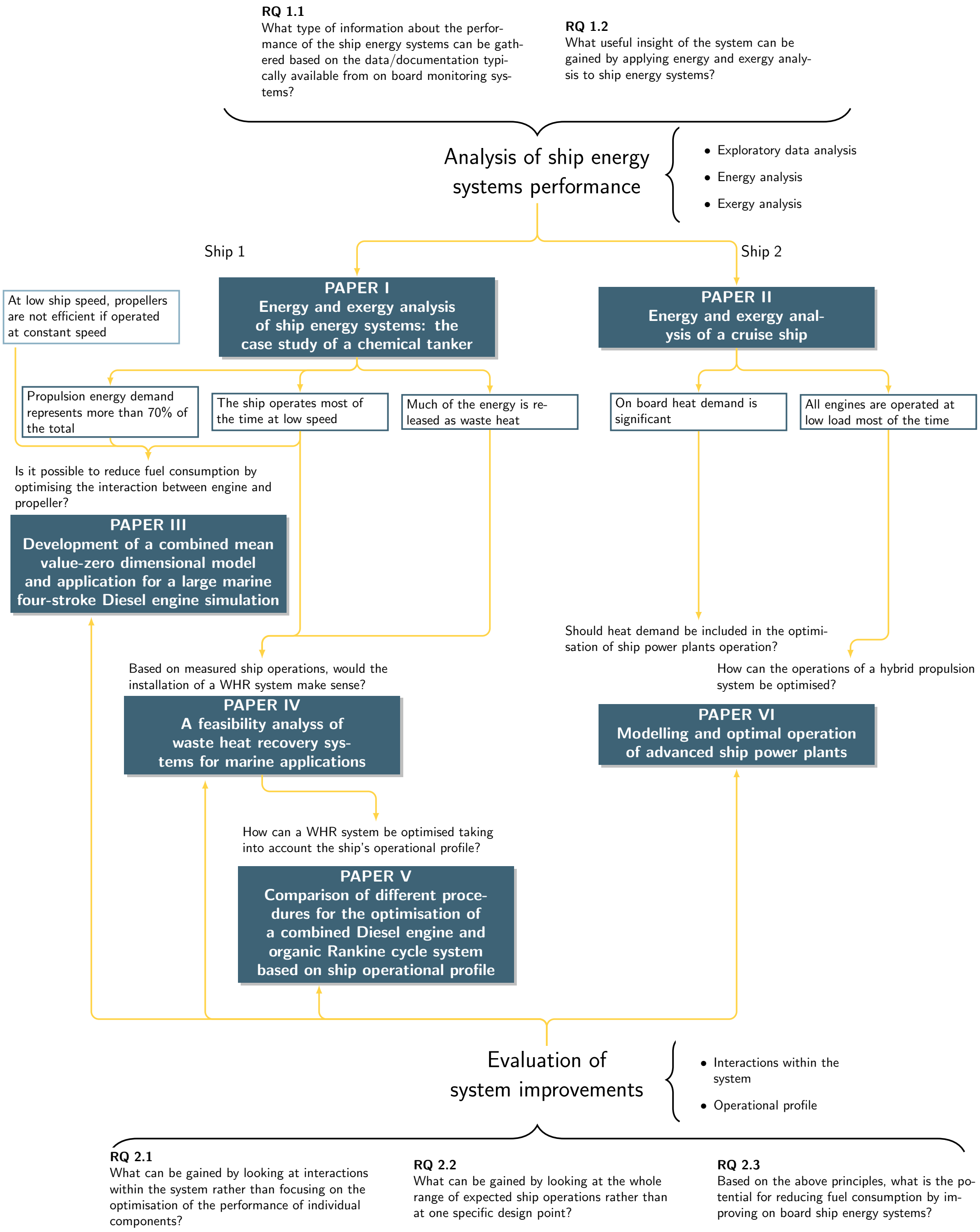


Figure 4.1: Overview of the methodology (1)

In order to approach this subject, the work of this thesis started from analysing the information available for the two case study vessels (both from monitoring systems and from technical documentation, as detailed in Section 4.3), and using it to gain an insight about the related energy systems.

The analysis of the available data was divided in two main parts:

Preliminary analysis (also referred to as *exploratory data analysis*), with the aim of getting a broad view of what type of data are available, and what can be understood about the operations of the vessel by a simple, structured observation of the data (Tukey, 1977). This phase included, for instance, understanding the typical operational profile of the ship in terms of speed, engine loads, power demands, etc.

Energy and Exergy analysis , with the aim of applying a more structured and systematic analysis of the ships' systems with the focus on their energy performance. This phase included the estimation of, among others, energy and exergy flows and efficiencies for the different parts of the ship.

The work related to this part of the thesis is the main focus of Paper I (in relation to Ship-1) and Paper II (Ship-2).

4.1.2 Synthesis

Starting from the insight gained in the previous part, the second objective of this thesis moves from the analysis of the existing systems to the synthesis and evaluation of ways to improve the energy efficiency of these systems. More specifically, this led to three applications:

- Engine/propeller interaction (Paper III)
- Waste heat recovery (Paper IV and Paper V)
- Ship power plant operational optimisation (Paper VI)

4.1.3 System boundaries and modelling

As a general principle, this thesis focuses on the **ship's power plant** as the main system of interest. This puts an ideal boundary of the system on the propeller shaft, on the switchboard, and on the steam pipes. The parts of the ship that are excluded from the main system of interest (propeller and hull, individual electric and thermal power consumers) are considered as power demands to the ship power plant. The choice of excluding the propeller from the main system of interest was challenged in Paper III, where the focus lies on the interaction between the engine and the propeller.

The models employed in this thesis depend on the specific aim of each of the Papers, and are further described in Section 4.4. As a general principle, the model employed in the first two Papers of this thesis are **descriptive**, as they are used for processing

Table 4.1: Summary of the level of detail in the modelling for Papers III to VI

	III	IV	V	VI
Propulsion	Op.Prof.	Op.Prof.	Op.Prof.	Op.Prof.
Aux. electric	Const.	Op.Prof.	Op.Prof.	Op.Prof.
Aux. heat	Const.	Op.Prof.	Not Incl.	Op.Prof.
Main engines	NonLin(M)	NonLin(E)	NonLin(E)	NonLin(M)
Auxiliary engines	Lin	Lin	Lin	NonLin(M)
Propeller	NonLin(E)	Not Incl.	Not Incl.	Not Incl.
Auxiliary boilers	Not Incl.	Lin	Not Incl.	NonLin(E)
WHR system	Not Incl.	Lin	NonLin(M)	NotIncl.

Op.Prof.: Operational profile
Const.: Constant demand
Not Incl.: Not included
Lin: Linear modelling (i.e. constant efficiency)
NonLin(E): Non-linear modelling , empirical
NonLin(M): Non-linear modelling , mechanistic

the measurements from ship operations, while the models used in Papers III to VI are **predictive**, as they are used to estimate the behaviour of the system given a set of operational conditions.

Furthermore, all models in this thesis are **steady-state**, and it was assumed that dynamic effects do not significantly affect the results of this work. All models are also **deterministic**, i.e. uncertainty in both model accuracy and inputs is not taken into account. Finally, the thesis makes use of a mixture of both **mechanistic** and **empirical** models, depending on the required accuracy, on the computational demands and on the available information on the system.

Table 4.1 summarises the main choices in terms of system boundaries and modelling detail for each of the parts of this thesis. The modelling choices and assumptions are then presented more in detail in the following sections, and in the respective papers.

4.2 Case studies

In this thesis the research questions were approached by looking at two case study vessels: a chemical tanker and a passenger vessel. These two vessels were selected mainly based on the availability of measured data and of technical documentation. In the case of Ship-2, the additional complexity of a system with high requirement of both mechanical, electric and thermal energy constituted a rationale for the choice of the vessel as case study.

4.2.1 Ship-1 (M/T Tambourin): A chemical/product tanker

The first case study (from now on referred to as Ship-1) is a handy-max tanker used for the transportation of different types of liquid bulk cargo, such as oil products (kerosene, gasoline, etc.), molasses, vegetable oils, etc. The ship is 183 m long and 32.2 m wide, with a maximum draft of 12.7 m, for a total cargo capacity of 53000 m^3.

The power plant of Ship-1 consists of two four-stroke main engines connected to a common gearbox (GB), which provides power to both the propeller and a shaft generator (S/G). Auxiliary power is also provided by two auxiliary engines, while heat demand is fulfilled by two exhaust boilers recovering energy from the exhaust gas of the main engines, and two auxiliary, oil fired boilers (see Table 4.2 and Figure 4.2)

For both electric power and heat, most auxiliary consumers are the same that can typically be found on most merchant ships. Special systems 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 flammable liquids are transported. Nitrogen compressors have a high power demand (4 compressors rated 285 kW each) 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 (11 pumps for a total rated power of 1310 kW).

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 a large amount of heat for a short time.

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.

4.2.2 Ship-2 (M/S Birka Stockholm): A passenger ship

The second case study ship (Ship-2) is a passenger vessel that operates daily tours in the Baltic Sea between Stockholm and Mariehamn on the Åland islands. The ship is 176.9 m long and 28.6 m wide and can accommodate up to 1800 passengers and entertain them with restaurants, night clubs and bars, as well as saunas and pools. Worth of mention, Ship-2 was built to fulfil the Det Norske Veritas' "Clean Design" rule relating to environmentally friendly design solutions (DNV, 2004).

According to its daily schedule, the ship leaves at around 6 PM from Stockholm and sails at reduced speed in the Stockholm archipelago until it reaches the open sea,

Table 4.2: Main components number and sizes of the two case studies

Ship 1			Ship 2		
Component	N	Size [kW]	Component	N	Size [kW]
Main engine	2	3840	Main engine	4	5850
Auxiliary engine	2	682	Auxiliary engine	4	2760
Shaft generator	1	3200	HRSG (ME)	2	1500
HRSG	2	390	HRSG (AE)	4	700
Auxiliary boiler	2	7600	Auxiliary boiler	2	4700

where it stops for the night; early in the morning, the ship starts sailing again and arrives in Mariehamn at around 7 AM. The ship then leaves Mariehamn at around 9 AM and arrives back to Stockholm at around 4 PM (see Figure 4.3).

The propulsion system consists of two propulsion lines composed of two main engines, a gearbox, and a propeller each (see Table 4.2 and Fig. 4.4). The MEs are four Wärtsilä 4-stroke Diesel engines rated 5850 kW each.

On board electrical power demand is fulfilled by the four Wärtsilä AEs, rated 2760 kW each. Electrical power is needed on board for a number of alternative functions, from pumps in the engine room to lights, restaurants, ventilation and entertainment for the passengers.

All AEs and one ME for each propulsion line (i.e. six engines in total) are equipped with HRSGs, which allow covering a large part of on board thermal power demand; in addition, the HT cooling systems of all engines are connected to a heat recovery system based on pressurised water which allows using the waste heat for the pre- and re-heater in the air treatment unit of the HVAC system and for water heating; finally, when thermal power demand is higher than the recoverable waste heat, two auxiliary boilers are used.

All engines are equipped with SCRs for NO_X emissions abatement. Although the Baltic Sea is only subject to TierII limits on NO_X emissions, the ship enjoys up to a 10% reduced harbour fees in Stockholm if these emissions are reduced below a certain level.

4.3 Data collection

4.3.1 Data sources

In this work, data collected from on board measurements and from available technical documentation were used for the analysis. The work included the collection of already existing datasets and other types of useful information, and did not involve additional measurements performed in situ. This part of the study therefore falls under the category of *observational studies*, i.e. *conducted on existing data that typically had been*

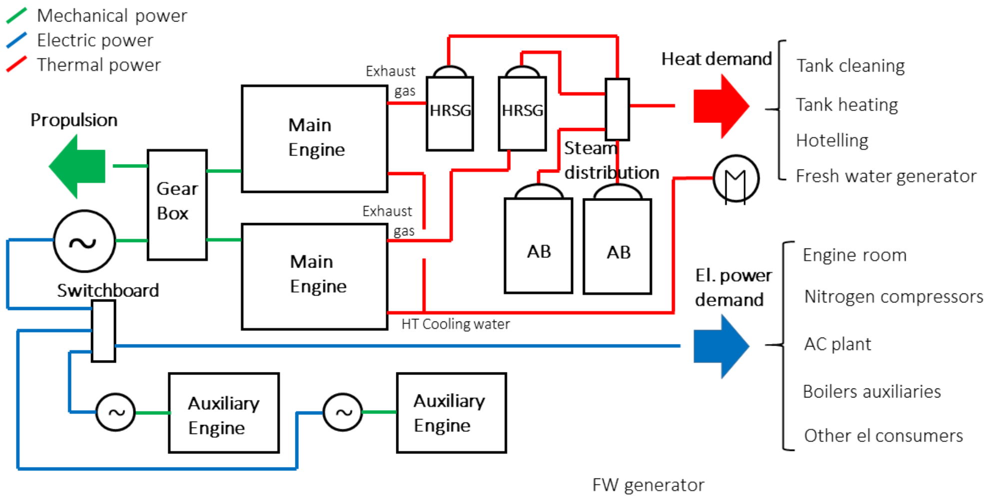


Figure 4.2: Conceptual representation of energy systems and flows of Ship-1

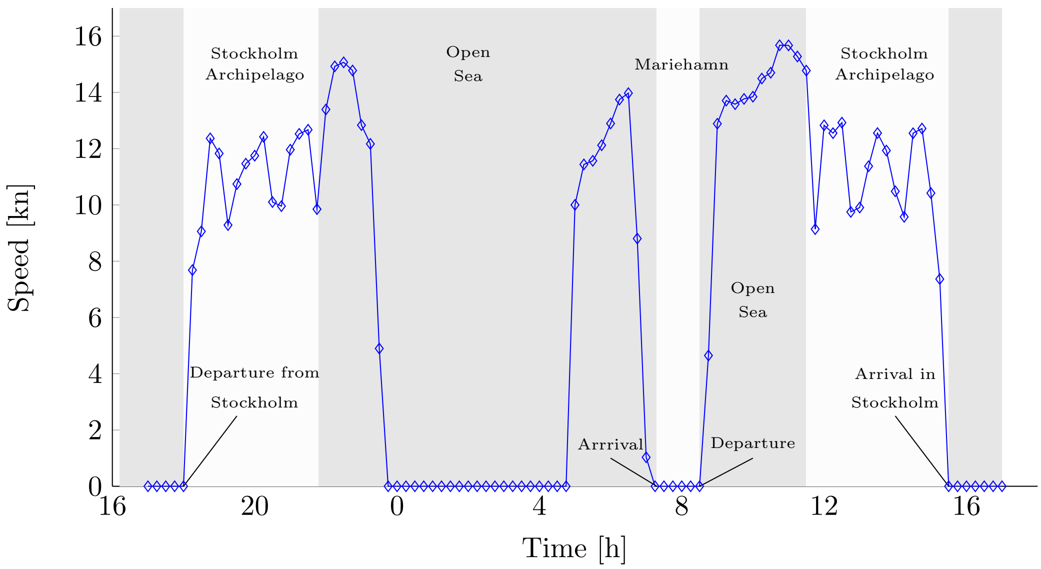


Figure 4.3: Typical operational profile of Ship-2

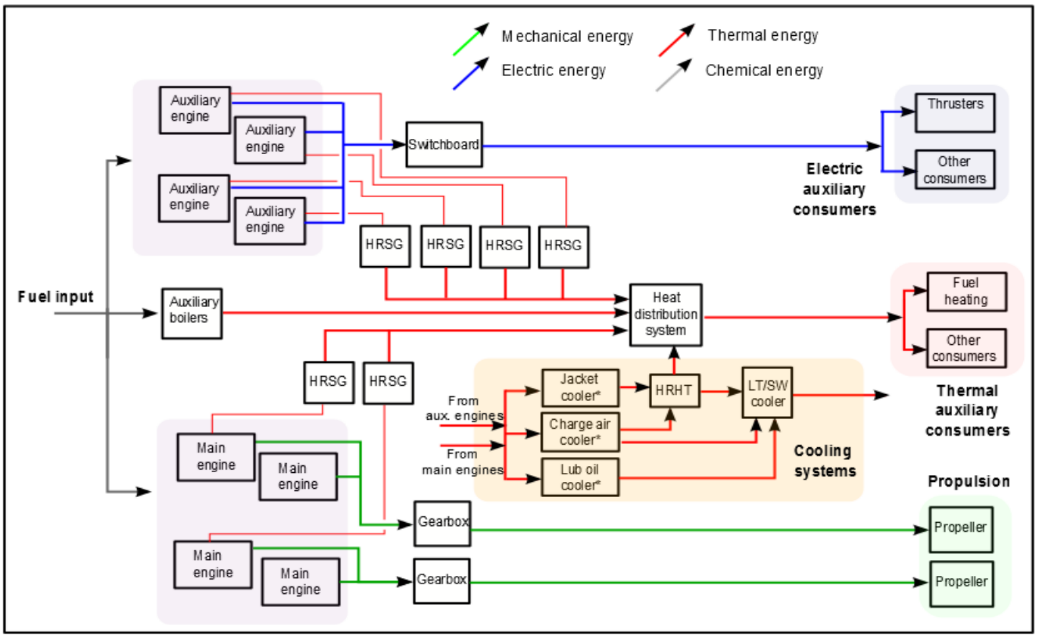


Figure 4.4: Conceptual representation of energy systems and flows of Ship-2

obtained for purposes other than to conduct (statistical) data analysis (Doganaksoy & Hahn, 2012).

Hereafter the available documentation for the two case studies analysed in this work is summarised.

Data logging system

Both Ship-1 and Ship-2 are equipped with a data logging system (DLS) which logs on board measurements on a dedicated server. In both cases, data were gathered for 1 year of ship operations. A list of the variables available from the DLS of Ship-1 and Ship-2 is presented in Table 4.3

Other sources

Not all variables of interest for this work were available from the data logging system on board. Quite extensive technical documentation was made available by the partner companies, and was used to gather additional information related to the ship systems performance.

These data relate to the nominal performance of the system and of some of its sub-systems and do not provide operational information. This documentation was therefore used for modelling the system, both in the phase of data processing and in the evaluation of possible improvements to existing systems.

Table 4.3: Summary of the available measurements from the data logging systems for the two case studies

Ship 1
Ship general
Speed over ground
Speed through water
Draft (fore, aft, starboard, port)
GPS heading
Power plant
Propeller torque
Propeller speed
ME fuel consumption
AE power
AE fuel consumption
SG power
Environment
Wind speed
Wind direction
Sea water temperature

Ship 2
Ship general
Speed over ground
Main engines
Fuel rack position
Exhaust gas temperature (before EGB)
Exhaust gas temperature (after EGB)
Charge air temperature
Charge air pressure
Auxiliary engines
Fuel rack position
Exhaust gas temperature (before EGB)
Exhaust gas temperature (after EGB)
Charge air temperature
Charge air pressure

Hereafter a short description of the different documents used in this work is provided, while Table 4.4 summarises what documents were available for the two case studies

Engines project guides contain information directly provided by the engine manufacturer and publicly available online. The 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.

Engine shop tests contain experimental data provided by test performed by a classification society and measured under well-defined conditions. Information on engine performance for different loads, 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 to verify that the actual vessel performance conforms to the requirements set by the customer. These documents provide propulsion and auxiliary power demand in conditions of clean hull, calm seas for different ship speeds and are therefore often used for benchmarking.

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 the propeller pitch, speed and power and for different ship speeds.

Combinator diagrams map the characteristics of the control system installed on board for engine-propeller interaction. The combinator diagram is used when the ship is run at variable propeller speed, 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 based on which the power plant was designed.

Ship heat balance is supplied by the shipyard and provides details on the different parameters used in the calculations for the design of the boilers and steam distribution systems, such as heat exchange areas and heat transfer coefficients.

Noon reports and their aggregates are manual measurements 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.*, 2015), they constitute an additional source of information and are used in this thesis when none of the previously mentioned sources could provide the required information.

Table 4.4: Summary of the technical documentation available for the two case studies. Documents marked with ✓ are available, those with × are not.

Document	Ship-1	Ship-2
Engine project guide	ME,AE	ME,AE
Engine shop test	ME	ME,AE
Ship sea trials	✓	×
Propeller curves	✓	×
Combinator diagram	✓	×
Electric balance	✓	✓
Heat balance	✓	×
Noon reports	✓	✓

4.3.2 Considerations about data quality

The quality of the data retrieved from the DLS is high in terms of sampling frequency, but low in terms of measurement accuracy. As measured values come from on board sensors, this does not allow an appropriate control of measurement accuracy and reliability. This is a situation that often occurs in observational studies and that is generally connected to limitations in data quality (Hahn & Doganaksoy, 2008).

The original data frequency measured by the monitoring system is of 1 point every 15 seconds on both Ship-1 and Ship-2. However, in both cases the amount of data points to be handled would become too large if the original sampling frequency was used for one year of ship operations.

For this reason, an averaging of the data was performed. In the case of Ship-1 the averaging was automatically performed by the energy management system provider, while in the case of Ship-2 the averaging was performed by the data logging system on board. In both cases, although it is most likely that the output of the averaging was generated using an arithmetic mean, it was not possible to get access to the computation algorithm.

Neither in the case of Ship-1 nor in that of Ship-2 it has been possible to perform an appropriate test and calibration of the sampling probes. However, general considerations concerning the accuracy of the meters installed on board are hereafter reported:

Ship speed (LOG) : The speed of the ship through the water (LOG speed) is generally measured using a small impeller or paddle wheel attached to the bottom of the hull. This type of measurement device is known to be often unreliable as a consequence of the fact that the flow through the measurement device can be disturbed by the interaction with the hull or by other environmental conditions (Insel, 2008).

Ship speed (GPS) : The speed of the ship compared to a fix reference (speed over ground, or GPS speed) is measured by on board GPS sensors. GPS speed measurements are rather reliable; however, the GPS speed does not account for the influence of currents, which can be as strong as 2-3 knots depending on time and location, and is therefore of lower interest compared to the LOG speed.

Fuel consumption : In the case of Ship-1, fuel consumption is measured using a mass flow meter based on the Coriolis effect. This type of meter allows reducing measurement uncertainty when compared to volumetric flow meters (more commonly installed on board ships), as the latter are sensitive to errors in the calculation of fuel density.

Fuel energy content (LHV) : Measurements of fuel lower heating value (LHV) are rarely available, thereby introducing an additional element of uncertainty in the analysis. Fuel LHV is mostly influenced by its sulphur content, water content, and carbon/hydrogen ratio for variations that could reach up to $\pm 5\%$. In this thesis, a constant value of 40.4 MJ/kg is used, following the fact that no measurement of fuel LHV was available (Bengtsson *et al.*).

Propeller torque : is calculated based on optical measurements of the shaft's elastic deformation. The estimated accuracy is $\pm 1\%$ based on information provided by the shipyard.

Propeller speed : Propeller speed is measured optically on the propeller shaft, with an accuracy estimated to $\pm 0.1\%$ based on information provided by the shipyard.

Electric power : The electric power demand is calculated starting from the power delivered by the electric generators (shaft generators, auxiliary generators) based on measurements of electric current and voltage. Although detailed information was not available for the specific instruments installed on both ships, electrical measurements are generally accurate and reliable (Blackburn, 2001).

Flow temperatures : Temperature measurements available from data logging systems are measured with thermocouples, which are widely used industrially due to their reasonable accuracy and reliability and low cost (Kutz, 2013). Nominal accuracy ranges from $\pm 1K$ for T type thermocouples, normally used for temperatures up to 540 K, and $\pm 2.2K$ for K type thermocouples, for up to 1530 K. In practical applications, however, the accuracy is generally lower due to decalibration over time and to perturbations in the electric signal (Kutz, 2013).

4.3.3 Data cleaning

Data cleaning refers to the process of detecting and correcting (or excluding from the analysis) corrupt or inaccurate values from a dataset (Doganaksoy & Hahn, 2012).

The detection of faulty measurements is a particularly challenging task:

> *While it may be obvious that a value is missing from a record, it is often less obvious that a value is in error. The presence of errors can (sometimes) be proven, but the absence of errors cannot. There is no guarantee that a data set that looks perfect will not contain mistakes. Some of these mistakes may be intrinsically undetectable: they might be values that are well within the range of the data and could easily have occurred. Moreover, since errors can occur in an unlimited number of ways, there is no end to the list of possible tests for detecting errors. (de Veaux & Hand, 2005)*

In this work an automatic, rule-based data cleaning process was applied to the original dataset. This process led to the elimination of specific data points which did not pass checks of consistency and of belonging to a specific range.

In the case of Ship-1, the following selection rules were used:

Total fuel consumption Data points for $\dot{m}_{fuel} > 1500kg/h$, which would correspond to fuel flow above the maximum permitted value, were excluded.

Main engines power Data points for $P_{prop} + P_{S/G} > 8000$, which would correspond to $P_{ME} > MCR_{ME}$, were excluded.

Main engines efficiency The main engines' break specific fuel consumption (BSFC) was calculated based on measurements of the engine power and of the fuel consumption: $BSFC_{ME} = \frac{\dot{m}_{ME}\left[\frac{kg}{h}\right]}{10^3 P_{ME}[kW]}$. According to the engine project guide, the engine maximum efficiency in ISO conditions is estimated at $178\frac{g}{kWh}$. Consequently, all points for which $BSFC_{ME} < 178\frac{g}{kWh}$ were considered invalid. For these values, the error was assumed to originate from faulty measurements of the fuel consumption, which is more fault-prone than propeller or S/G power. These values were hence corrected by providing a new calculated value for the engine $BSFC = P_2(\lambda_{ME})$, where $P_2(\lambda_{ME})$ is a 2^{nd} degree based on a polynomial regression based on the entire dataset.

In the case of Ship-2, the following selection rules were used:

Seawater temperature For some of the points in the dataset, the measurement of the seawater temperature was missing. In this cases the measured air temperature was used as a reasonable estimation of seawater temperature.

Auxiliary engines, exhaust gas temperature All values for which $T_{eg,turbine,in} < 0K$ and/or $T_{eg,turbine,out} < 0K$ were substituted by $T_{eg,turbine,in} = 650K$ and/or $T_{eg,turbine,out} = 550K$ respectively. This allowed not to eliminate these data points, while maintaining a conservative approach to the estimation of the waste energy flows.

Auxiliary engines on/off For data points with $\lambda_{AE} < 0.05$ the auxiliary engines were assumed not to be running, and therefore all inputs and outputs were set to 0.

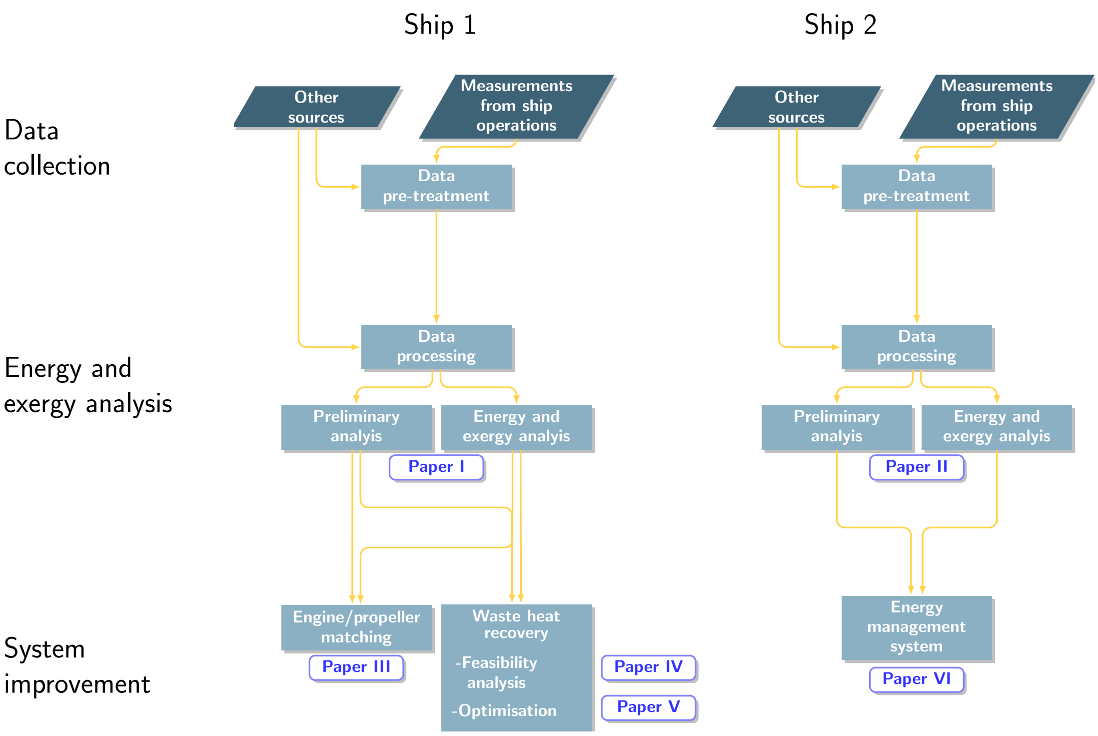


Figure 4.5: Overview of the methodology (2)

4.4 Summary of the approach of the appended papers

In Section 4.1 the general approach of energy systems engineering that was applied in this thesis was presented. This section introduces how the different papers presented in this thesis relate to the central theme of this thesis (see also Figures 4.1 and 4.5).

Each of the papers is presented by describing its main aim and the methods specifically employed. In addition, the novel element of each paper compared to the existing literature is highlighted, together with how the paper contributes to the main subject of the thesis.

4.4.1 Data processing for energy and exergy analysis (Paper I and II)

Aim : To investigate the energy flows of the case study ships (Ship-1 and Ship-2) over one year of operation and, hence, to improve the understanding of these systems.

Method : The energy and exergy flows for each time step of the datasets are calculated by elaborating available measurements. This elaboration is performed using models based on a combination of white- and black-box approaches.

Novelty : Existing literature aiming at the estimation of ship energy flows mostly focuses on energy flows (Thomas *et al.*, 2010; Basurko *et al.*, 2013). Only Marty (2014) included exergy in the analysis. Paper I and II constitute additional case studies for the application of energy and exergy analysis to ship energy systems and, therefore, towards an improved understanding of these systems.

Red thread : From a systems engineering perspective, the use of energy and exergy analysis for analysing the behaviour of a system based on operational measurements represents the systems analysis phase, in which the existing system is investigated to identify possibilities for improvement.

4.4.2 Propeller/engine matching (Paper III)

Ship-1 can operate in two alternative operational modes:

Fixed speed : The engine and propeller are operated at fixed speed. The auxiliary power is fulfilled by the shaft generator.

Combinator mode : The propeller speed is left free to vary adapting to the best conditions for propeller efficiency. The auxiliary power demand is fulfilled by the auxiliary engines.

In the first case, auxiliary power is generated at a higher efficiency, since the main engines are more efficient than the auxiliary engines. In addition, the main engines are operated at higher load and therefore, in principle, more efficiently. However, in the second case the propeller can operate at variable speed and closer to its optimal point.

Aim : To investigate the trade-off between these two opposites contributions and to compare the two modes of operations based on the expected difference in fuel consumption.

Method : The propulsion system is modelled and simulated for a range of ship speeds (10 to 15 kn). The engine was modelled using a combined 0D-MVEM model which enabled to make predictions of the influence of the speed of the engine on its energy efficiency, while the propeller was modelled based on the Wageningen B-series polynomials.

Novelty : Although many authors before have modelled the entirety of the propulsion system (Benvenuto & Figari, 2011; Theotokatos & Livanos, 2013), there is no documented effort of explicitly analysing the consequences of the interaction between the engine and the propeller when comparing operations at fixed speed versus in combinator mode. Furthermore, the requirements of the problem led to the development of an innovative combined 0D-MVEM engine model suitable for use in ship energy system models.

Red thread : The work presented in Paper III is intended to show how the identification of optimal ship operations in different sailing conditions can be improved when interactions within the system are studied more in detail.

Table 4.5: Details of the conditions in the WHR cases investigated in Paper IV

Case	Waste heat source	Final use
A1	Exhaust gas	Electric power
A2	Exhaust gas	Electric and propulsion power
B1	Exhaust gas and HT cooling	Electric power
B1	Exhaust gas and HT cooling	Electric and propulsion power
C1	All primary waste heat sources	Electric power
C2	All primary waste heat sources	Electric and propulsion power

4.4.3 Waste heat recovery systems (Paper IV and V)

The potential for waste heat recovery for Ship-1 was evaluated in two different studies: Paper IV and Paper V.

WHR feasibility analysus

Aim : To present and test a method for evaluating the potential for WHR on board of a ship starting from measurements of ship operations without designing the recovery system. The method is tested on Ship-1.

Method : The potential of the installation of a WHR system is calculated starting from the exergy flows of Paper I. The energy generated by the WHR system is presented as a function of the the WHR's exergy efficiency, which is treated as an independent variable. According to this approach, the exergy efficiency of a system is used as an indicator of the technological level of the system (e.g. the quality of its components, the complexity of the thermodynamic cycle, the size of the heat exchangers). The evaluation was performed for different scenarios, depending on the final use of the recovered energy and on the waste energy sources used for recovery (see Table 4.5).

Novelty : Differently from other literature on the subject, the paper puts its focus on the estimation of the feasibility of the WHR system rather than on the optimal design of the system itself.

Red thread : The work presented in Paper IV is intended to show the importance of accounting for how the ship is operated in the systems engineering process, and in particular in the process of designing a WHR system.

Modelling and optimisation of an ORC system

Aim : To propose and optimise the design of a WHR system for Ship-1 based on the knowledge of its operational profile.

Method : A WHR system based on a Rankine cycle was modelled on a component-by-component basis (see Figure 4.6)[1]. The design and operational parameters of a WHR system have to be defined in the design phase, requiring an optimisation process. In this paper four different optimisation procedures (see Table 4.6) are compared based on:

- The extent to which part-load operations were accounted in the definition of the objective function. In the "simplest" optimisation procedure the system was optimised only based on its performance at design load. In the "most advanced" procedure, the objective function was calculated as a weighted average of the performance of the WHR system at different engine loads, where the weights were assigned based on how often the ship was found to operate at that specific load.
- The parameters included in the optimisation. In the simplest case, only typical cycle parameters (design pressure, fluid) were included. In the most advanced case, also the switching load between one- and two-engines operations and the maximum operational range for the WHR system were included as optimisation parameters.

The engine outputs (efficiency and energy flow in the exhaust gas) were modelled using polynomial interpolations as functions of engine load based on the model presented in Paper III. In addition, it was assumed that the entire waste heat available in the main engines' exhaust gas could be used for conversion to electric power. This implies that the on board heat demand was assumed to be fulfilled using the energy in the cooling water.

Novelty : Differently from other literature on the subject, design parameters of the WHR system are optimised based on the ship's operational profile rather than on one operating point. Furthermore, some engine operational parameters are also allowed to be part of the optimisation process instead of only focusing on the WHR system.

Red thread : The work presented in Paper V is intended to show the benefits that can be achieved, when designing ship energy systems (a WHR system in this specific case), by optimising the system based on its operational profile and by broadening the boundaries of the system of interest (in this case, from the WHR system alone to including the main engines).

4.4.4 Ship power plant operational optimisation (Paper VI)

Aim : To propose an on board energy management system capable of allocating the energy demand to different prime movers (namely: main engines, auxiliary engines, and boilers) while minimising the fuel consumption.

[1]It should be noted that the paper stems from a collaboration with Ulrik Larsen, who provided the most significant contribution to the modelling of the Rankine cycle.

Table 4.6: Details of the WHR optimisation procedures investigated in Paper V

Case	Description
DP	WHR system optimised at the propulsion system's design point
DP$_+$	As in DP, but the system is also evaluated at 50% of the propulsion system's design point. If the system cannot work in these conditions, the design is discarded
OP	The WHR system is optimised on the measured operational profile of the ship
OP$_+$	As in OP, but some engine operational parameters are also included in the optimisation procedure

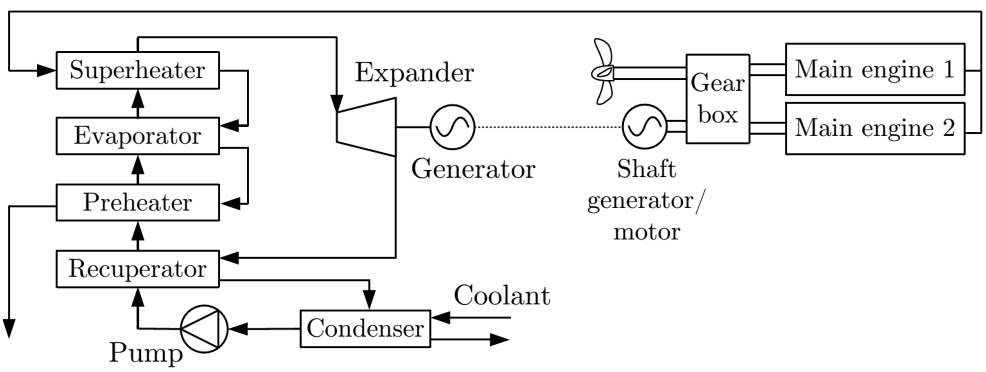


Figure 4.6: Layout of the waste heat recovery systems proposed for Ship-1

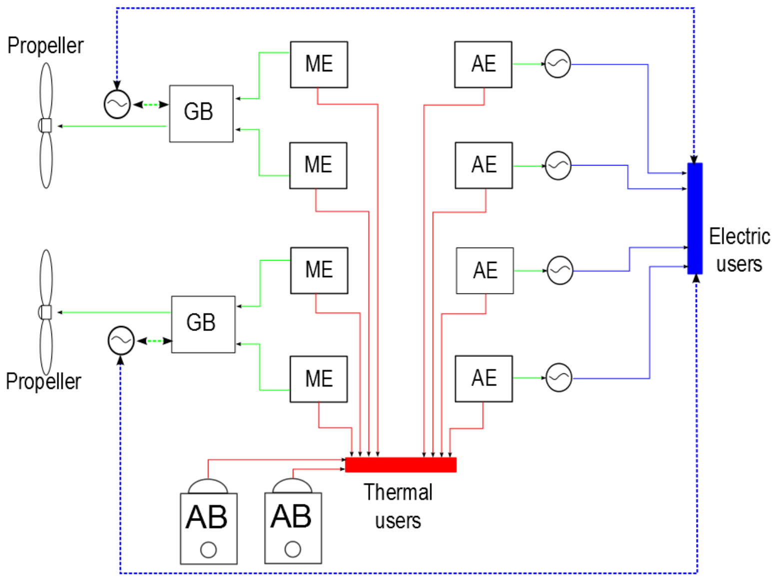


Figure 4.7: Layout of hybrid propulsion system proposed for Ship-2. The dashed connections represent the additions compared to the existing system

Method : The proposed energy management system is applied to both the existing power plant installed on Ship-2, and as means to evaluate the potential for a proposed hybrid propulsion system which includes the installation of a shaft motor/generator on each of the propulsion lines (see Figure 4.7). The main engines are modelled using a combination of white- and black box modelling approaches, while all other components on board are modelled using empirical correlations. The optimisation of the load-allocation is performed by stating the problem as a mixed integer and nonlinear programming (MINLP) problem, which is solved using a SQP algorithm (for the NLP part) and a brach-and-bound method (for the integer part).

Novelty : Compared to existing literature on the subject (e.g. Solem *et al.* (2015)), the proposed method also includes the fulfilment of heat demand (and, therefore, fuel consumption from the boilers).

Red thread : The work presented in Paper V is intended to show the benefits of system modelling and optimisation in the evaluation of ship power plants where the load allocation problem is not trivial. Furthermore, the work shows how considering additional interactions within the system (i.e. heat demand and boilers) allows achieving further fuel savings.

Chapter 5

Results

Analysis and synthesis of ship energy systems

Chapter 5 presents the results for the application of the principles of energy systems engineering to the two case studies considered in this thesis, with a particular focus on underlining how the proposed approach represents an improvement compared to standard non-systemic practices. Section 5.1 focuses on the analysis of the existing systems, laying the ground for the synthesis and evaluation of possible improvements presented in Sec. 5.2.

5.1 Energy system analysis: Improving the understanding of the system

The work presented in the first part of this thesis aims at improving the understanding of the ships selected as case studies from an energy perspective. The content of this section is a summary of what presented in Paper I and Paper II.

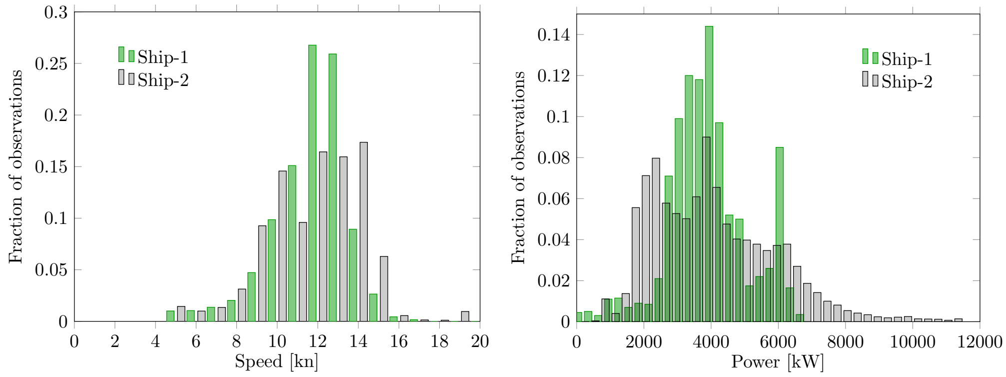
5.1.1 Energy analysis

Both Ship-1 and Ship-2 show large variations in their power demand, particularly for propulsion (Fig. 5.1) but also for heat and electric power (Fig. 5.2). This observation is particularly of interest as it highlights the importance of accounting for this variability in the design process, which will be further discussed in the following section.

In addition, the results suggest that, although propulsion demand appears predominant in both case studies, auxiliary heat and electric power demand also represent a significant share of the total energy demand (20% and 12% for Ship-1, 33% and 25% for Ship-2 respectively, see also Figure 5.4a and 5.4b).

This situation is related to two main observations:

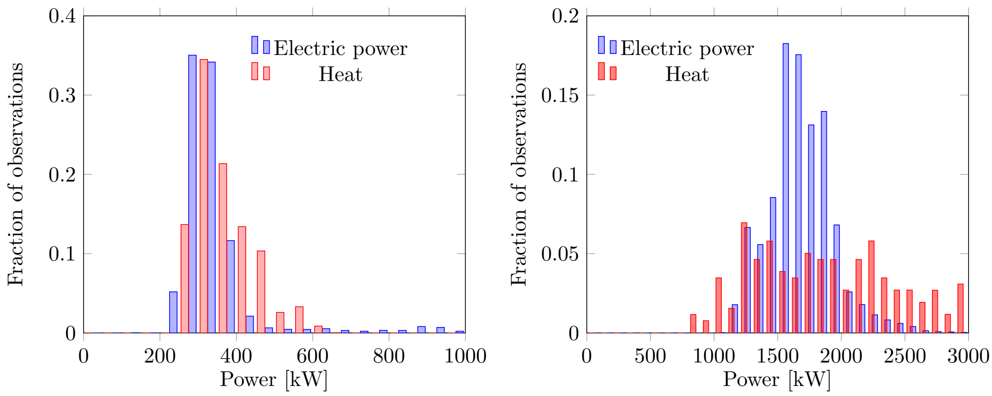
- Both ships spend a large amount of time in port (see Fig. 5.3), where there is no propulsive power demand.



(a) Speed

(b) Propulsion power

Figure 5.1: Case studies operational analysis: Speed and propulsion power distribution



(a) Ship-1

(b) Ship-2

Figure 5.2: Case studies operational analysis: Auxiliary power distribution

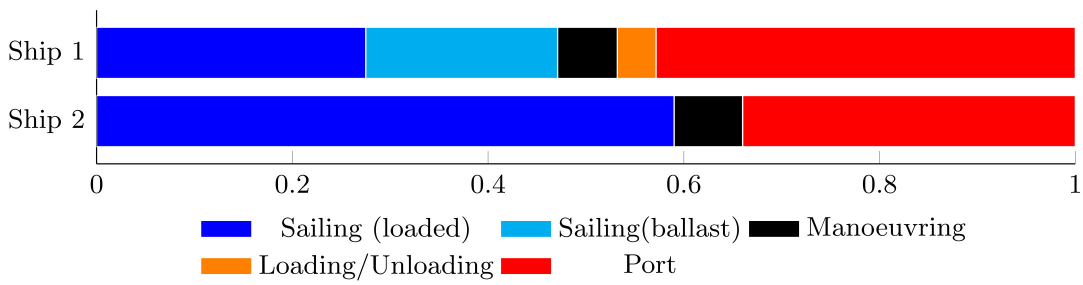


Figure 5.3: Operational share, time-based

- Both ships, for different reasons, generally operate far from the design speed of the vessel. When the ship operates at low speed, the power demand for propulsion is reduced, while auxiliary heat and electric demand tend to remain approximately constant.

An additional observation resulting from the energy analysis relates to the availability of waste heat. In both cases, in spite of the installed HRSGs, the exhaust gas contains a significant amount of energy that could be recovered for other purposes. Most of the heat demand on board is already satisfied without the need of the use of oil-fired boilers (64% and 63% for Ship-1 and Ship-2 respectively), whose fuel consumption represent only a minor part of the total (resp. 4.1% and 5.2%).

The fact that there is waste heat available and, at the same time, that the oil-fired boilers are necessary for satisfying heat demand can be explained by the large amount of time spent in port, when the main engines are not running. During sea voyages, the amount of waste heat available for recovery often exceeds the heat demand, and it could be used for generating electric power. In these regards, however, the different sources of waste heat from the engines have different potential, in relation to their different temperatures.

5.1.2 Exergy analysis

Exergy analysis, by taking into account both energy quantity and quality, allows a more realistic estimation of the potential for waste heat recovery.

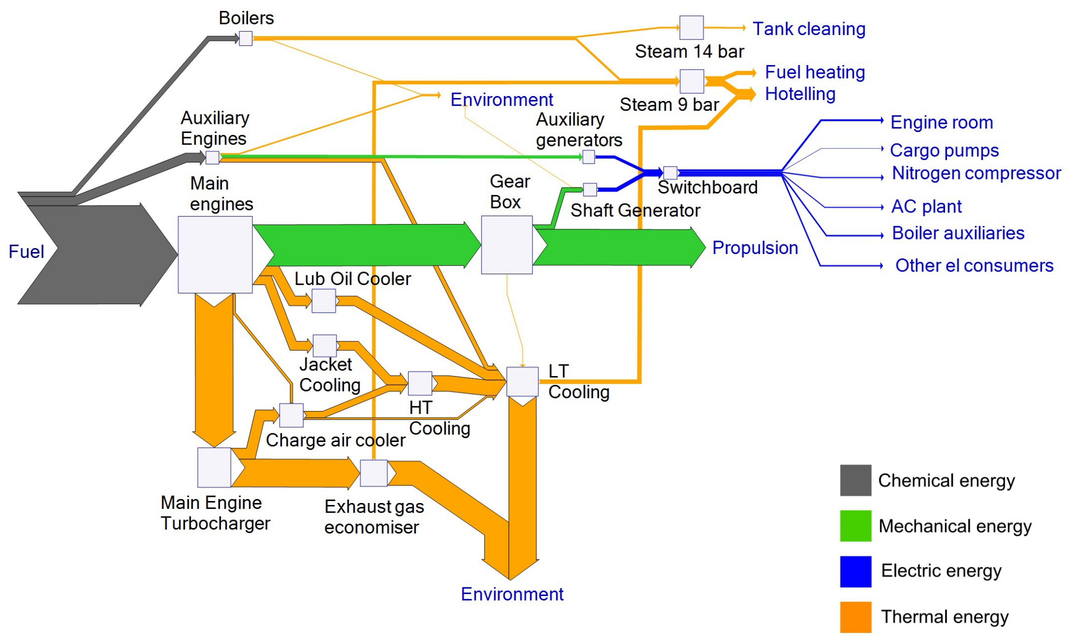
In the case of Ship-1, the exergy loss to the environment through the exhaust gas of the main engines (after the HRSG) equals to 14 TJ/year, to be compared to a total exergy output for propulsion of 68 TJ/year. In the case of Ship-2, the same flows accounted for 20 TJ/year and 75.2 TJ/year respectively, with 8.7 TJ/year more from the auxiliary engines.

This results in only 11% of the waste energy (or 10% of the waste exergy) being recovered on board in the case of Ship-1. These numbers are higher in the case of Ship-2 (23% and 25%), showing that the energy system of Ship-2 makes a more efficient use of the energy on board.

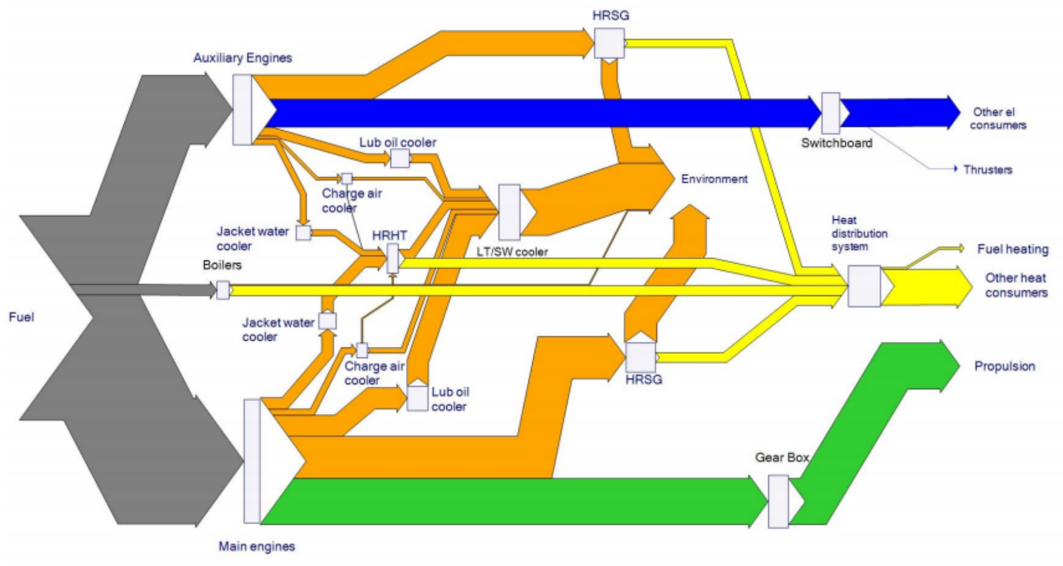
5.1.3 About on board measurements

The process of gathering and analysing data obtained from ship operations, and in particular the process of energy and exergy analysis, allows a reflection on the relative importance of different measurements. In particular, the fact that the two case study vessels did not have the same amount and type of measurements allowed the comparison of the two experiences:

Propulsion power can be obtained from measurements of speed and torque on the propeller shaft. Having accurate data related to this variable is of utmost importance for the estimation of propulsion power demand, engine efficiency, fouling effects on hull and propeller.



(a) Ship-1



(b) Ship-2

Figure 5.4: Sankey diagram for ship energy systems. Note that the scale is not the same for the two diagrams, so flow sizes can be compared within each diagram, but not between them

Electric power is normally measured at the output of the generators, providing a reliable estimation of the total electric power demand. However, component-by-component measurements would allow more detail in the analysis, and especially in sight of optimising the energy usage of individual consumers, such as pumps, HVAC compressors, and fans.

Thermal power is hardly measured at all. On Ship-2 it was possible to estimate part of the contribution based on measurements of the temperature of the exhaust gas before and after the HRSG. On Ship-1, instead, all information was based on the technical documentation provided by the shipyard. If thermal systems are to be included in the process of improvement of the system, more accurate information is required, both on the demands and on the waste heat flows from the engines. More specifically, these should include **temperature** and **flow measurements** on:

- Steam distribution network
- Air and exhaust gas flows to and from the engines.
- Cooling water systems (both HT and LT).

5.2 Synthesis: Proposing solutions for system improvement

The second, core part of an energy systems engineering approach consists in the synthesis and evaluation of possible solutions for improving the systems from an energy efficiency perspective.

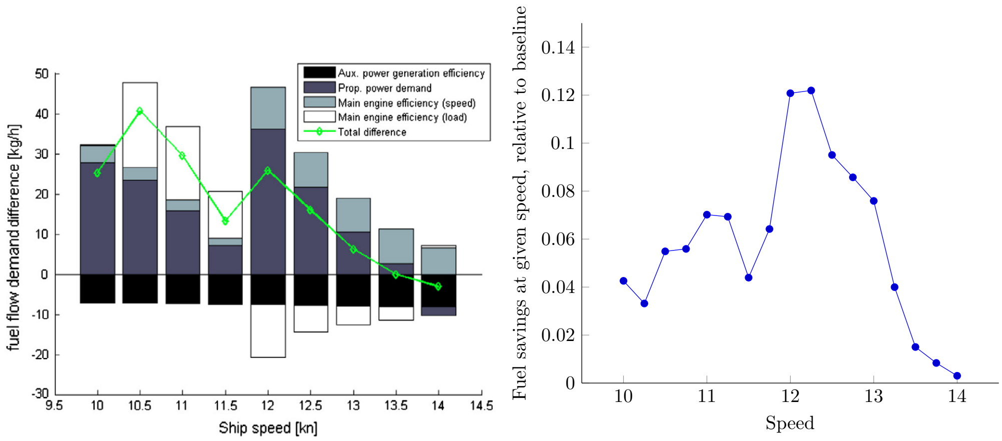
5.2.1 Potential for energy efficiency

Based on the results of the initial phase, different alternative solutions were proposed and evaluated for improving the performance of the studied systems from an energy perspective.

Engine-propeller interaction

In Paper III, two alternative operational modes for Ship-1 were compared, based on whether the propeller was operated at fixed or variable speed.

The results show that operating the propulsion system at variable propeller speed can lead to lower fuel consumption in the 10-13 kn range. The estimated improvements range from a minimum of $0kg/h$ at $13.5kn$ to a maximum of $41kg/h$ at $10.5kn$ (see Fig. 5.5a). As a consequence of the ship's operational profile, the fuel savings are concentrated in the range between 12-13 kn (see Fig. 5.5b and amount approximately to 1.9% of the yearly fuel consumption.



(a) Speed-based difference (b) Yearly operations

Figure 5.5: Engine-propeller interaction, comparison between fixed- and variable-speed operations.

The reduction of fuel consumption comes as a combination of different contributions, as shown in Figure 5.5a[1]. In particular, it can be noted that:

- When operating at variable speed, the positive effect on propeller efficiency largely overcomes the negative effect on the efficiency of the generation of auxiliary power.
- At low speed, the effect of the main engines' load is positive (i.e. it contributes to reduce fuel consumption, compared to the baseline case). At speeds above 12 kn, as soon as engine operations switch from one- to two-engines running, the effect of main engines' load becomes negative instead.
- Operating the engine at lower speed leads to a small, yet positive impact on the engine's efficiency

Waste heat recovery

As presented in Section 5.1, there is a significant amount of heat wasted from the existing systems, in both case studies. This thesis, focused on the evaluation of the possibility of taking advantage of this potential in the case of Ship-1[2].

The results of the initial feasibility analysis (see Fig. 5.6) confirmed the expectations on the existence of a potential for heat recovery on board, as recovering heat from the exhaust gas alone (A) can generate fuel savings between 4% and 7%. This choice would constitute the simplest and least costly retrofit, also in view of the fact that there would

[1]Note: positive values refer to higher fuel consumption in the fixed engine speed case

[2]For an evaluation of potential WHR systems for Ship 2, the reader can refer to Ahlgren *et al.* (2015).

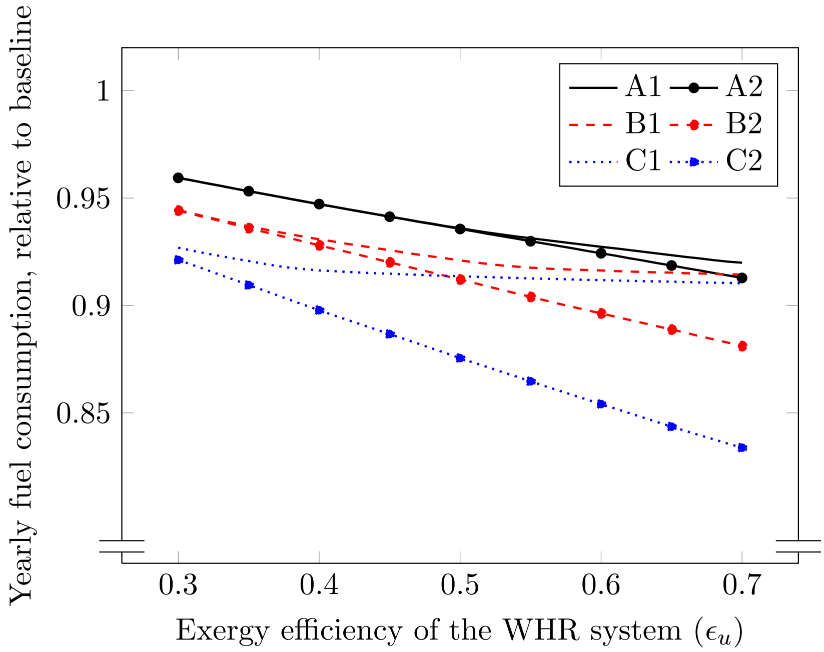


Figure 5.6: Calculated yearly fuel consumption with the installation of a WHR system on Ship-1, compared to baseline

be no sufficient extra power to be used for propulsion and, therefore, no need to install an electric motor on the propeller shaft.

Adding the HT cooling to the recovered sources (B) could improve the results; however, such improvement would be limited to approximately 1% unless i. the WHR system had a high performance ($\epsilon_u > 0.5$) and ii. the energy generated by the WHR system was also used for propulsion (B2).

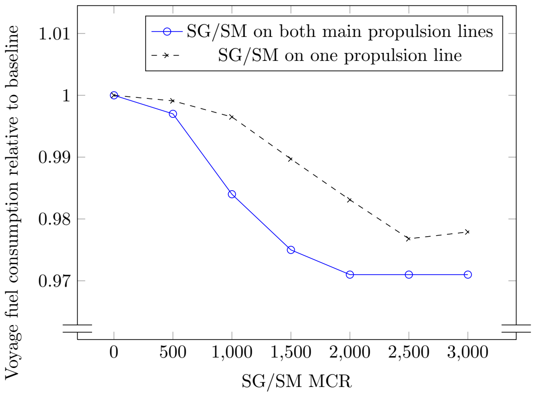
Finally, more for a matter of comparison than foreseeing a real installation, the potential of WHR when accounting for all waste heat sources on board (C) was calculated. In this case hypothetical savings could sum up to over 15%.

In Paper V, the possibility of installation of a WHR system, particularly based on a Rankine cycle, was studied in further detail, showing that yearly savings of up to 10.8% could be achieved based on the installation of an ORC-based WHR system on the engine exhaust gas line.

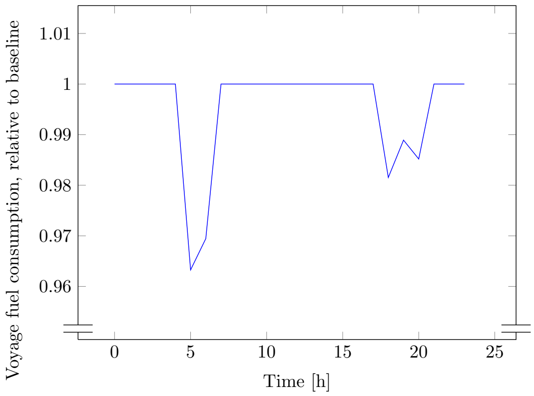
Hybrid propulsion systems

In Paper VI, the performance of the existing power plant of Ship-2 was compared to a power plant retrofitted for allowing more flexibility in the generation of both propulsion and electric power.

The results, as shown in Figure 5.7a, show that the hybrid propulsion system would allow fuel savings of up to 3% for the reference voyage. Lower savings, but with a lower



(a) Relative fuel consumption versus shaft generator/motor design power



(b) Relative fuel consumption, effect of including heat demand in the optimisation[1]

Figure 5.7: Ship-2: Estimated savings from the hybridisation of the propulsion system

capital cost, can be achieved if only one of the two shaft lines is equipped with a shaft motor/generator.

The savings achieved through the hybridisation of the propulsion system relate to the possibility of operating the engines closer to their design load and, hence, at a higher efficiency. On the other hand, the additional conversion steps through generators, motors and frequency converters imply higher transmission losses, thereby reducing the benefits in fuel consumption.

5.2.2 Operational profile

The main driver for the research presented in Paper III relates to the realisation that the ship operates most of the time far from its design conditions. As showed in Figure 5.5b the benefits from operating at variable propeller speed can only be observed at low ship speeds, with the break-point located at around 14 kn. As the ship was designed for operating at 15 kn, the choice of operating at constant propeller speed appears reasonable, if only design conditions are taken into account.

In the latest year, however, Ship-1 has been operating most of the time at speeds between 11 and 13 kn (see Figure 5.1a), which is where the variable speed drive provides the largest efficiency improvement. Including the yearly operational profile into the picture allows a more accurate estimation of the expected benefits, as shown in Figure 5.5b.

However, the clearest contribution to showing the importance of the operational profile presented in this thesis relates to the work included in Paper V, where an

[1]The figure shows the ratio between the fuel consumption when the thermal part of the energy demand and the fuel consumption are included in the optimisation procedure, over the reference case where only the fuel consumption of the Diesel engines is optimised.

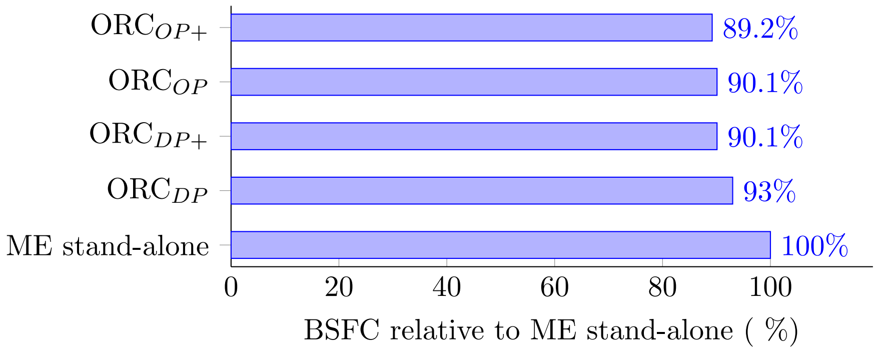


Figure 5.8: Comparison between alternative procedures for WHR systems optimisation: yearly fuel consumption compared to the baseline case

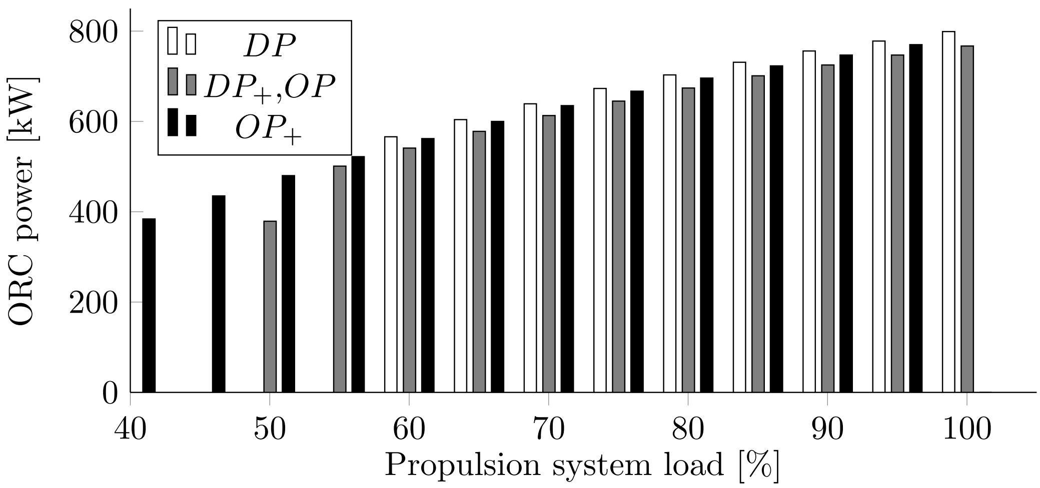


Figure 5.9: Comparison between alternative procedures for WHR systems optimisation: WHR power production at different loads

optimisation procedure based on the evaluation of the system's performance only at the design point was compared to one where the whole operational profile of the ship is accounted for.

Looking at the results of Paper V, it can be observed that the system optimised according to the DP procedure shows the largest fuel savings (10.4%) when evaluated at the design point of the propulsion system (i.e. both engines operated at 90% of their MCR). However, when the part-load performance of the system is included in the analysis and the performance of the DP design is evaluated against the full operational profile of Ship-1, the calculated fuel savings are reduced to 7.0% (see ORC$_{DP}$ in Figure 5.8).

When the whole operational profile is instead included in the optimisation (i.e. the WHR system performance is calculated, for each evaluation of the objective function, at different values of the load of the propulsion system), the results are different. The power produced by the cycle at design conditions is slightly lower (767 kW instead of 799 kW) but the yearly savings are increased to 9.9% of the yearly fuel consumption of the original propulsion system (see ORC_{OP} in Figure 5.8), mostly because the system can operate at lower load (see Fig. 5.9).

However, the results of the application of the optimisation procedure DP_+ suggest that it might not be needed to simulate the WHR design over the whole operational profile for the optimisation to converge to the optimal design. In fact, the DP_+ procedure reaches the same conclusion of the OP procedure, while only requiring two simulations: one at the design point of the system, and one at the minimum load at which the system is expected to be required to operate.

In Paper VI, similarly to Paper III, although the full operational profile is not included in the optimisation procedure, the subject under study stems in itself from the observation of a variable operational profile and from the fact that this requires an improved flexibility of the power plant.

5.2.3 Interactions

The results presented in this thesis suggest that the wider the system boundaries included in the modelling and in the evaluation, the larger the benefits to the systems engineering process. Expanding the boundaries of the system of interest directly implies including more components and, hence, a larger number of significant interactions into the analysis.

The work presented in Paper III is the most prominent example in this thesis of the importance of systems interaction. The results indicated that including the whole propulsion system in the analysis allows not only a more complete estimation of the advantages and disadvantages of the two options, but also an improved understanding of what are the effects that play a role in the overall behaviour of the system.

Although the work presented in Paper V focuses on the importance of the operational profile, it also includes aspects related to the interaction between the main engines and the WHR system. In particular, the OP_+ optimisation procedure also includes one engine operational parameter in the optimisation of the system.

Compared to an optimisation procedure based on the WHR system alone, the expected yearly savings increased from 9.9% to 10.8%. This improvement is mainly due to the fact that the WHR system can also operate at lower loads (40%-50%, see Fig. 5.9). This is achieved without requiring any additional capital expense compared to the "non-systemic" optimised system.

In Paper VI, the heat demand and boiler fuel consumption were included in the objective function of the optimisation, compared to the standard practice of optimising the operations of the system only based on propulsion and electric power demand. As shown in Figure 5.7b, depending on the instantaneous demand, this can lead to up to 4% fuel savings. In practice, this means that it can be sometimes more efficient to operate the engines at a load which does not maximise their mechanical efficiency, but that allows to recover more waste heat therefore operating the whole power plant more energy efficiently.

Chapter 6

Discussion

Chapter 6 elaborates on the results of the thesis in three different ways. First, the results are discussed as part of a broader perspective, and their contribution to the field is highlighted. Secondly, the methods and assumptions used in the thesis are discussed and put under scrutiny, based on the experience gained at the end of the work. These aspects are discussed separately for the two main parts of this thesis: systems analysis (Sec. 6.1) and synthesis (6.2). The results are also discussed in relation to the potential for energy efficiency of the technologies evaluated in this thesis (6.3), i.e engine-propeller interaction, waste heat recovery, and hybrid power plants. The chapter is concluded with a reflection on the generalisability of the results (6.4), i.e. on the extent to which the findings of this thesis can be considered to be representative of the shipping sector as a whole.

6.1 A systematic procedure for analysing ship on board energy systems

In this thesis, the use of energy and exergy analysis as systematic tools for improving the understanding of ship on board energy systems was proposed.

6.1.1 Significance and contribution to the field

Energy and exergy analysis are widely employed tools for land-based energy systems. In shipping, however, only three papers could be found in scientific literature that explicitly aim to analyse ship energy flows (Thomas *et al.*, 2010; Basurko *et al.*, 2013; Marty *et al.*, 2012). Compared to these publications, the work presented in this thesis presents a combination of different aspects:

Yearly operations : Most of the work related to the analysis or design of ship on board energy systems focuses either on a limited amount of operating points or voyages (e.g. Marty (2014)). The work presented in this thesis, similarly to what proposed by Thomas *et al.* (2010) and Basurko *et al.* (2013), bases the analysis on the ship operations over an extended period of time and therefore provides a more accurate picture of the importance of different energy demands.

Heat demand : Of the work available in the scientific literature, only Marty (2014) takes the heat demand into account. Although this contribution is often limited, the work presented in Paper I suggests that the heat demand can constitute a non-negligible contribution to the yearly energy demand also for cargo vessels.

Waste heat : Many authors who presented work on WHR systems included an evaluation of the available waste heat from the main engines' exhaust gas. Including waste heat from the charge air cooling is rare (Dimopoulos *et al.*, 2011)), while even fewer also include evaluations of other cooling-related waste heat flows (e.g. Marty (2014); Grimmelius *et al.* (2010)). The work presented in this thesis represents a new case of the estimation of the available waste heat in the cooling systems accounting for ship operations.

Exergy : The use of exergy analysis is substantially new in the field of ship on board energy systems. Dimopoulos *et al.* (2012) applied the concept of exergy as an aid in the process of optimising a marine WHR system, while Zhao & Zhaofeng (2010) analysed a combined marine power plant from an exergetic perspective. However, similarly to the point previously discussed, an estimation of the availability of waste heat from the ship on board energy system which included all sources of waste heat over the ship's operational profile had not been presented before.

Concerning its practical application, the proposed method has two main advantages:

First, it represents a **systematic and effective tool** for the analysis of ship on board energy systems and, consequently, for the process of determining how energy efficiency should be addressed on a vessel.

Secondly, the ensemble of actions required for successfully performing all the steps of the process (gathering of on board measurements, assessment of data quality, data processing) allows getting an **improved insight of the energy system of a vessel**. Consequently, even when the numerical results of the energy and exergy analysis do not provide clear suggestions for improvement, the designers will be able to propose solutions based on their improved knowledge of the ship's energy systems.

6.1.2 Validity: Methodological choices and assumptions

The data processing phase required for the energy and exergy analysis, given the absence of many relevant measurements, proved particularly challenging both in the case of Ship-1 and Ship-2. Hereafter, the most "sensitive" assumptions are summarised:

- On **Ship-1**, a number of assumptions were made in the attempt of **subdividing the electrical energy demand among different groups of consumers**. In the case of **Ship-2**, this was done only for the case of **bow thrusters** given the large amount of electrical consumers on board.

- On both **Ship-1** and **Ship-2**, the modelling of the main engines had to be substantially simplified, especially for what concerns **heat losses**[1]. This concern becomes even larger concerning some assumptions related to the **cooling water mass flows**, which needed to be estimated for calculating exergy flows but for which there was no information available aside of the pumps design flows.

- On **Ship-2** there were no measurements available for the amount of **heat recovered from the HT cooling systems**. This contribution had to be estimated based on assumptions[2]. The estimation of heat demand and its subdivision among different consumers was also challenging in the case of **Ship-1**.

These uncertainties could have been reduced by either improving the detail of the modelling (e.g. by modelling the details of the cooling systems in terms of pumps, valves and heat exchangers, as proposed by Marty (2014)) or by excluding the uncertain elements from the analysis.

In general, the approach used in this thesis was an attempt to achieve a good compromise between providing as much information as possible based on the available data without requiring a too extensive modelling effort. This choice related to the intention of proposing a method that could be used in conditions of limited time and resources.

6.2 The benefits of an energy systems engineering approach

In this thesis, the matter of increasing ship energy efficiency was addressed by employing an energy systems engineering approach, which involved a specific focus on interactions within the system and on the impact of the ship's operational profile on its performance.

6.2.1 Significance and contribution to the field

Modelling the interactions between different parts of the system of a ship has been done many times before in the field of marine engineering. This is particularly true for the interaction between engine and propeller, whose role is of utmost importance in the determination of the behaviour of the system during manoeuvres (see the work of Benvenuto & Figari (2011); Coraddu *et al.* (2014); Shi (2013)).

Similarly, accounting for the operational profile in the optimisation of ship energy systems is not uncommon in available literature in the field (see Motley *et al.* (2012) for the application to propeller design and Dimopoulos *et al.* (2011); Choi & Kim (2013) to WHR system design).

[1]When the engineers on board of Ship-2 looked at the result of our work, they were very puzzled by the amount of waste heat going to the lubricating oil cooling systems.

[2]See Paper II. These assumptions were strongly questioned by the reviewers.

The novelty of the work presented in this thesis lies in the combination of the two aspects, which can be observed in all of the papers presented in this thesis related to system synthesis (Paper III to Paper VI[1]).

The work proposed in this thesis aimed at providing evidence for the need of extending the boundaries of ship energy systems modelling, and of accounting with additional detail for how the energy system will be operated in the foreseeable future. Although none of the models presented in this work claimed to be holistic, it was showed that more accurate results and higher potential for energy savings were found every time the system boundaries were enlarged and ship operations were included with additional detail.

- Paper III showed the improvements related to both the engine and the propeller operating more efficiently at variable speed, which offsets the lower efficiency of the auxiliary engines. The yearly savings, estimated to a total of 1.9% of the yearly fuel consumption, are estimated based on the ship's real operational profile. Looking at the engine and the propeller separately would have led to an inaccurate estimation of the potential savings; similarly, looking at the ship's performance only at its design point would not have allowed to identify any saving at all.
- In Paper IV the aim was to provide tools for choosing whether to consider the installation of a WHR system or not and, in case, what yearly savings could be expected based on the expected efficiency of the WHR system, on the sources of waste heat recovered and on the final use of the generated power. The combination of these aspects, evaluated over the whole operational profile provides a simple, yet reliable tool for supporting decisions in relation to WHR systems in shipping. The challenge of the optimal design of the recovery system, which requires additional time, resources and competences, is postponed to after the evaluation of the convenience of the investment.
- In Paper V a WHR system was optimised for its application on Ship-1. Optimising the system for performance over the whole ship operational range **and** modelling the interaction between the operations of the engines and of the WHR system was estimated to allow yearly fuel savings of 10.8%. In the same study, the performance of a WHR system optimised only at its design point and with no modifications to the engine management strategy was tested. When this WHR system was evaluated over one year of ship operations, it allowed "only" 7.0% savings. These findings are in line with what previously proposed by Larsen *et al.* (2015), where it was pointed out that when a WHR system is added to a Diesel engine, the system's most efficient operating point does not coincide with the engine's most efficient load.

[1]In the case of Paper VI the analysis was performed on a "reference voyage" rather than on the whole measured operations. It should be noted, however, that the ship operates on a fixed route and, therefore, the variations of power demand are less sensitive compared to ships operating on the spot market.

- In Paper VI an on board energy management system for the optimal allocation of the load to the different parts of the power plant of Ship-2 based on a given demand was proposed. Although there are examples in literature of similar tools for optimal load-allocation (e.g. Zahedi *et al.* (2014); Kanellos *et al.* (2012)), none of these included heat demand as part of the modelling, nor was the the fuel consumption of the boilers included in the optimisation. As shown in Paper VI, this can lead to operating the system in sub-optimal conditions and to up to 4% higher fuel consumption, according to the investigated scenario.

From measurements to predictions, what will the operational profile look like in the future?

In this thesis, the systems were both optimised and/or tested on the measured operational profile in the previous year of ship operations. This implies the assumption that ship operations in the future will be equal, or at least similar, to what observed in the previous year of operation. However, the work presented by Banks *et al.* (2013) suggests that in correspondence with fast changes in fuel prices and freight rates ship speed distributions change remarkably over the years.

In the case of Ship-1, given the extension of the available database, it was possible to provide a comparative analysis of some operational years. Figure 6.1 shows how the operational speed of the ship evolved in the 2012-2014 period. It appears that any improvement based on the operational profile as measured in 2012 would have overestimated the amount of time spent at high speed, compared to what happened in 2013 and 2014.

More in general, the savings estimated in an optimisation study such as that presented in Paper V represent an ideal maximum based on a system that is tested on the same operational profile it was optimised for. If real operations after the installation of the optimised system changed compared to the dataset used for optimisation, fuel savings would most likely be lower.

As a consequence, the optimisation procedure applied in Paper V is most advised in those cases where the operational profile is little dependent on external conditions, such as market forces or environmental conditions. This is typically the case of e.g ferries and cruise ships. For other ship types, for which the operating speed is more fluctuating, the results of the application of the proposed method should be taken with additional care.

6.2.2 Validity: Methodological choices and assumptions

In spite of dealing with a systems approach, none of the work presented in the attached Papers included the modelling of the full system. In addition, not all components were modelled with the same level of detail.

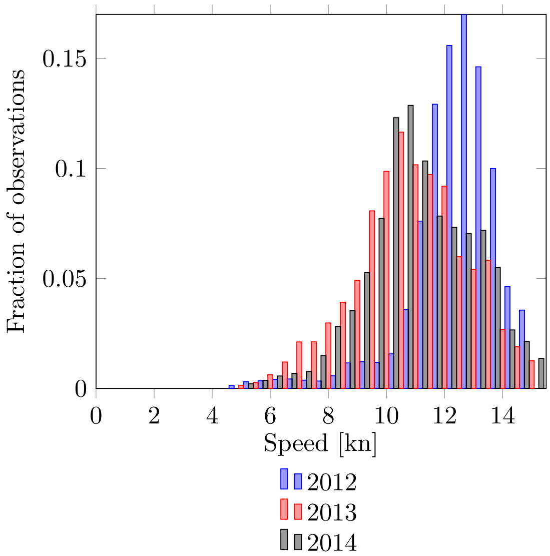


Figure 6.1: Comparison of the yearly operational profile of Ship-1 from 2012 to 2014

System boundaries

In this thesis, the power plant on board was selected as the main system of interest. This includes all the components on board that are responsible for the conversion of chemical energy (fuel) to energy in the form required for the use by other subsystems on board (mechanical energy for the propeller, electric energy for the auxiliary systems, and heat for accommodation and fuel heating).

This choice implied that many relevant subsystems were not included in the analysis. Based on the aforementioned principle that every extension in the system boundaries improves the quality of the assessment, excluding components limits the scope and reliability of the study.

The choice of excluding the propeller from the main system of interest in all but one of the studies (see Paper III) represents the most notable of the choices. As the work presented in Paper III showed, there is a significant interaction between the engine and the propeller, suggesting that future studies in connection to the ship power system should not overlook this contribution. In Paper V, for instance, the optimisation of the WHR system did not include the possibility of operating the propeller at variable speed, which would influence the engine operational point and, therefore, the quantity and quality of the heat available to the WHR system. Similarly, the energy management problem addressed in Paper VI would have been even more complex to solve, had the speed of each of the two propellers been added to the variables to be optimised.

In practice, from the perspective of the ship's hydrodynamics, the boundaries could have been extended even further by including the hull in the model through the estimation of ship resistance and of the effects of the interaction between hull and propeller. In Paper III, although the propeller was included in the model, it was decided to exclude the effects of the ship's added resistance in wind and waves, as well as the effects of biofouling on the hull. These aspects are known to have an influence not only on the power required for sailing at a given speed, but also on the matching between the engine and the propeller.

Similarly, with reference to auxiliary components on board, it was chosen not to model any of the parts of the system which contribute to the on board auxiliary energy demand (i.e. pumps, fuel heaters, HVAC systems, etc.). This choice was made based on the limited amount of information about the system and especially for the validation of the models. The addition of these components to the system model would have brought additional depth to the analysis and, most likely, allowed the identification of further potential for energy savings. Including the details of each of the components of the heat demand in Paper VI could have allowed, for instance, including the heat recovery from the LT systems, or proposing solutions for adapting the energy demand for optimal operations of the full system (demand-side management).

Extending the boundaries of the system comes, however, at a cost. The higher the amount of components, the more complex the model, and the higher the computational burden. But what makes the difference is the time required to the modeller for gathering sufficient information and data for achieving a satisfactory level of fidelity in the models. A compromise is required. In this thesis, it was decided to focus on the power plant on board, and to leave the task to broaden the boundaries of the system even further to future research.

Component modelling

Enlarging the boundaries of the system comes at the cost of additional computational effort. Assuming that the available computational power is constant and that the employed algorithms cannot be improved, the only choice is to decrease the computational requirement for each (or, at least, part of) the models that build up the full system.

The level of detail required on each model depends on the required amount of inputs and outputs that need to be handled. The case of the Diesel engine will be used in the following text as an illustrative example.

The Diesel engine is part of the on board energy system of both the ships included in this study, and was therefore modelled in all the four "synthesis" papers. In Paper III, the engine model had one, main requirement: it should be able to predict the influence of both the required torque and speed on the engine's energy efficiency.

As no measured data was available in connection to the influence of engine speed on its efficiency, a more detailed modelling effort was required. The engine speed influences the amount of air entering the cylinder, and therefore the combustion process. The model should therefore be able to capture these phenomena, which led to the choice of the hybrid 0D-MVEM.

The use of these models in energy systems modelling is, however, rare, and not always advised given the high computational time required for the model to converge. A common practice, which was in this thesis applied both in Paper III and Paper V, is that of using the output of the model to create a performance map to be used via interpolation in the energy system model.

As shown in Table 3.2, this approach is the most common in existing literature in ship energy system modelling. Exceptions to this principle can be identified in the work of Benvenuto & Figari (2011); Campora & Figari (2003); Schulten (2012); Theotokatos (2008). Their choice was, however, justified by the need of accurately simulating engine dynamics. In this thesis, and particularly in Paper III, the direct use of the 0D-MVEM was also proposed in order to evaluate the influence of the use of a variable geometry turbine (VGT) for the selected engine. In this case, given the intrinsic influence of the VGT on the engine operations, it was not possible to use a simplified version of the model.

Similar considerations could be added for the models used for, e.g., the electric machinery and the boilers. In this thesis, these components were modelled using as constant efficiencies, or as simple regressions as suggested in dedicated literature (McCarthy *et al.*, 1990). This approach was deemed sufficient for the scope of the thesis and it represents an improvement when compared to other studies (e.g. (Dedes *et al.*, 2012)). However, other researchers in the field have adopted more complex models, particularly for electric machines (e.g. Zahedi *et al.* (2014)).

6.3 Advanced marine power plants

Albeit the main focus of this thesis consists in the evaluation of the benefits of a methodological approach (energy systems engineering) to a specific area of engineering (marine engineering), the thesis included results concerning the applications of specific technologies, which should be seen as a contribution to the respective fields.

6.3.1 Propulsion systems versus power plants

After the beginning of the *slow-steaming era*, the attention on off-design performance of ship systems, and in particular of the propulsion system, has increased significantly. Therefore, for practitioners in the field, concluding that *at low speed it is better to operate at variable rather than fixed propeller speed* does not come as a surprise.

The main point of this part of the work lies in the more general consideration that the interaction between the engine and the propeller is of utmost importance for a proper and efficient functioning of the the propulsion system and they should therefore not be considered separately in the phase of ship design.

The choice of the engine, in particular, requires further attention. The engines installed on Ship-1 are efficient, both at design point and at low load. However, their operational envelope is narrow, posing very restrictive limits on reducing the engine speed, which is the typical case of heavily turbocharged Diesel engines. In retrospective, the choice of installing a less efficient, but more speed-flexible engine could have been a better choice with reference to the overall efficiency of the system.

Similarly, it was shown in this work (see Paper V), as well as in previous literature

(Larsen *et al.*, 2015), that the installation of a WHR system impacts many choices in relation to the remaining part of the propulsion system, and in particular of the engine. If a WHR system is used, it could be more efficient to install a less efficient engine with higher exhaust gas temperature.

6.3.2 Waste heat recovery systems

The results of Paper IV showed that, for the specific case of Ship-1, the focus should lie on the installation of a medium-performance system which only recovers energy from the engine exhaust gas. This solution would be the most cost effective, as it would allow minimizing installation costs while providing significant fuel savings (estimated to 4-7% on a yearly basis).

These results were confirmed once an ORC was optimised for this application, based on the ship's operational profile. As it was assumed that on board heat requirements could be fulfilled using heat from the cooling systems, the heat recovery potential was even higher, and a 10.8% improvement was calculated.

This also resulted in a low payback time for the system, which ranged from less than 2 to 5.5 years depending on the fuel price and on the assumptions made for the installation cost of the WHR system. This is in agreement with previous results presented in the scientific literature: Dimopoulos *et al.* (2011) and Theotokatos & Livanos (2013) calculated a payback time of around 8.1 and 2.4 years for a medium-sized containership and for a large bulk carrier, respectively.

These results suggest that, in theory, WHR systems should be very common in shipping. Given that merchant vessels normally have a long operative life, ranging from 10 years for tankers to more than 30 years for, e.g., ferries, a payback time of 6 years appears more than reasonable and leaves extensive possibilities for WHR to be a profitable choice.

As a matter of fact, however, the payback time allowed for such investments in the shipping business is normally 2 years, rarely going up to 5 (DNV, 2012). As a consequence, although research in WHR technology can still lead to improvements in system performance, it can be argued that the focus should shift to understanding how to allow for companies to broaden their time perspective for this type of investments[1].

6.4 Generalisability of the results

The work presented in this thesis is based on two case studies: a chemical tanker and a passenger vessel. Although the methods proposed in this work are applicable to any ship type, the question is whether the benefits obtained are specific of the two case studies, or could be expected to be observed on any other ship.

[1]Note that this reasoning does not only apply to WHR systems, but to energy-savings technologies in general.

6.4.1 Complex systems

Although employing a systems approach improves the understanding and the accuracy of the analysis for any type of system, it is generally the case that the higher the complexity of the system, the larger the benefits.

In this sense, the two case studies presented in this thesis can be used as reference for a rather broad set of ship types. Ship-2 is an example of a system characterised by a high system complexity, with a large number of elements in the power plant (four main engines, four auxiliary engines, two boilers) and an energy demand which varies in time over ship operations. In relation to the findings presented in Paper VI, for instance, it is likely that the effect of including the heat demand in the optimisation would not be as high had the energy system of a containership been taken into account instead. The operational pattern and the energy demand of Ship-1, on the other hand, are similar to those of many cargo vessels, such as tankers, bulk carriers and containerships.

6.4.2 Data availability and quality

Garbage in - garbage out. When modelling or analysing a system, the access to relevant information is of utmost importance. For the two case studies, thanks to the competence and professionalism of the two shipping companies involved[1], access to extensive datasets from on board measurements and technical documentation was available.

The models and methods employed in both the analysis and synthesis part of this thesis are flexible to different levels of information available. It is clear, however, that in the absence of on board measurements and of technical documentation related to the installed machinery on board, the work presented in this thesis would have been different[2].

6.4.3 Engine/propeller matching

That the optimisation of the interaction between engine and propeller is not an easy question is nothing new (Woodward, 1972). This is however particularly true for the case of vessels powered by controllable pitch propellers, where the additional degree of freedom given by the possibility to change the propeller pitch poses additional challenges to the optimal design and control.

Although FPPs are more common, there are today more than 18000 ships in the world powered by CPPs and four-stroke engines, as in the case proposed in Paper III. In particular, almost 3500 vessels have specifically an MaK engine of the same series (M32C) as the ones installed on Ship-1; the propulsion system of these vessels is

[1] And to the hard work of my colleague Fredrik Ahlgren from Linnaeus University, who went on board Ship-2 to download logged data from the on board alarm system, to whom go my warmest thanks

[2] During my PhD experience, I have had the chance to supervise two very smart Master Students, Alexander and Kari. Their work on hybrid propulsion system was made much harder by the fact that, in their case, on board measurements were scarce to say the least, and technical documentation of the machinery on board (engine, propeller) had been mysteriously lost on the way.

therefore expected to behave in a very similar way compared to the one presented in Paper III.

6.4.4 Waste heat recovery systems

The work proposed in Paper IV and V relates to the installation of a WHR system on board Ship-1. The results presented in this thesis suggest that there is a lot to gain from the installation of WHR systems on ships.

Although this conclusion is supported by an extensive literature on the subject, and by an increasing use of such system on board, it should be noted that the results presented in this thesis refer to the application of WHR to one specific case.

In particular, it should be noted that, as it is widely accepted, four-stroke engines have higher exhaust gas temperatures and, therefore, take more advantage from the installation of WHR systems when compared to two-stroke engines. As previously pointed out in literature this leads to WHR systems performing better in the former case (see for instance Theotokatos & Livanos (2013), who showed that the achievable efficiency increase in the case of two-stroke and four-stroke engines was in the range of 0.4%-1.4% and 3.0%-3.3% respectively).

Engine size is also an important factor, although this generally does not appear from the simulations. Steam turbines become inefficient at low power levels ($<$ 1 MW Invernizzi (2013)) and, in general, the performance of every component decreases with size. In this sense, WHR applications are generally more convenient for larger vessels.

Chapter 7

Outlook

Future research and recommendations to stakeholders

7.1 Suggestions for future research

Research is just as much about finding new questions to ask as it is about replying to known questions.

- The extent of methods for energy systems analysis departing from the 2^{nd} law of thermodynamics goes beyond what proposed in this work. More advanced methods for exergy analysis, such as those looking at **endogenous** and **exogenous**, **avoidable** and **unavoidable exergy losses**, as well as **exergoeconomic analysis**, could be applied for further improving the insight of the ship energy systems.
- The work presented in Paper III suggests that the operational envelope of the main engines installed on board limits the possibilities for operating the whole propulsion system in optimal conditions. Future research should investigate alternative solutions for broadening the range of engine operations, such as **variable geometry turbine (VGT)** and **sequential turbocharging**, and their effect on the efficiency of the whole propulsion system.
- This work focused on the steady-state performance of ship energy systems. Although most ships operate in constant conditions for long periods of time, they still require a **control system**. Complex energy systems such as those presented in this paper are challenging from a control perspective, and future research should look further into optimal control strategies for hybrid power plants and waste heat recovery systems.
- This work focused on three main energy demands: propulsion, auxiliary electric power, and auxiliary heat. In many applications, the demand for **refrigeration** is also relevant. The existence of systems such as absorption coolers provides

additional challenges to the integrations of such systems with the rest of the on board energy systems for optimal efficiency.

- The existence of a number of heat sources and heat sinks suggests that benefits could be achieved through the use of **process integration**. Process integration is a collection of methods aimed at finding the network of heat exchangers that minimises the need for external heating and cooling given a set of heat and cooling demands to be fulfilled. Process integration could prove particularly useful in those cases where there is a large and diversified heat demand on board.

- In this work, every study involved the generation of "ad-hoc" algorithms and models. This approach was considered to be suitable given the specific conditions of this work. However, with a long-time perspective in mind, the approach to energy systems modelling should become more systematic. In particular, the development of a **standard, flexible modelling platform** to be used for the implementation of different sub-models and for the simulation of different conditions is considered as a necessity if a research group aims at strategically invest in this field.

- More research should be performed in the future to improve the understanding of **ship auxiliary energy demand**, both electric and heat. This would allow including these parts of the energy systems in the retrofitting process by improving their efficiency and their integration into the system. This step is seen as a requirement for improving the potential for optimising the full energy system, rather than keeping the focus on the propulsion system.

- In this work, different solutions where proposed for improving the efficiency of ship energy systems. The optimisation of engine-propeller interaction proposed in Paper III led to estimated savings of approx. 2%. The WHR system proposed in Paper V was expected to provide up to almost 11% savings. However, in the future, the demand for reduction of ship fuel consumption will achieve another level of magnitude, as ships will be expected to consume 50-90% less fuel as they do today. Research should therefore also focus on more **radical ship designs**, such as wind propulsion, utilisation of fuel cells, or improvements in the logistic chain to allow for slower sailing speeds.

- The process of modelling of ship energy systems, as any modelling effort, involves many uncertainties, both in relation to the system's inputs and to the behaviour of individual parts of the system. Therefore, it is here suggested that for making the process of design, evaluation and optimisation of ship energy systems more accurate and complete, it should also involve **stochastic modelling**[1].

[1] This aspect was briefly investigated during the thesis, leading to a poster publication (Baldi, 2015).

7.2 Recommendations to stakeholders

- The presented methodology for energy and exergy analysis allows achieving an increased insight of the ship energy system, as a consequence of both the analysis of the results and of the process of generating them. It could therefore be applied as part of a routine for improving ship energy efficiency, and particularly as a milestone of a **SEEMP**.

- Future ships will be designed by naval architects, and in this sense it will be important that technologies for sustainability will be given a much higher focus in their **education**. The same should apply for skills related to data analysis for future ship operators.

- Knowledge is power, and **data analysis** is a good way to achieve knowledge. Although a promising trend can today be observed in the shipping industry, shipping companies should make sure that they invest enough resources in taking relevant measurements on board and in their analysis to keep control on ship performance.

- Whenever considering retrofitting options on their vessels, shipowners should make sure that the **influence of the new component on the rest of the ship energy system** is correctly investigated, as well as their behaviour in **all the expected operational conditions** of the ship. This will require a deep understanding of the energy system, and the development of holistic ship models will be a useful tool in this direction.

- **Policies and decisions** based only on the performance of a vessel in its design point (i.e. the EEDI) should be questioned in their validity and possibly improved, in order to better account for **how a ship is operated in reality** and, therefore, provide a more accurate evaluation of a ship's performance.

Chapter 8

Conclusion

The aim of this thesis was to contribute to the subject of improving ship energy efficiency by answering the question "what is there to gain by looking at this matter from an energy systems engineering perspective?".

The study was based on two case studies, a chemical tanker and a passenger vessel, and was divided in two main parts. First, it included an in-depth analysis of the energy systems of two existing vessels based on the available information in terms of on board measurements and technical documentation, leading to improve the understanding of the system. The process included the use of energy and exergy analysis as structured, systematic methods to investigate the energy flows on board.

In a second part, improvements to energy efficiency were proposed and evaluated: variable propeller speed operations (Ship-1), waste heat recovery (Ship-1), and hybrid propulsion (Ship-2). The evaluation was based on accounting also for the performance at off-design conditions, and on focusing on interactions between different parts of the system. This was achieved by building ad-hoc mathematical models for each study, and by using the models to simulate the performance of the system in different conditions.

The results of this thesis confirmed the initial hypothesis, that looking at the energy system of the ship with a systems perspective leads to an increased understanding of the system, to a more accurate estimation of the benefits deriving from the installation of additional components and to the achievement of higher energy savings:

Energy and exergy analysis are a good complement to existing methods and practices, and constitute a structured and systematic way to gather information concerning the ship's energy systems, thus allowing improving the understanding of these systems. This comes as a consequence of the results of the analysis, in terms of energy and exergy flows and efficiencies, but also of the process itself of gathering and processing data and information concerning the ship under study.

Accurate and reliable measurements on board are a crucial requirement for providing an accurate and, hence, useful analysis of the system, which can in turn be used for its improvement. From the experience gathered from the two case studies it can be concluded that there is need for more focus on measuring thermal energy demand on board, and on adding details to the limited knowledge of the electric energy demand.

Thermal energy is an important part of the analysis, and including this element in the system analysis and synthesis process could lead to remarkable fuel savings. This is particularly true for ships like passenger vessels, where this energy demand represent a large share of the total. In addition, the results of this thesis showed that **waste heat** is available on both of the two vessels investigated in this thesis. The potential for improving ship energy efficiency through the application of WHR systems was estimated to be in the range of approximately 5-10% when taking advantage of the wasted heat that is the easiest to recover, but that savings of up to 15% could be foreseen in the case higher levels of heat integration were achieved.

Interactions among the different parts and the **operational profile** must be taken into account when dealing with the analysis of ship energy systems. This allows improving the accuracy of the evaluation of design or retrofitting options: if only individual parts of the systems are considered, or if the system is only evaluated at one operating condition, there is the risk of sub-optimisation and of providing an inaccurate estimation of the expected savings. The work presented in this thesis reinforced this view by providing examples of situations where the systems approach brings a clear advantage: the interaction between the propeller and the engines (estimated savings by improved practice: 1.9%), the installation of a WHR system (from 9.0% to 10.8%), and the optimal energy management of a hybrid propulsion system.

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Postface

Whenever I read other people's theses, this is how they appear to me: rational; logically structured; straight forward in their approach, from problem identification, to background and method, through the results and discussion and finally to the conclusion. They look like they were carefully planned in detail from the beginning. Like someone had sat down on day one and drew the plan for how all the work would be done in the coming five years.

I also wrote my thesis according to the same principle, as this is what is normally required by the academic community. If I succeeded, after reading my thesis you will think that I had a plan. That I had a clear picture of the problem to be solved, of how to solve it, and then I simply started building up my models and analysing my data, which of course was carefully gathered according to the initial plan.

Well, that's not how it went.

The whole process has been messy, to say the least. I started by thinking I could easily model alone the whole ship, and that I would start from the Diesel engine as it is, clearly, the most important part. That's how I ended up spending a good part of the first two years of my PhD, stubbornly polishing my model to the finest detail, keeping repeating myself everyday "OK, this is the last day I work on this, tomorrow I will start with something else". And if you look at the contribution of this part of the work to the final thesis, you probably will feel like "well, I actually missed that". And it's not your fault, because it is hidden in one of the papers, outside of the main scope of this thesis.

The data came thanks to Hannes Johnson, who had a good collaboration with Laurin Maritime, and to the fact that they had just decided to install an on board monitoring system when I started my PhD. This came very handy, but it was not planned. Also when it comes to the second dataset: it might look like it was all well prepared, but hadn't I met Fredrik Ahlgren right after my Licentiate, and hadn't we found out that he had a lot of data that we could use together for something interesting, that whole half of my PhD thesis would not be there.

So, if you are a PhD student and, reading these words, will think "oh, really? Because in my case, everything worked smoothly according to the plan", then I can tell you that you are lucky, because that makes things much easier. But if you are a student that, reading my thesis felt ”oh, damn, this looks so logical and consequential, my research instead is a mess”, than my message is: don’t worry, it is normal. That’s how research works most of the times (would it be really research if you already knew from the beginning what to expect?), especially for PhD students’ research. We are STUDENTS, so we are supposed to learn, and make mistakes in the process.

One more thing. Many people say that the PhD thesis is the final result of five years of a PhD student’s work. That all your work as a PhD student is included, summarised there, in that thick bunch of text, tables and figures.

Well, that’s wrong.

The five years of my PhD are way, way more than what you can read in my thesis. And I am not only talking about the ”other publications”, each only briefly mentioned in the beginning of this thesis, each requiring months of work and effort. I have been to conferences and met people, present and future researchers to collaborate with. I have been on board of real ships, talked to the crew, learned about their experiences and lives. I have talked with other PhD students in the department, learning about all sorts of things such as VTS, biofouling, effects of oil spills on meiofauna, social aspects of implementing energy efficiency, and much more. I have planned the structure of a whole MSc course on marine propulsion systems, something I knew nothing about only 5 years ago. I have supervised students on a variety of subjects, ranging from hybrid propulsion systems to cost-benefit analysis of shore connection. I have applied for many different scholarships for doing anything from going to conferences to financing my networking. I have learned a new language, and have become part of new communities (both the shipping and the Swedish ones). I participated to the organization of two conferences and to the redaction of a book. I have made three posters. I have taken courses on design of experiments, on leadership, on project management, on programming and on data analysis. Most importantly, I have (hopefully) learned about what it means to be a researcher, about how to channel my inner curiosity, how to critically assess information and knowledge, how to proceed to transform a simple question to something that will contribute to human knowledge.

So, if you are a PhD student and you are reading this postface, here’s my advice. Remember, always, that the final result of your PhD is not your thesis. It is not your papers either.

It is you.

Therefore go out, don’t be afraid to make mistakes; try, experience, learn, knowing that even if doing this might not contribute to writing a better thesis, it will probably help in making you a better researcher.

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The journey to becoming a doctor of engineering is a long and, often, lonely one. And yet, when looking back at these past five years, it feels that this journey would not have been the same fun, or even possible, hadn't it been for those many, amazing people that I have had the honour to share this journey with.

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