Decision support method for ship energy systems synthesis with environmental and economic sustainability objectives

By

Nikoletta Loukia Trivyza

A thesis submitted to the University of Strathclyde

for the degree of

Doctor of Philosophy

Department of Design, Manufacture and Engineering Management

University of Strathclyde

Glasgow, UK

2019

Declaration of Authenticity and Author’s Rights

This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date:

Nikoletta Loukia Trivyza

To my father who always believed in me but is not here to see

‘Ιθάκη δεν υπάρχει. Υπάρχει μονάχα η θάλασσα, κι ένα καραβάκι μικρό
σαν το κορμί του ανθρώπου κι ο καπετάνιος ο Νους.’
Νίκος Καζαντζάκης, Αναφορά στον Γκρέκο

‘Ithaca does not exist. The only thing that exists is the sea, and a barque
as tinny as a man’s body, with Mind as captain.’
Nikos Kazantzakis, Report to Greco

Acknowledgement

Firstly, I would like to express my deep gratitude to my supervisors Dr. Athanasios Rentizelas and Dr. Gerasimos Theotokatos for guiding me at every step of this journey. Their insightful comments and sometimes hard questions gave me the incentive to approach my research from various perspectives. I will forever be grateful for their commitment, support and motivation during all the time of research and writing this thesis.

In addition, I would like to thank my friends and colleagues for all the stimulating conversations and fun moments we shared the last four years. I want to especially express my gratitude to Aineias, Giota and Andrea that endured and supported me over the course of these years. I would not have been able to go through this trip without them.

Last but not least, I would like to thank my beloved Parents, Sister, Aunt and Grandma who always supported me no matter how far apart we were, throughout this research study and in every step of my life.

Abstract

Shipping industry's significant economic and environmental impact along with the enforcement of stringent environmental regulations led to growing interest in enhancing shipping operations sustainability. In recent years, various technologies and alternative fuels were introduced to address the ship energy systems contribution to energy consumption and air pollution during the ship lifetime. The abundance of the available technologies and potential combinations renders ship energy systems selection process very challenging during the early design phase. The novelty of this research lies in the decision support method developed to optimise the ship energy systems synthesis at the early stage design with respect to environmental and economic objectives, as well as considerations of the ship lifetime operating requirements.

Mathematical models of established and emerging technologies were developed to estimate the ship energy systems performance. The integrated ship energy systems synthesis was formulated as a multi-objective combinatorial optimisation problem, with the objectives of life cycle cost and exhaust gas emissions minimisation, whilst considering the environmental regulations as constraints. NSGA-II was employed to solve the ship energy systems synthesis problem.

The developed method was evaluated with two case studies, an Aframax oil tanker and a cruise ship. The visualisation of the optimal configurations on the Pareto front allows decision makers understanding and managing trade-offs between the environmental and economic objectives. The comparison of the optimal solutions estimated carbon emissions with the EEDI values indicated that the index does not capture the real carbon impact of the configurations. An uncertainty analysis assessed the robustness of the solutions. The sensitivity analysis of the two case studies indicated that changes in the fuel prices and emerging technologies have different implications on the two ships. The optimal configurations for different operating profiles were identified and insights were gained on the most promising future configurations under derived carbon pricing scenarios.

Keywords: ship energy systems, multi-objective, optimisation, mathematical modelling, uncertainty analysis, life cycle cost, emissions, operational profile

Contents

Research Outputs

The following research outputs have been published as a part of the undertaken research in this thesis.

Journal articles

J1: Trivyza, NL, Rentizelas, A & Theotokatos, G 2018, 'A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability' *Energy Conversion and Management*, vol. 168, pp. 128-149. https://doi.org/10.1016/j.enconman.2018.04.020

J2: Trivyza, NL, Rentizelas, A & Theotokatos, G 2019, ‘Impact of carbon pricing on the cruise ship energy systems optimal configuration’ *Energy,* vol 175, pp. 952-966. https://doi.org/10.1016/j.energy.2019.03.139

Conference papers

C1: Trivyza, NL, Rentizelas, A & Theotokatos, G 2016, 'The influence of ship operational profile in the sustainability of ship energy systems' Paper presented at International Conference of Maritime Safety and Operations 2016, Glasgow, United Kingdom, 13/10/16 - 14/10/16.

C2: Trivyza, NL, Rentizelas, A & Theotokatos, G 2017, 'Sustainability assessment of ship energy systems at the design phase: integrating environmental and economic aspects' Paper presented at 4th International EurOMA Sustainable Operations and Supply Chains Forum, Milan, Italy, 27/02/17 - 28/02/17, pp. 1-10.

C3: Trivyza, N. L., Rentizelas, A., & Theotokatos, G. (2018). ‘Environmental and economic sustainability assessment of emerging cruise ship energy system technologies’. Paper presented at the 31st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems ECOS, Guimaraes, Portugal.

List of Figures

List of Tables

Nomenclature

	Parameters	**Description and units**
A	AR	absorption rate of Carbon Capture (%)
B	bsfc	brake specific fuel consumption (g/kWh)
C	C_c	capital cost factor (€/kW)
	C_{con}	consumables cost (€/tonne)
	cf	correction factor from ISO conditions (-)
	C_f	fuel cost factor (€/t)
	c_l	generator correction factor (%)
	C_m	maintenance cost factor (€/kWh)
	C_p	specific heat of gas (kJ/kg^{o}C)
	C_u	urea concentration (%)
D	df	deterioration factor of the engine (%)
	dr	discount rate (%)
E	E	annual emissions (g)
	EF_{eb}	emission factor energy based (g/kWh)
	EF_{fb}	emission factor fuel consumption based (g/g of fuel)
	ega	exhaust gas amount (kg/s)
	egt	exhaust gas temperature (^{o}C)
F	fi	increase in the fuel consumed from the emission reduction technologies (%)
H	h	time per operational phase (hours/year)
	h_d	enthalpy drop (kJ/kg)
	h_f	enthalpy of saturated liquid (kJ/kg)
	h_g	enthalpy of saturated vapour (kJ/kg)
	h_{out}	Enthalpy of the mixed steam at economiser outlet (kJ/kg)
	h_{sup}	Enthalpy rise of superheated steam from feedwater inlet to superheater outlet (kJ/kg)
I	i	operational phases i=1..I
K	k	input parameters of uncertainty analysis
L	L	load (-)
	LHV	lower heating value (kJ/kg)
M	M	number of uncertainty analysis simulations
	M_{con}	consumables amount (tonne)
	$\dot{m}_{f,b}$	fuel mass flow (kg/h)
	$\dot{m}_f$	fuel amount mass flow (kg/h)
	$\dot{m}_s$	saturated steam mass flow (kg/h)
	$\dot{m}_{sup}$	amount of superheated steam produced from the waste heat recovery system (kg/h)
N	n	maximum operating speed (rpm)
	NP	number of pollutants
O	OPEX1	fuel cost (€)
	OPEX2	maintenance and consumables costs (€)
P	p	pollutant

	P	power (kW)
	P_b	main engine's power output (kW)
	P_{el}	electric energy produced from the turbo-generator of the waste heat recovery system (kW)
	P_n	nominal power (kW)
Q	$q_{CO2,bp}$	CO_2 emissions quantity of that is bypassed (kg)
	$q_{CO2,tot}$	quantity of total CO_2 emissions (kg)
R	r	economiser recirculation ratio (-)
	rpm	nominal speed at maximum continuous rating (r/min)
	R_u	number of replacement units over the ship life (-)
S	S	content of sulphur on fuel (%)
	sec	specific energy consumption (kJ/kWh)
	sfc	specific fuel consumption (g/kWh)
	sgc	specific gas consumption (g/kWh)
	spoc	specific pilot oil consumption (g/kWh)
	s_{rate}	steam rate for electric production kg/kW$_e$h
	ss	percentage of saturated steam used for thermal needs (%)
T	T	target of CO_2 reduction (%)
	t_{ECA}	Time ship sails on ECA (%)
	T_L	lowest temperature of gas on high pressure generating bank exit (^oC)
	T_p	cost per pollutant (€/tonne)
V	V_u	urea solution consumption (l/h)
Y	Y	lifetime operation (years)
	Greek letters	
	Δh	specific enthalpy difference from feed water to saturated steam (kJ/kg)
	ΔNOx	NOx reduction (NOx from engine-NOx after Selective Catalytic Reactor) (g/kWh)
	η_g	generator efficiency (%)
	η_s	shaft efficiency (%)
	η_b	thermal boiler efficiency (%)
	μ	distribution mean
	Subscripts	
A	ae	auxiliary engine
E	ECA	emission control areas
	ed	electric demand
	ep	electric power
G	g	global waters
M	me	main engine
	mpr	minimum power requirements
P	p	pollutant
	pd	propulsion power demand
	pp	propulsion power
S	sg	shaft generator
	ss	sub-system
T	td	thermal demand

	th	thermal boiler
	tp	thermal power
U	u	unit

	Independent decision variables	**Description**
B	$b_{er,p}$	the binary variable that equals 1 if the emission reduction technology $t_{er,p}$ is selected and 0 if it is not
	b_{ee}	the binary variable that equals 1 if the energy efficiency technology t_{ee} is selected and 0 if it is not
E	ee	the vector that includes decision variables for the energy efficiency sub-system
	er	the vector that includes decision variables for the emission reduction sub-system
	es	the vector that includes decision variables for the electric sub-system
F	f_{ae}	electric auxiliary engine fuel type
	f_{me}	main engine fuel type
	f_{th}	thermal boiler fuel type
N	N_{ae}	the discrete variable for the number of auxiliary sets
	N_{me}	the discrete variable for the number of main engines
P	$P_{n,me}$	the discrete variable for the nominal power of the main engine
	ps	the vector that includes decision variables for the propulsion sub-system
T	t_{ae}	the discrete variable of auxiliary electric engine type
	t_{ee}	the energy efficiency technology type
	$t_{er,p}$	the emission reduction technology type
	t_{me}	the discrete variable of main engine type
	ts	the vector that includes decision variables for the thermal sub-system
	t_{th}	the discrete variable of thermal boiler type

	Decision Variables Sets	**Description**
O	o_{tae}	the set of auxiliary electric alternative types $o_{tae} = \{1\ldots O_{tae}\}$
	o_{ee}	the set of energy efficiency technologies $t_{ee} \in o_{ee}=\{1\ldots O_{ee}\}$
	o_{er}	the set of emission reduction technologies $t_{er,p} \in o_{er,p}=\{1\ldots O_{er,p}\}$
	o_{fae}	the set of fuel type alternatives for auxiliary engine $o_{fae} = \{1\ldots O_{fae}\}$
	o_{fme}	the set of fuel type alternatives for main engine $o_{fme} = \{1\ldots O_{fme}\}$
	o_{fth}	the set of fuel type alternatives for thermal boiler $o_{fth} = \{1\ldots O_{fth}\}$
	o_{tme}	the set of main engine alternative types $o_{tme} = \{1\ldots O_{tme}\}$
	o_{Nae}	the set of number of auxiliary electric sets $o_{Nae} = \{1\ldots O_{Nae}\}$
	o_{Nme}	the set of number of main engines $o_{Nme} = \{1\ldots O_{Nme}\}$
	$o_{Pn,me}$	the set of nominal power of main engine $o_{Pn,me} = \{1\ldots O_{Pn,me}\}$
	o_{tth}	the set of thermal boiler alternative types $o_{tth} = \{1\ldots O_{tth}\}$

Abbreviations

	Abbreviations	Description		Abbreviations	Description
A	AHP	Analytic Hierarchy Process	**M**	M	Man Diesel &Turbo
C	$CaCO_3$	Calcium carbonate		MC	Monte Carlo
	CaO	Calcium Oxide		MCDM	Multi-criteria decision making
	CAPEX	Capital expenditures (€)		MCFC	Molten carbonate Fuel Cells
	CC	Carbon Capture system		MCR	Maximum Continuous Rating
	CO_2	Carbon dioxide		MDO	Marine Diesel Oil
D	D	Diesel engine		MGO	Marine Gas Oil
	DF	Dual Fuel engine		MOCO	Multi-objective combinatorial optimisation
	DFG	Dual Fuel Generator		MOEA	Multi-objective evolutionary algorithm
	DG	Diesel Generator	**N**	NaOH	Sodium hydroxide
	DOE	Design of experiments		NG	Natural Gas
	DWT	Deadweight		NOx	Nitrogen oxides
E	ECA	Emission Control Area		NSGA-II	Non-sorting genetic algorithm II
	EEDI	Energy Efficiency Design Index	**O**	O&M	Operational and Maintenance
	EF	Emission Factor		OPEX	Operational expenditures (€)
	EGR	Exhaust Gas Recirculation		ORC	Organic Rankine Cycle
	EU	European Union	**P**	PDF	Probability density function
	EU ETS	European Emissions Trading Scheme		PEMFC	Proton-exchange membrane fuel cell
F	FC	Fuel Cells		PPI	Producer price index
G	GA	Genetic Algorithm	**S**	SCR	Selective Catalytic Reactor
	GHG	Green House Gas		SG	Shaft generator
	GS	Generator Sets		SOFC	Solid oxide fuel cell
	GT	Gross Tonnage		SOx	Sulphur oxides
H	HFO	Heavy Fuel Oil	**U**	UN	United Nation
I	IMO	International Maritime Organisation	**W**	W	Wärtsilä
L	LCA	Life Cycle Assessment		WHR	Waste Heat Recovery
	LCC	Life Cycle Cost (€)			

	LHV	Lower Heating Value of fuel (kJ/kg)	
	LNG	Liquefied Natural Gas	
	LPG	Liquefied petroleum gas	
	LSHFO	Low Sulphur heavy fuel oil	

1 Introduction

1.1 Introduction to chapter

This chapter introduces the background information and motivation for this thesis. A brief introduction of sustainability in general and the need for sustainability in shipping is presented. The research question and the aim, as well as objectives of the undertaken research, are discussed. Finally, the structure of this thesis is described.

1.1 Background and motivation for the research

1.1.1 An introduction to sustainability and sustainable development

In recent years, sustainability and sustainable development have gained great attention and many researchers tried to provide their definition. Hay et al., (2014) have included an extended literature investigation about the subject and they support that sustainability is the ability to maintain a system over time. They defend that ‘what humans choose they want to sustain and for how long, depends upon what they value’. Now that our goal is for human society to continue as an integral part of the Earth system (Hay et al., 2014), we have to specify the process to achieve this.

In that respect from the late 1970s the concept of Sustainable Development has been established (IUCN, 1980) and it was well defined in 1987 on the World Commission on Environment and Development report, as a ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED 1987). These needs are economic, social and environmental, they replace the single goal approach of monetary performance, and must be provided with balance (Lior, 2006). As a result, Agenda 21 was established at the 1992 United Nations Conference on Environment and Development in Rio de Janeiro. This report was a commitment to sustainable development and it was agreed by governments worldwide (UNCED, 1992).

After the establishment of the concept of sustainable development, many definitions have been introduced. One very common definition was given by Pearce et al. (1989), which states that: ‘Sustainable development involves devising a social and economic system, which ensures that these goals are sustained, i.e. that real income rise, that educational standards increase that the health of the nation improves and that the general quality of life is advanced’. Therefore, the focus is shifting from a merely economic perspective to include also environmental and social factors; and a traditional reactive approach is replaced by a modern proactive policy. Edwards

(2005) mentions that the Sustainability Revolution has created a pervasive and permanent shift in consciousness and worldview, which has affected all facets of society.

Another important stepping-stone was on 1994, when Elkington introduced the Triple Bottom Line agenda, which focuses on the integration of the economic value with the environmental and the social value. This three pillars approach is intended for the sustainable development of business practises. He defends that the transition to sustainable capitalism will be one of the most challenging transitions our species has to make (Elkington, 2001). Along these lines, the ecological economist Norgaard (1994) has argued that the concept of sustainable development marks the beginning of a break from the dominant strand of faith in progress, which has been wedded for the past two centuries. He defends that in the past, people believed in progress and did not worry about the effects it would have on the environment and on their children’s future.

The concept of sustainability can be described in terms of three broad domains: environment and ecology, business and economics, equity and fairness. The relationship of those domains has been described as a three-legged stool or three intersecting circles, where each circle has equal size and each leg has equal weight (Collin and Collins, W., 2010). As Gibson (2006) stated in order to achieve sustainable development positive steps have to be supported on all fronts, because each one of the pillars is crucial and of equal importance.

A question arises on how sustainable development can be achieved. Two different perspectives are adopted in order to answer this question, either a non-anthropogenic or an anthropogenic. In the former, ‘a reduction in the societal demands on Earth’ is required, whereas, in the latter ‘an increase in the resources so that the gaps between supply and demand can be bridged’ (Williams and Millington, 2004). There are two main approaches to answer the question of how the ‘conjoint of demands and resources’ can be done, the ‘weak sustainability’ that aligns with the anthropogenic perspective and the ‘strong’ that aligns with the non-anthropogenic (Williams and Millington, 2004). According to the weak sustainability approach, the focus is on the technological development in order to identify solutions to address the environmental issues caused by the rising production of goods (Ekins et al., 2003). On the other hand, it is stated that strong sustainability ‘argues that the demands we make on the Earth need to be revised, for instance, we consume less’ (Williams and Millington, 2004). Therefore, according to the anthropogenic perspective, the natural resources should be sustained due to their significance on the human operations, whereas, following the non-anthropogenic perspective natural resources should be maintained due to their ‘biotic rights’ (Hay, 2015).

The undertaken research in this thesis focuses on the decision support of ship energy systems selection in order to support the improvement of their sustainability; as a result, an anthropogenic perspective is adopted.

1.1.2 Sustainability assessment

Since sustainability development became an imperative need in the modern world, in order to attain it, the first step is to set goals of sustainability and assess the performance against those goals. Lior (2015) expressed the challenges of quantifying sustainability and setting goals 'since it does not define what the current needs are, what the composition of future generations is, what their needs should be, which resources they would use, what the availability of these resources would be, and what the time frame is'.

In order to make this process easier to grasp, Hay et al. (2014) described the steps that have to be followed in order to achieve sustainable development. The first step is to set the goals, thus describe future situations that are better than the current. For this to happen, humans must interpret the behaviour of an activity, in order to formulate goals and suggest actions for the improvement of the situation. Then to implement those goals humans have to take actions. In the end, it is necessary to evaluate whether those goals have been achieved. However, since sustainability is a long term goal and may never be completely fulfilled, we track if we are closer to the goals that have been set (Hay et al. 2014).

So for the last 20 years, the scientific community has been struggling in providing efficient and reliable tools for the sustainability assessment (Ness et al., 2007). Devuyst et al. (2001) defined sustainability assessment as 'a tool that can help decision-makers and policy-makers decide what actions they should follow or not, in an attempt to make society more sustainable'. Along these lines, Kates et al. (2001) suggested that this tool will help the decision-makers with an evaluation of global to local integrated nature-society system in short and long term perspectives.

From the definitions that are provided it is derived that sustainability assessment is an assisting tool in the decision making process. Pope et al. (2004) suggested that sustainability assessment can be used either as an additional tool or as a stand-alone process. Sala et al. (2015) agreed that sustainability assessment is a helpful tool for decision and policymaking but mention that it is not an easy process, and in order to conduct sustainability assessment, many challenges have to be tackled, regarding the interdisciplinary character of sustainability and the holistic perception of reality. Gibson (2006) introduced another issue, he argued that sustainability is an integrative concept so the assessment of sustainability should also be an integrative process, and the pillars of sustainability should be treated together and not separately.

A great number of tools, methods and processes have been developed for the purpose of assessing sustainability, but there are only a few of them that have an integral approach and manage to take into consideration all the aspects of sustainability: environmental, social and economic (Singh et al., 2009). Another challenge is to find the fitting instrument in a particular situation in order to successfully measure sustainable development of the system and in the end improve sustainability (Poveda and Lipsett, 2011). Papers with specific guidelines and case study experiences of sustainability assessment have been published over the years (Basurko and Mesbahi, 2014; Krajnc and Glavic, 2005; Santoyo-Castelazo and Azapagic, 2014; Tarabella and Burchi, 2011).

The unprecedented development of the field of sustainability had led to an increase in sustainability tools and attempts to classify them. There have been many attempts into collecting and categorising various tools for sustainability assessment in general (Ness, et al. 2007b), (Poveda and Lipsett, 2011), (Gasparatos, et al., 2008), (Singh, et al., 2009) or specifically for evaluating the environmental sustainability in industrial systems, (Angelakoglou and Gaidajis, 2015). In addition, in some studies, authors introduced guidance in order to select the most appropriate sustainability assessment tool for a specific case (Gasparators and Scolobig, 2012) or introduced a framework for sustainability assessment (Hacking and Guthrie, 2008; Sala et al., 2015).

Findings from these studies show that there are four main categories of sustainability tools that can be used, as displayed in Figure 1.1. First, there are indices/indicators measures, mainly quantitative that can be used stand-alone or be combined into a composite indicator. They have to be simple, easy to grasp and they can express a measurement or goal in any of the three aspects of sustainability. Regarding the composite indicator, some kind of weighting is needed, which can be implemented from the stakeholders’ requirements. Another basic category that has a variety of applications is the life cycle analysis (LCA). According to this method, the environmental impact of a process or a product is evaluated throughout its lifetime. In addition, the life cycle cost of a product/process can be integrated with the LCA, however, there are challenges in this approach (Norris, 2001). In addition, the impact assessment methods incorporate concerns on environmental or social issues of different stakeholders into the assessment process. Material and/or energy flow analysis is another group, where the necessary material and/or the energy for a product or a process are estimated. Another category is the environmental accounting, where sustainability assessment is accomplished with methods that translate environmental costs and benefits into monetary units.

Angelakoglou & Gaidajis (2015) performed an evaluation on the sustainability assessment tools for industrial systems and concluded that composite indices and life cycle analysis based methods are the most prominent. On the other hand, Gasparators and Scolobig (2012) concluded that some potential ways to integrate/synthesise outputs from different assessment tools are by employing multi-criteria analysis.

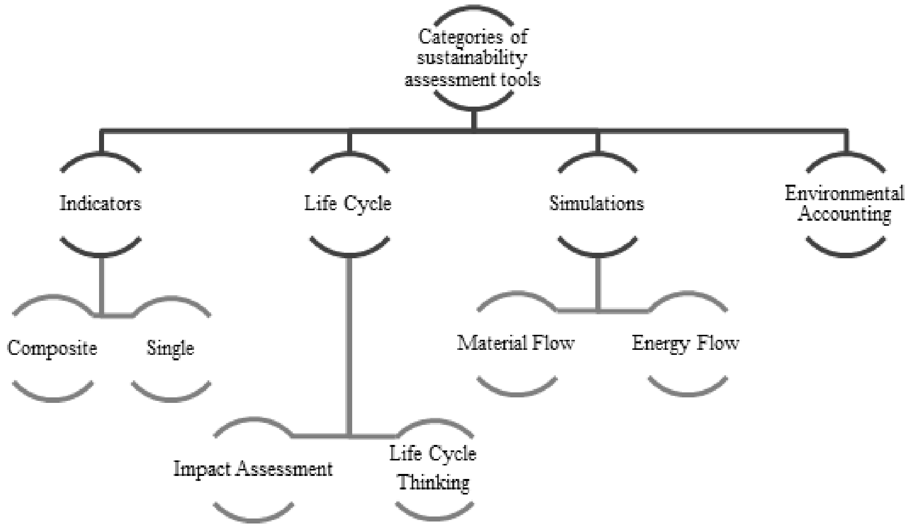

Figure 1.1 Categories of sustainability assessment tools (adapted from Angelakoglou & Gaidajis (2015))

Ness et al. (2007) highlighted 'the need for standardised tools that give more transparent results'. Therefore, it is important to introduce an industry-specific standardised tool with specific rules and instructions for the evaluation of the sustainable development of a specific sector. For example, even though ISO 14040 has been established and it describes the principles and framework for LCA, it is up to the decision maker to choose the boundaries and the environmental impacts that are going to be included. In order to reduce the subjectivity in the sustainability assessment of a specific sector, and make it easier to compare the sustainable development of different alternatives in the same sector, it is important to have a standardised tool. This tool should define exactly, what is sustainable development and the goals that are set to achieve it, as Ness et al. (2007) pointed out 'how one defines sustainability largely determines how one goes about assessing it'. In addition, it should explain how these goals are going to be assessed with specific guidelines; it should outline which environmental issues will be included and the boundaries, as well as the thresholds that should be applied.

Sustainability assessment methods have been used in many areas, for the measurement and evaluation of the environmental, social and economic impact. Sustainability assessment has gained great attention in the agri-food industry (Del Borghi et al., 2014; Goglio et al., 2015; Niccolucci et al., 2008), in order to support the quality and safety, as well as the economic prosperity of the industry. Another sector with a great interest in sustainable development is the energy production, because of the increase in energy demand, the need for security of the energy supply and the need for mitigation of the effects of climate change (Bazmi and Zahedi, 2011; Pohekar and Ramachandran, 2004; Santoyo-Castelazo and Azapagic, 2014). At last, a sector with an upcoming demand in sustainable development is the maritime sector. Sustainable performance of ships and especially ship energy systems is the scope of this thesis and it is discussed in the next section in more detail.

1.1.3 Sustainable development goals and shipping

During the United Nations Summit on September 2015, the UN Sustainable Development Goals were discussed and the 2030 agenda was agreed. The agenda seeks for actions regarding the people, the planet and the prosperity for the next decade until 2030. The world leaders agreed on 17 sustainable development goals. A great number of these targets have an impact on the shipping industry. Specifically, Goal 7 is to ‘ensure access to affordable, reliable, sustainable and modern energy for all’, Goal 13 is to ‘take urgent action to combat climate change and its impacts’ and finally Goal 14 is to ‘conserve and sustainably use the oceans, seas and marine resources for sustainable development’ (UN, 2015).

The aforementioned targets are highly related to the ship energy systems. First, the ship energy systems are the main producers of energy shipboard, therefore improving their sustainability addresses the UN goal for sustainable and reliable energy. Second, the ship energy systems have a significant impact on greenhouse gas emissions; as a result, the mitigation of their emissions is in line with the actions to combat climate change. Finally, the improvement of the ship energy systems environmental impact contributes to the conserved and sustainable use of the oceans as a mean of transporting goods.

1.1.4 Environmental sustainability of the shipping industry

Ship transportation is considered one of the most environmentally friendly modes of transport (Fagerholt and Psaraftis, 2015), however great attention has been placed on improving the environmental sustainability due to the magnitude of the shipping operations. Shipping operations play a significant role in the global economy and international shipping is estimated to carry around 90% of the global trade in volume, as well as more than 70% in value (Asariotis and Benamara, 2012). It is forecasted that by the year 2030 the annual seaborne trade volume will be two times greater than the year 2010, reaching around 20 bn tonnes (Lloyd's Register and UCL, 2014). This increasing market growth leads consequently to significant environmental impact and as a result, improving the sustainability performance of shipping operations will have a highly positive impact in achieving the sustainability targets of the transportation sector.

Global shipping has a great impact on the global carbon emissions. Overall the shipping sector accounts for approximately 3% of the global CO_2 emissions (Tillig et al., 2016) and it could be ranked the sixth carbon emissions producer in the case where international shipping was considered as a country (Harrould-Kolieb, 2008). As it is evident from Figure 1.2, the shipping industry is responsible for a great percentage, almost 11% of the CO_2 emissions from the transportation sector, while the CO_2 emissions from the transportation sector constituted around 29% of the global emissions on the year 2016 (EPA, 2016). It is forecasted that the CO_2 emissions from international shipping will experience a significant rise between 50% to 250% by 2050 (Peters et al., 2012) and it might reach 17% of the global emissions, if no measures are taken (Johnson, 2018).

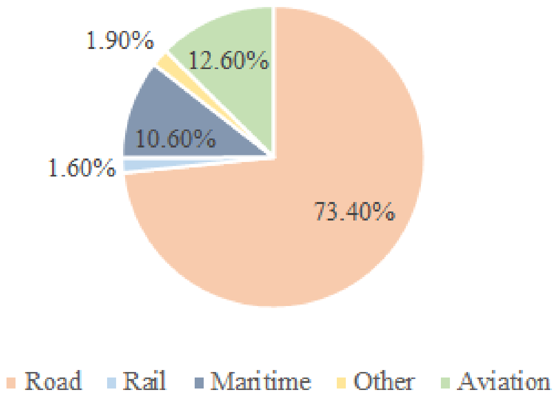

Figure 1.2 Global greenhouse gas emissions from the transportation sector in 2014 (EC, 2014)

Furthermore, with regard to other anthropogenic emissions, 4-9% of global SOx and 15% of NOx emissions are attributed to shipping operations (Eyring et al., 2010) and a further increase by around 40-50% is anticipated from 2000 to 2020 (SA Risk -Sea, 2010). In addition, ocean-going ships are responsible for approximately 1.2–1.6 million metric tonnes of particulate matter emissions (Corbett et al., 2007). It is supported that the SOx along with the particulate matter and NOx emissions are responsible for the majority of the adverse effect on health and ecosystems from shipping operations (Winnes and Fridell, 2009), especially due to the proximity of the vessels operation on urban areas. It is estimated that due to particulate matter emitted near the ports from marine vessels, there have been around 60,000 cases annually of premature deaths (Corbett et al., 2007).

Ship engines consume more than 350 million tonnes of fossil fuels per year (Carlton et al., 2013). The fossil fuel consumed by ships corresponds to 5% of the total transportation sector energy consumption (U.S. Energy Information Administration, 2013). As a result, shipping operations have a great impact on global fossil fuel depletion. It is estimated that in the year 2040 the shipping industry will consume around 10 million oil-equivalent barrels per day, as shown in Figure 1.3.

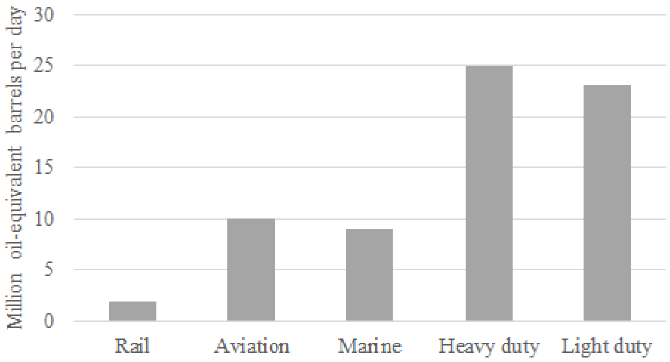

Figure 1.3 Projection of the fuel consumption in the year 2040 (ExxonMobil, 2017)

1.1.5 Economic sustainability of shipping industry

Improving the economic sustainability in shipping is also essential. First, due to the significant contribution of the fuel cost to the overall life cycle cost of the vessel, which has a great influence on the profitability of the shipping companies. In addition, the great volatility of the bunker fuels prices as it is evident from Figure 1.4. The volatility in the bunker prices is projected in the uncertainty on the ship-owners investment decision. For example, the fuel prices volatility affects highly the selection of the most cost-efficient abatement alternative in order for the ship to comply with the air pollution regulations. The relative price between low sulphur fuel and heavy fuel oil affects the decision of installing a scrubber or switching to a low sulphur fuel in order to comply with the regulations.

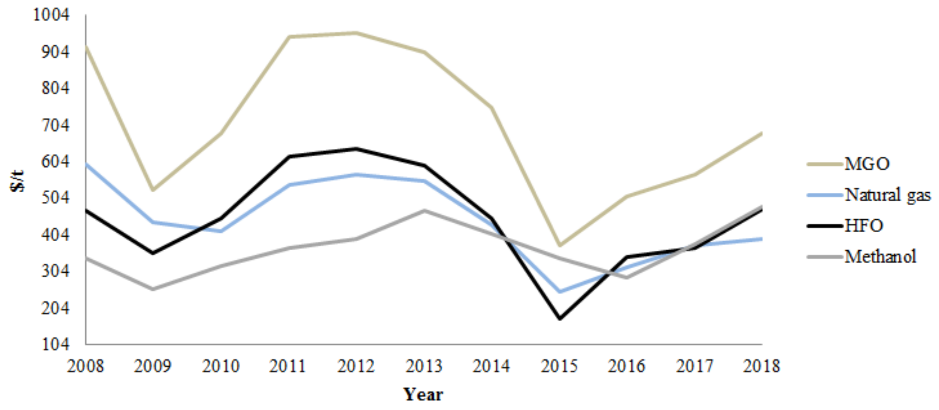

Figure 1.4 Historical price data for bunker fuels (Ship & Bunker, 2018)

Second, the strict environmental regulations lead to high expenses for more environmentally friendly technologies or fuels. Complying with the air pollution regulations leads to select a more expensive power plant that includes greener technologies like fuel cells, waste heat recovery, scrubber, selective catalytic reactor, therefore increasing the capital and in some cases operational expenditures of the ship. Another alternative is operating the ship with different fuels, like Marine Gas Oil (MGO), methanol, natural gas. For example, MGO is a solution for the ships with diesel engines in order to sail in the sulphur controlled areas, however, from Figure 1.4; it is evident that the price of MGO compared to the Heavy Fuel Oil (HFO) is very high.

Finally, due to the possibility of introducing market-based measures for carbon or other anthropogenic emissions. Consequentially, the ship-owners will come across the crossroad of either reducing the emissions and include zero emissions technologies, however having an increased investment or on the other hand, face the emissions taxes.

1.1.6 Air pollution regulations in the shipping industry

Due to the significant environmental impact of the shipping operations, the International Maritime Organisation (IMO), as well as national authorities, have imposed strict environmental regulations in the shipping industry. IMO has set limits on the NOx and SOx emissions from ship engines (IMO, 2011) and two areas are acknowledged, the global areas and the Emission Control Areas (ECA). In the latter, more stringent limits are imposed on SOx and NOx emissions from ships (IMO, 2011).

The limits that are set for the SOx and NOx emissions are shown in Table 1.1 and Table 1.2.

Table 1.1 MARPOL Annex VI Fuel Sulphur Limits (IMO, 2005a)

Sulphur Limit in Fuel (%)			
ECA waters	**Date**	**Global waters**	**Date**
1%	2010	3.5%	2012
0.1%	2015	0.5%	2020

The NOx emission limits (g/kWh) are set for marine engines depending on the engine maximum operating speed, n (rpm). Tier I and Tier II limits are global while Tier III standards apply only in NOx Emission Control Areas.

Table 1.2 MARPOL Annex VI NOx Emission Limits (IMO, 2005b)

Tier	Date	$n<130$	$130 \leq n<2000$	$n \geq 2000$
I	2000	17	$45 \cdot n^{-0.2}$	9.8
II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
III	2016[1]	3.4	$9 \cdot n^{-0.2}$	2.0

The ECAs are near the coasts of North America, Caribbean and Northern Europe seas and it is expected in the future that possibly more areas are going to be included, like the Mediterranean sea (Yoo, 2017). In Figure 1.5, the current and possible future areas are displayed. In addition, stringent sulphur limits are going to be implemented for the global waters from 2020 (IMO, 2005a).

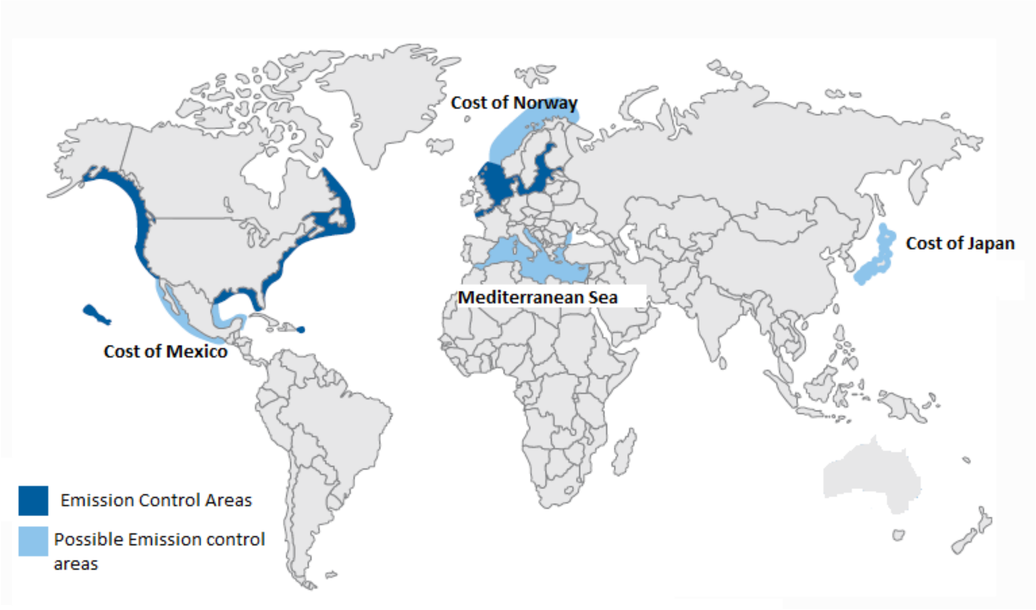

Figure 1.5 Current and possible ECAs (FuelTrade, 2014)

---

[1] For North American and the United States Caribbean Sea or 2021 for Baltic Sea and the North Sea

Regulations to improve the ship energy efficiency and reduce the GHG emissions have also been introduced and further pressure is foreseen in the future. IMO introduced the first maritime energy efficiency regulation in 2011 (IMO, 2011), which is highly related to the reduction of CO_2 gas emissions. All new ships have to comply with the Energy Efficiency Design Index (EEDI) (IMO, 2014) and all new and existing ships are required to have a specific Ship Energy Efficiency Management Plan (SEEMP) (IMO, 2012). In addition, a Monitoring, Reporting and Verification (MRV) system for carbon dioxide emissions was introduced by the European Union (EU, 2014).

Furthermore, a reduction of CO_2 emissions around 90% is required from 2010 to 2050 (Anderson and Bows, 2012) in order for the shipping industry to contribute to the global target of keeping the temperature increase below 2^oC. The IMO Marine Environmental Protection Committee (MEPC), acknowledging the great contribution of the shipping sector to the global CO_2 emissions, on 2018 set a target to reduce the CO_2 emissions from the shipping sector by 50% until 2050 (Ancona et al., 2018). The United Nations climate change executive secretary reported that this consists of a “major milestone in addressing climate change” (Churchill, 2018). In addition, the International Chamber of Shipping secretary general claimed that it will be a motivation for developing zero CO_2 fuels (Johnson, 2018). Along these lines, it has been discussed to introduce shipping operations into the European Emission Trading Market Scheme (EU ETS) for CO_2 emissions, as well as to tax the carbon emissions (Koesler et al., 2015; Shi, 2016), similarly to the land-based power plants.

Summarising, shipping operations have a great impact on both the global economy, as well as emissions and the continuing growth of the global trade anticipates a future increase of this impact. Therefore, the attention is placed in mitigating the exhaust gas emissions from the ship energy systems and therefore strict regulations are implemented. However, the regulations have a high impact also on the economic sustainability of the ship energy systems, since in order to comply with the regulations more expensive, greener technologies or fuels are needed. Along with the bunker fuel prices volatility and the possibility of future more stringent regulations and emission taxation policies, a focus on the improvement of the economic sustainability of the ship energy systems is placed. As a result, a method to support the assessment and optimisation of the ship energy systems sustainability considering both the economic and environmental aspect of sustainability is required.

1.1.7 Research question

The aforementioned problem that is discussed in this thesis is summarised in the following question:

How can the environmental and economic performance of the ship energy systems synthesis be optimised over the ship lifetime during the early design stage?

1.2 Aim

The aim of this research is to contribute towards improving the lifetime environmental and economic performance of ship energy systems by developing a Decision Support method. The proposed method will support decisions on the synthesis of the systems by identifying configurations that offer the most environmentally and economically sustainable performance during the ship operational lifetime, considering the specific characteristics of the ship type and the expected operating profile.

1.3 Objectives

The following objectives were defined in order to achieve the research aim:

Objective 1

Investigate, map and analyse the existing decision support methods for optimal ship energy systems synthesis.

Objective 2

Identify the key environmental and economic indicators for the ship energy systems sustainability and formulate mathematical expressions to describe them.

Objective 3

Identify and analyse the ship energy systems that have the greatest impact on ship sustainability.

Objective 4

Investigate the established and emerging technologies to improve the ship energy systems sustainability and develop models to describe their performance.

Objective 5

Formulate the optimisation problem of the ship energy systems synthesis, identify the optimisation algorithm that suitably addresses the complex problem, and evaluate the efficacy of the selected optimisation algorithm.

Objective 6

Develop the computational model of the proposed decision support method for the ship energy systems synthesis.

Objective 7

Evaluate the applicability of the proposed method.

Objective 8

Validate the derived results from the method application under different conditions.

1.4 The scope of the research

The research presented in this thesis is confined by the following boundaries:

i. In this thesis, the ship energy systems constitute the main systems of interest, which are defined as the main components shipboard that are involved in the conversion of chemical energy in order to cover the energy demand requirements, including the mechanical, electric and thermal. These systems have the greatest impact on the ship lifetime operating expenditure and air pollution as it is discussed in the Critical review in Chapter 2. The hull, propulsor, ballast system and the auxiliary machinery of the main energy systems are excluded. This decision on the system boundaries is in alignment with previous studies regarding the ship energy systems analysis and optimisation (Baldi, 2016). In addition, the technologies that improve the main energy systems performance, the emission reduction and energy efficiency technologies are considered.

ii. The focus of this research is on the early design phase of the ship energy systems. The early stage design of the ship energy systems configuration is considered as the most influential stage of the ship lifetime performance. It is recognised as the phase with the highest potential for improvement of the environmental and economic performance of the ship energy systems. This statement is discussed in detail in Section 2.3 of this thesis.

iii. The environmental impact of the ship energy systems is considered in terms of gas emissions, which are identified as the most important environmental issue in Section 2.3. The combustion process of the power plant machinery emits the largest amount of gas emissions from ships. In addition, the exhaust gas emissions are highly regulated, as it was discussed in previous sections, thus challenges arise regarding the selection of the optimal ship energy systems configuration to face the aforementioned regulations.

iv. Only the operational lifetime emissions of the ship energy systems are considered. According to life cycle assessment studies on the ship energy systems, it was identified that the predominant phase over the ship lifetime regarding the gas emissions is the operational (Section 2.3). Therefore, in this work, the gas emissions from the building and decommissioning of the ship energy systems are excluded.

v. Regarding the ship energy systems life cycle cost calculations only the capital and operational costs are considered. There are limited resources for the ship end of life analysis (Chatzinikolaou and Ventikos, 2015a) and many assumptions are required rendering the results uncertain (Nikolaisen, 2014). In addition, previous studies on the disposal phase of ships indicated that the economic impact is less than 1% of the life cycle cost (Nikolaisen, 2014). For these reasons, the disposal phase is excluded from the economic calculations.

vi. The focus of this work is on the environmental and economic sustainability of the ship energy systems, whereas the social aspect is not included. It is discussed in Section 2.2 that the tools, which are currently developed to assess the social impact do not manage to address the marine technologies and specific impact categories, as well as databases are required, to express the ship energy systems social impact.

vii. Finally, in this work the weight and size of the technologies is not considered. In specific, the impact the selected technologies have on the cargo capacity, the resources that are carried by the ship, the machinery space design and the structural ship design is not discussed. The focus of this work is on the energy interactions of the ship energy systems.

1.5 Thesis outline

The research presented in this thesis is organised in eight chapters presented in Figure 1.6.

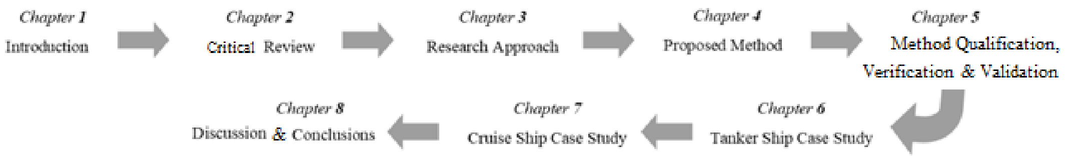

Figure 1.6 Thesis structure

Each of the presented chapters addresses the following content:

Chapter 1 provides the background and motivation of this work, as well as states the aim and objectives of this research.

Chapter 2 presents a critical review of the research area that is addressed in this thesis.

Chapter 3 describes the research approach followed in this work to address the aim and objectives.

Chapter 4 presents the decision support method developed in this thesis.

Chapter 5 reports the qualification, verification and validation process followed for the developed method.

Chapter 6 and *Chapter 7* report the results from the case studies performed.

Chapter 8 provides the research reflections, proposals for future research and the concluding remarks.

1.6 Chapter summary

In this chapter, a brief introduction into the sustainable development and sustainability assessment, as well as the importance of sustainable development in the shipping sector, were presented. The air pollution and energy efficiency regulations in the shipping industry were summarised. Furthermore, the aim and objectives, as well as the scope of this work, were addressed and an outline of this thesis chapters was included. In the following chapter, a critical review of the research area is presented and lastly, the research gaps that are addressed in this thesis are discussed.

2 Critical Review

2.1 Introduction to chapter

This chapter presents the critical review performed in this research. The main area of interest of this research is the decision support methods for the synthesis of ship energy systems with sustainability considerations. The critical review is driven from the aim of this work and is the conjoint of two research areas, the sustainability in ship energy systems and the decision support methods for sustainable energy systems. The links of the research areas considered in this thesis are presented in Figure 2.1.

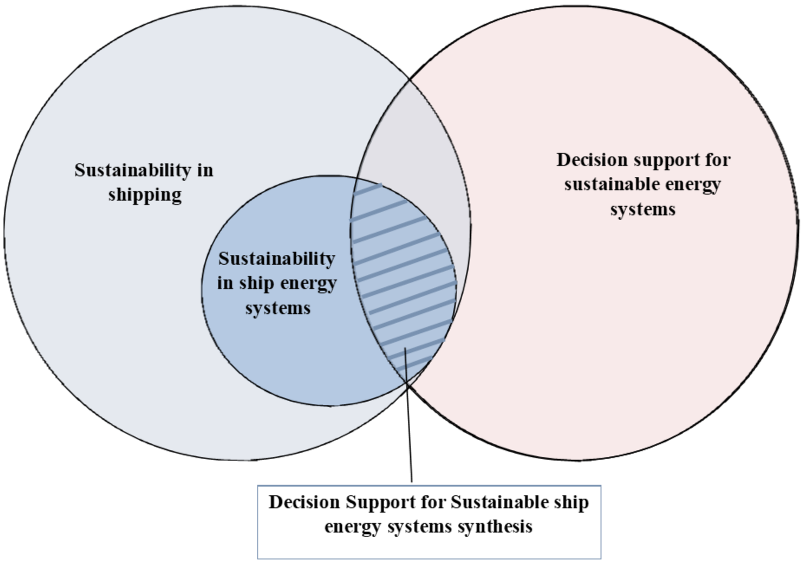

Figure 2.1 Research areas included in the critical review

First, an overview of sustainability in shipping (Section 2.2), and specifically in ship energy systems is introduced and the factors that affect significantly the ship energy systems sustainability are identified (Section 2.3). Due to the focus on sustainable ship energy systems, the basic characteristics and technologies in order to improve the ship energy systems sustainability are discussed in Section 2.3. Moreover, the decision support methods employed for sustainable energy systems (Section 2.4) are presented. Due to the energy systems similarities with the ship energy systems, the key findings of the decision support methods for sustainable energy systems will drive the undertaken research. A state-of-the-art literature review is performed, in Section 2.5, for the decision support methods for the ship energy systems with sustainability objectives with a focus on the existing methods for synthesis.

Finally, the key findings and gaps identified from the critical review are presented in Section 2.6.

2.2 Sustainability in shipping

Sustainability is a relatively new area of focus in the shipping industry (Armstrong and Banks, 2015; Basurko and Mesbahi, 2014; Cabezas-Basurko et al., 2008). As a result, there has not been great progress like in other modes of transportation and there is not an established way to define it exactly or guidance for defining it, leading in confusion (Cabezas-Basurko et al., 2008). Sustainability objectives in shipping operations such as economic, environmental, energy efficiency cannot be achieved simultaneously, because they are conflicting (Mansouri et al., 2015). In addition, there are various stakeholders with different goals, time terms and key performance indicators to assess those goals (Armstrong and Banks, 2015). Among the various stakeholders involved in shipping sustainability, the most relevant ones for decision making are the ship-owners, charterers, shipbuilders, classification societies, regulators and the public.

In the literature, there have been some attempts that are discussed in the following paragraphs, to define and assess sustainability or some aspects of sustainability in shipping. Mansouri et al. (2015) performed a systematic literature review on environmental sustainability decision support methods employed in shipping for the years 2000-2015. It is evident from the paper findings that researchers aim for improving environmental sustainability through operational solutions, like speed and schedule optimisation or other operational approaches; however, no interest has been shown on design solutions.

Life Cycle Assessment (LCA) is an environmental management tool employed to quantify the life cycle environmental impact of a product or process (Azapagic, 1999). It has been widely applied to assess the environmental impact of transportation and some studies specifically adopted LCA in the shipping sector. Fet (2002) performed an environmental accounting and reporting for marine transportation based on LCA. Kameyama et al. (2007) and Tincelin et al. (2010) developed LCA software to estimate the environmental impact of ships. Other authors focused on the LCA of gas emissions from ships (Chatzinikolaou and Ventikos, 2015a, 2015b; Daskalakis et al., 2015; Gratsos et al., 2010). In other studies, only the power plant of ships was addressed; Ling-Chin and Roskilly (2016) and Koch et al. (2013) investigated alternative retrofit power plants with respect of their life cycle environmental performance according to LCA. Alkaner and Zhou (2006) performed an LCA on fuel cells comparing them with traditional diesel generators. Finally, in the literature, interest has been placed in performing

LCA on marine fuels (Bengtsson et al., 2011; Brynolf, Fridell, et al., 2014; Corbett and Winebrake, 2008; Gilbert et al., 2018).

The focus of the above studies is on the environmental aspect of sustainability only, whereas other aspects of sustainability have also been addressed in the literature. Basurko and Mesbahi (2014) presented a method to assess the three pillars of sustainability, but since each dimension is assessed separately it is challenging to manage the trade-offs. Landamore et al. (2007) tried to overcome this challenge by employing LCA, as well as Life Cycle Cost (LCC), and compare the alternatives by estimating the cost per environmental improvement against a benchmark technology. Other authors combined LCA with either the required freight rate (Hasegawa and Iqbal, 2000) or the material financial impact. The aforementioned practices do not manage to capture the economic life cycle performance of the vessel. Finally, Ellingsen et al. (2002) and Jeong et al. (2018) presented a method to support decisions on the environmental and economic sustainability of ships by combining LCA and LCC, the former focused specifically on fishing ships, whereas the latter only on the propulsion system of the ship.

Even though LCA has been used to assess the environmental sustainability of ships, this method is not quite compatible with ships (Cabezas-Basurko et al., 2008; Chatzinikolaou and Ventikos, 2014) or has to be critically used (Fet, 2002). Currently, there are no available databases for LCA in shipping so the databases of the land-based power plants have to be used. However, some parts of the LCA methodology are not consistent with sea transportation (Chatzinikolaou and Ventikos, 2014), leading to inaccurate results. Another issue is that in the maritime sector there is no model available for assigning the emissions found in the inventory, to the midpoint impacts (Chatzinikolaou and Ventikos, 2015b). This process requires the location and if it is not known it is not possible to evaluate the impact of emissions (Daskalakis et al., 2015). In addition, it is highlighted that information on emissions from some processes on the dismantling phase are generally not available (Chatzinikolaou and Ventikos, 2015b). Scholars support that the existing LCA software cannot meet the specific ship design (Tincelin et al., 2010) and many simplifications and assumptions need to be made for complex systems like ships. Finally, the impact categories on LCA are too generic and some polluting agents are not identified by the categories.

In the literature, there are various social sustainability assessment tools like Social Life Cycle Assessment; however, only a few cases found in the literature that assess the social impact of marine technologies (Basurko and Mesbahi, 2014; Ren and Lützen, 2015). Most of the existing social impact assessment tools are based on subjective assumptions (Cabezas-Basurko et al., 2008). This leads to two drawbacks. First, it is difficult to aggregate and compare the social impact assessment tool results with the results of the other dimensions of sustainability, since for the former the results are mostly qualitative, whereas for the other dimensions are quantitative. Secondly, due to the nature of the social impact assessment tools that are highly based on the user's input through questionnaires or interviews, the results might be considered biased (Basurko and Mesbahi, 2014). Moreover, social assessment tools are developed for land-based activities, since social impacts are influenced by the location and the socioeconomic situation (Basurko and Mesbahi, 2014), which is difficult to consider while assessing the sustainability of ships, where there is no specific location. As a result, they need to be altered to be applied to shipping operations (Cabezas-Basurko et al., 2008).

In this section, the literature related to assessing sustainability in shipping was discussed. It is identified that the majority of impact assessment methods do not manage to address the sustainability of marine technologies (Basurko and Mesbahi, 2014; Cabezas-Basurko, 2010; Fet and Sorgard, 1999). The focus of the majority of the studies is on the environmental aspect of sustainability, on some occasions, the economic aspect is integrated and in very few cases, the social dimension is considered. The challenges to perform LCA and assess the social impact in shipping were recognised. Finally, impact categories and databases need to be developed that will reflect the environmental and social impact of marine technologies (Basurko and Mesbahi, 2014).

2.3 Sustainability in ship energy systems

As the aim of this work is to improve the ship energy systems environmental and economic sustainability, the factors that affect significantly the ship energy systems sustainability are discussed in the following paragraphs of this section.

2.3.1 Importance of the design phase for ship energy systems sustainability

The design phase of energy systems is the phase of 'recognition of a need or economic opportunity', it is a critical stage because the decisions made define up to 80% of the capital cost of the system (Bejan et al., 1996). In addition, during the early design phase, the freedom to choose among the alternatives is quite high and the cost to make the changes is low, whereas, while the designing process continues the freedom is reducing and the cost is rising (Steen, 1999). For example, some emission abatement technologies can be installed only during the design phase, otherwise, they are more expensive when being retrofitted (Gaspar et al., 2014); in some cases, the retrofitting cost might be 40% more than a new built (Jiang et al., 2014).

According to Winnes & Ulfvarson (2006), the design phase is also critical in order to achieve better environmental performance over the ship lifetime. Along these lines, Princaud et al. (2010) support that environmental impacts can be improved in the design phase. After assessing all the economic, technical and environmental parameters and consider the trade-offs between them, the design variables can be defined (Boonstra et al., 2006). In addition, it is supported that the sustainability assessment of new alternative designs is crucial in order to obtain a design with a more sustainable performance (Basurko and Mesbahi, 2014). Including the environmental concerns in early design phases is preferred. Even though there are ways to retrofit older ships in order to improve their environmental performance and comply with the gas emission regulations, implementing emission control technologies on new designs is much easier and also some future regulations might prove hard to be satisfied if not considered in the design phase (Balland et al., 2012). Finally, it is supported that models used for the conceptual design of ships that incorporate and optimise all the considered objectives in the early design stage help avoid sub-optimal solutions (Whitfield et al., 1999).

Consequently, the early design stage of the vessel configuration is the most critical stage in terms of opportunities for improvement on the environmental and economic performance of ship energy systems. Finally, considering all the significant criteria in the early design phases helps to identify optimal designs.

2.3.2 Design for operation- the impact of the operating profile

According to traditional ship energy systems design techniques, the machinery is based on the previous experience or empirical criteria (Dimopoulos et al., 2008b) aiming to address only one design point requirement. Thus, disregarding the variable operating profile and the off-design conditions, which characterise the ship real-life operation. However, the vessel during its lifetime follows a variable operating profile (Banks et al., 2013), usually far from the design point (Coraddu et al., 2014). In one case examined in the literature, even though the design speed of the vessel was 21 knots, the measured data shipboard showed that the ship barely reached 16 knots during her operation (Shu et al., 2017). This results in underuse of the systems and as a consequence, leads to higher costs, potential reliability and safety issues (Dimopoulos and Kakalis, 2010), as well as less efficient operation.

According to Solem et al. (2015), the variable operating profile of the ship needs to be considered in the design process of a new systems configuration. The need for an expected variable operating profile in the systems configuration selection is implied by the variant response and efficiency of the engine in different load conditions. It is proposed that in order to accurately assess the performance of a system in the design phase, the expected operating profile of the ship has to be employed (Ahlgren et al., 2015). Depuis & Neilson (1997) have stressed how significant it is to consider the whole operating profile of the ship, even though it can be complex since it is affected by many parameters. Motley et al. (2012) also suggested that in order to improve the energy efficiency of the vessel for its lifetime operation, it is important to include an expected operating profile of the vessel and not just a single design point. As a result, there is rising interest in the academia (Baldi, Ahlgren, et al., 2015; Baldi, Gabrielii, et al., 2015; Mondejar et al., 2017; Sciberras and Norman, 2012) for the operating profile inclusion when evaluating the ship systems performance.

This growing body of literature adopting the operating profile for the ship energy systems simulation or optimisation demonstrates that the assessment of the energy systems has to be performed not only in the design conditions but include a full operating profile with off-design conditions.

2.3.3 Importance of gas emissions during the operational phase

The operational phase is considered the main and most significant phase of the ship life cycle in terms of the ship energy systems environmental impact. Kameyama et al. (2007) estimated that 98.3% of the environmental impact of the ship life cycle comes from the operational phase and more than 83% of the environmental impact is related to gas emissions. In respect to the exhaust gas emissions, more than 95% of the life cycle SOx, NOx and CO_2 emissions come from the machinery and are related to the ship operational phase (Chatzinikolaou and Ventikos, 2014, 2015b; Daskalakis et al., 2015). Moreover, it was derived that the hull subsystem does not have an impact on the emissions during the operational phase (Chatzinikolaou and Ventikos, 2015b) and the main contributor were the ship energy systems. In addition, Walsh and Bows (2011) reported that the greenhouse gas emissions, as well as the energy use during the shipbuilding phase, are less than 3% for the ship energy systems life cycle. On the other hand, the operating phase is by far the most impactful for the whole ship life cycle with respect to energy consumption from the ship energy systems (Andersson et al., 2016).

Furthermore, the results of studies on LCA performance of marine fuels showed that the highest impact comes from the tank-to-propeller phase, with percentages from 50-99% on the total life cycle depending on the fuel (Bengtsson et al., 2011).

Therefore, it is inferred that for the ship energy systems the dominant phase over the ship life cycle is the operational lifetime and their environmental impact is derived from the high exhaust gas emissions and the energy consumption.

2.3.4 Integrated ship energy systems

The interest of this work is the ship energy systems that consist of various components and sub-systems. Ship energy systems have many functions including propulsion, electric power generation and distribution, fuel treatment and supply, cargo heating, tank cleaning, fresh water, ventilation, bilge water, ballast water and firefighting systems (Woud and Stapersma, 2002). However, under the light of energy efficiency and environmental considerations, equipment like the ventilation or navigation are considered to have a trivial contribution to the aforementioned objectives (Baldi, 2013).

Ship energy systems are complex and are characterised by interconnections between the components. The following attributes accurately describe them: interactions among the various systems, a large number of components and non-linear interrelations of the systems (Baldi, 2016). For this reason, in order to assess the performance of the ship energy systems a more integrated approach is required. All the complex interactions between the components have to be considered, as changes in one sub-system of the ship energy systems might affect other subsystems with positive or adverse effects, due to the interconnections among the various components.

Therefore, a shift from component level to a system level with an integrated approach has to be adopted in order to address the systems complexity. In addition, it is recognised that a ‘whole system’ approach, generally in energy systems design is a necessary step for sustainable design (Stasinopoulos et al., 2009).

2.3.5 The influence of traditional and emerging technologies on the sustainability of ship energy systems

A variety of traditional and emerging technologies developed to reduce the ship energy consumption and to mitigate harmful emissions exists. According to the aim of this work to improve the economic and the environmental (air pollution) performance of ship energy systems, the most promising technologies are presented in Table 2.1 and discussed in this section.

Table 2.1 Promising technologies for ship energy systems

Prime Mover							
diesel engine	*dual-fuel engine*	*gas engine*	*fuel cells*	*gas turbines*			
Electric auxiliary engine							
diesel generator set	*dual-fuel generator set*	*fuel cells*					
Thermal boiler							
oil fired boiler	*gas fired boiler*						
Fuels							
HFO	*MDO*	*MGO*	*LSHFO*	*natural gas*	*methanol/ ethanol*	*hydrogen*	*biofuels*
Renewable energy sources							
solar panels	*wind turbines*						
SOx emissions abatement technologies							
scrubber							
NOx emissions abatement technologies							
SCR	*EGR*						
CO_2 emissions abatement technologies							
Carbon capture system							
Technologies to improve energy efficiency							
WHR	*shaft generator*						
Energy storage							
batteries	*thermal storage*						

Prime mover and electric auxiliary engines

The ship prime mover is responsible to convert the fuel chemical energy to mechanical in order to move the ship and it is one of the energy systems with the greatest impact on the fuel consumption and gaseous emissions. The capital cost is one of the main drivers of selecting a prime mover; therefore, the low capital cost diesel engines operating with fuel oils, such as HFO have been the traditional ship prime mover (Biert et al., 2016). The diesel engines had a percentage of 96% of installed power on board of all civilian ships above 100 GT in the year 2010 (Eyring et al., 2010). Another prime mover is the gas turbines that are mainly used in advanced ship types and naval vessels or Liquefied Natural Gas (LNG) carriers. Gas turbines have greater power to weight ratio than diesel engines (Woud and Stapersma, 2002). Another advantage is the reduced maintenance need, as well as low emissions. Their disadvantage is the high initial and operational cost (Harrington, 1992). In addition, they have lower efficiency than the diesel engines but this can be overcome when gas turbines are in a combined cycle. However, a combined cycle plant is not as efficient as a plant with the reciprocating engines (diesel or dual fuel) when operating in part load conditions (Dzida and Olszewski, 2011), which is very common for vessels. Previous studies showed that an operational optimisation on the combined cycle plant is required for achieving a better efficiency (Cwilewicz and Górski, 2014; Packalén and Karlsson Nord, 2017); however, it is not certain that a greater efficiency than the one of a plant with diesel engines will be ensured. Results comparing the combined cycle plant with the diesel electric system indicate that the inefficiency of the combined cycle in low loads leads to high energy consumption (Mrzljak, 2016).

Recently, the preference of the diesel engine as the optimal prime mover is challenged and the last decade other alternatives were introduced, due to the environmental legislation, the increase on fuel prices and the social pressure for more sustainable operation. Switching from the conventional cheap heavy fuels and the diesel engines or oil fired boilers to options with improved environmental impact has challenged the shipping industry. A conventional alternative is the fuel switch to a low sulphur content fuel, as the Marine Diesel Oil (MDO), Marine Gas Oil (MGO) or Low Sulphur Heavy Fuel Oil (LSHFO). However, in that way, only the SOx emissions are reduced and at the same time, the cost of these low sulphur content fuels is much higher than the HFO.

The dual fuel engines (two-stroke and four-stroke) have also been introduced, capable of operating with different fuels and switch between gas and liquid, like HFO, natural gas, Liquefied Petroleum Gas (LPG) methanol, ethanol as well as biofuels with improved environmental footprint. There are two technologies for dual fuel engines, the high-pressure solution is the direct injection, it is based on the Diesel cycle, where the pilot fuel starts the combustion and the gas or the liquid is injected after. The low-pressure one is the pre-mixed solution, which is based on the lean-burn Otto cycle, where fuel and air are premixed and burned at a relatively high air-to-fuel ratio. Other technologies are the gas engines (spark ignited) operating in the Otto cycle only with gas. The marine gas engines are only four-stroke with a limited range of nominal powers (0-9MW) (Rolls Royce Plc, 2017). In addition, recently there have been applications of fuel cells, operating with hydrogen, natural gas or methanol used for electricity production.

Fuel cells can be used for electric energy production and manage to reduce the emissions and improve the efficiency of ship energy systems. There are three types of fuel cells that have been applied to ships, the Proton exchange membrane (PEMFC), the Molten Carbonate (MCFC) and the Solid Oxide (SOFC). Fuel cells are still under development for commercial use and especially for the application on vessels, for this reason, the capital cost is very high.

In addition, they require the stack replacement every five years, thus increasing the maintenance costs (Alkaner and Zhou, 2006). Currently, the fuel cells types that are more prominent for marine applications are the MCFC and PEMFC (Welaya et al., 2011).

MCFCs as well as SOFCs can be internally reformed and thus provide fuel flexibility compared to other fuel cell types that can only use hydrogen (Horvath et al., 2018; Mcphail et al., 2015). They can operate with methane, methanol or even diesel. The nickel anode of MCFC works as a catalyst, which converts carbon monoxide and water to hydrogen that as a result releases the electrons and generates electric current (Mcphail et al., 2015). This is advantageous because even though hydrogen is a clean, environmentally friendly fuel there are safety and design issues regarding the storage of hydrogen (6 times larger than HFO (Taljegård, 2012)) and limitations on the design (Balsamo et al., 2017). In addition, sizeable tankers are required due to the low energy density of the hydrogen, as well as supply infrastructures that are viable for the marine industry need to be developed. On the other hand, PEMFCs operated by using pure hydrogen, therefore it is likely that their usage will be limited to hydrogen-fuelled ships (Welaya et al., 2011).

MCFC and SOFC are high-temperature fuel cells compared to PEMFC. Thus, greater system efficiency can be obtained by combining them with a waste heat recovery technology (Alkaner and Zhou, 2006). SOFC operate at a higher temperature than MCFC, which leads to challenges regarding the very high temperature and the electrolyte material (Ahn et al., 2018; Zhu, 2009)**.** Therefore, compared to the MCFC they exhibit lower technological maturity (Sharaf and Orhan, 2014). SOFCs are an emerging technology but their potential for scale-up in marine applications is linked with further technological developments (Milewski and Budzianowski, 2014).

MCFCs are one of the dominant technologies used in large scale stationary power plants (Wee, 2011) and are even used to cover a part of the electric requirements in South Korea, USA, Europe (Mcphail et al., 2015), after decades of development (Hart et al., 2018). MCFC also constitute an increasingly high percentage of the worldwide fuel cells installations in megawatts (EPA and CHP, 2015). Finally, MCFCs are a mature technology and have been successfully used on board ships (Bensaid et al., 2009; Han et al., 2012; Ovrum and Dimopoulos, 2012). Thus, they seem a prominent solution for the ship energy systems.

Fuels

Natural gas is a mix of hydrocarbons and consists of more than 90% of methane. Engines operating with natural gas reduce NOx emissions to 85-90% and almost completely particulate matters. In addition, natural gas has zero sulphur content and very low carbon content. Natural gas is transported and stored mainly in a liquid form, LNG. Other advantages of using LNG are the lower demand in electricity and heating compared to HFO, from not heating and separating the fuel like it is required for the HFO (Wärtsilä, 2009). However, due to the lower energy density of LNG compared to HFO and MGO, LNG fuelled vessels require approximately 2.3 and 1.5 times larger tanks respectively (Livanos et al., 2012) with specific characteristics that increase the overall cost of the ship (Taljegård, 2012).

LNG dual fuel engines are an established technology and currently, there are 120 LNG fuelled ships operating and additionally 120 that are recently built or ordered (Nilsen, 2018). Studies show that by the year 2020 the LNG fuelled ships are going to reach up to 500 (Nilsen, 2018). The highest growth of LNG vessels is identified on passengers ferries with 19% of the market, tankers with 17%, containers with 10% and cruise ships with 7% (Nilsen, 2018). It is forecasted that in the year 2030, fuel oil will still dominate the marine fuel market and natural gas will be second fuel in use, whereas in the year 2040 they will have an equal share (Taljegård, 2012).

LPG is a gaseous fuel with similar properties and handling as the LNG, however, it has not yet entered in a significant level the marine sector and has mainly been used in small commercial or recreational ships (WLPGA, 2018). Historic prices of LNG and LPG indicate that over the years 2008-2016, LNG had a significantly more competitive price compared to LPG. It was identified that LPG price reached almost 4.5 times higher than LNG and the lowest difference was two times higher (Brinks and Chryssakis, 2017). In addition, even though LPG is a mature fuel there are still barriers for the shipping sector due to the limited bunkering infrastructures (Brinks and Chryssakis, 2017).

Another clean fuel that has potential as a solution for reducing emissions from ships operation is methanol. IMO recently published a study discussing the possibilities of the use of methanol (IMO, 2016a). Methanol is one of the simplest alcohols and can be produced predominantly from fossil fuels or biomass. Similarly, to natural gas, it has almost negligible sulphur content and half of the natural gas carbon content. Methanol operating marine engines emit very low particulate matters and it is expected to reduce NOx emissions around 60% (DNV-GL, 2016; Maritime Knowledge Center; TNO; TU Delft, 2018).

The storage cost for methanol is comparably lower than the LNG, due to the fact that methanol is liquid at ambient temperature and there is no need for cryogenic technology. It is estimated that the cost of converting a ship to methanol fuelled is 75% less than LNG fuelled (Penjic, 2018). However, due to the lower heating value of methanol that is half of the HFO and the natural gas, in order to have the same power output, the amount of fuel required is almost doubled compared to natural gas. In addition, the fuel storage facilities required need to be larger than the ones for diesel and natural gas. Finally, methanol currently is not as competitive as the LNG, due to the high prices that in the last years are even higher than MGO (WLPGA, 2018).

In a comparison performed on the three preceding fuels, it was identified that they have the same impact on the SOx and particulate matter emissions reduction, however, LNG manages to performed better regarding the mitigation of NOx and CO_2 emissions (ClassNK, 2018).

Renewable energy sources

Renewable energy sources, like wind energy or solar manage to reduce the emissions from the ships and improve energy efficiency. There have been some applications of solar power and the benefits of the augmented auxiliary electric power were demonstrated (Atkinson, 2016; Lan et al., 2015). However, both renewable energy sources rely on the availability of intermittent natural resources like wind and solar, so it is not a stable source of energy and depends on the location of the ship journey. In addition, both options have low efficiency and require equipment that is costly and occupies great space and weight.

Emission reduction technologies

Another alternative to reduce the emissions from the exhaust gas of the engines are the after-treatment systems. The scrubber is described as ‘the main competitor’ of natural gas and it is estimated that natural gas is preferred for new built, however, the scrubber is highly used for retrofitting (Nilsen, 2018). There are three types of scrubbers wet, dry and hybrid. The first employs fresh (closed loop) or sea (open loop) water and the second uses a dry chemical. The last one is a combination of the two other types of scrubber. Open loop scrubber is the most commonly used scrubber type consisting of 63% of the scrubber towers installed currently (EGCSA, 2018).

Regarding the NOx emissions, the most common emission abatement technologies used are the Selective Catalytic Reactor (SCR) and the Exhaust Gas Recirculation (EGR). Diesel engines manage to comply with the Tier III limits only with the SCR. Both technologies require consumables and have an energy penalty on the ship energy systems due to their auxiliary systems operation.

An end of pipe solution for CO_2 emissions is the carbon capture and storage technology. It is a novel technology for ships and there are significant challenges to be addressed in order to be installed on ships, due to the ships nature of not being land-based. Therefore, the space for the carbon by-products and the resources to treat the carbon are limited. In addition, the extra space that the technology and by-products occupy reduces the potential carrying capacity (payload) of the ship and subsequently the profits of the shipping operations. However, there are some feasibility studies regarding the use of carbon capture on board ships and the results show a reduction of CO_2 emissions above 60% (PSE Ltd, 2013; Zhou and Wang, 2014).

There are three modes of carbon capture employed in onshore applications: the oxy, pre and post-combustion. In the first mode, the fossil fuel is burned with pure oxygen instead of oxygen with air, as a result, the products of the combustion are CO_2 and water; therefore, the CO_2 is captured from the flue gases condensing (Zhou and Wang, 2014). The pre-combustion takes place before the combustion process and first the fuel is converted into a mixture of hydrogen and CO_2 by gasification and then the CO_2 is captured before the combustion (Vasudevan et al., 2016). Finally, in the post-combustion, the CO_2 is captured from the flue gas after the combustion process (Wang et al., 2011). The solvent-based post-combustion carbon capture that employs chemicals to absorb the carbon from the flue gas (Wang et al., 2017) is the most promising technology used in land-based power plants (Luo and Wang, 2017). The greatest advantage of this technology is that it can be integrated into the existing type of power plants without affecting the combustion process (Cebrucean et al., 2014). One of the most promising alternatives of solvent-based post-combustion carbon capture that manages to reduce the energy penalty of the carbon capture technology is the calcium looping process known as the 'hot' combustion (Cebrucean et al., 2014).

Technologies to improve energy efficiency

A technology extensively used to improve the energy efficiency of the ship energy systems is the waste heat recovery (WHR), the applications of which have been extensively discussed (Rech et al., 2017; Singh and Pedersen, 2016; Song et al., 2015; Theotokatos and Livanos, 2013a). The heat content of the exhaust gas is used in order to generate saturated steam for the heating services or superheated steam that is provided to a steam turbine, which drives an electric generator producing electric power. Another way to exploit the heat content of the exhaust gas is through an Organic Rankine Cycle (ORC) that operates with an organic fluid and recovers energy from low-temperature sources. However, selecting the optimal fluid for the ORC is complex (Larsen et al., 2013) and optimising the selected fluid has gained great attention in the literature. It is estimated from the manufacturers that for new ships the waste heat recovery can offer up to 20% of the main engine power (Wärtsilä, 2009).

Another alternative, frequently used for electric energy production and improves the ship energy efficiency is the shaft generator. The main engine drives a shaft generator and therefore, the auxiliary generators that generally have higher fuel consumption are not operated, whereas the main engine operates on a stable and efficient load. In some cases, the shaft generator can be coupled with electric energy storage, so that the excess energy is stored and can be used for peak power requirements.

Energy storage

Electric energy storage (EES) technologies like batteries or ultra-capacitors have great potential on ships with a varying operating profile in order to smooth the fluctuating operating loads and improve the reliability and efficiency of the prime mover (Radan et al., 2016). Electric storage technologies assist the inclusion of renewable energy sources, like solar panels or wind turbines. In the literature, the electric energy storage systems shipboard have recently gained great attention. The analysis, size optimisation or power management of EES systems requires a specific transient profile of the ship and has been addressed in relevant literature for ships with long dynamic periods (Balsamo et al., 2017; Dedes et al., 2016; Lan et al., 2015; Ovrum and Bergh, 2015; Radan et al., 2016; Wen et al., 2016). However, transient operating profiles increase drastically the complexity of the optimisation problem.

The thermal energy storage improves the energy efficiency by storing the excess thermal energy. The thermal energy requirements shipboard is associated with the accommodation, as well as the fuel tanks heating. The heating requirements are provided from thermal boilers and from the heat content of the exhaust gas of the prime movers. In other industrial sectors, thermal storage has been extensively used and discussed; however, in the shipping industry, it has not gained great interest with few exceptions (Baldi, Gabrielii, et al., 2015).

From the preceding analysis, it is identified that there is a variety of technologies and fuels that manage to improve the energy efficiency and environmental impact of ship energy systems. The great number of alternative technologies and the possible combinations, as well as the various criteria to assess the configurations renders the selection of the ship energy system components a challenging process. In the next sections, the decision support methods for sustainable energy systems configurations existing in the literature and specifically for ship energy systems are discussed.

2.4 Decision support for sustainable energy systems

In this section, the relevant work in the literature regarding the decision support for sustainable energy systems is discussed. Ship energy systems have similarities with land-based energy systems. They are both complex systems that are related to energy production and consumption. Similar technologies are employed in land-based and ship energy systems and in some cases, the power plant of a big ship resembles the plant of a small town. They are both controlled by regulations, especially regarding their environmental impact. However, ship energy systems are more complex and restricted due to the offshore nature of their operation, as well as the fact that they do not have a stable operating location like the land-based power plants. In addition, the air pollution regulations for ship energy systems are only recently becoming stricter leading to the inclusion of new technologies, compared to the conventional power plant systems.

The decision support for sustainable energy systems has been extensively discussed in the literature and a variety of developed methods were presented. Accordingly, the literature related with the sustainability assessment and selection of energy systems is included in this work in order to complement the critical review and to gain a better understanding of the practises related with energy systems sustainability decision support.

2.4.1 Decision-making process

'Decision-making is the cognitive process leading to the selection of a course of actions among alternatives' (Lu et al., 2007). Decision support models are often used in order to aid the decision maker during the decision making process. The main factors responsible to make 'efficient and effective decisions' are the available, reliable information, as well as the decision maker's experience (Whitfield et al., 2007). During the decision making process, various criteria are taken into consideration because the evaluation of a decision from various point of views can lead to a clearer 'elicitation of preferences' (Roy, 2005).

Decision-making is a complex task and the greatest problem is how to assess the various alternatives with respect to the considered criteria (Triantaphyllou, 2010). The great number of parameters related in each decision has as a result, the requirement of computerised decision support tools to assist the decision maker (Lu et al., 2007). Multi-criteria Decision Making (MCDM) is a part of Operational Research that focuses on decision-making problems, when multiple criteria are involved (Pohekar and Ramachandran, 2004), specifically in the presence of criteria that are conflicting (Zavadskas et al., 2014).

MCDM methods can be divided into two groups, namely the Multi-attribute decision making (MADM) and the Multi-Objective Decision Making (MODM) (Kumar et al., 2017; Mardani et al., 2015; Pohekar and Ramachandran, 2004). The main differentiation between these two groups of methods is the number of alternatives that are evaluated. In the first group, there is a discrete number comparing to the latter, where there is theoretically an infinite number of alternatives (Mateo, 2012; Zavadskas et al., 2014). Figueira et al. (2005) presented a variety of methods and their applications; belonging to the first group are the Multi-attribute Utility Theory, the Analytic Hierarchy Process (AHP), the Outranking Methods (Electre, Promethee etc.), whereas methods of the second group are the Multi-objective Optimisation Methods (epsilon constraint, weighted sum method, multi-objective evolutionary algorithms).

AHP is a leading method in multi-criteria decision making (Krajnc and Glavic, 2005). AHP is applied to both qualitative and quantitative decisions; however, it is time consuming when there is a great number of criteria. On the other hand, Multi-attribute utility theory is more effective when there are many alternatives and criteria. Outranking methods are easily applied and manage to estimate the weaknesses and strengths of each alternative. In the aforementioned methods, a solution that performs best in one criterion and might have very low performance in others, in the end, is very low ranked, due to the fact that these methods face challenges in managing the trade-offs among the criteria. In addition, due to the interference of the decision maker, subjectivity and bias are introduced in the decision-making process. In contrast, multi-objective optimisation models manage the trade-offs among the objectives. Finally, they are effective in problems with a great number of alternatives; however, in some cases, they require considerable computational time.

2.4.2 Decision support for sustainable energy systems design

Henggeler and Henriques (2005) support that ‘the concern of sustainable provision of energy meeting the present needs without compromising the ability of future generations to meet their needs is inescapable in the development of decision support models in the energy sector’. Decision making in the energy sector is a challenging process and multiple criteria are considered.

Santoyo-Castelazo and Azapagic (2014) support that there is no best solution and trade-offs among the criteria are required to identify the most sustainable option. Tsoutsos et al. (2009) support that in the energy sector, multiple actors with different objectives are involved and an

MCDM method allows to integrate their objectives in the form of criteria. In addition, it is a method friendly to the user and provides meaningful and easy to communicate results. MCDM is widely known with different versions that can be applied to various problems and can capture the multifaceted aspect of sustainability with the multiple, usually conflicting objectives. Thus, MCDM methods are identified as an appropriate tool for sustainability in the energy sector and have been extensively used in the literature (Frangopoulos and Keramioti, 2010; Giannantoni et al., 2005; Lazzaretto and Toffolo, 2004; Mansouri et al., 2015; Pelet et al., 2005; Santoyo-Castelazo and Azapagic, 2014). Improving the sustainable performance of energy systems requires adopting an approach that integrates the techno-economic and environmental assessment (Gong and You, 2015; Santoyo-Castelazo and Azapagic, 2014).

Previous research on the decision support for sustainable energy systems design is presented in Table 2.2. The criteria considered for the assessment of the energy systems and the methods employed are discussed.

In the greatest majority of the presented cases, economic criteria are included in the decision support process. Therefore, it is indicated that for supporting decisions for sustainable energy systems, the economic criteria need to be considered. The possible economic criteria for the energy systems are namely the life cycle cost, internal rate of return, payback period (Frangopoulos and Keramioti, 2010), and total investment cost (Kong et al., 2015). Life cycle cost has been widely used in the literature for the energy systems design (Gerber et al., 2013; Ko et al., 2015; Mavrotas et al., 2007; Pelet et al., 2005; Wang et al., 2015) or in other cases, the annualised life cycle cost (Di Somma et al., 2017).

Regarding the environmental criteria in many cases the reduction of the main pollutants quantities (Afgan et al., 2000; Frangopoulos and Keramioti, 2010; Gerber et al., 2013; Ko et al., 2015; Pelet et al., 2005; Wang et al., 2015) or the maximisation of the technologies emissions reduction potential (Mavrotas et al., 2007) are considered. In other cases, the waste produced is considered as an environmental criterion (Afgan et al., 2000). Finally, it is identified that reducing the environmental impact should be a distinct objective even when the pollution cost is included in the economic objective (Frangopoulos and Keramioti, 2010; Lazzaretto and Toffolo, 2004).

Table 2.2 Studies on decision support for sustainable energy systems design

Authors	Criteria					Method						
	Ec	En	S	E	T	Rank	MAUT	WSM	AHP	SOO	MOO	Optimisation method
(Afgan et al., 2000)	✓	✓	✓					✓				
(Chatzimouratidis and Pilavachi, 2009)	✓			✓	✓			✓	✓			
(Di Somma et al., 2017)	✓			✓				✓		✓		
(Frangopoulos and Caralis, 1997)	✓	✓								✓		
(Frangopoulos and Keramioti, 2010)	✓	✓						✓				
(Gerber et al., 2013)	✓	✓									✓	MOEA
(Ko et al., 2015)	✓	✓			✓						✓	MOEA
(Kong et al., 2015)	✓	✓									✓	MOEA
(Krajnc and Glavic, 2005)	✓	✓	✓					✓	✓			
(Lazzaretto et al., 2018)				✓						✓		
(Lazzaretto and Toffolo, 2004)	✓	✓		✓							✓	MOEA
(Mavrotas et al., 2007)	✓	✓									✓	ε-constraint
(Pelet et al., 2005)	✓	✓									✓	MOEA
(Santoyo-Castelazo and Azapagic, 2014)	✓	✓	✓				✓					
(Streimikiene, 2010)	✓	✓				✓						
(Wang et al., 2015)	✓	✓										
(Wang et al., 2018)	✓			✓							✓	MOEA
(Yousefi et al., 2017)	✓			✓							✓	MOEA

Ec: Economic, En, Environmental, S: social, E: energy/exergy related, T: technical
Rank: Ranking methods, MAUT: Multi-attribute Utility theory, WSM: weighted sum method, AHP: Analytic hierarchy process, SOO: single objective optimisation, MOO: multi-objective optimisation, MOEA: Multi-objective Evolutionary Algorithm

In few cases in Table 2.2, other criteria like energy or exergy efficiency of the system (Frangopoulos and Keramioti, 2010; Di Somma et al., 2017; Wang et al., 2018) were also considered. Technical criteria like the reliability (Ko et al., 2015), the availability or capacity (Chatzimouratidis and Pilavachi, 2009) of the system were also included.

Finally, the social aspect is considered only in few studies focusing namely on new jobs indicators (Afgan et al., 2000), accidents (Krajnc and Glavic, 2005), public acceptability (Santoyo-Castelazo and Azapagic, 2014). Limited studies assess the social aspect, due to the limited resources of data to assess the social impact of energy systems (Frangopoulos and Keramioti, 2010). In specific, applications on optimising the social impact of complex energy systems are limited and identification and definition of quantitative criteria is required (Frangopoulos, 2018).

In the majority of the studies, optimisation methods are employed in order to identify the optimal energy systems configuration, design or operation and in the majority of the presented studies, the optimisation objectives were economic and environmental (Gerber et al., 2013;

Kong et al., 2015; Mavrotas et al., 2007; Pelet et al., 2005). In the decision support process of energy systems, there are multiple alternatives and possible combinations, resulting in a great number of energy systems designs to be evaluated. For this reason, optimisation techniques are employed to facilitate the evaluation process and support the decisions. According to Rao (2009) when designing engineering systems the decision maker aims to optimise the objectives considered and as a result optimisation is a method suitable in the design process.

In multiple objective optimisation techniques, the computational time is significantly increased, however, all the best know optimal solutions are discovered and the decision maker can be involved and make a decision with 'all the information on the table' (Mavrotas et al., 2007). Multi-objective optimisation techniques allow the decision maker to have a wide understanding of a set of optimal solutions of the energy systems, compared to a single objective (Lazzaretto and Toffolo, 2004). In single objective optimisations of energy systems, the results might satisfy one of the sustainability objectives but probably not the others, for example, a solution that has optimal cost in most cases does not have the optimal environmental impact (Frangopoulos, 2018). The objectives are often contradicting and there are trade-offs among them, however when these trade-offs are illustrated, the decision maker can make an informed decision (Pelet et al., 2005).

Addressing an optimisation problem with multiple objectives requires either transforming the problem into a single objective or solving it by employing multi-objective algorithms. It is evident from the literature presented that a potential method for the sustainable energy systems, when multiple objectives are considered, is to monetise external costs (Frangopoulos and Caralis, 1997). The environmental and social impact is translated into economic cost by employing coefficient factors in order to translate them into economic objectives and transform the multiple objectives problem into a single objective optimisation (Frangopoulos and Caralis, 1997). However in order to evaluate the external costs, first the environmental factors, the source of emissions, the geographical location, the population and the meteorological conditions have to be identified (Holland et al., 2005). Thus, the evaluation of external costs of emissions from ship energy systems include high uncertainty and many assumptions have to be made, due to the offshore nature of ship operations.

Another potential method to solve the multi-objective optimisation problem for sustainable energy systems are the multi-objective evolutionary algorithms, which were predominant in the presented studies (Gerber et al., 2013; Ko et al., 2015; Kong et al., 2015; Lazzaretto and Toffolo, 2004; Pelet et al., 2005; Wang et al., 2018; Yousefi et al., 2017). In specific the Non-sorting genetic algorithm II was employed in the majority of the cases (Ko et al., 2015; Kong et al., 2015; Wang et al., 2018; Yousefi et al., 2017). Therefore, it is inferred that the multi-objective evolutionary algorithms manage to address the decision support for optimal energy systems with respect to sustainability objectives.

Summarising, the practises to support decisions for the energy systems sustainable design were presented; the following key points were derived from the analysis. It is inferred from the analysis that the economic objective is significant and should be considered for the decision support of sustainable energy systems. In specific, the life cycle cost considerations were employed in the majority of the presented studies. In addition, regarding the environmental criteria for the energy systems, the reduction of the exhaust emissions amount was identified as the most predominant. In few studies, other criteria like technical, social or energy systems efficiency related, were included. In addition, the significance of optimisation methods and in specific multi-objective methods to support decisions for the energy systems due to the multiple alternatives and combinations, as well as objectives is underlined. Finally, it was underlined that multi-objective optimisation algorithms and specifically the Non-sorting genetic algorithm II was preferred in the majority of the studies.

2.5 Decision support for sustainable ship energy systems

In this section, the existing literature for supporting decisions on ship energy systems with sustainability considerations is discussed.

Covering the energy demand of a ship and in general of any consumer, there are various issues to be addressed. Accordingly, questions arise for the optimal system type, the various parts of the configuration, the technical characteristics of the technologies and the optimal operational conditions (Frangopoulos et al., 2002). As a result, for identifying the optimal energy system, the criteria of optimality need to be satisfied. In specific, when optimal sustainable energy systems are investigated, objectives that reflect different aspects of sustainability should be evaluated (Frangopoulos and Keramioti, 2010).

In the literature, few studies address the sustainability assessment of alternative marine technologies with a multi-criteria analysis technique. Ren and Lützen (2017) investigated the performance of energy sources for shipping in environmental, social, economic and technological criteria. From their work, it was inferred that the selected weights have a significant impact on the results. Similarly, Basurko and Mesbahi (2014) used LCA and LCC, in order to assess the performance of different technologies employed various sustainability indicators that were aggregated into one by introducing weights. Both approaches proposed a ranking of alternative marine technologies according to specific indicators; however, none of these methods manages to capture the complexity of the ship energy systems and simplifications were made regarding their performance.

Classification societies have compared and discussed alternative emission reduction technologies that can improve the environmental impact of ship energy systems. Alvik et al. (2009) presented the average abatement curves for alternative technologies and operational solutions to mitigate CO_2 emissions and it is derived that the inclusion of alternative fuels, renewable or waste heat recovery technologies manage to have the greatest reduction on CO_2 despite the fact that increases the cost. Lloyd's Register (2015) highlighted the challenges due to the air pollution regulations and compared the performance of alternative technologies to comply with the NOx and SOx emissions regulations.

In Table 2.3, previous studies that focused on the decision support for sustainable ship energy systems are presented and discussed in the following paragraphs. In the last column of the table, the focus of the optimisation method used is displayed. For energy systems, three levels of optimisation are identified: synthesis, design and operation (Frangopoulos et al., 2002). The components that appear on energy systems are defined as synthesis; therefore, the synthesis optimisation is the selection of the optimal components. In more detail, the generation of a number of possible alternative systems and selection among them according to their performance analysis is part of the synthesis process (Bejan et al., 1996). Synthesis entails the set of components and their interconnections, the design of a given system is related with the technical characteristics and the sizing of the components and finally operation of a given system expresses the operating specifications (Frangopoulos et al., 2002).

As it is evident from Table 2.3, an extended number of studies focused on alternative emission reduction solutions to reduce gas emissions from ships. Authors investigated the economic impact and possibilities of SOx emission reduction technologies (Gu and Wallace, 2017; Schinas and Stefanakos, 2014) or performed a cost-benefit analysis of sulphur reduction alternatives (Jiang et al., 2014). J. Corbett et al. (2010) assessed the economic and gaseous emissions reduction performance of black carbon technologies, whereas Yang et al. (2012) of NOx and SOx emission reduction technologies. In addition, researchers discussed the integrated performance of specific propulsion systems with emission abatement technologies regarding economic criteria (Wik, 2013) or including the technologies emission reduction performance (Gaspar et al., 2014). Others on the same topic evaluated the energy and emission

Table 2.3 Studies on decision support for sustainable ship energy systems (PS: propulsion system, HR: waste heat recovery, EC: emission compliance, TB: thermal boiler, EA: electric auxiliary, ECN: economic, GE: gas emissions, EEDI: Energy Efficiency Design Index, EE: energy efficiency, T: technical)

Authors	Ship Energy Systems					Criteria					Pareto based	Method	Optimisation of
	PS	HR	EC	TB	EA	ECN	GE	EEDI	EE	T			
(Ahlgren et al., 2015)		•							×	×		simulation &optimisation	ORC liquid
(Ahn et al., 2017)	•					×	×	×		×		simulation & AHP	
(Ammar and Seddiek, 2018)		•				×	×					simulation	
(Ancona et al., 2018)	•			•	•	×	×		×			simulation & optimisation	load allocation
(Armellini et al., 2018)	•		•				×		×	×		simulation	
(Baldi and Gabrielii, 2015)		•				×			×			simulation	
(Baldi et al., 2013)	•	•					×		×			simulation	
(Baldi, Ahlgren, et al., 2016)	•			•	•	×						optimisation	load allocation
(Baldi et al., 2017)	•	•							×			optimisation	design (sizing)
(Baldi et al., 2018)	•	•	•	•	•				×			simulation	
(Baldi et al., 2019)					•	×						optimisation	design
(Balland et al., 2014)	•		•			×		×				optimisation	synthesis
(Benvenuto et al., 2014)	•	•			•	×		×	×			simulation	
(Burel et al., 2013)	•	•				×	×		×			simulation	
(Corbett, Lack, et al., 2010)			•			×	×					simulation	
(Dimopoulos et al., 2008b)	•	•				×						optimisation	synthesis/ design/ operation
(Dimopoulos et al., 2016)		•			•				×	×		optimisation	design
(El Geneidy et al., 2017)		•						×	×			simulation	
(Gaspar et al., 2014)	•		•			×	×					simulation	
(Grljušić et al., 2015)		•							×			simulation	
(Gu and Wallace, 2017)			•			×						simulation	
(Hountalas et al., 2012)		•							×			simulation	
(Jiang et al., 2014)			•			×	×					simulation	
(Jianyun et al., 2018)	•				•	×	×		×		✓	optimisation	design (sizing)
(Kalikatzarakis and Frangopoulos, 2015)		•				×	×					MC analysis & optimisation	design/ operation

(Kalikatzarakis and Frangopoulos, 2016)		•				×						optimisation	synthesis/ design/ operation
(Kyriakidis et al., 2017)		•	•						×			optimisation	design
(Lan et al., 2015)					•	×	×				✓	optimisation	design (sizing)
(Larsen et al., 2013)		•								×		optimisation	ORC liquid
(Livanos et al., 2014)	•	•	•			×		×				simulation	
(Mavrelos and Theotokatos, 2018)	•						×			×		simulation	
(Mondejar et al., 2017)		•							×			simulation	
(Sakalis and Frangopoulos, 2018)	•	•		•	•	×						optimisation	synthesis/ design/ operation
(Schinas and Stefanakos, 2014)			•			×						simulation	
(Sciberras and Norman, 2012)	•				•				×	×	✓	optimisation	design (sizing)
(Rech et al., 2017)	•	•							×	×		simulation	
(Shu et al., 2017)		•				×				×		simulation	
(Soffiato et al., 2015)		•							×			optimisation	design
(Solem et al., 2015)	•					×						optimisation	load allocation
(Tadros et al., 2019)	•								×			optimisation	design
(Theotokatos and Livanos, 2013a)		•				×				×		simulation	
(Tzortzis and Frangopoulos, 2018)	•	•		•	•	×						optimisation	synthesis/ design/ operation
(Wen et al., 2016)					•	×						optimisation	design (sizing)
(Wik, 2013)	•		•			×						simulation	
(Yang et al., 2012)			•			×	×			×		simulation & AHP	
(Yang, 2015)		•				×						optimisation	design
In this research	•	•	•	•	•	×	×				✓	*optimisation*	*synthesis*

reduction efficiency, as well as including technical criteria (Armellini et al., 2018). Finally, Balland et al. (2014) optimised the selection of a propulsion system with NOx and SOx emission reduction technologies with regard to economic criteria while considering the EEDI.

The WHR system was also investigated as an alternative to improve the ship power plant efficiency and as a result, reduce the fuel energy consumption and the gaseous emissions. The potential of different WHR systems was reviewed in Singh and Pedersen (2016). Several authors investigated the performance of a WHR system on a specific ship type; either considering economic and technical criteria (Baldi and Gabrielii, 2015; Shu et al., 2017; Theotokatos and Livanos, 2013a), just technical (Mondejar et al., 2017), economic and gaseous emission reduction (Ammar and Seddiek, 2018) or considered the energy efficiency of the system (El Geneidy et al., 2017; Grljušić et al., 2015; Hountalas et al., 2012). Finally, models were developed to simulate the performance of WHR from dual fuel engines in off and on design conditions (Rech et al., 2017).

A variety of studies discussed the design or fluid selection optimisation of an ORC integrated on a ship power plant regarding various technical, economic and efficiency criteria. Fluid selection for an ORC is a challenging task with more than 75 fluids available (Kalikatzarakis and Frangopoulos, 2015). For this reason, the fluid optimisation of an ORC with regards of energy efficiency and technical criteria was reported in Ahlgren et al. (2015) or considering only technical criteria in Larsen et al. (2013).

The synthesis of the ORC with multi-criteria analysis and then the design, as well as operation optimisation (Kalikatzarakis and Frangopoulos, 2015) considering economic objectives was presented. The economic synthesis, design and operation optimisation (Kalikatzarakis and Frangopoulos, 2016) or just the design optimisation (Soffiato et al., 2015; Yang, 2015) of an ORC was addressed in the literature. The ORC optimisation integrated with other ship energy systems was also discussed. The design optimisation of an ORC combined with an MCFC for electric energy production was performed with technical and energetic considerations (Dimopoulos et al., 2016). Finally, the energy efficiency optimisation of an integrated ORC with an after-treatment technology was presented in Kyriakidis et al. (2017).

The investigation of alternative propulsion systems and their integration with emission reduction or WHR technologies considering different objectives was reported in the literature. The cost-benefit analysis regarding economic, technical, environmental criteria and the EEDI index of a propulsion system for a liquefied hydrogen tanker was addressed (Ahn et al., 2017). The introduction of the LNG fuel for propulsion with a WHR, in order to reduce CO_2 emissions as well as the operational costs while improving the energy efficiency, was presented (Burel et al., 2013). Baldi et al. (2013) examined the carbon footprint reduction and exergy efficiency of alternative propulsion systems for a tanker, including dual fuel engines and a WHR system. The techno-economic and EEDI performance of alternative propulsion systems for Ferries and RoRo ships including dual fuel and diesel engines, Selective Catalytic Reduction (SCR) and WHR technology was investigated (Livanos et al., 2014). Different configurations of a tanker including the propulsion system, the electric auxiliary engines and a WHR were analysed with economic and energy efficiency criteria, as well as considering the EEDI (Benvenuto et al., 2014). Finally, the exergy and energy analysis of the integrated system of a cruise ship, including the main energy systems, emission reduction technologies and a WHR system was presented (Baldi et al., 2018).

Furthermore, several studies employed optimisation techniques to support decisions for the propulsion system of the ship integrated with other ship energy systems. In very few cases, the simultaneous optimisation of the synthesis, design and operation of the ship energy systems was addressed by employing the superstructure approach. Dimopoulos et al. (2008) performed the three levels optimisation of a cruise ship propulsion system with a gas turbine and heat recovery for steam and electric production with respect to economic objectives. Similarly, the economic optimisation of an integrated power plant configuration of an LNG carrier that includes a WHR was presented (Tzortzis and Frangopoulos, 2018). Finally, the economic three levels optimisation of the integrated ship energy systems of a superstructure including the main engine, the electric and thermal auxiliaries, as well as the heat recovery was developed (Sakalis and Frangopoulos, 2018).

In other studies, the design optimisation of the propulsion system was discussed. Proposing more innovative propulsion systems, the sizing optimisation of a hybrid propulsion system was performed with objectives the fuel consumption and the installation weight (Sciberras and Norman, 2012). The parametric optimisation of a two-stroke dual fuel engine with respect of the NOx and CO_2 emissions reduction was investigated (Mavrelos and Theotokatos, 2018). Baldi et al. (2017) performed an energy efficiency optimisation for the sizing of a cruise ship power plant, including the propulsion system and a WHR. The design optimisation of a four-stroke diesel engine with objective the fuel consumption reduction and the NOx, as well as CO_2 emissions was reported (Tadros et al., 2019). Finally, the sizing optimisation of a hybrid propulsion system for a tug vessel with objective the fuel consumption, the CO_2 emissions and the cost was presented (Jianyun et al., 2018).

Regarding the operational optimisation of the propulsion system, a variety of studies was presented focusing on complex ship power plants, like hybrid systems. The economic optimisation of the load allocation of the configurations of complex ship power plants including the propulsion, electric and thermal systems was presented (Baldi, Ahlgren, et al., 2016). Ancona et al. (2018) in a similar work optimised the load of two different propulsion systems and further analysed the energy efficiency and environmental impact of the alternatives. Solem et al. (2015) proposed the economic optimisation of an electric propulsion system.

Finally, innovative technologies that provide electric and thermal auxiliary power leading to an improved environmental impact were investigated. The possibility of employing fuel cell systems on maritime applications as auxiliary electric power in order to reduce the ship emissions was discussed by Biert et al. (2016). In addition, the optimal hybrid system sizing including photovoltaic systems, batteries and diesel generators with economic objectives (Wen et al., 2016) or minimising economic CO_2 emissions (Lan et al., 2015) was addressed. The design optimisation of the cogeneration of SOFC and PEMF along with battery storage with economic objectives was also developed (Baldi et al., 2019).

From the preceding discussion and Table 2.3, it is inferred that the criterion that is used in the majority of the studies is the economic, either considering the investment, maintenance, fuel consumption cost or addressing all of them. The social aspect of sustainability is not considered in any of the approaches. In addition, the energy or exergy efficiency is frequently used as an objective, because improving the energy consumption of the systems leads to decreasing the operational cost and the gaseous emissions. Furthermore, there is a growing interest to incorporate the EEDI index in the assessment process. Only in few occasions, the technical objectives and the emissions from the exhaust gas of the engines were considered, even though there is a rising concern for the reduction of the emissions.

The gaseous emissions are a vital part when evaluating the ship energy systems, due to the increasing regulations regarding their mitigation. This is evident by the fact that the gaseous emissions are used as a criterion to compare the alternatives considered in a large number of studies. However, the minimisation of the gaseous emissions was included in the objective function of the optimisations only in two cases. In both approaches, the CO_2 emissions were employed as an objective for the sizing optimisation of the main engine of a hybrid configuration (Jianyun et al., 2018) or a diesel engine with photovoltaic and battery configuration (Lan et al., 2015).

It is highlighted in Table 2.3 that there are limited studies considering the integrated ship energy systems. The majority have focused on the assessment of one or two specific components, a specific predefined propulsion system or in few cases performed a comparative assessment of a limited number of potential alternatives. The greatest part of the literature focuses on the propulsion system and the waste heat recovery from the exhaust gas of the engines. The emission reduction technologies and alternatives to reduce emissions have been also gaining attention. On the other hand, the auxiliary electric system is included only in few cases, especially when there is focus on the design or operational optimisation of a hybrid configuration. Finally, the thermal auxiliary boiler is considered only in few studies that either focus on a specific configuration, or perform exergy analysis.

In the previous section, the benefits of multi-objective optimisation for supporting decisions for sustainable energy systems were discussed. However, from the literature review of the ship energy systems decision support methods, it was identified that in the majority of the cases the authors employed a single objective method and only in very few applications, a multi-objective optimisation approach was employed (Jianyun et al., 2018; Lan et al., 2015; Sciberras and Norman, 2012). In those cases, a multi-objective evolutionary algorithm named Non-sorting genetic algorithm II was used in order to identify the Pareto front of the optimal solutions. It is also highlighted from Table 2.3 that all the multi-objective optimisation approaches focused on the design optimisation regarding the sizing of the configurations, whereas there was no evidence of studies that performed multi-objective optimisation for the synthesis of the ship energy systems.

A final comment is that the optimisation methods on the studies presented are mainly focused on the operation or design optimisation of the ship energy systems. The synthesis optimisation is discussed only by few authors (Balland et al., 2014; Dimopoulos et al., 2008a; Kalikatzarakis and Frangopoulos, 2016; Sakalis and Frangopoulos, 2018; Tzortzis and Frangopoulos, 2018). Synthesis optimisation of energy systems is the most challenging among the other levels of optimisation and in most of the cases, the design and/or the operational optimisation can be addressed effectively by existing methods (Frangopoulos, 2018). In specific, it is indicated that the design and operation of a given system can be attained with quantitative methods with the configuration performance evaluation, whereas in cases that the synthesis is not known, both quantitative and qualitative decisions need to be made (Frangopoulos et al., 2002). The multitude of alternatives makes it impossible for the designer to assess all the energy systems and select the optimal, therefore an ‘automated procedure’ would be imperative (Frangopoulos et al., 2002; Sakalis and Frangopoulos, 2018).

Finally, as it was identified in Section 2.4, in the decision support method for energy systems that there are several alternatives to be evaluated; therefore, optimisation techniques are suitable to facilitate the decisions support process. As a result, the decision support methods that employ optimisation techniques for the synthesis of the ship energy systems are further discussed in the following section.

2.5.1 Ship energy systems synthesis optimisation

In the previous section, the different studies focused on the decision support of ship energy systems with sustainability objectives were presented. In this section, the methods developed specifically for the synthesis optimisation of the ship energy systems in order to improve their sustainability are discussed.

Several methods to select an optimal energy system exist in the literature and have been applied for the ship energy systems synthesis. A complete enumeration of all alternatives considered is a simple but computationally demanding method that guarantees the optimal identification of the solution, however, it is preferred in smaller problems (Gong and You, 2015). A method frequently used for the optimisation of energy systems synthesis is the superstructure approach, where all the possible technologies, as well as their interconnections, are considered (Frangopoulos et al., 2009). This approach succeeds in finding the optimal, though it is not appropriate when a great number of alternative technologies have to be investigated, making the problem very large and complex (Gong and You, 2015). Finally, the optimal solution is restricted by the initial superstructure configuration considered (Frangopoulos et al., 2002) and there is a limit of alternative technologies introduced to the superstructure due to the rising complexity.

In Table 2.4, the synthesis optimisation approaches identified in the literature regarding the ship energy systems with sustainability objectives are presented. Balland et al. (2014) introduced the single-objective economic optimisation of emission control alternatives to satisfy the regulations over the ship lifetime including installation, maintenance and emission control replacing cost. In this work, the possibility of installing an emission control alternative and the propulsion system configuration, as well as the fuel type were the decision variables. The authors underlined the significance of concurrently optimising the propulsion system with the emission control solutions, in order to avoid sub-optimal solutions and stated that it leads to life-cycle economic optimal configurations.

Dimopoulos et al. (2008b) proposed the annual capital and operational cost optimisation of a gas turbine co-generation configuration. In this approach, the synthesis, design and operation were optimised with an evolutionary algorithm with objective the total capital cost and annualised operational costs. A predefined propulsion system that consisted of gas turbines that operate with MGO was considered. The synthesis variables were the number of gas turbine units, the existence of another set of similar gas turbines with moderate nominal power, the type of a heat recovery system and the possible interconnections with the gas turbines and the existence of a steam turbine unit. As a result, the engines type and fuel type were predetermined, in addition, the emission control technologies, as well as the auxiliary boiler, were not included.

Kalikatzarakis and Frangopoulos (2016) performed a synthesis, design and operation optimisation of an ORC system aiming to minimise the present worth life cycle cost of the system. The synthesis decision variables in the latter work were related to the ORC system layout, the heat source the interconnections and the fluid type used.

Sakalis and Frangopoulos (2018) optimised the present worth life cycle cost of the synthesis, design and operation of ship energy systems. The integrated ship energy systems were considered in the analysis due to the importance of the interconnections, including the propulsion, electric and thermal sub-system as well as the waste heat recovery. A predetermined ship energy systems configuration was considered and the synthesis decision variables in the optimisation problem were the number of the main engines, electric auxiliaries, thermal boiler and the layout of the heat recovery system.

Finally, Tzortzis and Frangopoulos (2018) performed a dynamic optimisation of the present worth cost life cycle cost of a superstructure configuration. Similar with the previous study, a predetermined ship energy systems configuration was considered and the synthesis decision variables were the number of main engine, auxiliary generators, boilers and the heat recovery system layout.

Table 2.4 Studies on decision support for sustainable ship energy systems synthesis optimisation (ME: main engine, HR: waste heat recovery, EC: emission compliance, TB: thermal boiler, EA: electric auxiliary)

Authors	Ship Energy Systems Synthesis decision variables												Optimisation Objective		Optimisation stage
	ME			HR		EC	TB			EA			Economic	Environmental	
	type	#	fuel type	existence	layout	type	type	#	fuel type	type	#	fuel type			
(Balland et al., 2014)	•	•	•			•							Present worth life cycle cost	-	synthesis
(Dimopoulos et al., 2008b)		•		•	•								Annual capital & operational cost	-	synthesis, design, operation
(Kalikatzarakis and Frangopoulos, 2016)					•								Present worth life cycle cost	-	synthesis, design, operation
(Sakalis and Frangopoulos, 2018)		•			•			•			•		Present worth life cycle cost	-	synthesis, design, operation
(Tzortzis and Frangopoulos, 2018)		•			•			•			•		Present worth life cycle cost	-	synthesis, design, operation
In this research	•	•	•	•		•	•		•	•	•	•	***Present worth Life cycle cost***	***Lifetime exhaust gas emissions***	***synthesis***

In the presented studies the authors underlined the importance of taking into consideration the various operating conditions, due to the impact they have on the decisions regarding the synthesis and design of the ship energy systems (Sakalis and Frangopoulos, 2018). Different operational modes were included, instead of the traditional one design point. The performance of the systems was optimised according to an operating profile and the authors assumed representative operational stages like sailing in deep sea (ballast, laden), transit, and loading in port. They considered only the maximum power for each stage. Even though more than one design points were included, in none of the existing synthesis optimisations methods the variable operating profile, including all the potential off-design conditions, was identified. An expected operating profile with both on and off design conditions was employed in operational optimisation (Ancona et al., 2018; Baldi and Gabrielii, 2015) or assessment of specific alternatives of ship energy systems (Baldi et al., 2013), indicating the importance of the variable profile inclusion on the optimisation process.

In all the cases, an economic single objective optimisation was performed and in the majority of the studies the present worth life cycle cost was considered and it is identified as an appropriate indicator to evaluate the economic performance of ships (Ahn et al., 2017). Furthermore, from Table 2.4 it is evident that none of the existing studies included the environmental impact of the ship energy systems. In addition, it was identified that in the pertinent literature, the synthesis optimisation does not support decisions for the type of the integrated energy systems: the type of the main engine, the auxiliary electric and the boiler system, or their fuel type. The attention is identified on the number of units, or the heat recovery system layout. Finally, only in one occasion, the emission control technologies alternatives were considered in the optimisation process.

In the next section, the summary and the research gaps identified from the presented critical review are discussed.

2.6 Key findings and Research Gaps

The following key findings were identified from the presented literature:

- Sustainability in shipping is a relatively new area and the majority of the research and decision support methods developed aiming at the improvement of the ship environmental sustainability focuses on solutions at the operational stage. However, the design phase is the most critical in order to improve the ship energy systems environmental and economic sustainability. Therefore, it is derived that a requirement for a decision support method that aims to improve the ship energy systems sustainability is that the method should be designed for the early design phase when the ship energy systems are selected.

- LCA has been used as a tool to assess ship environmental sustainability; however, there are great challenges in implementing it in shipping. In addition, limited studies focused on the social impact assessment of energy systems and specific ship energy systems due to the limited resources of data. As a result, in order to reduce subjectivity in the decision support method the social impact should not be included and an alternative method than LCA should be selected to assess the environmental performance of ship energy systems.
- A realistic operating profile needs to be considered for the ship energy systems assessment and not only a design point. The operational phase of the ship energy systems life cycle is the most important regarding the gaseous emissions and energy consumption. These findings indicate that the proposed decision support method should assess the ship energy systems performance according to a realistic operating profile and the focus should be on the ship energy systems operational phase.
- It was identified that a variety of alternative technologies and fuels exist in order to comply with the strict environmental regulations. The proposed decision support method should include the technologies that are the most promising for the ship energy systems. Therefore, an analysis is required to screen these technologies and include the most prominent.
- The literature indicated that an integrated approach of the ship energy systems is required to address their complexity, as well as to achieve sustainable design. This finding denotes that the proposed decision support method requires that the systems are modelled following an integrated approach that considers their interconnections.
- Sustainable decision making in the energy sector is a complex process and environmental, as well as economic objectives, need to be considered in order to improve the energy systems sustainability. As a result, there is not only one optimal solution derived and trade-offs among the objectives need to be managed. In energy systems design, optimisation methods were extensively used and specifically with multiple objectives. It was also identified that the multi-objective evolutionary algorithms address the complexity of energy systems design and the Non-sorting genetic algorithm II was used in the majority of the problems.

- In the majority of decision support studies for ship energy systems sustainability, the criteria considered were economic and energy-related, and only in few cases, the emissions were included. In specific, the gaseous emissions as an objective function on the optimisation of the ship energy systems were considered only in few cases, where the sizing of specific components was optimised.
- For the ship energy systems synthesis optimisation, the authors in the existing literature performed a single objective optimisation, with economic objectives. In addition, they included representative operating stages and not an extended operating profile with off-design conditions. Finally, none of the synthesis optimisation studies presented optimised the type of the main engine, the auxiliary electric and the boiler system, or their fuel type.

This thesis aims to address the following gaps in scientific knowledge:

Improving the energy systems sustainability entails the simultaneous consideration of environmental and economic objectives. For this reason, the existing methods for supporting decisions for sustainable energy systems include both environmental and economic objectives in the optimisation process. In addition, it is important to include the ship variable, expected operating profile in order to accurately assess the performance of the ship energy systems for the ship lifetime operation. However, decision support methods for ship energy systems synthesis optimisation considered only the traditional economic objective and optimised the ship energy systems performance according to representative operating stages.

Gap 1: Therefore, there is a lack of approaches that optimise the environmental objective along with the economic objective in order to support decisions for the ship energy systems synthesis, whilst evaluating the systems according to a variable expected operating profile. As a result, the existing studies on ship energy systems synthesis do not manage to simultaneously evaluate the environmental and economic performance of ship energy systems, thus derive optimal solutions that improve both aspects of sustainability over the ship lifetime performance.

The ship energy systems include a large number of components and there are many alternative technologies, therefore increasing the potential solutions and making their evaluation challenging. In the existing literature, studies have focused on the assessment of one or two specific components, the optimisation of a specific predefined propulsion system or in other cases performed a comparative assessment of a limited number of potential alternatives.

Gap 2: However, there is a lack of a more general approach that supports decisions and optimises the integrated ship energy systems synthesis. Specifically, one that supports the selection of the main ship energy systems type, the type of fuels and the type of technologies to improve the energy efficiency and environmental performance of the systems.

2.7 Chapter Summary

In this chapter, the review of the existing literature was presented. Initially, the sustainability in shipping and in specific in ship energy systems was discussed. The factors that affect significantly the ship energy systems sustainability were presented. Following, the current status on decision support for sustainable energy systems was described, focusing on the criteria as well as the methods employed. Moreover, a state-of-the-art literature review on the decision support for sustainable ship energy systems and in specific ship energy systems synthesis was performed. The key points derived from the presented literature review were summarised and finally, the gaps in the existing literature were discussed. The research approach adopted in this thesis to cover the identified gaps is presented in the following chapter.

3 Research Approach

3.1 Introduction to chapter

This chapter introduces the research approach adopted in this thesis. In Section 3.2, the philosophical assumptions of this research are discussed. The research methodology approach as it was directed from the philosophical assumptions is presented in Section 3.3. The methodological steps followed to ensure that the research aim and objectives are respected, are elaborated in Section 3.4. Finally, the overall research design is outlined in Section 3.5.

3.2 Research Philosophy

The research philosophy adopted underlines significant assumptions regarding the way the research views the world (Saunders et al., 2009). The philosophical ideas behind the research, even though are mainly hidden they have a strong influence on the research and have to be recognised (Creswell, 2009). The main influence is regarding the researcher’s view on the relationship between knowledge and the process that knowledge is developed (Saunders et al., 2009). There are different approaches for conducting research that can be explained through two dimensions: ontology and epistemology. These two dimensions are further elaborated in the following paragraphs.

3.2.1 Ontology

Parmenides a Greek philosopher was one of the first to introduce the philosophy called ‘ontologia’, which deals with the examination of the meaning of ‘being’. Ontology is defined as the nature of reality and existence (Easterby-Smith et al., 2012). It is related with the assumptions in respect of the nature of reality (Saunders et al., 2008). The main ontologies according to Saunders et al. (2008) are objectivism and subjectivism. Objectivism adopts the position that reality exists regardless of external social actors (Saunders et al., 2008), the truth exists independent of whom observes it. Objectivism focuses on the facts, deals with causality and fundamental laws, is reductionism and operationalises ideas in order to quantify and measure them. On the other hand, subjectivism adopts the position that entities are created from ‘the perceptions and consequent actions of social actors’ (Saunders et al., 2008). In comparison with the previous approach, subjectivism focuses on meanings and aims to understand peoples’ interpretations as well as the reality of the details behind a situation (Remenyi et al., 1998).

3.2.2 Epistemology

Epistemology is ‘a set of assumptions about ways of inquiring into the nature of the world’ (Easterby-Smith et al., 2012). Guba and Lincoln (1994) defend that epistemology inquires: what is the nature of the relation between the knower and what can be known? According to Saunders et al. (2009), the researcher’s assumptions regarding human knowledge about reality, frame how the research question is understood and how the research is designed. Four approaches are acknowledged (Saunders et al., 2009): positivism, realism, interpretivism and pragmatism. The first two philosophies that adopt a clear objective worldview and are most prominent for engineering research (Reich, 1994), which is the subject of this research are elaborated.

According to Kumar (2011), the researcher that adopts a positivist approach should not be biased and should maintain objectivity regarding the process of the research, as well as the analysis of the findings and conclusions. Positivistic statements are descriptive, factual and researchers try to identify the cause that influences the outcome (Creswell, 2009). The following principles according to Easterby-Smith et al. (2012) complement the characteristics of the positivist approach:

- independence of the observer from what it is observed
- the choice of the research study and methods is made with objective criteria
- deduction of observations that will demonstrate the truth or falsity of the hypothesis
- empirical operationalisation of concepts so that the facts can be measurable
- reduction of the problem to simpler ones
- generalisation.

The researcher is not dependent on the data of the research undertaken, he is not biased and holds an objective position, thus the research is considered as value-free as possible (Saunders et al., 2009).

Realism’s essence is that ‘what the senses show us as reality is the truth: that objects have an existence independent of the human mind’ (Saunders et al., 2009). It is defined by Phillips as “the view that entities exist independently of being perceived, or independently of our theories about them” (Phillips, 1987). Realism, similarly to positivism, embraces an objective worldview. However, realism assumes that a reality exists independently of the human mind and humans can access it indirectly through their senses (Saunders et al., 2009). On the other hand, positivism embraces that reality can be observed, is measurable and can be analysed and verified through logic. Another difference with positivism is the fact that realism understands causality as a potential and not an automatic correlation of actions and events (Easterby-Smith et al., 2012). Two types of realism exist, the direct one that considers that what we feel through our senses depicts reality and the critical realism that argues that what we experience is sensations, which in the end portray the reality (Saunders et al., 2009). Finally, the research is value-laden, in other words, bias is introduced by worldview or culture and experiences that will have an effect on the research (Saunders et al., 2009).

3.2.3 Adopted philosophical approach

From the proceeding analysis, it is argued that the ontology embedded in this research is objectivism and the philosophical stance behind the methodology is positivism for the following reasons.

Firstly, the aim of this research is to support decisions for ship energy systems synthesis in order to contribute towards the environmental and economic sustainability improvement of ship energy systems over the ship lifetime. This requires analysis of the ship energy systems and their interconnections, as well as develop models to estimate the systems performance. A computational multi-objective optimisation model is required to identify the optimal configurations, regarding economic and environmental objectives. Therefore, the study presented in this thesis focuses on engineering design and sustainability assessment science. In the domain of engineering science and design, positivism is a predominant epistemological stance (Horváth, 2004; Reich, 1994; Wang and Duffy, 2009). In addition, sustainability development science research with a positivist approach aims at describing, explaining and predicting the environmental quality as a function of the human behaviours (Boersema and Reijnders, 2009), which is a part of this study.

Secondly, ship energy systems operate according to physical laws, their performance is estimated from observation and prediction of the outcome according to measurements provided by manufacturers’ experiments, so the scientist opinions do not affect the outcome. In that respect, the researcher is detached and his/her values and subjective feelings do not interfere with the research and the findings.

Thirdly, the reality is viewed as deterministic, following the cause and effect law. In addition, the researcher aims to identify mathematical statements about the facts under investigation and explores their causal connections. A reductionism approach has to be embraced to express the complexity of the ship energy systems. Finally, the performance of the ship energy systems and the results from the optimisation are measurable and quantifiable. It is evident from the analysis that the assumptions of the research presented in this thesis follow the positivist approach and the objective worldview.

3.3 Research Methodology

Methodology, the ‘theory of methods’ (Reich, 1994) is defined as ‘the combination of techniques used to inquire into a specific situation’ (Easterby-Smith et al., 2012). In other words, it is described as the way the methods and techniques are connected together in order to provide a ‘coherent picture’ (Easterby-Smith et al., 2012), it is the way knowledge is acquired (Reber, 2011).

3.3.1 Methodological Approach

There are two approaches to reasoning that the researchers adopt in order to acquire knowledge, either a deductive methodological approach or an inductive (Saunders et al., 2009). Deductive reasoning starts from an established theory or generalisation and aims to identify if this theory can be applied to specific cases. On the other hand, the inductive reasoning, commences with observations of specific cases and seeks for generalisations of the under investigation phenomenon and to find patterns. Therefore, the emphasis lies to whether the theory is first (deductive reasoning) or the data (inductive reasoning) (Pathirage et al., 2008). The deductive approach is often used in quantitative research, whereas the inductive approach is applied in qualitative (Saunders et al., 2009).

Deductive reasoning is often related to positivism epistemology approach (Creswell, 2009; Meredith et al., 1989), in the previous section it was argued that this research adopts a positivist approach, therefore this work is following deductive reasoning. This reasoning is dominant in natural sciences (Collis and Hussey, 2003) and it is supported that researchers come to conclusions through a logical way (Ghauri and Gronhaug, 2005). Accordingly, the research presented starts from the general field of sustainability in shipping and decision support and then moves to the specific, which is the method to support decisions for the ship energy systems synthesis with respect to sustainability objectives. According to the deductive reasoning, a conceptual framework is first developed and then the methodology is tested by using data (Saunders et al., 2008). This approach is followed in this research and therefore the developed method is applied and tested on multiple case studies.

3.3.2 Research Methods

Research methods are defined as the techniques and procedures required to acquire and analyse the data of the research (Saunders et al., 2009). The researchers can select between a qualitative, quantitative or mixed methods study (Creswell, 2009). Based on the methodological approach embraced in this work, a quantitative study was considered appropriate. Quantitative methods include ‘structural equation models that incorporate causal paths and the identification of the collective strength of multiple variables’ (Creswell, 2009).

Accordingly and following the framework presented by Meredith et al. (1989) for a positivist perspective, a mathematical simulation quantitative model is an appropriate method for this research. The analytical modelling of the systems under investigation includes both a conceptual model through mathematical equations and the simulation of the systems. In the next section, the methodological steps are discussed and the methods and techniques involved in these steps are described. The relations between the methods and the phases of this research are displayed in Figure 3.8.

Finally, the philosophical assumptions adopted in this research and the methodological perspective that was directed by the assumptions regarding the nature of reality and inquiry are depicted in Figure 3.1.

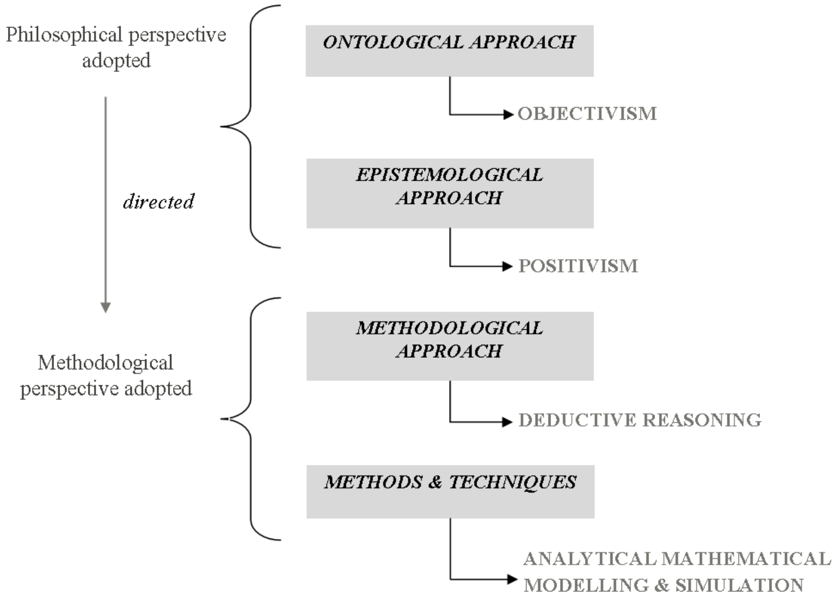

Figure 3.1 Philosophical and methodological approach adopted in this thesis

3.4 Methodological steps

The research methodology is defined as ‘the approach to the entire process of research study’ (Welman et al., 2005). In this work, the research methodology consists of nine methodological steps as they can be seen in Figure 3.2. The methodological steps are going to be discussed in the following paragraphs.

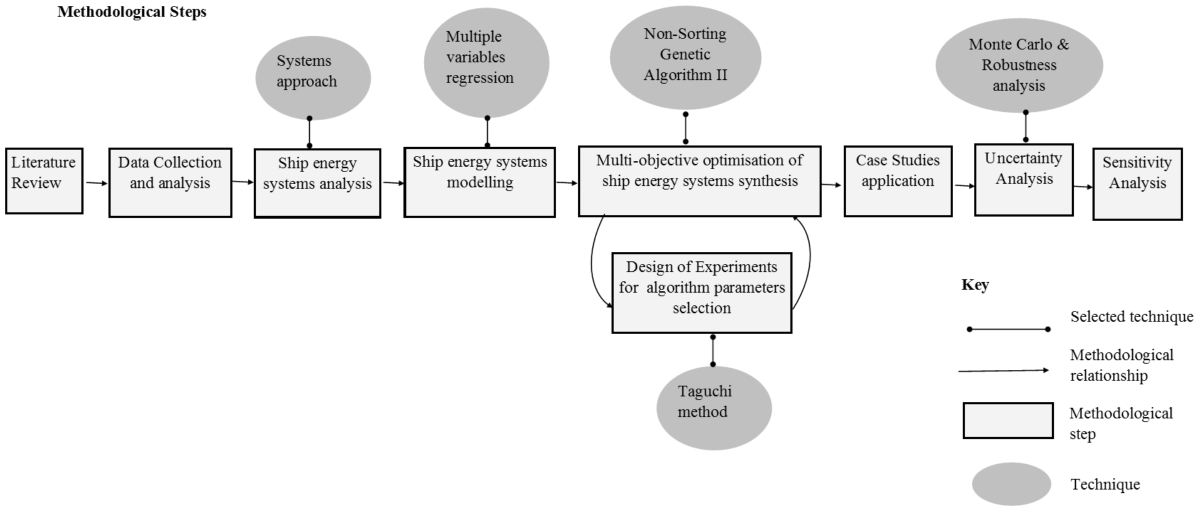

Figure 3.2 Flowchart of the methodological steps

3.4.1 Literature Review

A search on the current literature and information regarding the ship energy systems sustainability was carried focusing on specific bodies of literature as they were presented in the Critical Review in Chapter 2. The bodies of literature investigated in this thesis were guided from the aim of this work to support decisions for the ship energy systems synthesis with sustainability objectives. Therefore the literature was divided into three areas:

First, the sustainability in shipping and specifically in ship energy systems was addressed in order to gain a better understanding of the investigated research area in this thesis. The key aspects that have an impact on the sustainability of the ship energy systems and the most promising traditional and emerging technologies were identified. The most promising technologies were later modelled and included in the developed decision support method. Second, a review was performed on the existing decision support methods for sustainable energy systems, leading to significant findings that were incorporated in the development of the decision support method for the ship energy systems synthesis with sustainability objectives. One of the most critical findings was the importance of optimisation methods to support decisions for the energy systems and specifically multi-objective optimisation methods in order to address all the dimensions of sustainability. Finally, a state-of-the-art literature review was performed on the methods to support decisions for the ship energy systems synthesis, design and operation, with a focus on the existing optimisation methods for the ship energy systems synthesis.

A traditional non-structured technique is followed for the literature review in this thesis, according to Cooper (1989). First the keywords derived from the aim of this work according to the groups presented in Figure 3.3 were used in different combinations to search for relevant research in electronic databases.

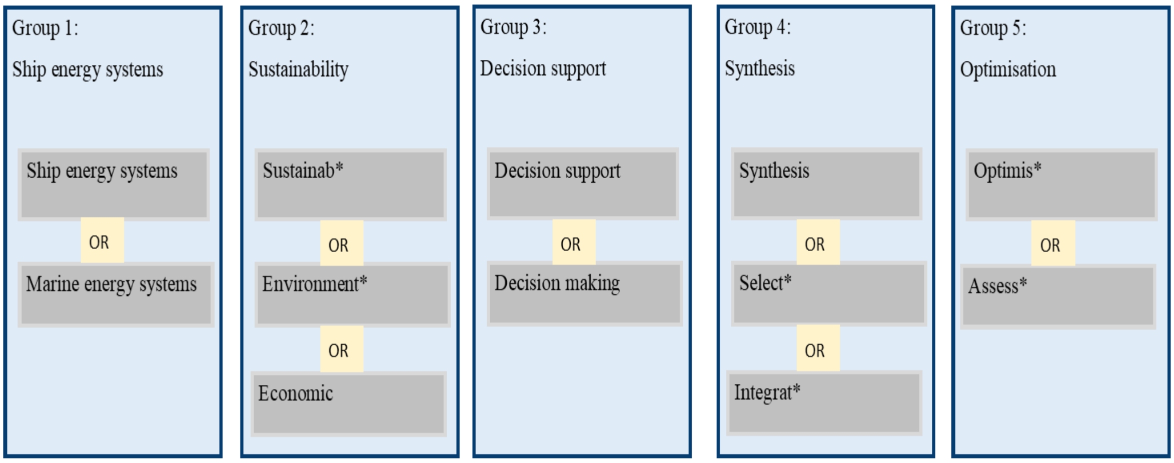

Figure 3.3 Keywords used in the literature review

The databases selected were Scopus and ScienceDirect due to the extensive collection of peer reviewed journals in the field of engineering. In addition, beyond these databases relevant technical reports and white papers were considered. This procedure helped to scope the research field and an iterative process was followed where the keywords were refined. Consequently this procedure led to more specific books and articles and then the references mentioned in the relevant work were further followed. The advantage of this ‘snowball’ technique according to Ridley (2012) is that through the process key authors in the area were identified. In addition, with the snowball technique the ‘research becomes more focused and the researcher becomes more familiar with the literature in the field’(Ridley, 2012). Through this process a saturation level is reached to the point where no new papers are identified. As a result, the state-of-the-art work on the field was recognised and critically reviewed. Finally, the findings of this critical review led to the identification of the gaps.

3.4.2 Data Collection and analysis

Data regarding the technical, economic and environmental performance of ship energy systems were collected from the available literature and technical reports. The data used for the case studies of this thesis are presented in Chapter 4 along with the reference sources. In addition, the decision support method requires a number of input parameters from the user, regarding the operating profile, the voyage details and the ship characteristics. The user input parameters for the case studies are presented in Chapters 6 and 7 under the case studies description. For the purposes of the case studies, actual operating data from measurements shipboard were analysed in order to derive the operating profiles.

3.4.3 Ship energy systems analysis

In systems science ‘a systems description of a situation is an assembly of elements related in an organised whole’ (Flood and Carson, 1988). A system is viewed as a whole, when not just considering the components separately but also including the components interactions (Blanchard and Fabrycky, 1981). In other words, a system is defined as a group of components with interactions among them that operate together in order to fulfil their purpose (Vanek and Albright, 2008). The purpose of a system needs to be explicitly defined so that system components are able to provide the required output for every given input and as a result, their effectiveness can be quantified (Blanchard and Fabrycky, 1981). The function of a system is defined as the action performed by a system (Vanek and Albright, 2008).

Systems approach is proposed as a methodology in order to deal with problems related to complex systems (Flood and Carson, 1988). Systems approach does not consider each component and performance of the component separately like the unit approach (Vanek and Albright, 2008). Systems approach follows a synthetic thinking approach and is inferred that even if each part of a system might perform well, the system as a whole might not (Misra, 2008). Applying a systems approach to analyse complex systems allows to tackle the complexity and address the integrated system including the involved interactions (Blanchard and Fabrycky, 2014).

Systems approach deals with complexity, by decomposing the whole system into as many parts until the complexity is understood (Gaspar et al., 2012). Finally, black box system representation is considered as a key concept approach for problem-solving, where ‘the representation is based on an external view of the system’ (INCOSE, 2015).

Energy systems are considered complex systems because they involve combinations of mechanical, electric and thermal energy, in order to fulfil their purpose; in addition, each energy system interacts with various inputs from other systems as well as human operators (Vanek and Albright, 2008). In specific, each sub-system of ship energy systems consists of components that have different performance and are highly interconnected (Baldi, 2016). Therefore, sub-systems design parameters or variables is possible to influence other sub-systems, or the various sub-systems might influence a single design parameter or variable. Systems approach is employed for complex energy systems problem solving (Vanek and Albright, 2008).

The focus of this work is to support decisions for the ship energy systems synthesis, by optimising the life cycle performance of the integrated ship energy systems and avoid suboptimisation. For this reason, a systems approach was employed to analyse the ship energy systems, similar to previous works (Baldi, 2016; Dimopoulos et al., 2014). According to systems approach principles as they were discussed in Blanchard and Fabrycky (1981) and Flood and Carson, (1988), the ship energy systems are decomposed into sub-systems that consist of input, output and process. Each of them has characteristics and properties that cannot be recognised in any other sub-system. In addition, the sub-systems have interrelations and function together for a common purpose. Understanding of these interrelations, specifically at the early design phase of a system is significant in order to avoid making the wrong decisions (Todd, 1997). Finally, it is very important to specify the boundaries of the system under investigation and anything lying outside of these boundaries is not part of the system (Vanek and Albright, 2008). In this work, the system boundaries, the sub-systems, their inputs and outputs as well as their interrelations are discussed in the following chapter.

Furthermore, a fundamental concept of the systems approach is the understanding of the system life cycle (Blanchard and Fabrycky, 1981; INCOSE, 2015; Vanek and Albright, 2008), as a result in this thesis, the analysis of the ship energy systems adopts life cycle and lifetime considerations.

For the representation of the economic aspect of sustainability, the Life Cycle Cost (LCC) indicator is employed. According to Utne (2009), the life cycle costs should be considered when making a financial decision, since apart from the capital cost, operating cost is a considerable cost element. As it was identified from the critical review, both in energy systems design (Section 2.4) and ship energy systems (Section 2.5), present worth life cycle cost was considered an appropriate tool to evaluate the economic performance of the systems. Particularly for the shipping operations, techno-economic studies on the annualised machinery cost of various power plant alternatives demonstrated that the operating costs are more than three times higher than the capital costs (Livanos et al., 2014). In addition, it was stated that the fuel cost for a 20 years investment period, is responsible for 91% of the total lifetime expenditure (Solem et al., 2015). Finally, the Life Cycle Cost is a useful tool to assess the economic impact of the ship energy systems, as it is suitable for detailed financial analysis (Cabezas-Basurko et al., 2008) and it is helpful when making sustainable investment decisions (Utne, 2009).

On the other hand, the environmental impact of the ship energy systems is expressed in terms of the gaseous emissions during the ship lifetime. This approach was recognised from the review performed on decision support methods for energy systems (Section 2.4) as appropriate to express the environmental dimension of sustainability. In addition, lifetime gas emissions indicators have been extensively used in the literature in order to express the environmental impact of the ship power plant (Fet et al., 2013; Gaspar et al., 2014) since gaseous emissions indicators representatively reflect the environmental impact of the ship energy systems (Chatzinikolaou and Ventikos, 2015b). Is should be noted that only the gaseous emissions from the ship operating phase are addressed in this work. The operating phase is by far the most impactful for the whole ship life cycle in respect to energy and to gaseous emissions, as it was discussed in the Critical Review. A full life cycle environmental assessment analysis is beyond the scope of this work; therefore, the building and decommissioning phases are not considered herein from an environmental impact perspective.

The analysis of the ship energy systems according to the systems approach is presented in Chapter 4 and Section 4.3.

3.4.4 Ship energy systems modelling

Appropriate models are required for the purpose of this work, in order to estimate the performance of each ship energy sub-system as they were analysed according to the systems approach. ‘Models are designed to represent the system under study by an idealised example of reality in order to explain the essential relationships involved’ (Blanchard and Fabrycky, 1981). Systems modelling has been widely used for the visualisation, the analysis and the optimisation of ship energy systems (Ancona et al., 2018; Armellini et al., 2018; Baldi, 2016). The use of models offers an insight into the function of the systems and the interactions between the sub-systems, without requiring experimentation or prototypes (Blanchard and Fabrycky, 2014).

This work employs mathematical models to estimate the ship energy systems performance; this type of models use the language of mathematics to represent the system and can be used when modelling engineering systems according to the systems approach (Blanchard and Fabrycky, 1981). The transient stages of the ship energy systems operation are not included because when considering the lifetime operation of the vessel their impact is limited (Sakalis and Frangopoulos, 2018). In addition, the uncertainty of the optimal solutions is investigated separately so the systems are not modelled as stochastic. For these reasons deterministic mathematical models that represent the system steady-state conditions were developed, a common practise in the pertinent literature (Armellini et al., 2018; Baldi, 2016; Dimopoulos et al., 2008a).

Empirical models, also called black box, are a type of mathematical models that are often used since they do not require knowledge of the system physical laws and can predict the output using a limited number of input parameters (Baldi, 2016). The empirical model's approach is selected as the most appropriate in this study, due to the following reasons:

- Only high-level details are needed, because a large number of technologies is modelled, including novel technologies that are not yet established and their exact performance is not known.
- There is interest only on the gaseous emissions and the cost of the systems.
- An exact representation of reality is not needed for the assessment of energy systems at the early design stage.

The mathematical models developed to estimate the performance of the ship energy systems are presented in Chapter 4 of this thesis, in Section 4.4.

3.4.5 Multi-objective optimisation of ship energy systems synthesis

The aim of this work is to support decisions for the ship energy systems synthesis with sustainability objectives. The synthesis optimisation of energy systems identifies the configuration, in other words, the components that are included (Frangopoulos and Sciubba, 2009; Piacentino and Cardona, 2008). The independent synthesis decision variables are discrete variables, indicating whether a component should be in the system or not in alignment with the literature (EDUCOGEN, 2001). The variables can be binary (0,1) to signify whether a component is included in the system, or a set of discrete variables, each value representing an alternative technology that could be a part of the ship energy systems. In addition, improving the sustainability performance of energy systems requires adopting an approach that integrates the techno-economic and environmental assessment according to the pertinent literature in Chapter 2; therefore, multiple objectives are considered for the optimisation. The formulation of the optimisation problem is presented in Chapter 4, Section 4.7.

3.4.5.1 Multi-objective Combinatorial Optimisation methods

The optimisation of the ship energy system synthesis is defined as a Multi-Objective Combinatorial Optimisation (MOCO) problem since the decision variables are discrete and the objective functions, as well as the constraints, can take any form (Coello Coello et al., 2010). MOCO methods are considered integer programming and the number of optimal solutions rises exponentially with the problem size (Ehrgott and Gandibleux, 2000). MOCO problems are an important category of the multi-objective optimisation problems and have a great number of applications in different fields like manufacturing, scheduling, as well as in systems engineering. Combinatorial optimisation is a tool that has successfully been applied to model real-world applications (Ulungu and Teghem, 1994).

The outcome of a MOCO problem is a spectrum of optimal solutions, in comparison with the single objective optimisation (Coello Coello et al., 2010). This makes it challenging to identify an optimal solution and therefore, the Pareto optimal front is introduced. A solution obtained from a multi-objective optimisation process belongs to the Pareto front and is considered Pareto-optimal and non-dominated. All Pareto front solutions are 'inherently superior' in at least one objective, when they are compared to the other solutions (Sen and Yangi, 1995); there is no other solution in the solution space that performs equal in all objectives and better in at least one of them. Finally, the presentation of the solutions on the Pareto front allows the trade-offs among the objectives to be demonstrated, and subsequently, it is possible for the user to make more informed decisions (Pelet et al., 2005).

MOCO problems are NP-hard (nondeterministic polynomial time), thus the complexity of these problems is exponentially related to the number of decision variables (Coello Coello et al., 2010). A great number of methods is identified in the literature for solving MOCO problems that can be found in Coello Coello et al. (2010), Coello Coello, Lamont and VanVeldhuizen (2007) and Ulungu and Teghem (1994).

MOCO problems can be transformed into single-objectives, common methods used according to Zitzler and Thiele (1998) include the weighted sum, where the objective functions are aggregated, and the goal programming. The former method is often used in supporting decisions for enhancing sustainability (Wang et al., 2009), however using weights leads into leaving regions of solutions unmapped (Quariguasi Frota Neto et al., 2009). These methods are user-friendly; however, they require the users to assign weights or set goals according to their preferences. As a result, the process is biased by the decision maker's preferences and becomes subjective. For the former method, the set of optimal solutions depends highly on the weight vector used, so different vectors do not offer the same results. In addition, in the latter method, the result of the optimisation is one solution, instead of a set of solutions that the decision maker can select among them.

The aforementioned methods require 'a priori' knowledge of the decision makers preferences (Coello Coello et al., 2010), making it challenging for them to quantify accurately their preferences beforehand (Mavrotas, 2009). Furthermore, the 'a priori' techniques limit the exploration of the whole search space (Coello Coello, Lamont and VanVeldhuizen, 2007). On the other hand, ‘a posteriori’ techniques explore as widely as possible the search space aiming to generate a set of optimal solutions (Coello Coello, Lamont and VanVeldhuizen, 2007). In the latter case, the generation of the problem optimal solutions, or a sufficient representation of them, allows the decision maker to select according to his/her preferences among the optimal solutions (Mavrotas, 2009). In light of the preceding discussion, an ‘a posteriori’ technique is adopted in this research. For this reason, ‘a posteriori’ methods used for MOCO problems are discussed further in the following paragraphs.

Branch and Bound, which is an implicit enumeration algorithm is often used for combinatorial optimisation problems. This method first partitions the problem into exhaustive sub-problems and then bounds are computed for them until the optimal solution is found. However, in MOCO problems because of their non-dominated vectors, the bounds of the sub-problems are challenging to estimate (Ehrgott and Gandibleux, 2008). Another ‘a posteriori’ method used in MOCO problems is the ε-constrained. According to this method, one of the objective functions is minimised, while the others are bounded by adding constraints. The challenge with ε-constraint lies on the inflexibility of the constraints, especially, when there are many objectives (Ehrgott and Ruzika, 2008) and the selection of the initial conditions, as well as slack values, as they greatly affect the results.

In the last years, multi-objective evolutionary methods (MOEA) have been proposed to solve MOCO problems (Coello Coello, Lamont and VanVeldhuizen, 2007; Ehrgott and Gandibleux, 2008) and have received great acceptance in the industry and the academia (Trautmann et al., 2009). MOEA methods manage to successfully generate a combinatorial optimisation problem solutions (Ulungu and Teghem, 1994). They offer to the decision maker the opportunity to come to a decision after examining all the optimal potential solutions without ‘prior judgment’ (Chaudhari et al., 2010) and manage to solve complex problems (Stojiljković et al., 2014). Compared to the traditional gradient-based optimisation techniques, evolutionary algorithms do not require a predefined algebraic function but only the returned value of the objective function; in addition, they manage to address discontinuities (Sciberras and Norman, 2012). The advantage of these methods is that they do not require derivatives of the functions, or even the objective functions, until the evaluation of the objectives in order to perform the optimisation (Sciberras and Norman, 2012). In addition, MOEA address simultaneously the objectives allowing to identify a set of solutions that belong to the Pareto front with one run (Coello Coello, Lamont and VanVeldhuizen, 2007). However, there are challenges selecting the best evolutionary algorithm for each specific problem and finally, it is possible to not manage to attain convergence to the global optimal.

In the majority of the engineering cases, optimisation problems cannot be expressed only by analytic equations and deriving the objective functions is computationally intensive, as well as they exhibit a great number of constraints and local optima (Dimopoulos, 2009). In addition, the independent variables depend on each candidate solution generated from the algorithm and they are different for each possible synthesis. Therefore, there is no analytic expression for the objective functions, which are derived after the energy systems performance simulation models. The great number of technologies and potential combinations renders the exploration of the whole search space of the synthesis optimisation problem challenging (Dimopoulos et al., 2008a). Finally, there is a great number of alternative solutions, leading to a non-continuous problem. The evolutionary algorithms manage to address successfully these complexities of the ship energy systems synthesis optimisation problem (Dimopoulos, 2009; Sakalis and Frangopoulos, 2018). Therefore, an MOEA is employed in this research in order to address the multi-objective combinatorial problem of the ship energy systems synthesis.

Most MOEA approaches incorporate the Pareto optimality in the selection mechanism (Coello Coello et al., 2010). The most prominent MOEA algorithms are the Non-dominated Sorting Genetic Algorithm II (NSGA-II) and the Strength Pareto Evolutionary algorithm 2 (SPEA2) (Coello Coello, Lamont and Veldhuizen, 2007). Other algorithms that are often used are the Niched-Pareto Genetic Algorithm 2 (NPGA2) and Multi-objective Genetic Algorithm (MOGA) (Coello Coello, Lamont and Veldhuizen, 2007). Despite the fact that MOEA are widely used for many applications there are still some challenges regarding the computational complexity of non-dominating sorting, the diversity of the solutions and the lack of elitism (Deb et al., 2002; Li et al., 2018).

NPGA2 compared to the other approaches does not consider the elitism mechanism, therefore, it does not ensure that the optimal solutions identified will be maintained until they are dominated. As a result, the lack of elitism leads to the loss of optimal solutions. MOGA, despite the wide applicability, has a disadvantage compared to NSGA-II, due to the fact that it applies the fitness sharing process on the objective space, whereas NSGA-II does it in the decision variable space. As a result, in the former case two solutions with the same objective function cannot exist, which is not desirable in the specific problem since different systems might have the same performance. In addition, MOGA, SPEA2 and NPGA2 employ the fitness sharing or niching approach in order to ensure the diversity of the solutions, whereas NSGA-II uses the crowding distance. In the former case, the number of individuals that are dominated by each solution in its predefined niche radius is estimated, however the actual distance of each individual is disregarded. The fitness decreases proportionally with the individuals sharing the same neighbourhood. However, the NSGA-II crowding distance is more efficient considering the actual distance of each individual (Coello Coello, Lamont and Veldhuizen, 2007), therefore the surviving solutions are selected according to the crowdedness metric measured for each objective function.

As a result, the NSGA-II manages to overcome the diversity of the solutions and the lack of elitism issues (Li et al., 2018) as it is discussed in more detail in the following section. NSGA-II is one of the most frequently used methods for solving MOCO problems (Coello Coello et al., 2010), it has been extensively used in a variety of problems from different domains (Minella et al., 2008) and it has been demonstrated that it manages to outperform many of the other MOEA (Jianyun et al., 2018; Li et al., 2018).

3.4.5.2 Non-dominated Sorting Genetic Algorithm II

The NSGA-II process developed by Srinivas and Deb (1994) is presented in Figure 3.4.

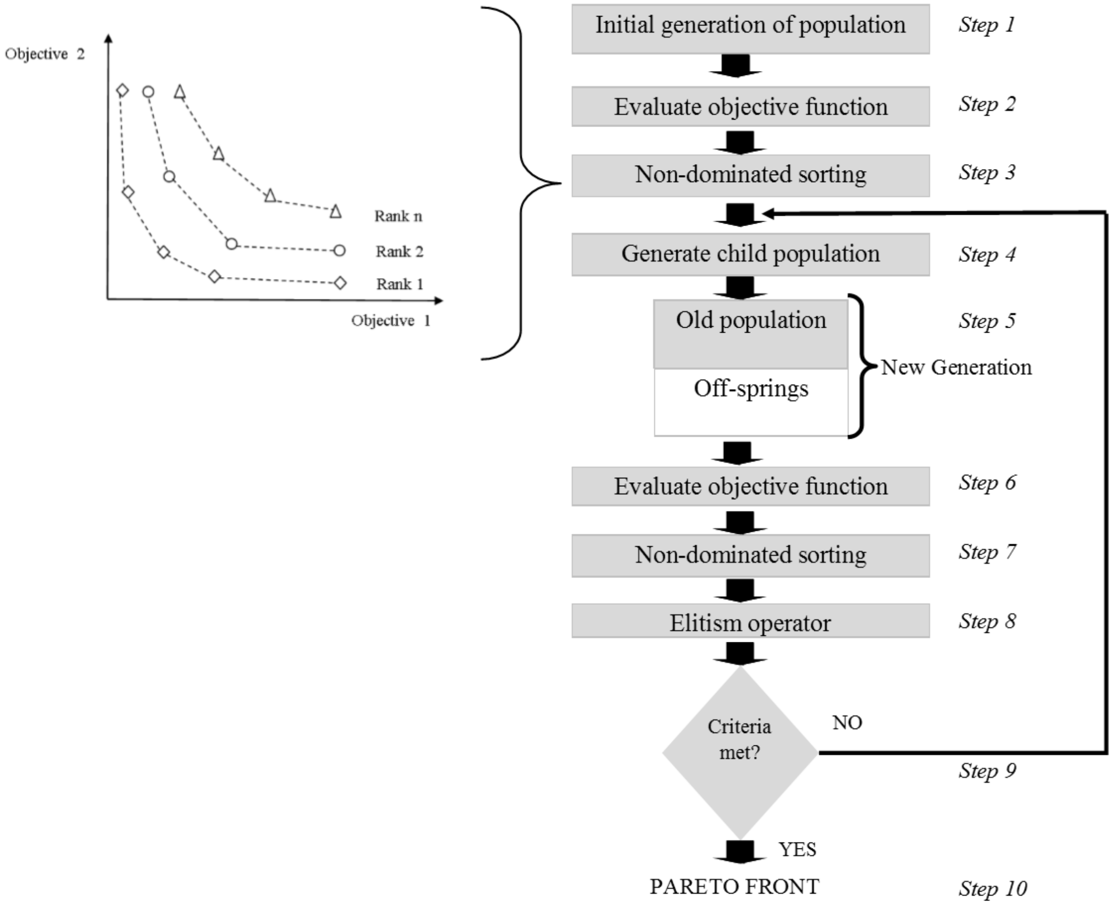

Figure 3.4 NSGA-II process

Following a population generation (Step 1), the objective functions are evaluated (Step 2) and each individual of the population is allocated into a rank according to the number of individuals it dominates and is dominated by (Step 3). The fitter solutions are allocated to the highest rank based on the objectives values. The population with the best individuals of the generation enters a mating pool. The generation of new individuals (Step 4) by using the offspring operators, the selection of parents as well as the crossover and mutation are performed, according to the genetic algorithm principles. During the reproduction process, the mating pool will include more solutions that belong in the highest rank. In the selection process, the crowding distance measure is employed in order to obtain a uniform and diverse Pareto front; thus, the solutions that are not crowded will be given higher preference. The crowding distance is estimated for each individual of the same rank and indicates how close the individuals are between them, the aim is to have a greater crowding distance in order to have a more diverse population. For the selection process, a binary tournament is used (Deb et al., 2002) and two random individuals are compared and the fittest becomes a parent. The selection criterion is the individuals' fitness, therefore, the rank they belong and in the case that they are in the same rank then the crowding distance measured is compared.

Once the parents are selected, the mutation and crossover operators are employed on the parents in order to produce the offsprings. According to crossover operator, the two parents are crossed based on the operator's probability and produce children that share the genetic information of the two parents, whereas the mutation makes small changes to one chromosome of the parent. The produced offsprings and the current population are combined into the new generation (Step 5) and ranked (Step 6 & 7) according to the process described above. After the ranking process, the new population is formed with the best solutions. According to the elitism operator (Step 8), a percentage of the solutions that belong to the highest rank passes unchanged to the next generation (Deb et al., 2002). This process is repeated (Step 9) until the termination criteria are met and the final Pareto front of optimal solutions is visualised (Step 10).

The termination criteria of the optimisation process include the maximum number of the generations and the maximum stall generations. The algorithm ends when the average change in the spread of the Pareto front over the stall generations is less than tolerance specified from function tolerance.

A great number of studies have employed NSGA-II and confirm that it is an approach that can be effectively used to optimise the complex energy systems and identify a well distributed

Pareto front. It is a method widely used for energy systems design (Ko et al., 2015; Shang et al., 2016; Sheikholeslami and Ganji, 2016; Wang et al., 2013, 2018; Yousefi et al., 2017), ship energy systems design (Etghani et al., 2013; Jain and Sachdeva, 2017; Lan et al., 2015; Lee et al., 2014; Niu et al., 2018; Sciberras and Norman, 2012; Turkmen and Turan, 2007) as well as optimisation of energy systems with sustainability considerations (Abul'Wafa, 2013; Deb et al., 2016) and in some cases ship energy systems operation optimisation with sustainability considerations (Jianyun et al., 2018).

Three features define this method and improve the convergence compared to the other MOEA. First, the best solutions found in every generation are transferred directly to the next generation due to the elitism operator, and thus optimal solutions found remain safe until better ones dominate them. Second, the crowding distance operator ensures the diversity of the solutions, which is the sum of distances between either sides of the neighbours of a solution in every dimension of the objective space. In that respect, it manages to explore a wide range of the feasible areas of the objective space and identifies solutions in less populated areas (Sciberras and Norman, 2012; Xie, 2011). In addition, this method identifies the level of non-dominance of each solution and ranks them accordingly. Finally, the selection operator uses both the ranking and the crowding values to select the best individuals for the next generation. As a result, NSGA-II is an effective method that guarantees diversity and ensures that optimal solutions will not be lost, while offering a promising sorting process.

According to the preceding discussion and due to the advantageous characteristics of the NSGA-II on MOCO problems and the previous successful applications, the NSGA-II method is used for the optimisation of the ship energy systems synthesis and to generate the Pareto front.

3.4.6 Design of Experiments for algorithm parameters selection

Genetic algorithms employ variation and selection operators. The algorithm is considered parameter-sensitive and requires the fine-tuning of the parameters of these operators, in order to accurately identify the optimal solutions. It was identified that some of these parameters values are problem specific and have complex interactions (Bagchi, 1999). In addition, they have a great number of levels, leading to many combinations, thus making it challenging to select the optimal parameters for each problem (Majumdar and Ghosh, 2015). It is highly important to investigate the significance of the parameters and evaluate in a systematic way all the possible combinations, in order to identify the optimal. This process requires performing many runs (Kucukkoc et al., 2013) and it is time demanding.

The optimisation of the GA parameters, in order to achieve faster and better convergence has been performed in the existing literature by employing the method of Design of Experiments (DOE) (Stewardson and Whitfield, 2004), with focus on the population and elite concept, mutation and crossover related parameters of the genetic algorithm (Bagchi, 1999; Chang, 2011; Majumdar and Ghosh, 2015; Stewardson and Whitfield, 2004; Yang et al., 2005).

DOE is considered an effective and efficient method for investigating and evaluating the effect of multiple factors. The basic principles for performing a DOE method are to identify the parameters or factors that are significant and to define the range of variability or region of interest for each factor (Cavazzuti, 2013). The number of levels, in other words, the number of different values assumed for each factor is an important decision. The size of the experiment depends on the aforementioned decisions, as well as the method selected for performing the DOE.

The design of experiments method developed by Taguchi and Wu (1980) has been extensively applied in order to select the optimal parameters for the genetic algorithms (Chang, 2011; Chapman and Day, 2012; Majumdar and Ghosh, 2015; Yang et al., 2005). It is efficient, easy to adopt and frequently used in engineering design, where it manages to achieve robust results (Semioshkina and Voigt, 2006). It is considered a method highly effective for setting robust, as well as optimal parameters for problems like the genetic algorithm parameters, whilst requiring the least possible number of experiments (Majumdar and Ghosh, 2015).

According to this method a normalised table, orthogonal array matrix is used to design the experiment. The proposed orthogonal arrays can be used to estimate the main effects of the parameters by performing a few experimental runs. Taguchi method makes a distinction between the control variables, which can be controlled, and the noise variables, which cannot. This approach can provide information regarding the interaction among these variables, thus providing robust solutions (Cavazzuti, 2013).

The formulation of the DOE for the algorithm parameters setting and the results are presented in Section 4.7.2.

3.4.7 Case studies

The developed method was demonstrated with two case studies in order to evaluate the method. Two different ship types of merchant ships were selected to apply the method, an oil Aframax tanker and a cruise ship 140,000 GT. Actual operating data were employed and expected operating profiles were used as inputs to evaluate the ship energy systems performance and finally, the findings were analysed. The case studies and the results are discussed in Chapters 6 and 7 of this thesis, findings were disseminated through the papers J1, J2 and C3. The reasoning behind the selection of these ship types is justified in this section.

Crude Oil Tankers

Crude oil tankers are essential to transport the oil and liquid chemicals over the world in order to balance the uneven distribution of the resources. They are responsible to transport crude oil to the refineries from the point it was extracted.

Tankers are one of the dominating ships in the shipping sector, corresponding to a great percentage of the merchant fleet. Cargo ships like tankers and bulk carriers are the ships with the greatest number corresponding to 80% of the global fleet (Hsieh and Felby, 2017). Tankers are the second largest after dry bulk carriers by tonnage and number, consisting 20% and 14% of the merchant fleet, respectively (Hsieh and Felby, 2017). In addition, in the year 2012, tankers were responsible for almost 3.07 billion tonnes of goods transported globally, which accounts for one-third of the total global goods (Narula, 2014).

Oil tankers along with the bulk carriers are dominant in the merchant fleet, however comparing to the bulk carriers the tankers require high thermal power at berth and during the at-sea operating phase due to the heating requirements for the cargo, making the energy system of the latter more complex and demanding. As it is evident from Smith et al. (2014), the thermal requirements for the tankers are exceptionally high compared to other merchant vessels. As a result, on top of the power requirements for the cargo handling and the propulsion of the vessel, the extensive operation of the thermal boiler leads to higher emissions compared to the bulk carrier.

Regarding carbon emissions, it was estimated in the year 2012 that they emitted around 130 million tonnes of CO_2 emissions (Smith et al., 2014). According to Figure 3.5, tankers were the third larger polluters, being responsible for 16% of the total emissions from ships. In addition, it was identified that tankers have a great impact on the SOx emissions; especially, they contribute around 40% of the SOx emissions on ports, as it is evident from Figure 3.6. Additionally, tankers contribute to the global NOx emissions. Studies on the Baltic Sea show that oil tankers are the primary polluters (Figure 3.7). Finally, along with the other emissions, crude oil tankers during the loading, unloading and transport of the oil emit a great amount of hydrocarbons (Eyring et al., 2005).

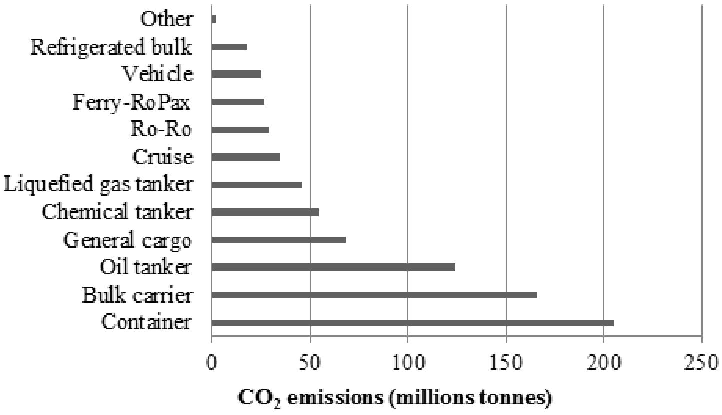

Figure 3.5 CO$_2$ emissions in 2012 according to the IMO study (Smith et al., 2014)

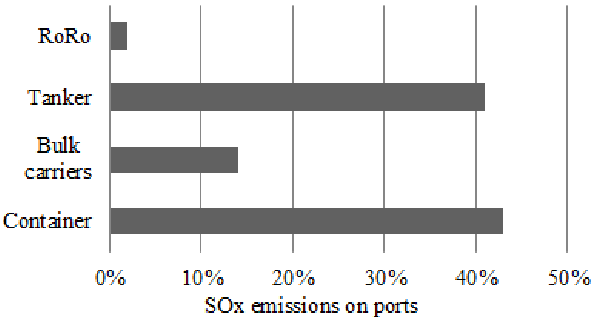

Figure 3.6 SOx Emissions in Ports (Merk, 2014)

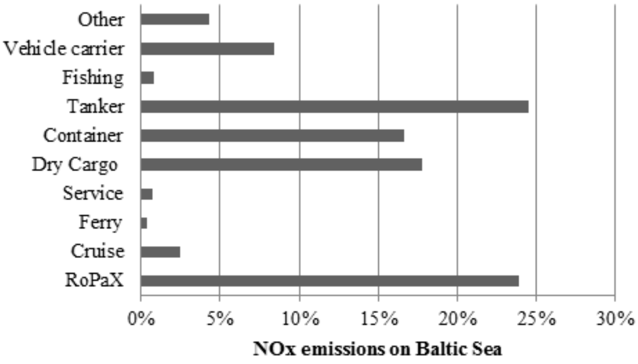

Figure 3.7 Annual total NOx emissions from Baltic Sea 2015 (Johansson and Jalkanen, 2016)

Despite the recent drop of the shipbuilding activities, a great increase has been observed from the beginning of 2018. This increase is detected in all the cargo ships with almost 5 million DWT of new orders on tankers (Reinikainen, 2018). Specifically, Aframax crude oil tankers on the year 2017 had the majority of the orders among the tankers fleet and in the next years, they are expected to be one of the highest (Williams, 2017). An Aframax crude oil tanker is a medium-size oil tanker with a size between 80,000-119,999 DWT. Their size accounts for a great part of the overall tanker fleet, around 23% and it is expected to continue to hold this percentage for the next 20 years (2014-2034) (Smith et al., 2014).

The first application of the proposed method is a multi-objective optimisation of a crude oil tanker energy systems synthesis. As it was discussed, tanker ships adequately represent the merchant vessels, regarding both the dominant size of the tankers' fleet and their global emissions. In addition, it is worth investigating the gas emissions and fuel consumption of these vessels due to the high demand for thermal power. In specific, the case study is on an Aframax crude oil tanker that currently and in the next 20 years will adequately represent the tankers fleet.

Cruise Ships

The cruise ship industry is a growing sector and in recent years, it is one of the fastest rising segments of the tourism sector (Sun et al., 2011). Due to this continuous growth, it has been reported that around \$25 bn worth of cruise ships have been ordered from 2016 to 2022 (Kizielewicz, 2017). In addition, in 2014 the revenues from cruise ship operations globally accounted for approximately \$37 bn (Maragkogianni and Papaefthimiou, 2015).

At the same time, it is estimated that the annual global cruise ships fuel consumption can be more than 30 million tonnes of fuel oil, constituting a 10% of the overall annual consumption of ships and leading to 96 million tonnes of carbon emissions (Buhaug et al., 2009). As a result, even though in Figure 3.4 and Figure 3.6, the emissions from cruise ships were relatively low, the environmental impact of cruise ships is very high compared to the other passenger transportations means. Estimations show that cruise ships have approximately 160 kg CO_2 emissions per passenger per day (Brynolf et al., 2016), which correspond to higher carbon emissions per passenger-kilometre than economy class aviation (Howitt et al., 2010). In addition, cruise ships sail the majority of their time on coastal routes and spend more than 30% of their time in the port (Baldi, Ahlgren, et al., 2015). As a result, they emit a significant amount of emissions in the coastal areas leading to serious health problems for the population in the surrounding area (Corbett et al., 2007).

Furthermore, cruise ships sail mostly on current or future ECA waters; as a result, they require energy systems that can comply with the strict regulations in the most efficient way. The most popular area for the cruise ships operation is the Caribbean, which is considered as a dominant market for the cruise industry, and lately the Mediterranean, where especially during the summer seasons operations increased considerably (Rodrigue and Notteboom, 2013).

Together these regions account for 70% of the global cruise industry in bed-day terms. In addition, during the summer seasons, Alaska and Northeast Atlantic, as well as Australia, share the rest of the cruise ship market (Rodrigue and Notteboom, 2013). The Asian market has also gained a share of the cruise ship market and according to the Cruise Lines International Association in the year 2017, it consisted of around 10% of the global market (CLIA, 2017). The aforementioned areas are either included on the ECA waters or are going to be in the future as it was discussed in Chapter 1.

Cruise ships are highly energy intensive ships with complex energy systems, in order to cover the high energy demand of the passengers' accommodation and services (Dimopoulos et al., 2008b). Cruise ships along with the power essential for the propulsion, electric power and auxiliary systems, compared to the other ship types, require a great amount of power for the ventilation, air conditioning, as well as heat for fresh water and to provide comfort to the passengers. This is evident in Figure 3.8, where the energy breakdown of a cruise ship is presented, derived from shipboard measurements collected from five years of operation of a particular ship. Similar results are found in the literature for different cruise ship sizes (Baldi, Ahlgren, et al., 2015; Marty et al., 2012).

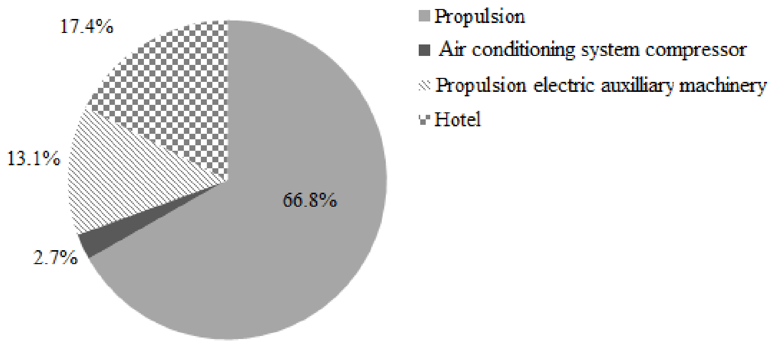

Figure 3.8 Energy breakdown of a 140,000GT cruise ship according to shipboard measurements[2]

Therefore, the developed method is demonstrated on a cruise ship in Chapter 7. The cruise ship energy systems configuration is optimised for two objectives, the life cycle cost and the lifetime CO_2 emissions. This investigation is focused on the mitigation of the carbon emissions from cruise ships, due to their significant contribution to the global carbon emissions, the current target of IMO on the CO_2 emissions and the fact that they are among the most carbon-intensive means of tourism industry (Baldi et al., 2018).

---

[2] The operating data were derived from industry sources and due to anonymity the source could not be provided.

In specific, in this work, the optimisation of a 140,000 GT cruise ship energy systems is demonstrated. The specific cruise ship size accounts for a great part of the overall tonnage of the cruise ship fleet and it is identified as a representative high-efficiency conventional cruise ship (El Geneidy et al., 2017). The cruise ships with tonnage 130,000-160,000 GT correspond to approximately 60% of the large cruise ships operating currently (GlobalCruiseShip, 2018). Finally, according to the cruise ship outlook for new builds until the year 2027, it is evident that 20% of the new orders consists of cruise ships with tonnage 130,000-160,000 GT (CIN, 2018).

As a result, in order to demonstrate the applicability of the method and validate the method and the results, two applications are displayed on ship types with different characteristics and requirements.

3.4.8 Uncertainty analysis of ship energy systems optimal solutions

‘Decision analysis should aim to provide the decision maker with a realistic picture of the current knowledge and its deficiencies, by utilising all the relevant information available’ (Uusitalo et al., 2015). Decision support methods are developed to assist the decision maker, by identifying and evaluating the possible alternatives. However, in every decision regarding an investment, the uncertainty is high and any solution to an engineering optimisation problem could be affected by changes in the environment (Gaspar-Cunha and Covas, 2008).

The majority of the decisions made for the energy sector are significantly affected by data uncertainty (Conejo et al., 2010). As a result, it is significant to understand the input data uncertainty and it is beneficial to quantify and provide it along with the optimal solutions. The optimal solution should be ‘insensitive’ in any change that might occur in the parameters of the model (Gaspar-Cunha et al., 2014). The degree to which a solution is ‘insensitive’ to the environment is defined as the robustness of a solution (Mavrotas, Pechak, et al., 2015). When the robustness of the optimal solutions is not included, then, it is possible for the decision maker to select a solution that is very sensitive to the parameters of the model.

In operational research, the concept of robustness analysis in optimisation was first introduced by Soyster (1973), however, the robustness analysis of multi-objective optimisation problems is an area that has not been yet fully investigated compared to the single objective problems (Mavrotas, Figueira, et al., 2015). The majority of the existing approaches available to investigate the robustness of the solutions of multi-objective problems due to the uncertainty of the parameters are restricted to altering the problem to a single objective one by using weights to aggregate the objectives and then investigate the robustness of the solutions

(Mavrotas, Pechak, et al., 2015). Other authors, transformed a single objective optimisation problem into bi-objective by adding the robustness objective in the optimisation process (Zhen and Chang, 2012). Finally, the stability radius for each solution on the Pareto front was investigated by adjusting the coefficients of the objective functions (Roland et al., 2012). The previous methods integrate the robustness with the optimal solutions generation. Therefore, increasing the complexity of the optimisation and influencing the generation of the optimal solutions.

An 'a posteriori' approach, where the robustness of the optimal solutions is estimated after the Pareto front is derived was proposed by Mavrotas, Figueira, et al. (2015). As a result, the decision maker is provided with both the optimal solutions for the current status of the input parameters and the robustness of the solutions on an uncertain environment. Their proposed method was developed specifically for MOCO problems, which have integer decision variables. The robustness analysis is based on the Monte Carlo (MC) simulation method. The frequency of appearance of each solution on the Pareto front over the multiple runs of the MC simulation is quantified. MC is a common method to explore how the simultaneous changes on the input parameters of a model affect the results in a systematic way.

The MC simulation is a popular method to study stochastic uncertainty (Mavrotas, Figueira, et al., 2015), which uses the developed deterministic decision support model as a black-box. A significant step of the uncertainty analysis is the identification of the presented model uncertain parameters and then, the quantification of the parameters uncertainty (Burhenne et al., 2013). 'In uncertainty analysis, the model inputs are sampled from certain distributions to quantify the consequences of the uncertainties in the model inputs, for the model outputs' (Kleijnen, 2011). Probabilistic models are often utilised to express the uncertainty of the model parameters, by considering the range and the probabilities of the values (Uusitalo et al., 2015). Probability density functions (PDF) have been highly used from uncertainty analysis methods, in order to describe the uncertainty of the parameters of interest.

The performance of the ship energy systems is influenced by a number of parameters that are characterised by uncertainty in real life. These uncertainties might lead to suboptimal decisions, when the assumed parameters differ from the ones in reality, as well as changes to the values of the model parameters might lead to the solutions 'instability' (Mavrotas, Figueira, et al., 2015).

In this work, the uncertainty of the input parameters of the model is considered and introduced in the decision support method. An 'a posteriori' approach is employed for the investigation of the robustness of the optimal solutions, according to Mavrotas, Figueira, et al. (2015). The MC simulation is used for the robustness analysis of the multi-objective optimisation problem of the ship energy systems synthesis. The robustness of the solutions of the Pareto front is estimated offering to the decision maker another piece of information of the solutions instead of only the performance on each objective. The uncertain parameters considered in this work and their PDFs are discussed in Chapter 4, and the results of the analysis are presented in Chapters 6 and 7 for each case study.

3.4.9 Sensitivity analysis of optimal ship energy systems

In the previous section, the robustness of the solutions in the uncertain environment was discussed, whereas, in this section the impact of the key input parameters that are characterised by uncertainty in real life, on the optimal solutions performance is investigated.

Sensitivity analysis is 'the systematic investigation of the reaction of model outputs to extreme values of the model inputs' (Kleijnen, 2011). It is an effective method to investigate the uncertainty of specific parameters on deterministic decision support models and thus, explore how the changes of the specific input parameters affect the results (Morris, 1991; Uusitalo et al., 2015). Sensitivity analysis is the investigation of the input parameters impact on the optimal solutions performance (Sharafi and ELMekkawy, 2014). This procedure allows the decision maker to understand, which factors 'trigger' the greatest change on the results (Hirst and Schweitzer, 1990).

Sensitivity analysis entails altering one or a combination of the input parameter values to investigate the variation of the optimal solutions performance. In this study, a sensitivity analysis was performed focusing on the uncertain variables that were considered more influential for the decisions regarding the ship energy systems synthesis (Chapters 6 and 7). According to previous work regarding the design and operating optimisation of the ship energy systems, the most important parameters that have the greatest impact on the systems design are the fuel prices and the capital cost of the technologies (Dimopoulos et al., 2008b; Tzortzis and Frangopoulos, 2018).

3.5 Research Design

The research design is defined as 'the plan to conduct research' (Creswell, 2009). The research design of this work is presented in Figure 3.9 and is divided into eight phases. The research methods used in every phase are presented and the research outputs (method and case study results) in terms of journal and conference papers are outlined. The research phases with the chapters that correspond to each phase are as follows.

Research Design

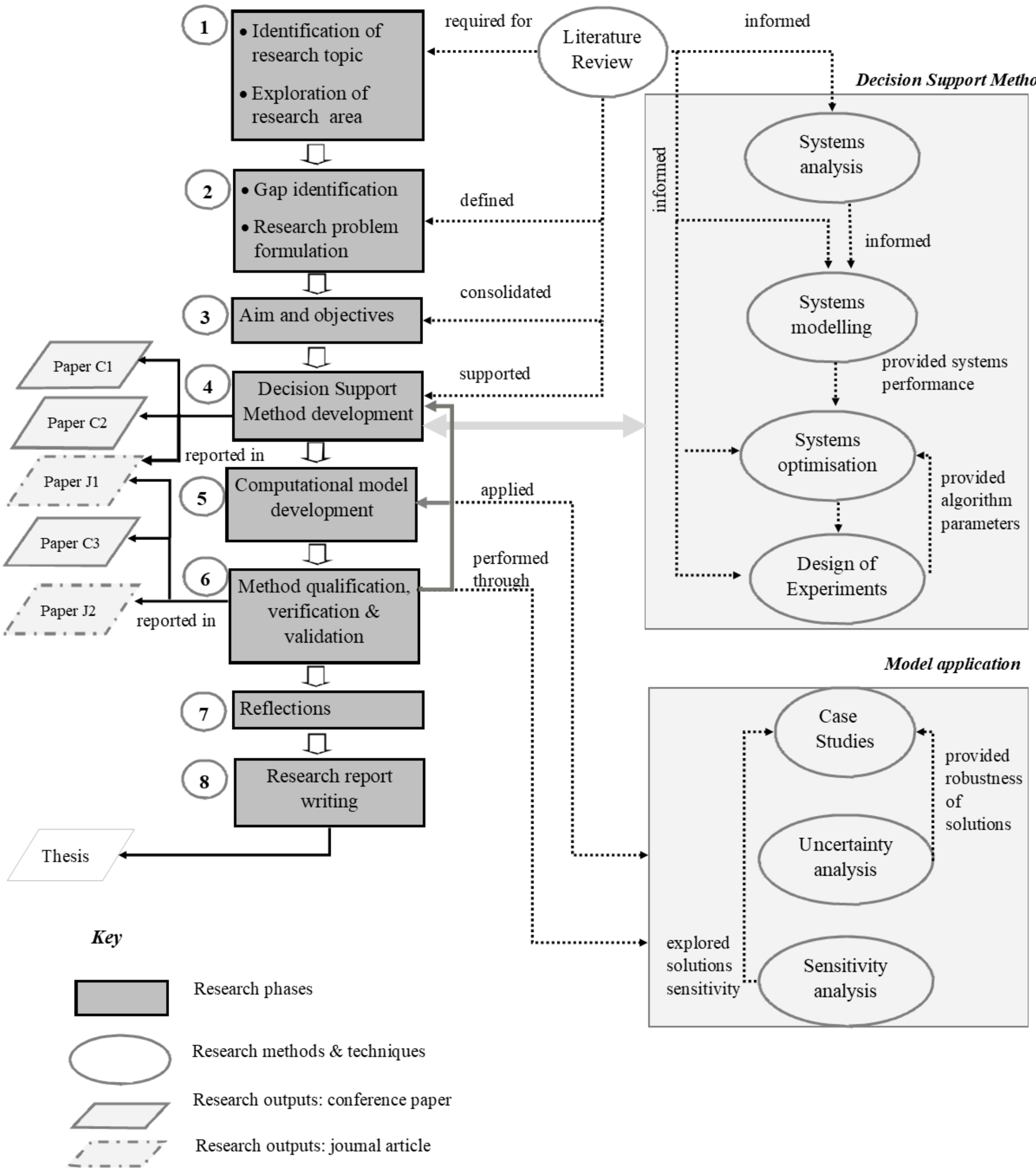

Figure 3.9 Research Design

The *review* of the pertinent *literature*, the current state of knowledge (Welman et al., 2005) led to the exploration of the research areas related to this study (Chapter 2). As a result of the comprehensive critical review, the *research topics and academic as wells as industry challenges* were identified (Chapter 2). The critical review findings led to the identification of the *research gap*, which indicated the original areas of research and led to the definition of the *research problem* (Welman et al., 2005) (Chapter 2). According to the research problem formulated in phase 2, the *aim*, as well as the objectives of this research, were defined (Chapter

1). The proposed *Decision Support method* was developed to address the aim of this research (Chapters 3 & 4).

The *computational model* corresponds to the developed Decision Support method, which was validated with two different case studies (Chapters 6 and 7). The *method was evaluated* (Chapter 5) with respect to (a) the qualification of the conceptual and mathematical model to represent reality, (b) the verification of the computational model to accurately express the conceptual and mathematical model developed and finally (c) the validation of the computational model to accurately describe the reality. There is a feedback loop between the method qualification, verification and validation and research phases 4 and 5. The following phase was the *reflection* of this research: the findings of the case studies were analysed (Chapters 6 and 7), synthesised, and the general benefits, novelties and limitations of the method were considered and the future work directions were presented (Chapter 8). The final phase that is considered as the 'culmination of the research process' is the writing and reporting (Welman et al., 2005) of the research that has as output this thesis.

Research Outputs

Journal articles published on a peer-reviewed journal:

J1: 'A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability'. The decision support method and the application of it on the tanker case study was presented. A sensitivity analysis on the most critical economic and technical parameters was performed.

J2: 'Impact of carbon pricing on the cruise ship energy systems optimal configuration'. The bi-objective application of the developed method was applied on the cruise ship case study and the optimal configurations were identified for different carbon policy scenarios.

Conference papers presented on peer-reviewed international conferences:

C1: 'The influence of ship operating profile in the sustainability of ship energy systems'. In a preliminary stage of the conceptual model development, the impact of the operating profile on the emissions and the life cycle cost was investigated for a tanker ship.

C2: 'Sustainability assessment of ship energy systems at the design phase: integrating environmental and economic aspects'. In a preliminary stage of the conceptual model development, the environmental an economic performance of different configurations for the ship energy systems of a tanker ship was performed.

C3: **'***Environmental and economic sustainability assessment of emerging cruise ship energy system technologies'*. The developed decision support method was applied on a cruise ship and a parametric sensitivity analysis was performed on the most critical economic parameters, including the fuel prices and emerging technologies capital cost.

Finally, the complete research is reported in this thesis.

3.6 Chapter Summary

In this chapter, the research approach adopted in this thesis was presented. The philosophical perspective adopted, which is positivism directed the methodological approach. Accordingly, the nine methodological steps of the undertaken research were presented and discussed, along with the techniques employed. Finally, the research design including the phases of this research and the research outcomes was elaborated. In the next chapter, according to the research approach and assumptions discussed in this chapter, the proposed method to support decisions for the ship energy systems synthesis with sustainable objectives is presented.

4 Proposed Method

4.1 Introduction to chapter

The aim of this chapter is to introduce the developed method for supporting decisions on ship energy systems synthesis. The chapter is structured as follows. First, an introduction to the decision support method with an outline of the tools employed and their connections is presented in Section 4.2. Then the ship energy sub-systems and their interactions are illustrated in Section 4.3, followed by the mathematical models used for the technical, economic and environmental performance analysis of the ship energy systems in Section 4.4. Moreover, the input parameters employed in the method application are presented in Section 4.5. The ship energy systems lifetime performance is discussed in Section 4.6. The mathematical formulation of the multi-objective optimisation problem of the ship energy systems synthesis is presented in Section 4.7. The uncertainty analysis of the near optimal ship energy systems is illustrated in Section 4.8. Finally, the limitations and assumptions of this method are summarised in Section 4.9.

4.2 Introduction to the proposed method

The purpose of the developed method is to support the decision maker to make an informed decision regarding the integrated ship energy systems synthesis with sustainability objectives. The method presented in this chapter was published in articles J1 (Trivyza et al., 2018) and J2 (Trivyza et al., 2019a). The proposed method as it is illustrated in the flowchart shown in Figure 4.1 includes a ship energy systems lifetime performance model and a multi-objective optimisation algorithm that are both employed for the identification of the Pareto optimal front.

The input section requires information from the decision maker and the relevant shipping stakeholders. A number of input parameters need to be provided including the ship characteristics (ship type and deadweight), as well as the expected voyage details including the period of time the vessel sails in ECA. The expected operating profile is derived from measured operational data of similar vessels, details regarding the operating profile can be found in Section 4.6. The limits of the regulated NOx and SOx emissions (IMO, 2005a, 2005b), the EEDI regulation and the minimum propulsion power requirement (IMO, 2013) are calculated according to IMO regulations. Finally, the cost and environmental factors employed by the ship energy systems model are derived from the literature and manufacturer reports and are presented in Section 4.5.

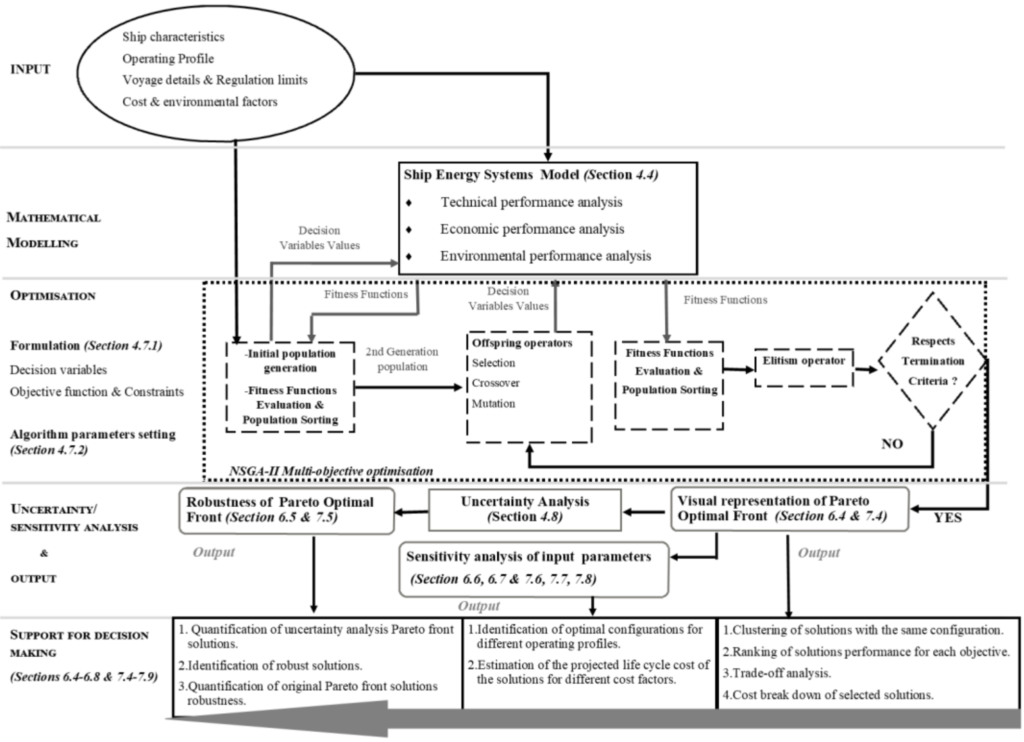

Figure 4.1 Flowchart of the developed decision support method for ship energy systems synthesis

Mathematical models were developed in order to estimate the performance of ship energy systems. First, the ship energy systems are analysed according to the systems approach as it was discussed in Section 3.4.3. The main energy sub-systems are identified and their inputs, outputs, processes, as well as the interconnections among them, are discussed in Section 4.3. Then the technical performance of the ship energy systems is addressed in Section 4.4.1, where the most promising technologies identified in the Critical Review (Section 2.3.5) are modelled. Moreover, the analysis of the economic performance of the ship energy systems is presented in Section 4.4.2, considering the present value life cycle cost. Finally, the environmental performance in respect to lifetime exhaust gas emissions is discussed in Section 4.4.3.

The output of the ship energy systems model is employed to obtain the specific parameters required for the calculation of the fitness functions of the multi-objective optimisation algorithm. The decision variables along with the optimisation objective functions and constraints of the ship energy synthesis problem are described in Section 4.7.1. The developed optimisation problem is a multi-objective combinatorial one, as it was discussed in Section 3.4.5. The NSGA-II algorithm is selected to solve the synthesis optimisation problem. The algorithm parameters are selected in Section 4.7.2, in order to achieve a sufficient approximation of the Pareto front. The optimisation algorithm is used to evaluate simultaneously the environmental and economic objectives and the respective solutions are identified according to the NSGA-II non-dominating sorting described in Section 3.4.5. The optimisation process is repeated until the termination criteria (see Section 4.7.2) are met.

The visual representation of the Pareto front of the most sustainable ship energy systems is provided, as an output of the optimisation, allowing the decision maker to attain an understanding of the trade-offs between the objectives. Furthermore, a sensitivity analysis (Section 3.4.9) of the most influential input parameters is performed and their impact on the near optimal configurations performance is investigated.

An uncertainty analysis is performed according to Section 3.4.8. The process followed and the probability density functions used are described in Section 4.8. The robustness of the solutions is estimated, providing additional information, in order to support the decision maker to identify the near optimal configurations under the input parameters uncertainty.

Final step of the proposed method is to support the decision maker make a choice regarding the optimal ship energy systems synthesis. This procedure is broken down to specific steps as it is depicted in Figure 4.1 for the original case results analysis, the uncertainty analysis and the sensitivity. First the solutions of the original Pareto front are clustered into groups according to their configuration in order to facilitate the analysis. Then the percentage difference of the solutions from the best performing configuration for each objective is used and the near optimal configurations are ranked for each objective. A trade-off analysis is performed among the solutions quantifying the cost of the benefit achieved from more environmental configurations therefore providing an insight to the decision maker regarding the expected improvement. The life cycle cost of selected solutions is further analysed and broken down into capital and operating costs for each sub-system, this contributes in attaining a better understanding of the life cycle cost of the solutions. Next the effect of the operating profile on the optimal solutions is investigated and the near optimal solutions for different operating profiles are identified and compared with the original case. This helps the decision maker select a configuration along with the nominal power according to the preferred operating management policy. In addition, the impact of the most significant cost parameters on the life cycle cost of the solutions provides a better understanding of the ranges of the life cycle cost of the configurations in an uncertain environment. Regarding the uncertainty analysis, the solutions that are identified on the Pareto front of the uncertainty analysis and the best performing configurations on each objective are identified and demonstrated. The outputs from the uncertainty are compared with the findings from the original case, thus supporting the decision maker select a robust configuration in an uncertain environment. This analysis is further elaborated in Chapters 6 and 7 where the results from the case studies are presented and discussed.

4.3 Ship energy systems analysis: a systems approach

This work employs a systems approach in order to analyse the complex ship energy systems, according to Section 3.4.3. For this reason, the operating parts of the ship energy systems are decomposed into five key sub-systems, as it is displayed in Figure 4.2. The five sub-systems include the three main energy sub-systems, which are the main engine sub-system, the electric and the thermal auxiliary sub-systems. These sub-systems form the main energy systems that produce work and have the greatest energy consumption, as well as emit the majority of the gaseous emissions over the ship operation. Considering that the aim of this work is to contribute towards improving the ship energy system sustainability, two more sub-systems that have an impact on the energy systems environmental footprint are included in this research, the emissions reduction technologies and the energy efficiency technologies sub-systems.

According to the systems approach, a black box system representation is employed, where each sub-system consists of input, output and process. The input coming from the optimiser (engine, fuel type, the existence of technology, number of sets and nominal power) and the input from the user (emission limits, operating profile and minimum power requirements) are depicted through solid arrows in Figure 4.2. All the sub-systems have output parameters that contribute to the calculation of the environmental and economic performance of the ship energy systems. The process for each sub-system is identified, modelled and discussed in the next section.

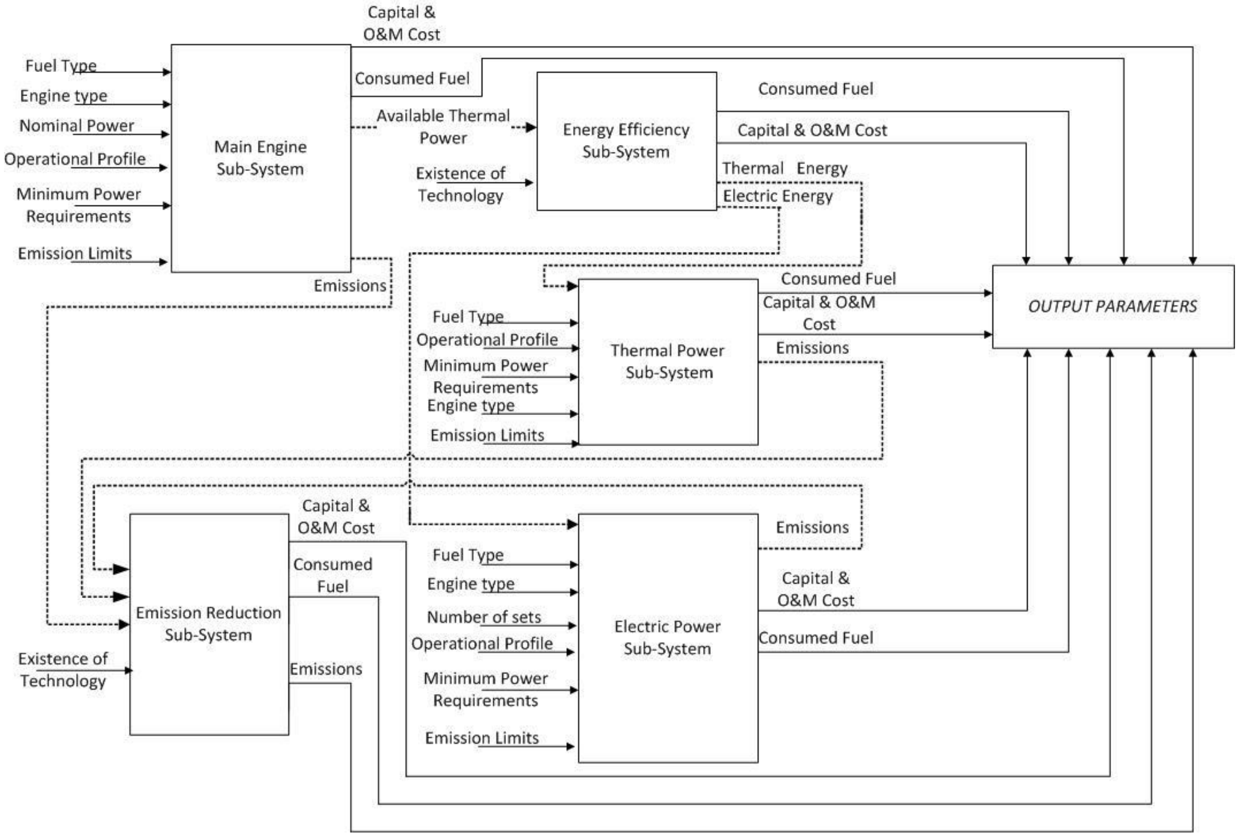

Figure 4.2 Ship energy sub-systems and interactions

Another important part of the system according to the systems approach is to identify the relationships among the sub-systems. Each sub-system properties, as well as behaviour, have an impact on the whole system. The interconnections among the subsystems are identified, wherever they exist. Each sub-system performance is modelled separately, whilst considering the sub-systems interactions. The interactions between the sub-systems are displayed through the dashed lines in Figure 4.2. It is highlighted that only the interactions that are of importance for the sub-systems analysis in this work are included.

For each sub-system, several alternative technologies exist, which in some cases can be installed together and in others, are mutually exclusive.

4.4 Mathematical Modelling

The models developed to estimate the performance of the ship energy systems are presented in this section. As it was discussed in Section 3.4.4 mathematical models are appropriate, when modelling engineering systems according to the systems approach.

The modelling of each technology included in this work requires three sets of models; the model for the technical performance assessment described in section 4.4.1, the model for the economic assessment including the capital and operational costs displayed in 4.4.2 and the model for the environmental assessment discussed in section 4.4.3. The mathematical equations presented in the section have been previously published in articles J1, C3 and J2.

The technologies considered in this work after the screening performed in Chapter 2 are presented in Table 4.1 and are discussed in detail in the following sections. These technologies were investigated, as they are considered promising for the specific ship type applications. Further details for the technologies selection in Table 4.1 is included in Sections 6.2 and 7.2.

Table 4.1 List of alternative technologies

Sub-systems	Alternative Technologies	Section
Propulsion	two-stroke diesel engine	4.4.1.1
	two-stroke dual fuel engine	4.4.1.2
	four-stroke diesel engine	4.4.1.3
	four-stroke dual fuel engines	4.4.1.4
	molten carbonate fuel cells	4.4.1.5
Electric Auxiliary	diesel generator set	4.4.1.6
	molten carbonate fuel cells	4.4.1.5
	dual fuel generator set	4.4.1.6
Thermal Auxiliary	gas fired boiler	4.4.1.7
	oil fired boiler	4.4.1.7
Energy Efficiency	Waste Heat Recovery with Turbogenerator	4.4.1.8
	Economiser	4.4.1.9
	Shaft Generator	4.4.1.10
Emission Reduction		
NOx emission reduction technologies	Selective Catalytic Reactor	4.4.1.11
	Exhaust Gas Recirculation	4.4.1.12
SOx emission reduction technologies	Scrubber	4.4.1.13
CO_2 emission reduction technologies	Carbon Capture	4.4.1.14

4.4.1 Technical performance analysis of ship energy systems

In this section, the models developed to estimate the performance of the considered ship energy systems presented in Table 4.1 are analysed.

4.4.1.1 Two-stroke diesel engines

An inventory of the two-stroke diesel engine was developed with data collected from the Project Guides of marine manufacturers (MAN Diesel &Turbo, 2017; Wingd, 2018). In total, the engines used to develop the models are presented in Table 4.2. A regression analysis of the provided data is performed to accurately represent the performance of the engines, a more complex and detailed model would be very computationally intensive (Tzortzis and Frangopoulos, 2018).

Response surface models are extensively applied for modelling in situations, where the output performance, called response, is influenced by several input independent variables (Carley et al., 2004). The relationships between the independent variables and the response are unknown. A series of tests are made, where the input variables are changed in order to investigate the influence they have on the response. As a result of this process, a suitable approximation of these relationships is identified. Response surface models have been employed in the literature to accurately model diesel engines performance (Ganapathy et al., 2011; Hassan Pour et al., 2018) and in specific for marine diesel engines (Tzortzis and Frangopoulos, 2018).

Therefore, in this work response surface models including parameters for all the possible linear, interaction and quadratic terms of the factors were developed in Minitab, with the available manufacturers data for the selected engines in Table 4.2.

The performance is modelled as a function of the engine load (L) and the engine nominal power (P_n).

Table 4.2 Database of two stroke diesel engines

#	Engine type*	Rated power per cylinder**(kW/cyl.)	Rated speed (rpm)	Available number of cylinders	Tier compliance
1	M40	1100	125	5,6,7,8	II
2	W40	1135	146	5,6,7,8	II
3	M45	1390	111	5,6,7,8	II
4	M50	1720	100	5,6,7,8,9	II
5	W52	1810	105	5,6,7,8	II
6	M60	2680	97	5,6,7,8	II
7	W62	2660	97	5,6,7,8	II
8	M70	3640	83	5,6,7,8	II
9	W72	3610	84	5,6,7,8	II

*Engine manufacturer: MAN Diesel & Turbo (M), WinGD (W)

**Cylinder power in L_1 for MAN Diesel & Turbo and R_1 for WinGD

The engine specific fuel consumption, the rated speed at MCR, the exhaust gas amount and the exhaust gas temperature of the two-stroke marine diesel engines are given by Equations 4.1, 4.2, 4.3 and 4.4, respectively.

$$sfc(\mathrm{L}, P_n) = a_1 + a_2\, L + a_3\, P_n + a_4 L^2 + a_5 P_n^2 + a_6 L P_n \tag{4.1}$$

$$rpm = a_7 + a_8 P_n \tag{4.2}$$

$$ega(\mathrm{L}, P_n) = a_9 + a_{10}\, L + a_{11}\, P_n + a_{12} L^2 + a_{13} L P_n \tag{4.3}$$

$$egt(\mathrm{L}, P_n) = a_{14} + a_{15}\, L + a_{16}\, P_n + a_{17} L^2 + a_{18} L P_n \tag{4.4}$$

The rated speed at MCR is independent of the load, therefore, is expressed as a function of the nominal power. It is inferred from the equations that the load and the nominal power, as well as their interactions, significantly influence the responses. In addition, in all the developed equations the relationship of the load with the investigated performances exhibits a curved line, whereas, in Equations 4.3 and 4.4, it is evident that the quadratic term coefficient of the nominal power at MCR is zero; therefore, it can be interpreted that the relationship between this factor and the exhaust gas emissions and temperature is not a curved line.

The regression constants for the performance parameters equations of the two-stroke diesel engines with nominal power varying between 5500-28880 kW can be found in Tables 4.3, 4.4, 4.5 and 4.6. The R^2 and R-adjusted values for the developed regressions are also estimated to indicate the regression analysis accuracy. R^2 coefficient is a 'measure of the proportion of the variance of the dependent variable about its mean that is explained by the independent, or predictor, variables' and is commonly used for predicting the accuracy of the regression model (Hair et al., 2014). In other words, it indicates the strength of the developed model and the dependent variables; thus, the highest this value is the greatest fit is expected. The R^2 increases with the number of independent variables added, whereas the R^2-adjusted adjusts to the number of terms in the model, therefore indicates whether the inclusion of terms benefits the regression accuracy or not (Hair et al., 2014). R^2 values above 0.75 are substantial, whereas above 0.50 are considered moderate (Hair et al., 2011). The estimated R^2 values are above 80%; therefore, the mathematical models represent the manufacturer data with substantial accuracy.

Table 4.3 Two-stroke diesel engines specific fuel oil consumption constants (R^2=83%, R^2-adjusted=80%)

a_1	a_2	a_3	a_4	a_5	a_6
184.89	-46.81	$-1.84\ 10^{-5}$	33.59	$-3.49\ 10^{-9}$	$-8.77\ 10^{-5}$

Table 4.4 Two-stroke diesel engines rated speed at MCR constants (R^2=90%, R^2-adjusted=89%)

a_7	a_8
125.99	$-136.5\ 10^{-5}$

Table 4.5 Two-stroke diesel engines exhaust gas amount constants (R^2=99%, R^2-adjusted=99%)

a_9	a_{10}	a_{11}	a_{12}	a_{13}
-0.81	2.35	$3.12\ 10^{-4}$	-3.05	$1.97\ 10^{-3}$

Table 4.6 Two-stroke diesel engines exhaust gas temperature constants (R^2=80%, R^2-adjusted=76%)

a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
198.42	159.95	$-1.18\ 10^{-3}$	-126.26	$4.28\ 10^{-5}$

The deterioration factor of the engine performance due to the fouling and wearing of its components causes an increase of the fuel consumption and it is modelled according to Cichowicz et al. (2015), as a varying parameter throughout the engine lifetime. The fuel consumption increase per operating hours due to the engines degradation is displayed in Figure 4.3. The figure represents a typical degradation of the engine performance; however, there are many factors that affect it, including the maintenance schedule. The fluctuations of the figure represent the overhaul intervals, according to the assumed maintenance schedule.

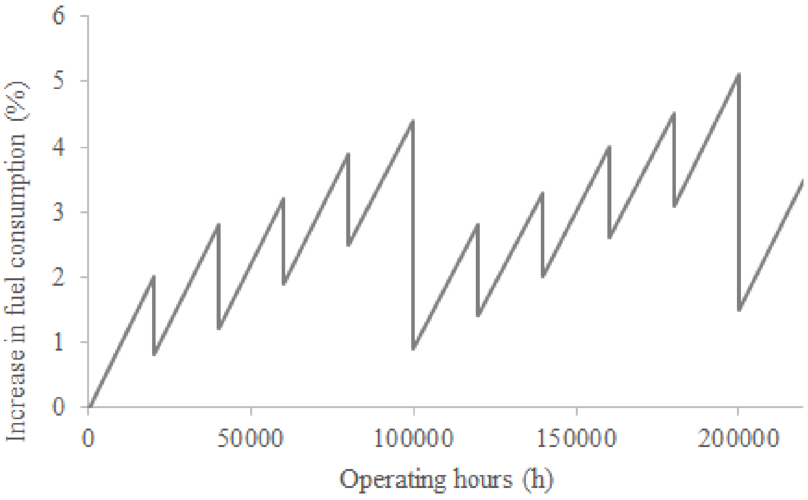

Figure 4.3 Typical performance degradation of a diesel engine (Cichowicz et al., 2015)

The diesel engines interact with the thermal subsystems in terms of the increased thermal power required to preheat the HFO before burning.

4.4.1.2 Two-stroke dual fuel engines

The two-stroke dual fuel engines performance is presented similarly with the diesel two-stroke engines with response surface models developed with data provided by marine manufacturers (Man Diesel & Turbo, 2017; Wingd, 2018). The engines database considered in this analysis is presented in Table 4.7. It is evident from the table that several engines do not comply with the Tier III regulation, despite the low NOx emissions factor compared to the diesel two-stroke engines.

Table 4.7 Database of two stroke dual fuel engines

#	Engine type*	Rated power per cylinder**(kW/cyl.)	Rated speed (rpm)	Available number of cylinders	Tier compliance
1	M40	1100	125	5,6,7,8	II
2	M50	1720	100	5,6,7,8,9	II
3	W50	1440	124	5,6,7,8	III
4	M60	2680	97	5,6,7,8	II
5	W62	2385	103	5,6,7,8	III
6	M70	3640	83	5,6,7,8	II
7	W72	3225	89	5,6,7,8	III

*Engine manufacturer: MAN Diesel & Turbo (M) gas-injected, WinGD (W) pre-mixed

**Cylinder power in L_1 for MAN Diesel & Turbo and R_1 for WinGD

The performance similarly with the two-stroke diesel engines is expressed as a function of the engine load (L) and the nominal power (P_n). The performance of the engine is modelled only in gas mode, which is considered the most energy efficient mode according to Figure 4.4, where, it is observed that the brake specific fuel consumption (BSFC) of the engine in diesel mode is much higher than in gas mode.

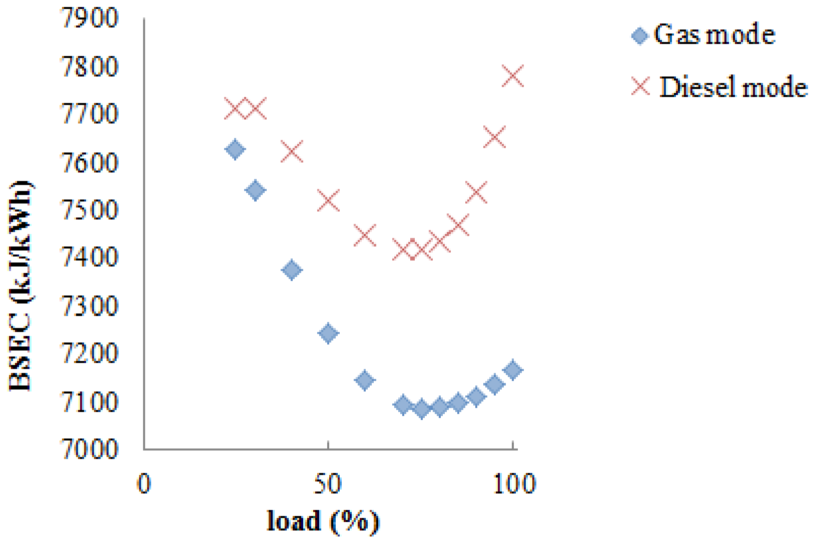

Figure 4.4 Energy consumption in gas and diesel mode of a two-stroke dual fuel pre-mixed engine

The developed response surface models for the dual fuel gas injected engines in the gas mode are provided in Equations 4.5, 4.6, and 4.7, whereas, for the pre-mixed in Equations 4.8, 4.9, 4.10 and 4.11. Separate models were developed for the pre-mixed and gas-injected engines, due to the differentiation on their performance, therefore, it was derived that one common model could not represent the two engine types with accuracy.

$$spoc_{gas-inj}\,(L, P_n) = b_1 + b_2\,L + b_3\,P_n + b_4L^2{+}b_5P_n^2{+}b_6L\,P_n \quad (4.5)$$

$$\mathrm{sgc_{gas-inj}\,(L, P_n) = b_7 + b_8\,L + b_9\,P_n + b_{10}L^2{+}b_{11}P_n^2{+}b_{12}L\,P_n} \quad (4.6)$$

$$\mathrm{egt_{gas-inj}\,(L, P_n) = b_{13} + b_{14}\,L + b_{15}\,P_n + b_{16}L^2{+}b_{17}P_n^2{+}b_{18}L\,P_n} \quad (4.7)$$

$$\mathrm{spoc_{pre-mixed}(L, P_n) = b_{19} + b_{20}\,L + b_{21}\,P_n + b_{22}L^2 + b_{23}P_n^2 + b_{24}L\,P_n} \quad (4.8)$$

$$\mathrm{sgc_{pre-mixed}(L, P_n) = b_{25} + b_{26}\,L + b_{27}\,P_n + b_{28}L^2 + b_{29}P_n^2 + b_{30}L\,P_n} \quad (4.9)$$

$$\mathrm{egt_{pre-mixed}(L, P_n) = b_{31} + b_{32}\,L + b_{33}\,P_n + b_{34}L^2 + b_{35}P_n^2 + b_{36}L\,P_n} \quad (4.10)$$

$$\mathrm{ega_{pre-mixed}(L, P_n) = b_{37} + b_{38}\,L + b_{39}\,P_n + b_{40}L^2 + b_{41}P_n^2 + b_{42}L\,P_n} \quad (4.11)$$

It is evident that the load and the nominal power, as well as their interactions influence the responses, in addition, they exhibit a curved line relationship with the performances. The detailed regression constants are also given in Tables 4.8, 4.9, 4.10 and 4.11 for dual fuel engines with nominal power varying between 5500 kW to 25800 kW. The function for the nominal speed of the dual fuel gas injected engines at MCR and the exhaust gas amount are similar with the Equations 4.2 and 4.3, respectively according to the manufacturer Project guide. The R^2 and R^2-adjusted coefficients indicate substantial accuracy of the regression models.

Table 4.8 Two-stroke dual fuel engines specific pilot oil consumption constants

b_1	b_2	b_3	b_4	b_5	b_6	R^2	R^2-adjusted
25.07	−48.78	$-4.83\ 10^{-5}$	30.09	$1.66\ 10^{-10}$	$4.24\ 10^{-5}$	94%	94%
b_{19}	**b_{20}**	**b_{21}**	**b_{22}**	**b_{23}**	**b_{24}**	**R^2**	**R^2-adjusted**
15.54	−7.95	$-1.38\ 10^{-3}$	3.05	$3.98\ 10^{-8}$	$1.37\ 10^{-4}$	98%	97%

Table 4.9 Two-stroke dual fuel engines specific gas consumption constants

b_7	b_8	b_9	b_{10}	b_{11}	b_{12}	R^2	R^2-adjusted
148.29	−32.15	$-7.73\ 10^{-4}$	31.03	$1.60\ 10^{-8}$	$-4.07\ 10^{-5}$	89%	88%
b_7	**b_8**	**b_9**	**b_{10}**	**b_{11}**	**b_{12}**	**R^2**	**R^2-adjusted**
166.16	−52.72	$-5.93\ 10^{-4}$	34.61	$1.99\ 10^{-8}$	$-7.88\ 10^{-5}$	99%	99%

Table 4.10 Two-stroke dual fuel engines exhaust gas temperature constants

b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}	R^2	R^2-adjusted
254.04	160.96	-0.01	−126.58	$3.50\ 10^{-7}$	$1.35\ 10^{-18}$	80%	77%
b_{31}	**b_{32}**	**b_{33}**	**b_{34}**	**b_{35}**	**b_{36}**	**R^2**	**R^2-adjusted**
276.53	-242.82	$1.40\ 10^{-3}$	184.01	$-3.11\ 10^{-9}$	$-1.00\ 10^{-3}$	97%	96%

Table 4.11 Two-stroke dual fuel engines exhaust gas amount constants (R^2=98%, R^2-adjusted=97%)

b_{37}	b_{38}	b_{39}	b_{40}	b_{41}	b_{42}
5.51	-24.37	$4.41\ 10^{-4}$	18.52	$1.29\ 10^{-9}$	$1.66\ 10^{-3}$

The deterioration factor similar to the diesel engines is modelled according to MAN Diesel &Turbo (2017a), as a varying parameter throughout the engine lifetime and is presented in Figure 4.5. The engine degradation due to fouling and aging is expressed, as an increase in the fuel consumption and it is influenced by the assumed maintenance schedule of the engine. Figure 4.5 in comparison with Figure 4.3 exhibits a lower fuel consumption increase, due to the cleaner natural gas fuel (Banawan et al., 2010). In addition, similar to the diesel engine degradation a drop on the fuel increase is observed on the 100,000 operating hours due to the maintenance overhauls. Finally, a differentiation on the assumed management schedule is observed between the two figures.

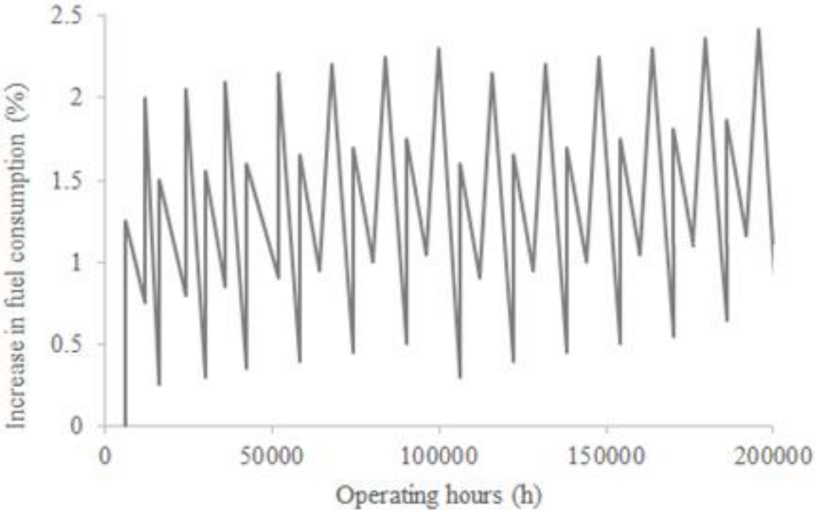

Figure 4.5 Typical performance degradation of a dual fuel engine (gas mode)

It is highlighted that dual fuel engines interact with the other subsystems, first with the electric subsystem in terms of increased energy consumption due to the spark plug ignition, which is energy intensive. In addition, the dual fuel engines due to the gasification system occupy more space on the ship compared to the diesel engines. Finally, the safety regulations force larger tanks for the LNG storing. The weight and space occupation of the subsystems and the impact it has on the ship structure and potential payload reduction is not addressed in this thesis as it was discussed in the scope of this work.

4.4.1.3 *Four-stroke diesel engines*

The response surface models for the marine four-stroke diesel engines performance are derived from data published in the manufacturers Project Guide (MAN Diesel & Turbo, 2016; Wärtsilä, 2017). The engines database employed in the regression analysis is presented in Table 4.12. The performance is expressed as a function of the load and the nominal power of the engine. The developed regression functions to express the specific fuel consumption, exhaust gas amount and exhaust gas temperature are provided by Equations 4.12, 4.13 and 4.14 respectively.

Table 4.12 Database of four stroke diesel engines

#	Engine type*	Rated power per cylinder**(kW/cyl.)	Rated speed (rpm)	Available number of cylinders	Tier compliance
1	W31	610	750	8,12,14,16	II
2	W32	580	720/750	6,7,8,9,12,16,18	II
3	M32	583	720/750	6,7,8,9,10	II
4	W46	1200	600	6,7,8,9,12,14,16	II

*Engine manufacturer: MAN Diesel & Turbo (M), Wärtsilä (W)

**Cylinder power in L_1 for MAN Diesel & Turbo and R_1 for Wärtsilä

$$sfc(\mathrm{L}, P_n) = c_1 + c_2\, L + c_3\, P_n + c_4 L^2 + c_5 P_n^2 + c_6 L P_n \tag{4.12}$$

$$ega(\mathrm{L}, P_n) = c_7 + c_8\, L + c_9\, P_n + c_{10} L^2 + c_{11} P_n^2 + c_{12} L P_n \tag{4.13}$$

$$egt(\mathrm{L}, P_n) = c_{13} + c_{14}\, L + c_{15}\, P_n + c_{16} L^2 + c_{17} P_n^2 + c_{18} L P_n \tag{4.14}$$

The regression analysis constants, as well as the R^2 and R^2-adjusted for the four stroke diesel engines models for engines with nominal power varying between 3480 kW to 19200 kW, are provided in Table 4.13, 4.14 and 4.15.

Table 4.13 Four stroke diesel engines specific fuel oil consumption constants (R^2=93%, R^2-adjusted=87%)

c_1	c_2	c_3	c_4	c_5	c_6
252.86	-98.75	-7.18 10^{-3}	47.75	3.74 10^{-7}	8.30 10^{-4}

Table 4.14 Four stroke diesel engines exhaust gas amount constants (R^2=99%, R^2-adjusted=98%)

c_7	c_8	c_9	c_{10}	c_{11}	c_{12}
2.25	9.54	-1.41 10^{-3}	-6.64	1.24 10^{-7}	1.49 10^{-3}

Table 4.15 Four stroke diesel engines exhaust gas temperature constants (R^2=81%, R^2-adjusted=75%)

c_{13}	c_{14}	c_{15}	c_{16}	c_{17}	c_{18}
560.81	-497.12	-1.82 10^{-2}	260.11	2.67 10^{-7}	1.43 10^{-2}

The deterioration of the engine leads to an increase of the fuel consumption over the ship lifetime and it is assumed similar to Figure 4.3.

4.4.1.4 Four stroke dual fuel engines

The four stroke dual fuel engines performance is simulated with regression analysis on data provided by marine manufacturer Project guides (MAN Diesel &Turbo, 2017; Wärtsilä, 2017). The four stroke dual fuel engines comply with the Tier III regulations, when operating in gas mode. The database of the engines considered in this work is displayed in Table 4.16.

Table 4.16 Database of four stroke dual fuel engines

#	Engine type*	Rated power per cylinder**(kW/cyl.)	Rated speed (rpm)	Available number of cylinders	Tier compliance
1	W34	480	720	6,8,9,12,16	III
2	M35	510	720	6,7,8,9,10	III
3	W46	1200	600	6,7,8,9,12,14,16	III
4	W50	975	500/514	6,8,9,12, 16,18	III
5	M51	1050	500/514	6,7,8,9,12,14,16,18	III

*Engine manufacturer: MAN Diesel (M), Wärtsilä (W)

** Cylinder power in L_1 for MAN Diesel & Turbo and R_1 for Wärtsilä

The engine performance is expressed as a function of the load and the nominal power of the engine. Equations 4.15, 4.16 and 4.17 display the specific energy consumption, the exhaust gas amount, as well as the exhaust gas temperature, respectively. The constants, as well as the regression coefficients for the surface response models, are provided in Table 4.17, 4.18 and 4.19.

$$sec(\mathrm{L}, P_n) = d_1 + d_2\, L + d_3\, P_n + d_4 L^2 + d_5 P_n^2 + d_6 L P_n \tag{4.15}$$

$$ega(\mathrm{L}, P_n) = d_7 + d_8\, L + d_9\, P_n + d_{10} L^2 + d_{11} P_n^2 + d_{12} L P_n \tag{4.16}$$

$$egt(\mathrm{L}, P_n) = d_{13} + d_{14}\, L + d_{15}\, P_n + d_{16} L^2 + d_{17} P_n^2 + d_{18} L P_n \tag{4.17}$$

Table 4.17 Four stroke dual fuel engines specific energy consumption constants

	d_1	d_2	d_3	d_4	d_5	d_6	R^2	R^2-adjusted
M	11425.60	−5834.08	−0.19	2506.67	$5.28\ 10^{-6}$	$5.37\ 10^{-2}$	99%	99%
							R^2	R^2-adjusted
W	11954.40	−8360.32	−0.05	3920.00	$1.07\ 10^{-6}$	$3.45\ 10^{-2}$	98%	96%

Table 4.18 Four stroke dual fuel engines exhaust gas amount constants

	d_7	d_8	d_9	d_{10}	d_{11}	d_{12}	R^2	R^2-adjusted
M	-13.21	24.38	$1.07\ 10^{-3}$	-17.66	$-2.64\ 10^{-8}$	$1.92\ 10^{-3}$	99%	99%
							R^2	**R^2-adjusted**
W	-84.06	-48.85	0.02	25.87	$-7.49\ 10^{-7}$	$2.04\ 10^{-3}$	99%	98%

Table 4.19 Four stroke dual fuel engines exhaust gas temperature constants

	d_{13}	d_{14}	d_{15}	d_{16}	d_{17}	d_{18}	R^2	R^2-adjusted
M	778.62	-478.04	-0.04	197.33	$1.19\ 10^{-6}$	$1.15\ 10^{-2}$	99%	97%
							R^2	**R^2-adjusted**
W	98.61	428.23	0.03	-280.00	$-9.29\ 10^{-7}$	$8.48\ 10^{-3}$	97%	92%

The fuel consumption increase due to the deterioration of the engine is assumed similar with Figure 4.5.

4.4.1.5 Molten carbonate fuel cells

MCFCs are considered more prominent among the available fuel cells types, according to the literature presented in Chapter 2. MCFC work at part load with practically unchanging efficiency (EDUCOGEN, 2001; Mcphail et al., 2015), specifically the MCFC efficiency at 50% of full load will typically decline less than 2% compared to the full load value (EIA, 2016). In addition, MCFC efficiency on primary energy to electricity does not vary much with system size (Turco et al., 2016) and is considered ‘scale and load-independent’ (Mehmeti et al., 2016). Along these lines, previous measurements of MCFC shipboard operation prove that the efficiency does not vary with load and size (Hestad and Aarskog, 2010).

The molten carbonate fuel cells considered to be of 500 kW_e nominal power. The consumption is derived from experimental data found in the literature (Alkaner and Zhou, 2006), including the reformer efficiency. The fuel consumption is expressed as a function of the load of the engine and is given in Equation 4.18. The constants of Equation 4.18 of the molten carbonate fuel cells are displayed in Table 4.20.

$$sfc = e_1 L^2 + e_2\, L + e_3 \tag{4.18}$$

Table 4.20 Specific fuel consumption constants for fuel cells

e_1	e_2	e_3
6.25	5.75	190.4

Each fuel cells unit produces exhaust gas flow rate of 0.212 kg/s (Silveira et al., 2001) at temperature 370ºC (EPA and CHP, 2015) and is assumed constant for every load.

4.4.1.6 Diesel and Dual Fuel Generator Sets

For the electric auxiliary sub-system, the database presented in Table 4.21 with the specific fuel consumption of diesel and dual fuel generator sets derived from manufacturers data (Man Diesel & Turbo, 2017; Wärtsilä, 2017), was used. The correction factor and efficiency of the electric generator are provided in Section 4.4.1.10.

Table 4.21 Database for auxiliary generators

#	Engine type*	Rated power per cylinder**(kW/cyl.)	Rated speed (rpm)	Available number of cylinders	Tier compliance
1	M16	95	1000	5,6,7,8,9	II
2	W20	146	1200	6,8,9	III
3	M21	215	1000	6,7,8,9	II
4	M28	210	720	5,6,7,8,9	II

*Engine manufacturer: MAN Diesel Diesel & Turbo (M), Wärtsilä (W)

** Cylinder power in L_1 for MAN Diesel & Turbo and R_1 for Wärtsilä

4.4.1.7 Thermal boiler

The fuel mass flow of the thermal boiler is estimated according to Equation 4.19 and is expressed as a function of the required saturated steam $\dot{m}_s$, the specific enthalpy difference Δh, the fuel lower heating value LHV and the boiler efficiency η_b.

$$\dot{m}_{f,b} = \frac{\dot{m}_s \, \Delta h}{\eta_b \, LHV} \tag{4.19}$$

The boiler efficiency is considered as a function of the load according to Figure 4.6. Equation 4.20 provides the boiler efficiency function and the constants are given in Table 4.22.

$$\eta_b = f_1 L^2 + f_2 \, L + f_3 \tag{4.20}$$

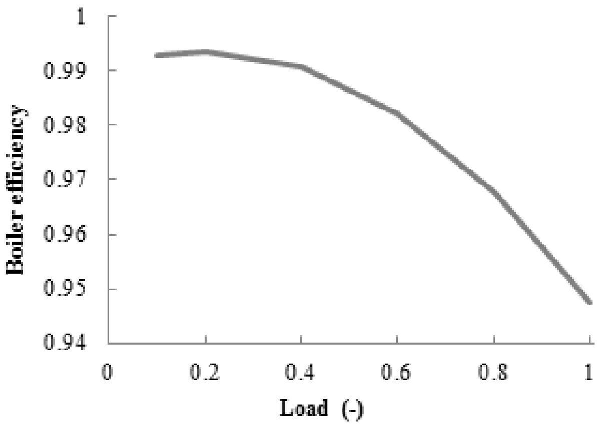

Figure 4.6 Thermal boiler efficiency (Baldi, Nguyen, et al., 2016)

Table 4.22 Constants for thermal boiler efficiency

f_1	f_2	f_3
-0.0735	0.0305	0.0305

4.4.1.8 Waste Heat Recovery System

The mathematical model used to simulate the performance of the WHR is according to Sname's Bulletin 3-49 (SNAME, 1990) with the following assumptions:

- The equations are for a single pressure turbogenerator.
- Heat recovery is considered only from the exhaust gas of the main engine.
- The steam conditions were selected according to the minimum recommended gas temperatures and the enthalpies, pressure and temperature were obtained from a Mollier diagram. The pressure level is assumed at 8 bars and saturated temperature 170 °C, the pinch point is considered 10 °C, whereas the temperature at the bank exit is 180 °C.
- The feedwater temperature at the recirculating valve is considered 100 °C and at the economiser outlet 160 °C.
- A 1.5% allowance is assumed for exhaust gas losses.
- The recirculation ratio is estimated 1.32 to keep the enthalpy rise at 140 °C temperature at the economiser inlet.
- For the steam rate of the turbogenerator a conservative approach regarding the efficiency and steam rate is adopted, whereas the commercially available units have a better performance. A 2.5% pressure drop is assumed for the superheated steam and a 5°C for the saturated.

The engine exhaust gas energy content is considered and the temperature and amount of exhaust gas are used as inputs for the calculation of the superheated steam produced from the WHR according to Equation 4.21.

$$\dot{m}_{sup} = \frac{0.985\, ega\ \ 3600\, C_p\, (egt-T_L)-((1-ss)\, \dot{m}_s(h_g+r\, h_f-(r+1)h_{out}))}{h_{sup}+r\, h_f-(r+1)h_{out}} \tag{4.21}$$

Using the superheated steam rate for electric production from the turbogenerator, the electric energy produced from the waste energy of the engine exhaust gas is calculated in Equation 4.22.

$$P_{el} = \dot{m}_{sup}/s_{rate} \tag{4.22}$$

The WHR interacts with the other subsystem as it was evident in Figure 4.2 by providing electric and thermal energy produced by the excess energy from the engine's exhaust gas.

4.4.1.9 Economiser

The saturated steam produced from the engine exhaust gas and used to cover the thermal needs, when an economiser is employed is estimated according to Equation 4.23, as a function of the temperature and amount of the exhaust gas. As a result, the economiser interacts with the thermal subsystem.

$$\dot{m}_s = \frac{3600\,(egt - T_L)\,ega\,C_p}{h_d} \tag{4.23}$$

4.4.1.10 Shaft Generator

The more efficient main engine drives the shaft generator that produces electric power, as a result the shaft generator interacts with the main engine subsystems as well as the electric (Figure 4.2). The equations used to describe the shaft generator efficiency and the part load correction factor, are estimated according to data found in the literature (SNAME, 1990). The generator efficiency, as a function of the nominal power is given by Equation 4.24, with the constants in Table 4.23 and is displayed in Figure 4.7.

$$\eta_g = g_1 P_{n,sg}{}^{g_2} \tag{4.24}$$

Table 4.23 Constants of generator efficiency

g_1	g_2
0.896	0.0086

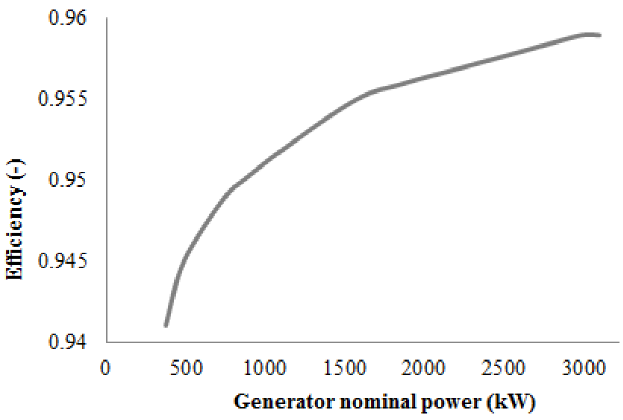

Figure 4.7 Generators efficiency as a function of the nominal power

The correction factor of the generator efficiency in Figure 4.8, as a function of the load, is calculated according to Equation 4.25, with the constants presented in Table 4.24.

$$cl = g_3 L^3 + g_4\, L^2 + g_5\, L + g_6 \tag{4.25}$$

Table 4.24 Constants of generator correction factor

g3	g4	g5	g6
0.233	−0.507	0.394	0.882

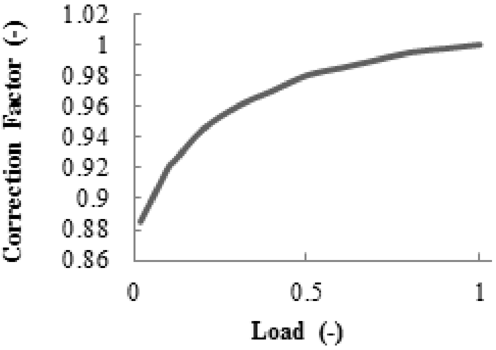

Figure 4.8 Generator correction factor, relative to the load

4.4.1.11 Selective Catalytic Reactor

The SCR technology performance is expressed considering the urea solution consumption required to reduce the NOx emissions, the SCR efficiency and electric consumption. These factors have an impact on the estimation of the economic and environmental objectives.

The urea solution consumed from the SCR operation is estimated, according to data provided in Wärtsilä (2015). The amount of urea solution consumed is displayed in Equation 4.26 and Table 4.25 and is expressed, as a function of the NOx emissions reduction, the engine's power output and the urea's concentration.

$$\dot{\mathrm{V}}\mathrm{u} = (h_1\, \Delta\mathrm{NOx} + h_2)\frac{\mathrm{P_b}}{\mathrm{C_u}} \tag{4.26}$$

Table 4.25 Constants of urea solution consumption

h1	h2
0.0593	0.0091

The SCR interacts with the electric subsystem and this is accounted with an energy penalty. For the SCR operation, an energy penalty on the engine's fuel consumption is considered due to the electrical demand from the SCR pumps operation, around 2 g/kWh (WinGD, 2005). The effectiveness of the SCR to reduce the NOx emissions is assumed to be equal to an average

85% below Tier I, regardless of the engine load according to the literature and technical reports (Armellini et al., 2018; Lövblad, G., Fridell, 2006; Wik, 2016).

4.4.1.12 *Exhaust Gas Recirculation*

The EGR performance is expressed considering the energy penalty, the amount of consumables and the effectiveness of the technology to mitigate the NOx emissions.

The EGR auxiliary equipment operation interacts with the electric subsystem and contributes to an energy penalty on the engine's fuel consumption, which is considered to be equal to 4 g/kWh (Raptotasios et al., 2015; WinGD, 2005). The EGR is not compatible with high sulphur fuels (Wik, 2010), therefore NaOH additive is applied to neutralise the sulphur in the EGR water, which corresponds to 0.15 l/h/MW of the engine (Hansen et al., 2014). Therefore, the energy penalty and the consumable is included in the calculations of the operational costs. The NOx emission reduction effectiveness is considered to be equal to 65% below Tier I (Wik, 2016; Woodyards, 2009) and the effectiveness of the EGR varies depending on the engine load according to Figure 4.9.

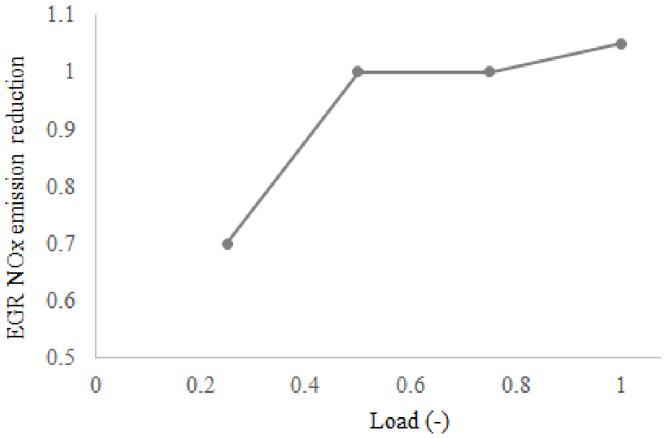

Figure 4.9 Normalised EGR emission reduction relative to load adapted from Weisser et al. (2011)

4.4.1.13 *Scrubber*

A seawater open loop scrubber is modelled in order to reduce the SOx emission. This technology has an impact both on the life cycle cost and the lifetime emissions of the ship energy systems.

The scrubber similar with the other emission reduction technologies requires electric energy to operate, therefore the interaction with the electric subsystems is expressed as an increase in the fuel consumed. The operation increases the engine fuel consumed around 2% (Brynolf, Magnusson, et al., 2014) and obtains a reduction on the particulate matter emissions around 25% (Brynolf, Magnusson, et al., 2014; Entec, 2005). It is assumed that the scrubber reduces the SOx emissions so that the ship complies with the ECA and global water regulations for SOx emissions.

4.4.1.14 Carbon Capture system

The performance of a post-combustion carbon capture systems is modelled according to Zhou and Wang (2014). The solvent-based post-combustion carbon capture that employs chemicals to absorb the carbon from the exhaust gas is modelled herein, as it was recognised the most promising that allows integrating into an existing ship power plant (see Chapter 2).

The CO_2 quantity (kg) is estimated, as a function of the carbon coefficient of the fuel and the fuel consumption. The quantity of the CO_2 bypassed is expressed in Equation 4.27, as a function of the absorption rate (AR) of the technology and the target (T) of CO_2 reduction.

$$q_{CO_{2,bp}} = \frac{q_{CO_{2,tot}}}{AR}\, T(\%) \tag{4.27}$$

The quantity of NaOH and CaO required to capture the carbon, are calculated proportional to the quantity of CO_2 bypassed, according to the stoichiometric chemical reaction, as it is provided in Zhou and Wang (2014).

The Carbon Capture requires thermal and electric energy for its operation. The interactions with the other subsystems are modelled as the energy required for the Carbon Capture operation, which is assumed 0.5 MJ/kg of CO_2 separated (Zhou and Wang, 2014). The carbon is stored in the form of $CaCO_3$, which is an industrial raw material that can be sold and reused, or disposed. A maximum 2% per day occupation of the ship DWT is assumed for the carbon by-products. The further impact of the carbon capture technology on the space and weight occupation is considered out of the scope of this work.

4.4.2 Economic performance analysis of ship energy systems

In this section, the economic assessment model of the ship energy systems is presented. The economic estimation includes both the capital cost of the ship energy systems, along with the operational, since this work focuses on the life cycle cost, as it was discussed in Section 3.4.3. The equations employed to estimate the system capital and operational costs are given.

4.4.2.1 *Capital expenditure*

The capital expenditure is defined, as the investment cost and entails the equipment cost of the system. Capital cost is modelled, as a function of the technology nominal power according to (Balland et al., 2014; Entec, 2005). In the cases of the emission reduction or energy efficiency subsystem, the cost is expressed as a function of the main engine nominal power. The capital expenditure of the ship energy systems is calculated according to Equation 4.28.

$$CAPEX = C_{c(t_{me})}\, N_{me}\, P_{n,me} + C_{c(t_{ae})}\, N_{ae}\, P_{n,ae} + C_{c(t_{th})}\, N_{th}\, P_{n,th} + \\ \sum_{p=1}^{NP} \sum_{o_{er,p}=1}^{O_{er,p}} (b_{er,p}\, C_{c(t_{er,p})}\;\; N_{me} P_{n,me}) + \sum_{o_{ee}=1}^{O_{ee}} (b_{ee}\, C_{c(t_{ee})}\;\; N_{me}\, P_{n,me}) \tag{4.28}$$

The capital cost of all the subsystems: main engine (me), auxiliary electric (ae), thermal boiler (th), emission reduction technologies (er) and energy efficiency (ee) is estimated. Where Cc (€/kW) is the cost factor for the capital cost calculation that depends on the type of technology and is derived from literature and manufacturer data (see Section 4.5.2). P_n denotes the subsystems nominal power expressed in kW, whereas N is the number of the identical subsystems.

4.4.2.2 *Operational expenditure*

Apart from the initial investment cost, it is important in the economic analysis to include the operational costs. The operational expenditure in this analysis includes the fuel and maintenance cost, which are considered the most significant similar to previous studies (Dimopoulos et al., 2008b; Sakalis and Frangopoulos, 2018).

Fuel cost

Fuel cost is the most important operational cost and in some cases can accounts for more than 50-60% of the ship total operating cost (Wang and Teo, 2013). The fuel cost of the ship energy systems is estimated for each one of the ship operational phases according to the following Equation 4.29. The fuel consumption amount per each phase is calculated based on the specific engine fuel consumption data and the operating profile.

$$opex1 = \frac{c_{f(f_{me})}}{10^6} \sum_{i=1}^{I} [cf_{(f_{me})} (\sum_{p=1}^{NP} \sum_{o_{er,p}=1}^{O_{er,p}} fi_{(b_{er,p})} + \; sfc_{i,me})\, P_{i,me}\;\, h_i\, (1 + d_{f,i,me})] + \\ \frac{c_{f(f_{ae})}}{10^6}\;\, N_{ae}\, \sum_{i=1}^{I} (cf_{(f_{ae})}\, sfc_{i,ae}\, P_{i,ae}\, h_i\, (1 + d_{f,i,ae})) + \frac{c_{f(f_{th})}}{10^6}\;\, N_{th} \sum_{i=1}^{I} \left(cf_{(f_{th})}\, sfc_{i,th}\, P_{i,th}\;\, h_i\right) \tag{4.29}$$

Where C_f (€/t) is the fuel cost factor that depends on the fuel type and is derived from online bunker prices data, displayed in Table 4.29; d_f is the deterioration factor of the engine performance due to the fouling and wearing of its components, causing an increase of the fuel consumption (derived from Figures 4.3, 4.5); fi (g/kWh) is the energy penalty from the emission reduction technologies that leads to an increase of the fuel consumption (see Section 4.4.1). The fuel amount consumed per operation phase with h_i (hour) denoting the operational hours of each phase is estimated in g according to the sfc (g/kWh) data provided by the manufacturer and the operating requirements P_i (kW). Therefore, the C_f is divided by 10^6 to transform the unit to g/€ from t/€ that is originally derived from the online fuel market prices. It is noted that the specific fuel oil consumption was derived from manufacturer operational data with a specific low heating value (LHV) of the fuel in ISO conditions, therefore for different LHV the ratio cf (-) is used to account for the engines not operating in ISO conditions and is calculated from Equation 4.30.

$$cf = \frac{LHV_{iso}}{LHV_{actual}} \tag{4.30}$$

Maintenance cost

The maintenance cost depends on the type of technology, the operational conditions and the maintenance plan. The maintenance cost and consumables from emission reduction technologies are calculated according to Equation 4.31.

$$opex2 = C_{m(t_{me})}\, N_{me} \sum_{i=1}^{I} (P_{i,me}\ h_i) + C_{m(t_{ae})}\, N_{ae} \sum_{i=1}^{I} (P_{i,ae}\ h_i) + C_{m(t_{th})}\, N_{th} \sum_{i=1}^{I} \left(P_{i,th}\ h_i\right) + \sum_{p=1}^{NP} \left(\sum_{o_{er,p}=1}^{O_{er,p}} (b_{er,p}\, C_{m(t_{er,p})} \sum_{i=1}^{I} \left(P_{i,me}\, t_{ECA}\, h_i\right)) + \sum_{o_{er,p}=1}^{O_{er,p}} (b_{er,p} C_{con(t_{er,p})}\, M_{con(t_{er,p})})\right) + \sum_{o_{ee}=1}^{O_{ee}} [b_{ee}\, C_{m(t_{ee})} \sum_{i=1}^{I} \left(P_{i,me}\ h_i\right)] + \sum_{ss} \frac{E_{p,ss}}{10^6} T_p \tag{4.31}$$

The maintenance cost is estimated per each operating phase i as a function of the operating requirements P_i (kW), the duration of the operating phase h_i (hour) and a maintenance cost factor C_m (€/kWh). For the energy efficiency and emission reduction technologies the maintenance cost is estimated proportional to the main engine operation. The operation of the emission reduction technologies is considered only while the ship sails in ECA areas which corresponds to a predefined percentage of time t_{ECA} (%). C_m depends on the technology type and is derived from literature and manufacturer data, as provided in Table 4.30. In addition, the cost of consumable chemicals required for the operation of the emission reduction technologies is estimated, C_{con} (€/t) is the prices of the chemicals derived from online prices and displayed in Table 4.31. The consumables amount (M_{con}) required for the emission reduction technologies is estimated according to Section 4.4.1. The last factor of Equation 4.31 corresponds to the exhaust gas emissions taxation cost, which is estimated proportional to the emissions amount E_p of each pollutant emitted from each subsystem ss. T_p (€/t) is the emissions cost that depends on the pollutant.

4.4.3 Environmental performance analysis of ship energy systems

In addition to the technical and economic performance of ship energy systems, the environmental performance is assessed. In this section, information regarding the environmental impact of the ship energy systems and the assessment process developed is presented.

During the ship operation, the ship engines and thermal boiler produce a significant amount of anthropogenic emissions that have an adverse impact on the environment and human health. Mitigating these emissions entails the selection of ship energy systems configurations that reduce them. Therefore, a method to quantify the emissions derived from ship energy systems is required.

The ship emissions are quantified through emission models. In recent years, great attention has been placed to ship emission modelling in order to derive emission factors (EF) to relate the mass emission rates of various pollutants to ship operation data, like fuel or energy consumed. EF are originated either from chemical reaction equations or are based on shipboard engine measurements (Miola et al., 2009). In the literature, several studies exist that estimate the EF (Entec, 2002; Lloyd's Register, 1995; Moreno-Gutiérrez et al., 2015; Murphy et al., 2013; Trozzi et al., 2006).

EF depend on the pollutant, the engine type, the fuel and the engine operational activity. EF are either energy based (EF_{eb}) (measured in g/kWh) or fuel consumption based (EF_{fb}) (measured in g pollutant/g fuel) (Smith et al., 2014).

For energy-based pollutants, the annual emissions emitted per sub-system are calculated according to Equation 4.32, whilst for the fuel consumption based pollutants the emissions are calculated according to Equation 4.33.

$$E_{ss,p} = \sum_{i=1}^{I} P_i \; h_i \; EF_{eb_{(p,ss)}} \tag{4.32}$$

$$E_{ss,p} = \sum_{i=1}^{I} sfc_i \; P_i \; h_i \; EF_{fb_{(p,f)}} \tag{4.33}$$

The most significant emissions from ships are the CO_2, NOx and SOx, particulate matter, carbon oxide and hydrocarbons emissions (Lloyd's Register, 1995). The CO_2, NOx and SOx emissions are currently highly regulated and strict targets are set to reduce them. Therefore, a variety of alternatives exists to mitigate them and great attention has been placed on identifying cost-efficient solutions to reduce them, as it was discussed in Chapter 2. For this reason, the application of the proposed method is focused on the three emissions, even though the method is flexible and more emissions can be introduced.

Carbon dioxide emissions are formed through the combustions process and have a high dependency on the fuel type and quality (EDUCOGEN, 2001). As a result, CO_2 emissions are proportional to the fuel consumed, so in order to estimate the emissions, a fuel-based EF is allocated per fuel type.

NOx emissions are formed during the combustion process from the nitrogen of the fuel or in the air. The NOx EF depend on the engine type and fuel (Corbett and Fischbeck, 1997), therefore they are energy based. In addition, the NOx EF varies for different engine loads according to the normalised curves in Figure 4.10.

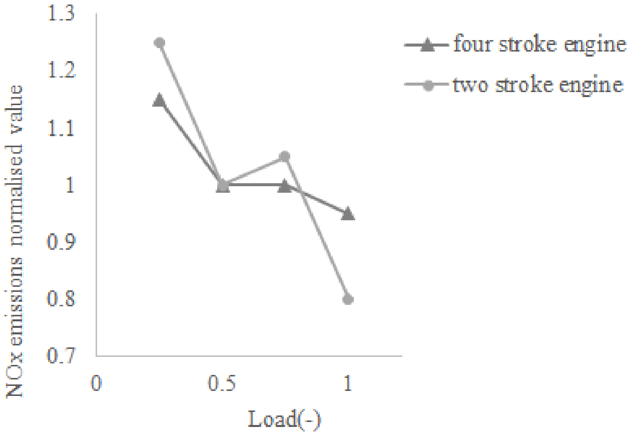

Figure 4.10 Normalised NOx emission factor relative to the load adapted from Weisser et al. (2011)

The presence of sulphur on the fuel has, as a result, to appear in the exhaust gas as sulphur oxides and therefore, SOx emissions depend solely on the fuel sulphur content (Kristensen, 2012). The SOx EF is proportional to the sulphur content on the fuel according to the empirical Equation 4.34 (Corbett and Fischbeck, 1997; Trozzi et al., 2006), where S is the percentage mass sulphur content in the fuel.

$$EF_{SOx} = 20\,S\%\ kg\ per\ t\ in\ fuel \qquad (4.34)$$

4.5 Models input parameters

In this section, the input parameters employed for the application of the mathematical models are presented. It is emphasised that the cost factors considered in this work are indicative and are derived from the literature or technical reports; the references of the employed data are provided. A common practise to account for the inflation, is the producer price index (PPI), which is estimated as the average price of a representative collection of goods prices for the specific year (Vanek and Albright, 2008). Accordingly, the technologies prices presented herein are adjusted to 2018 values using the PPI in the total industry EU-28, according to Eurostat, (2018).

4.5.1 Input parameters for the technical performance analysis models

The values for the performance analysis models presented in the previous sections and adapted in this work are displayed in Table 4.26. The lower heating values of the considered fuels are also presented in Table 4.27.

Table 4.26 Parameters for performance models

Parameters	Values	Source
AR	70%	(Zhou and Wang, 2014)
C_p	1.06 kJ/kg°C	(SNAME, 1990)
C_u	40%	(Wärtsilä, 2015)
dr	10%	(Livanos et al., 2014)
h_f	719 kJ/kg	(SNAME, 1990)
h_g	2769 kJ/kg	(SNAME, 1990)
h_{out}	676 kJ/kg	(SNAME, 1990)
h_{sup}	2328 kJ/kg	(SNAME, 1990)
dr	10%	(Livanos et al., 2014)
n_s	0.99	(Woud and Stapersma, 2002)
r	1.32	(SNAME, 1990)
S_{rate}	8 kg/kW$_e$h	(SNAME, 1990)
T_L	160 °C	(SNAME, 1990)

Table 4.27 Lower Heating Value of fuels

Fuel	Lower Heating Value (kJ/kg)
HFO	39000
LSHFO	41000
MDO	42700
Methanol	20100
MGO	42800
NG	48600

4.5.2 Input parameters for the economic assessment

The cost factors for the calculation of the capital cost can be found in Table 4.28.

Table 4.28 Capital cost factors parameters C_c

	Capital Cost (€/kW)	**Adapted from**
Carbon Capture system[1,4]	2600	(Luo and Wang, 2017)
Diesel Engine (4-stroke)	493	(Livanos et al., 2014)
Diesel Engine[2] (2-stroke)	462	(Theotokatos and Livanos, 2013a)
Dual Fuel Engine (4-stroke)	740	(Tzannatos et al., 2015)
Dual Fuel Engine[2] (2-stroke) gas-injected	700	(Tzannatos et al., 2015)
Dual Fuel Engine[2] (2-stroke) premixed	595	(Wärtsilä, 2013)
EGR[4]	80	(Clausen, 2015)
Molten carbonate fuel Cells[3]	3485	(Mcphail et al., 2015)
SCR[4]	39	(Livanos et al., 2014)
Scrubber[4]	135	(Lövblad, G., Fridell, 2006)
Shaft Generator[4]	147	(IRENA, 2012)
Thermal Boiler	22	(Vanwortswinkel and Nijs, 2010)
Waste Heat Recovery System[4]	100	(Livanos et al., 2014)

[1] *Tank storage of carbon included.*
[2] *The storage and treatment of the fuel are considered.*
[3] *Technology with an internal reformer.*
[4] *Cost per kW of the main engine.*

The average values from online bunker prices (Methanex, 2018; Ship & Bunker, 2018) for the last six months of the year 2018 were considered for the fuel cost estimation, as provided in Table 4.29. The maintenance cost factors, as well as the prices of the consumable chemicals required for the operation of the emission reduction technologies, are displayed in Table 4.30 and Table 4.31, respectively. The prices of the consumables were derived from online average prices of the year 2018 (Alibaba.com, 2018).

Table 4.29 Fuel Cost Factors (C_f)

	Price (€/t)
HFO (IFO 380)	300
LSHFO (LS 380)	350
MDO	480
Methanol	400
MGO	590
NG	250

Table 4.30 Maintenance cost factors parameters C_m

	Maintenance Cost	**Adapted from**
Carbon Capture system	3% of capex (€)	(Luo and Wang, 2017)
Diesel Engine (2-stroke)	0.002 (€/kWh)	(Smith, 2004)
Diesel Engine (4-stroke)	0.012 (€/kWh)	(Pelet et al., 2005)
Dual Fuel Engine (2-stroke)	0.003 (€/kWh)	(Smith, 2004)
Dual Fuel Engine (4-stroke)	0.012 (€/kWh)	(Pelet et al., 2005)
EGR	0.001 (€/kWh)	(Clausen, 2015)
Fuel Cells	0.035 (€/kWh)	(EIA, 2013)
Fuel Cells replacement cost	240 €/kW	(Biert et al., 2016)
Thermal Boiler	1% of capex (€)	(Vanwortswinkel and Nijs, 2010)
Scrubber	0.395 (€/kg SO_2 removed)	(Lövblad, G., Fridell, 2006)
SCR	0.006 (€/kWh)	(Tremuli, 2008)
Shaft Generator	0.001 (€/kWh)	(Listewnik, 1995)
Waste Heat Recovery System	0.004 (€/kWh)	(Dimopoulos et al., 2008a)

Table 4.31 Consumables cost factors parameters

Chemicals	**Consumable Cost Factors (€/t)**
Urea	250
NaOH	350
CaO	55

4.5.3 Input parameters for the environmental assessment

The CO_2 emissions factors for the fuels used in this work are presented in Table 4.32. The values are derived from the literature (Entec, 2002; Smith et al., 2014; Trozzi et al., 2006). The NOx emission factors for the engine types and fuel can be found in Table 4.33. Finally, the sulphur content values of various marine fuels, as they were derived from the literature (Entec, 2002; Smith et al., 2014; Trozzi et al., 2006) can be found in Table 4.34

Table 4.32 CO_2 Emission Factors

	CO_2 (kg/kg of fuel)
HFO	3.021
LSHFO	3.075
MDO	3.082
Methanol	1.375
MGO	3.082
NG	2.75
NG & MDO pilot fuel[1]	2.77

[1] $EF_{CO2}=0.94EF_{CO2,NG}+0.06EF_{CO2,MDO}$.

Table 4.33 NOx Emission factors

	NOx Emission Factor	**Adapted from**
Two-stroke Diesel Engine	According to Tier II & Tier III regulations	(IMO, 2005b)
Two-stroke Dual Fuel Engine (in gas mode) gas-injected	8.7 (g/kWh)	(MAN Diesel, 2013)
Two-stroke Dual Fuel Engine (in gas mode) premixed	1.9 (g/kWh)	(Stenersen and Thonstad, 2017)
Four-stroke Diesel Engine	According to Tier II & Tier III regulations	(IMO, 2005b)
Four-stroke Dual Fuel Engine (in gas mode)	Tier III compliance	(Wärtsilä, 2017) and (MAN Diesel &Turbo, 2017)
Molten carbonate Fuel Cell	0.0045 (g/kWh)	(EPA and CHP, 2015)
Oil Fired Boiler	5.6 (g/L fuel)	(Environmental Protection Agency, 1999)
Gas Fired Boiler	2.4 (g/L fuel)	(Environmental Protection Agency, 1998)

Table 4.34 Sulphur content (%)

HFO	2.7
LSHFO	0.1
MDO	0.1
MGO	0.1
NG	0
NG & MDO pilot fuel[1]	0.006

[1] $EF_{SOx}=0.94EF_{SOx,\,NG}+0.06EF_{SOx,MDO}$.

4.6 Ship energy systems operational lifetime performance

It was identified from the Critical review in Section 2.3.2 that the evaluation of the ship energy systems performance according to an operating profile is important in order to optimise the performance of the systems. The inclusion of the various operating phases throughout the ship lifetime determines the power requirements for each phase, therefore allows the optimisation of the ship energy systems for the expected lifetime operation.

Optimisation of ship energy systems is usually based on an assumption of the systems operational life; however, when historical data of the vessel power demand are provided then the assumptions for the optimisation are more reasonable. In the literature, there is a variety of studies that showed attention to the ship operating profile by deriving profiles from shipboard measurements (Ancona et al., 2018; Baldi, 2016; Banks et al., 2013; Coraddu et al., 2014).

In this work, the operating profile represents the ship mechanical, thermal, and electric power demands throughout the vessel lifetime. Each energy form including mechanical, electrical and thermal demand required has a specific operating profile. For the mechanical and electric profile, the power is provided in kW, whereas for the thermal profile as the saturated steam mass flow.

The operating profile is divided into I distinct operational phases (i=1..I), each phase i is expressed by the power demand and the duration of the operational phase, also defined as the frequency of occurrence. The duration of the total I operational phases expresses one year of operation and the ship energy systems performance is evaluated for I operational phases of one year of operation.

Another important aspect of this work, as it was highlighted on the research aim is to consider the interconnection among the various sub-systems. For this reason, a relationship among the mechanical, electric and thermal power requirements is developed. The electric and thermal loads for each operational phase are estimated, as a function of the brake power of the main engine according to Tzortzis and Frangopoulos (2018). The functions presented in Sections 6.3 and 7.3 are derived from a regression analysis on the operational data.

For the first case study of the Aframax tanker, the operating profile for the mechanical power was derived from existing data found in Banks et al. (2013) and operational data for the thermal and electric demand from shipboard measurements[3]. For the cruise ship, only operational data from shipboard[3] measurements were derived. The ship speed (knots), engines brake power (kW) and the boiler saturated steam, with time step 30 minutes for five years of operation, were used. The data were cluster into operational phases, where each phase is expressed as a percentage of time and a representative, average power demand. The number of the clusters, as well as the time step duration, is a trade-off between an accurate and computationally efficient evaluation (Stojiljković et al., 2014). For the tanker ship, 240 clusters of 50 kW power step were developed, whereas for the cruise ship 650 clusters of 100 kW step.

The developed profiles can be found in Figures 6.2, 7.2 and 7.3 for the case studies.

4.7 Multi-objective optimisation of ship energy systems synthesis

The multi-objective optimisation of the ship energy systems synthesis is described in this section. First, the formulation of the optimisation problem is presented and then the algorithm parameters setting for the specific problem.

---

[3] The operating data cannot be provided due to anonymity issues.

4.7.1 Formulation of the optimisation problem

4.7.1.1 Optimisation decision variables

The main target of this work is to support decisions for the ship energy systems synthesis. As it was defined in the literature the synthesis optimisation problem of energy systems identifies the configuration, in other words, the components that are included as well as their interconnections (Frangopoulos and Sciubba, 2009; Mavrotas and Diakoulaki, 2005; Piacentino and Cardona, 2008). The independent decision variables are discrete variables, indicating whether a component should be in the system or not (EDUCOGEN, 2001). The variables can be binary (0,1) to signify, whether a component is included in the system or a set of discrete variables each value representing an alternative technology that could be a part of the ship energy systems, as it was discussed in Section 3.4.5.

The decision variables are categorised for each sub-system, the propulsion (ps), the auxiliary electric (es), the thermal (ts), the energy efficiency technologies (ee) and the emission reduction technologies (er) sub-system and are presented in Table 4.35.

Table 4.35 Optimisation decision variables

Sub-system	Decision Variable	Description	Type of variable	Set of variable
Propulsion (ps)				
	N_{me}	Number of main engines	integer variable	$o_{Nme} = \{1 \ldots O_{Nme}\}$
	t_{me}	Main engine type	integer variable	$o_{tme} = \{1 \ldots O_{tme}\}$
	f_{me}	Main engine fuel type	integer variable	$o_{fme} = \{1 \ldots O_{fme}\}$
	$P_{n,me}$	Main engine nominal power	integer variable	$o_{Pn,me} = \{1 \ldots O_{Pn,me}\}$
Auxiliary electric (ae)				
	N_{ae}	Number of auxiliary sets	integer variable	$o_{Nae} = \{1 \ldots O_{Nae}\}$
	t_{ae}	Auxiliary engine type	integer variable	$o_{tae} = \{1 \ldots O_{tae}\}$
	f_{ae}	Auxiliary engine fuel type	integer variable	$o_{fae} = \{1 \ldots O_{fae}\}$
Thermal (ts)				
	t_{th}	Thermal boiler type	integer variable	$o_{tth} = \{1 \ldots O_{tth}\}$
	f_{th}	Thermal boiler fuel type	integer variable	$o_{fth} = \{1 \ldots O_{fth}\}$
Energy efficiency technologies (ee)	b_{ee}	The existence of a particular energy efficiency technology, where b_{ee}={1 if the technology t_{ee} is selected or 0 if it is not}	binary variable	$t_{ee} \in o_{ee} = \{1 \ldots O_{ee}\}$
Emission reduction technologies (er)	$b_{er,y}$	The existence ($b_{er,y}$) of a particular emission reduction technology for each pollutant p, where $b_{er,y}$ ={1 if the technology $t_{er,p}$ is selected or 0 if it is not}	binary variable	$t_{er,p} \in o_{er,p} = \{1 \ldots O_{er,p}\}$

4.7.1.2 Objective function

The objectives of this multi-objective optimisation problem, as derived from the aim of this study, are to evaluate at the same time and identify a set of near optimal solutions for the ship energy systems life cycle cost in present value (Equation 4.35) and various gaseous emissions (Equation 4.36).

$$min\ F1_{(ps,es,ts,ee,er)} = CAPEX + \sum_{k=1}^{Y} \frac{OPEX_k}{(1+dr)^k} \qquad (4.35)$$

$$min\ F2p_{(ps,es,ts,ee,er)} = \sum_{k=1}^{Y} (E_{me,p} + E_{ae,p} + E_{th,p} - \sum_{o_{er,p}=1}^{O_{er,p}} (b_{er,p}\ E_{er,p})) \qquad (4.36)$$

Where p expresses the various pollutants considered, p= {CO_2, NOx, SOx}, thus having in total four separate objective functions.

The energy systems capital expenditure in Equation 4.35 is calculated according to Equation 4.28. The yearly operational expenditure in Equation 4.35 is estimated from Equations 4.29, 4.30, brought to present value with an appropriate discounting function and added to the capital cost in order to calculate the life cycle cost objective.

The first three right-hand side terms in the environmental objectives of Equation 4.36 are calculated according to Equations 4.32 and 4.33 depending on the pollutant, whereas the last term represents the reduction of the emissions due to the emission reduction technologies. The energy efficiency technologies contribute on the emissions mitigation, by reducing the fuel consumption of the ship energy systems, therefore, they are considered in a lower level of calculations and for this reason they are not represented in Equation 4.36.

4.7.1.3 Constraints of the optimisation

The multi-objective optimisation is subject to regulatory, power demand, technical and design related constraints.

Regulatory constraints that are mandatory from the maritime regulators are considered.

The nominal power of the main engine has to fulfil the minimum power requirements, according to the regulations (IMO, 2013) as it is presented in Equation 4.37.

$$P_{n,me} \geq P_{mpr,me} \qquad (4.37)$$

The fuel sulphur content has to comply with the limitations introduced by IMO (IMO, 2005a) for outside the global waters, Equation 4.38, and inside the ECA waters, Equation 4.39, or otherwise a scrubber has to be employed.

$$S\%_{g,ss} \leq 3.5\% \tag{4.38}$$

$$S\%_{ECA,ss} \leq 0.5\% \tag{4.39}$$

Where ss is for the propulsion, auxiliary electric and thermal sub-system.

The engines have to satisfy the NOx limits Tier II in global waters (4.40) and Tier III inside ECA waters (4.41) according to regulations (IMO, 2005b).

$$EF_{NOx,ss,g} \leq EF_{NOx,Tier\ II} \tag{4.40}$$

$$EF_{NOx,ss,ECA} \leq EF_{NOx,Tier\ III} \tag{4.41}$$

Where ss is for the propulsion, auxiliary electric and thermal sub-system.

The EEDI value of the ship energy systems has to comply with the EEDI reference value for the specific ship type (4.42), which is calculated according to Appendix C.

$$EEDI \leq EEDI_{ref} \tag{4.42}$$

Demand-related constraints are also included in the optimisation as follows.

The operational profile is divided in I operational phases and the power demand for each operational phase *i* has to be satisfied for each type of energy vector (4.43, 4.44, 4.45).

$$P_{pp_i} - P_{pd_i} = 0 \tag{4.43}$$

$$P_{ep_i} - P_{ed_i} = 0 \tag{4.44}$$

$$P_{tp_i} - P_{td_i} = 0 \tag{4.45}$$

Where i=1…I denote the operational phases.

The nominal power of the thermal (4.47) and electric auxiliaries (4.46) selected has to satisfy the maximum power demand; otherwise, a capacity lower than the required levels might not satisfy the peak power demands.

$$N_{ae}\,P_{n,ae} \geq Max(P_{ed}) \tag{4.46}$$

$$N_{th}\,P_{n,th} \geq Max(P_{td}) \tag{4.47}$$

Technical constraints regarding the incompatibility of technologies are considered and modelled through constraints, so that non-compatible technologies are not selected within a single system configuration as presented in Figure 4.11. The grey cells represent the possible combinations, whereas the white cells the mutual exclusive technologies. In some cases, even though the technologies are compatible the combination is not considered according to the current regulations requirements. From the figure it is evident that the combination of different engine types is possible.

The incompatible combinations are provided in the optimisation and a static penalty approach is employed to handle the constraints similar with previous applications (Dimopoulos, 2009). Static penalty approach imposes a fixed penalty to the objective function, when the constraint is violated (Kulkarni et al., 2018).

		Engines			*Thermal Boiler*		*SOx reduction*		*NOx reduction*		*CO_2 reduction*	*Energy efficiency*	
		diesel	dual fuel	fuel cells	Oil fired	Gas fired	scrubber	fuel switch	SCR	EGR	CC	WHR	SG
Engines	diesel									do not comply with regulations			
	dual fuel						not required	not required	only for GI	only for GI			
	fuel cells						not required	not required	not required	not required			
Thermal Boiler	Oil fired				▨					do not comply with regulations			
	Gas fired					▨	not required	not required	not required	not required			
SOx reduction	scrubber		not required	not required		not required	▨						
	fuel switch		not required	not required		not required		▨					
NOx reduction	SCR		only for GI	not required		not required			▨				
	EGR	do not comply with regulations	only for GI	not required	do not comply with regulations	not required				▨			
CO_2 reduction	CC										▨		
Energy efficiency	WHR											▨	
	SG												▨

Figure 4.11 Compatibility table

A constraint is considered regarding the volume of the carbon by-products and chemicals for the carbon capture (CC) operation shipboard. The quantity and volume of the chemicals and the carbon by-products are estimated according to 4.4.1.14, depending on the target (T) considered for the CO_2 emissions reduction. Therefore, the percentage the chemicals and the carbon by-products occupy the vessel DWT for different targets T, is estimated. The maximum T is selected that keeps the percentage of the DWT occupation less than 2% per day.

Design constraints are considered in the optimisation as follows.

The selection of the number of the main engine, and multiple auxiliary and thermal boilers, in order to cover adequately the capacity of ship operation and comply with the redundancy requirements.

$$N_{me} \geq 1 \tag{4.48}$$

$$N_{ae} \geq 2 \tag{4.49}$$

$$N_{th} \geq 2 \tag{4.50}$$

4.7.2 NSGA-II algorithm parameters setting

4.7.2.1 Design of experiments for parameters setting

The Design of Experiments method developed by Dr. Taguchi and discussed in Section 3.4.6, is applied in order to identify the key factors that impact the convergence of the Pareto front and the near optimal values of the factors in order to attain a sufficient approximation of the Pareto front according to Figure 4.12.

According to Figure 4.12, first, the key parameters are selected including the population size, the percentage of solutions that are considered elite, the crossover fraction and the mutation (shrink and scale) related parameters. These parameters are considered most significant for the genetic algorithm convergence as it was discussed in Section 3.4.6.

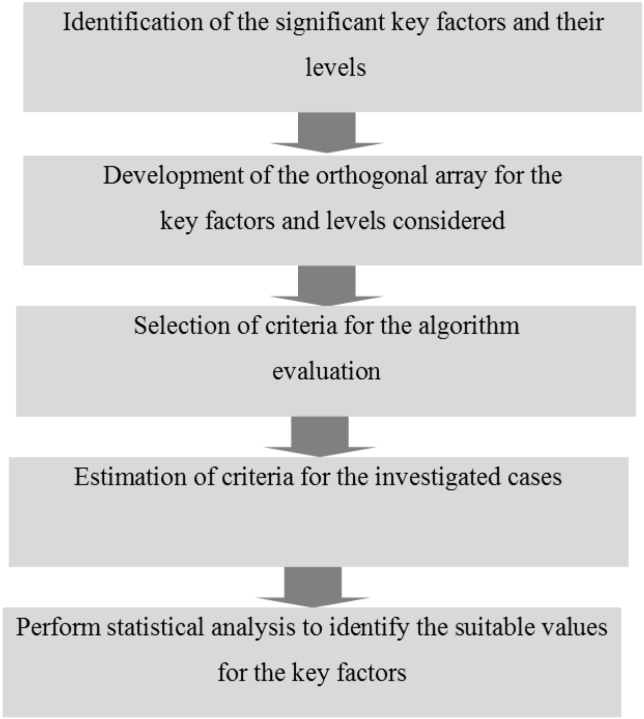

Figure 4.12 NSGA-II algorithm parameters setting

The following factors are investigated:

A. Pareto fraction dictates the number of solutions with the highest ranked performance that will survive and pass in the next generation, as elite solutions. The Pareto fraction value range is 0-1 and the default value is 0.35.

B. Crossover fraction specifies the fraction of the next generation other than elite offsprings that are produced by crossover. The crossover fraction value range is between 0-1 and the default value is 0.8.

C. Population size is the number of chromosomes that are generated and evaluated in every iteration

D. Shrink controls how the standard deviation of the Gaussian distribution used for mutation, shrinks as generations go by. The default value is 1 and the parameters range between -1 to 3. When the value is closer to zero then there is a greater mutation range and as a result, a suboptimal Pareto is avoided.

E. Scale determines the standard deviation at the first generation. The default value is 1 and the range of scale value is 0-10. The scale value is required to be larger for integer decision variables in order to achieve change during the mutation operation.

Three levels were considered for the genetic algorithm parameters, according to related applications in the literature (Stewardson and Whitfield, 2004). The levels considered for the investigated factors are presented in Table 4.36.

Table 4.36 Values of the investigated factors

		Levels		
Factors		**1**	**2**	**3**
A	Pareto Fraction	0.2	0.35	0.7
B	Crossover	0.6	0.8	0.9
C	Population Size	500	2500	4500
D	Shrink	-1	0.01	1
E	Scale	0.5	1	5

Minitab is employed in order to develop the orthogonal array and perform the experimental design for the preceding factors. The orthogonal array for the five factors with three levels L_{27} 3^5 is designed and presented in Appendix B; accordingly, 27 different cases are investigated.

The criteria that are employed to evaluate the algorithm convergence are discussed in Section 4.7.2.2. The optimisation is executed for all the investigated cases and the criteria are estimated. Statistical analysis is performed in order to find the algorithm parameters that have an impact on the accuracy and convergence of the algorithm (see in Appendix B). Finally, from the analysis, the near optimal values for the investigated parameters for the best convergence of the algorithm are identified and discussed in Section 4.7.2.3.

4.7.2.2 Evaluation of algorithm performance

The performance of the NSGA-II algorithm for the optimisation problem presented in this thesis is assessed by employing performance metrics. The metrics used to evaluate the Multi-objective evolutionary algorithms are divided into two categories (Coello Coello, Lamont and VanVeldhuizen, 2007).

The first category is the efficiency denoting the computational effort required in order to obtain the final solutions. Therefore, in order to evaluate the efficiency of the algorithm the computational time to attain the optimal Pareto front is considered as a metric.

The second group of metrics measures the effectiveness of the algorithm. Two aspects denote the effectiveness of the algorithm, the convergence to the Pareto optimal front and the diversity of the solutions (Deb, 2008). As a result, it is anticipated that the use of a single metric is not adequate in order to evaluate the performance of the algorithm. In the literature, three metrics are identified, the convergence, spread of the solutions and a combination of the two that is described from the volume of the solutions (Deb, 2008; Martínez-Vega et al., 2017). In other words, first, it has to be determined if the solutions are near the true Pareto front. Second important aspect is whether the solutions are spaced and spread. Third, it has to be investigated whether the non-dominated solutions extend to cover the whole Pareto front, therefore the volume of the non-dominated solutions on the solution space. For this reason, in this thesis, three metrics are selected to assess the effectiveness of the algorithm, the hypervolume, the dominance and the average distance.

The hypervolume metric calculates the space covered by the non-dominated solutions. A Monte Carlo approach is employed to estimate the hypervolume according to the existing literature (Bader et al., 2010), by estimating for each simulation the percentage of a set of random points which are dominated by the Pareto optimal solutions in the solution space. The average Pareto distance shows the average distance between the individual solutions and finally the dominance is the percentage of solutions obtained from the algorithm that belong to the true Pareto front. The hypervolume and dominance indicators are calculated according to Martínez-Vega et al. (2017), whereas, the average distance between the individual solutions of the Pareto front that denotes the spread of the solutions is provided as the output of the algorithm (Matlab, 2018).

As a result, the metrics selected to evaluate the NSGA-II performance for the specific problem are the computational time, in respect of the algorithm efficiency. Regarding the effectiveness of the algorithm the following metrics: dominance, hypervolume and spread are employed. The findings from the statistical analysis are presented and discussed in Appendix B.

4.7.2.3 Selection of NSGA-II algorithm parameters

It is demonstrated from the analysis (Appendix B) that the parameters of the genetic algorithm have complex interactions and the optimal value for each parameter varies according to the metric. In that respect, the selection of the value for each factor has to satisfy all the metrics in order to optimise the performance of the algorithm. In Table 4.37, the two first optimal levels for each factor per metric are displayed. The factors that were identified more statistically significant for each metric are highlighted and they are considered instrumental for the selection of the factors' levels. The selected values for the factors aim to satisfy at best the metrics, with greater importance on the metrics regarding effectiveness since the computational time is not as high, thus the values are going to be selected in order to improve the accuracy and convergence of the algorithm.

Table 4.37 Best levels for each factor and indicator

Factors	Computational time	Dominance	Hypervolume	Spread
A	3, 1	1,2	3, 1	**1, 2**
B	1, 2	2,3	2, 1	1, 2
C	**1, 2**	**3, 2**	3, 2	**1, 2**
D	2, 3	3,1	3, 1	1, 3
E	1, 3	**2,3**	**2, 3**	2, 3

For factor A, it is not very clear, which is the optimal level; however, the level 1 is selected because it is optimal for two out of three indicators for effectiveness and among the optimal for the rest indicators. For factor B, similarly, with factor A, level 2 is selected. For factor C it is evident that level 2, is considered among the optimal for all four metrics. Level 3 is selected for factor D since it is optimal in most of the metrics regarding effectiveness. Finally, for factor E it is evident that level 2 offers the best results regarding effectiveness. The selected values for the parameters for the algorithm are presented in Table 4.38.

Table 4.38 Selected parameters for the algorithm

Factors	Parameter type	Level	Value
A	Pareto Fraction	1	0.2
B	Crossover	2	0.8
C	Populations size	2	2500
D	Shrink	3	1
E	Scale	2	1

The termination criteria of the optimisation process are presented in Table 4.39 and include the maximum number of the generations, maximum stall generations and the function tolerance. The algorithm ends either, when the maximum number of generations is reached, or when the average change in the spread of the Pareto front over the stall generations is less than the tolerance specified from function tolerance. The number of generations is selected to be high, in order for the algorithm to reach convergence. Finally, the function tolerance and stall generations are derived according to the default values provided from Matlab.

Table 4.39 NSGA-II optimisation algorithm termination criteria

Termination criteria	Value
Function tolerance	0.0001
Generations	500
Stall Generations	100

4.8 Uncertainty analysis of ship energy systems synthesis

This section presents the method followed to investigate how robust is the Pareto front of the ship energy systems optimal solutions. In this work the term ‘dominant configurations’ is used to describe the solutions that have the highest percentage of appearance on the uncertainty analysis Pareto fronts. The Monte Carlo simulation method is employed and the robustness is assessed for the Pareto front solutions according to Mavrotas et al. (2015), as it was discussed in Section 3.4.8. This process helps to include the uncertain parameters in the decision making process and assess the robustness of the proposed configurations in an uncertain environment.

The uncertainty analysis process adopted herein employs the following steps. The steps two to four follow the Monte Carlo analysis, whereas the steps five to six the robustness method proposed by Mavrotas et al. (2015).

1. Identification of k model uncertain parameters.
2. Uncertainty quantification by allocating the probability density functions (PDF) of the uncertain variables.
3. Random generation of M samples for each of k uncertain input parameter according to a probability distribution.
4. M simulations evaluations of the deterministic model leading to M Pareto fronts.
5. Assessment of robustness of each solution on the reference Pareto front. This is achieved by quantifying the number of times across the M simulation a specific solution was obtained; in other words quantification of the frequency of occurrence of the optimal solutions throughout the M Pareto fronts (Mavrotas, Figueira, et al., 2015).
6. Identification of the ship energy system configurations that exhibit the optimal performance on the considered objectives in the majority of the M simulations.

The preceding steps are followed for the uncertainty analysis of the near optimal ship energy systems. First, the uncertain parameters of energy systems are identified. According to the literature, the uncertain parameters of power systems are divided into two categories, the economic and technical parameters (Soroudi and Amraee, 2013). In this work, the parameters required from the model are the fuel prices, cost of the technologies, operating parameters and emission factors. Among these parameters, only the three first are considered uncertain. The latter is considered known with good accuracy since the emission factors depend on the fuel type (carbon or sulphur content) and engine specifics (engine type), so their variations are assumed negligible.

Regarding the technical parameters, a range of operating parameters is considered for the systems modelling including the technologies efficiency, the steam enthalpy, and the fuels lower heating value along with the parameters derived from manufacturers' data for the simulation of the performance of the system. Only the last parameters category is included in the uncertainty analysis, as the others are derived from chemical reactions and experimentations and their values are established and cross-referenced in the literature. Therefore, these values uncertainty is assumed minimal. However, the parameters derived from the manufacturers' data are considered uncertain and according to the manufacturers' project guides, a variation on the values is expected.

Finally, the operating profile, voyage details, emission regulations and ship characteristics are considered as the model inputs. These parameters are provided as inputs from the user depending on the ship type and application, therefore they are not considered uncertain. However, their influence on the optimal solutions is investigated by exploring the near optimal configurations for different possible scenarios (see in Sections 6.6, 7.6, 7.7).

The parameters considered for the uncertainty analysis are presented in Table 4.40.

Table 4.40 Parameters included in the uncertainty analysis

	Parameters
Economic	Capital Cost
	Fuel Prices
Technical	Exhaust gas temperature
	Exhaust gas amount
	Brake specific fuel consumption

In the second step, the quantification of the parameters uncertainty and the probability distribution functions were identified according to the following paragraphs.

a) Fuel prices probability density function

The values for the fuel prices for the deterministic application of the method were selected according to current market values; however, the prices vary through time due to market changes. Thus, the fuel prices uncertainty has to be included, especially in an investment decision with a long lifetime. Monthly average fuel prices from 2009-2018 published online (BIX, 2018) were employed to identify the distribution for the uncertainty analysis of the HFO prices. The derived values are represented in a histogram in Figure 4.13, showing the frequency of occurrence of these values over the last 10 years.

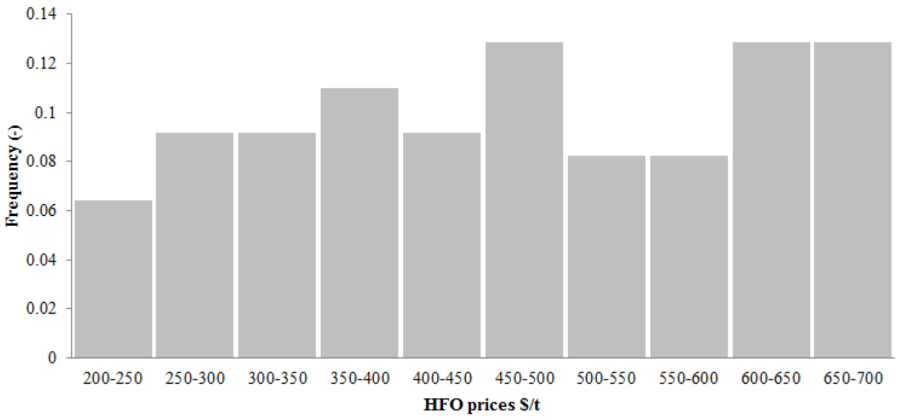

Figure 4.13 HFO historic prices from 2009-2018

According to the figure, it seems reasonable to assume that the HFO prices PDF follows a uniform distribution with ranges the minimum and maximum values, as presented in Figure 4.14.

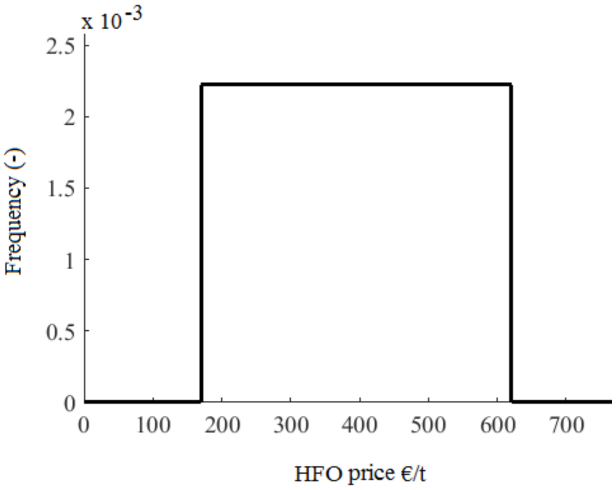

Figure 4.14 Probability distribution function of HFO price

The fuel prices values are considered highly correlated (Abadie et al., 2017; DNV-GL, 2018; Wik, 2016), in line with the historical market evidence, which are presented in Figure 4.15. The Pearson correlation coefficient was estimated between the HFO and the other fuel prices in Minitab. The results from the correlation coefficient are displayed in Table 4.41. A strong correlation on the prices is assumed for the first three fuels, whereas for methanol is considered a moderate correlation according to Cohen (1988). Therefore, the fuel prices are expressed as a function of the HFO prices with regression analysis on the historical data, as displayed in Table 4.41. The R^2 value was estimated to determine how close the data are to the fitted regression. The R^2 value for the first three fuels indicates a strong regression, whereas for methanol a moderate.

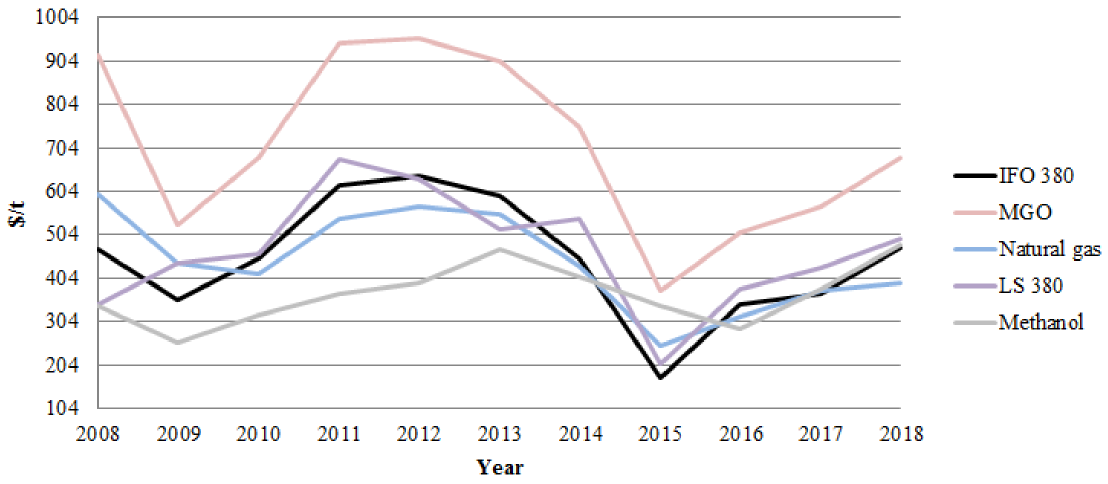

Figure 4.15 Bunker fuels historic prices

Table 4.41 Bunker prices correlations

Fuels	Pearson correlation	Prices correlations	R^2
MGO	0.940	$C_{f,\ MGO} = 91.73 + 1.380\ C_{f,\ HFO}$	0.94
LSHFO	0.879	$C_{f,\ LSHFO} = 85.77 + 0.846\ C_{f,\ HFO}$	0.89
NG	0.859	$C_{f,\ NG} = 131.60 + 0.694\ C_{f,\ HFO}$	0.84
Methanol	0.61	$C_{f,\ methanol} = 254.3 + 0.252\ C_{f,\ HFO}$	0.66

b) Capital Cost of technologies probability density function

The cost of the technologies is considered uncertain because it depends highly on the market conditions, thus the original cost assumed in the conceptual design phase might differ from the final one (Burhenne et al., 2013). Only the capital cost is considered for the uncertainty analysis, whilst the maintenance cost is neglected because it is much lower compared to the capital cost (Burhenne et al., 2013). The capital cost uncertainty is assumed according to the approach adopted in previous studies in the literature (Burhenne et al., 2013; Mavromatidis et al., 2018), where the energy systems investment cost uncertainty was investigated. Therefore, the assumed capital cost PDFs follow a normal distribution with the mean value the nominal capital cost of each technology and a standard deviation equal to 7% of the mean value. In this work, both established and emerging technologies are considered. For example, the carbon capture technology and the fuel cells are technologies that still undergo improvements and modifications in order to be implemented on ships. For this reason, the emerging technologies were assumed to follow a normal distribution with mean their nominal capital cost value and a standard deviation that manages to capture the greater uncertainty of their capital cost. IEA

(2012) proposed a range of carbon capture capital cost, whereas Mcphail et al. (2015) provided a range of MCFC capital cost prices. As a result, it is derived that an appropriate standard deviation for the emerging technologies is estimated to be around 12% of their capital cost nominal value.

c) Operational parameters probability density function

The operational parameters of the systems under real operational conditions might vary from the nominal values provided by their manufacturers. This uncertainty on the parameters performance is denoted by a half-normal distribution according to previous practice on energy systems performance (Giannakoudis et al., 2010; Mavromatidis et al., 2018). The mean value is considered equal to the nominal operating value and the standard deviation is 3% of the mean value so that the value does not exceed the tolerance provided by the manufacturer.

The PDFs employed for the investigation of the aforementioned parameters uncertainty are presented in Table 4.42.

Table 4.42 Uncertainty parameters Probability distribution function

Parameter	Uncertainty Quantification
HFO fuel price	Uniform distribution (μ_{min}, μ_{max})
Capital Cost of technologies	Normal distribution (μ, 7% μ) or (μ, 12% μ)
Operational parameters	Half normal distribution ((μ, 3% μ)

The flowchart of the uncertainty analysis of steps 3 to 6, after constructing the probability density functions of the uncertainty parameters is presented in Figure 4.16.

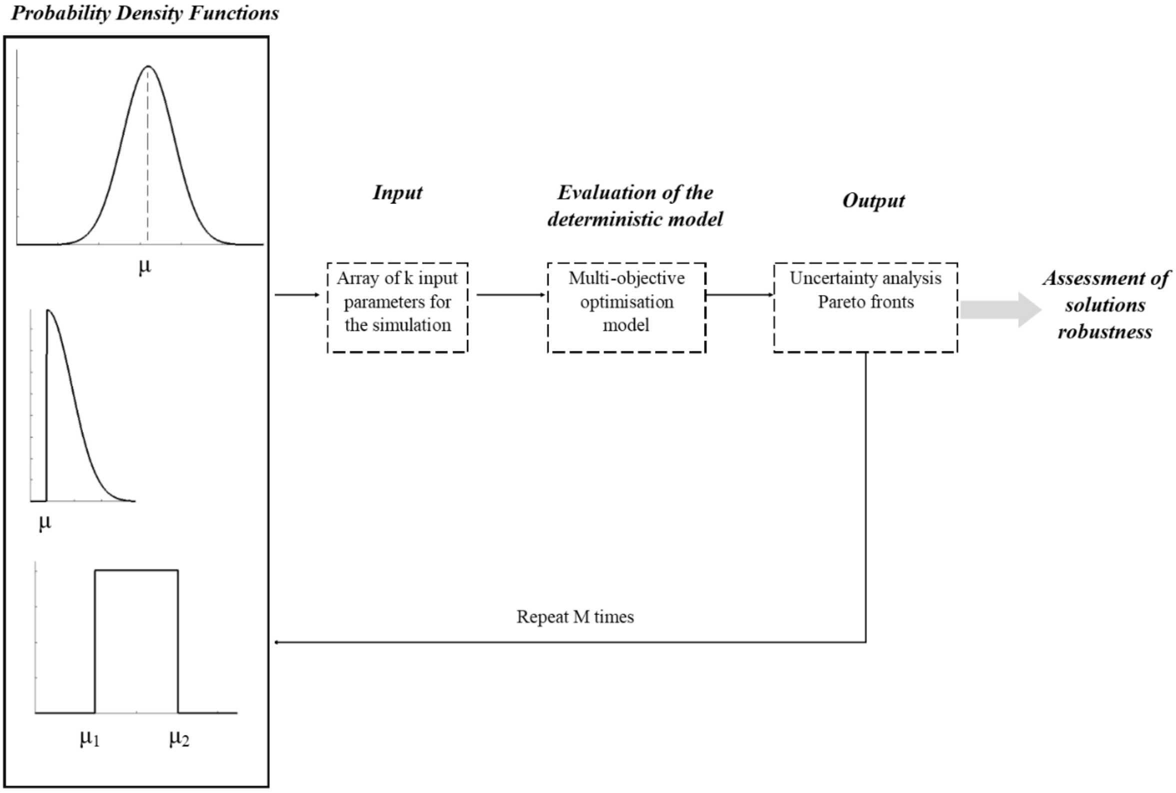

Figure 4.16 Uncertainty analysis process

4.9 Method limitations and assumptions

In this section, the assumptions made in this work as well as the limitations of the proposed method are discussed.

- The level of complexity of the models developed for each component has been kept low because detailed models would be computationally intensive to employ with the optimisation process. The presented decision support method focuses on the synthesis of the ship energy systems in an early design phase. Complex simulation models for the description of the performance of the components were out of the scope of this work; therefore, the given complexity of the models is adequate for the purposes of the undertaken research. The models accuracy to represent reality is evaluated in Chapter 5. However, the way the method is designed allows flexibility to the users and they can use different models for the performance of the components if required. The only limitation is that the input and output variables of each component model must be respected.

- In this work, the systems performance evaluation is performed for steady-state conditions and the transient operating periods are disregarded. The scope of this work is the optimisation of the ship energy systems synthesis considering the ship lifetime performance. This is a common practice in similar studies as the transient periods, even though they are important their duration is very short considering the lifetime horizon of the ship (Sakalis and Frangopoulos, 2018).

- The NSGA-II due to the nature of the genetic algorithms does not assure that all the optimal solutions are obtained. This is a limitation of the selected algorithm, as the optimisation stops when the termination criteria are met and not necessarily, when all the optimal solutions are obtained. For this reason the term 'near optimal' is used in this thesis to refer to the outputs of the optimisation. However, NSGA-II incorporates elitism, which prevents losing optimal solutions once they are found and the literature supports that this algorithm can accurately approximate the real Pareto front of complex energy systems optimisation. In addition, in order to have the best performance of the algorithm, the parameters of the optimisation were fine-tuned, as presented in Section 4.7.2. Finally, the performance of the algorithm is validated in Chapter 5.
- In the undertaken research, only the main energy systems and technologies affecting those systems are considered for the synthesis. In reality, additional energy systems components need to be selected, namely ventilation and steering systems that, however, do not have a great impact on the energy consumption of a tanker and cruise ship (Baldi, Ahlgren, et al., 2015; Baldi, Johnson, et al., 2015).
- The economic investigation of the ship energy systems focuses on the life cycle cost, whereas the profitability of the technologies is not evaluated, as would be the case in real market conditions. This is because the method presented aims at identifying all the potential near optimal configurations that can improve the performance of ship energy systems from a multi-objective perspective (environmental and economic objectives) and not just the profitable ones. Therefore, by including the profitability, emerging technologies that offer only environmental benefit would never be selected.
- A detailed analysis of the impact of the considered technologies on the ship design is not included. For the carbon capture technology, it has been assumed that it does not operate to its full capabilities and a constraint of less than 2% occupation of the DWT of the ship from the carbon by-products is considered in the analysis for practical purposes. In addition, the life cycle cost includes only the engines capital cost, whereas the cost of the structural changes for the gas operating systems natural gas storage is not incorporated.

- The hull and propeller systems interactions with the investigated ship energy systems configuration are not included in this work. In practice, the interactions of these systems with the ship energy systems considering the hydrodynamics perspective could be included, however, in this decision, there is a trade-off with the computational complexity of the method (Baldi, 2016). These interactions are important, specifically the interactions of the main engine and the propeller during the manoeuvring. This is depicted in the available literature, where a variety of studies focused on the main engine and propeller optimisation (Benvenuto and Figari, 2011; Coraddu et al., 2014). However, the proposed method supports decisions for the early design phase, therefore after the selection of the ship energy systems synthesis, a more detailed optimisation is required in order to match the optimal propeller and investigate the interactions of the power plant with the hull.

4.10 Chapter summary

The novel method to support decisions on the ship energy systems synthesis regarding environmental and economic objectives along with the major elements comprising the method was presented in this chapter. The inputs, methods and tools employed were demonstrated and discussed. Regression analysis of the data provided from manufacturers was performed in order to develop mathematical equations for representing the performance of the considered system. The input parameters used by the mathematical models are presented, along with their sources. Operating profiles were employed for evaluating the ship energy systems performance. A multi-objective optimisation method is used to evaluate the performance of alternative ship energy systems according to the developed mathematical models, in order to support decisions for the synthesis of the ship energy systems. The formulation of the multi-objective optimisation was presented, including the employed objective functions, the decision variables and the constraints. The selection of the optimisation parameters for the synthesis problem was performed according to the Taguchi design of experiments method. Finally, the uncertainty analysis method to investigate the robustness of the solutions derived from the multi-objective optimisation was presented. In the next chapter, the qualification, verification and validation of the developed method is discussed.

5 Method Qualification, Verification and Validation

5.1 Introduction to chapter

The method presented in the preceding chapters consists of a conceptual, mathematical and computational model to support decisions for the ship energy systems synthesis with sustainability considerations. The approach followed to assess the proposed method is discussed in this chapter.

5.2 Introduction to method Qualification, Verification and Validation

It is significant to assess the developed method in order to ensure the quality of the method and the derived results presented in this research and provide to the decision-maker the relevant information to make an informed decision. According to Schlesinger (1979) and Thacker et al. (2004) the procedure to assess the accuracy of the models of the proposed method includes three phases: the qualification, verification and validation and are defined in this section. The procedure followed in this work is presented in Figure 5.1.

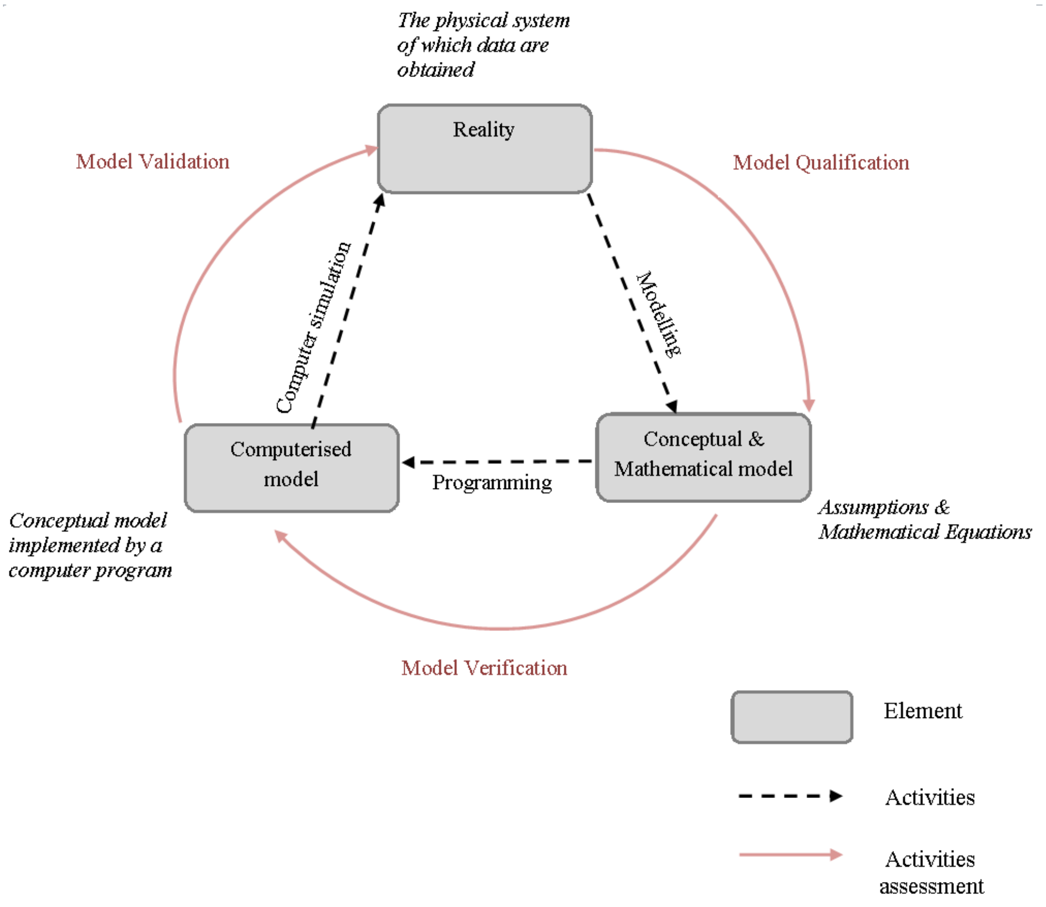

Figure 5.1 Method qualification, verification and validation adapted from Schlesinger (1979) and Thacker et al., (2004)

The purpose is to assess the accuracy of the developed method to support decisions for the ship energy systems synthesis and it includes three basic elements. First, is the reality that represents the physical system of interest selected for analysis. Second, the Conceptual and Mathematical model entails the relevant information that is required to describe the system of interest and includes the mathematical equations and the modelling assumptions. Finally, the computerised model is a computer program that implements the conceptual and mathematical model. The inner arrows describe the activities connecting these elements and the outer arrows are the actions required for the assessment of these activities.

Modelling is the ‘mathematical approximation’ of reality (Thacker et al., 2004). *Qualification is defined as the ‘determination of the adequacy of the conceptual model to provide an acceptable level of agreement for the domain of intended application’ (Schlesinger, 1979).* In other words, investigate how useful the proposed model is and whether it fits the purpose it was intended (Hay, 2015). The ability of the conceptual/mathematical model to accurately represent the problem addressed in this research, therefore, the usefulness of the proposed conceptual/mathematical model to support decisions for ship energy systems synthesis was assessed.

Programming links the conceptual/mathematical model to the computerised model by implementing a computer code. *Verification process confirms that the computerised model manages to represent the mathematical and conceptual description of the model accurately (Oberkampf and Roy, 2010).* Verification is defined as the process of ‘determining that a model’s implementation accurately represents the developer’s conceptual description of the model and the solution to the model’ (AIAA, 1998). Evidence is required to demonstrate that the code is working efficiently and as it was intended (Oberkampf and Roy, 2010). This stage aimed to investigate whether the developed computerised model accurately represents the conceptual/mathematical model developed. The mathematical equations and assumptions made for the conceptual model were translated into code that was programmed in Matlab; as a result, during the verification stage the accuracy of the programming implementation of the mathematical/conceptual model was investigated.

Finally, *validation is defined as ‘the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model’ (AIAA, 1998)*, thus validation quantifies how accurately the computerised model represents reality through computer simulation. In addition, validation determines the degree ‘of truth’ of the derived results (Duffy and O’Donnell, 1998). The computational model developed to support decisions for the ship energy systems synthesis is validated by investigating the degree of accuracy of the derived results to represent reality.

5.3 Qualification, verification and validation of the proposed method

Following the definitions adopted for the qualification, verification and validation of the models in this thesis, the criteria and actions taken to assess those criteria are presented in Table 5.1. The actions performed are further discussed in the following paragraphs.

Table 5.1 Qualification, verification and validation of the proposed method

Activities assessment	Criteria	Action
Qualification	Usefulness of the developed conceptual/mathematical model to support decisions for ship energy systems synthesis with sustainability objectives	semi-structured interviews with experts
Verification	The accuracy of the computational model to represent the conceptual/mathematical model	manual exploration of numerical examples
Validation	The degree of accuracy of the computational model to represent reality	multiple case studies presentation of results to industry and academic experts comparison with results from previous publications complete enumeration

5.3.1 Model Qualification

The conceptual and mathematical model presented in this research addresses the modelling and optimisation of the ship energy systems with sustainability objectives. The development of the model was according to literature sources; thus in order to investigate if the model accurately represents the real situation and consequently its usefulness to support decisions for the ship energy systems synthesis, the industry input is required. Therefore, the industry perspective is integrated with the academic.

The proposed decision support method is intended to be used by shipping industry stakeholders, including ship-owners and policymakers. For this reason, semi-structured interviews were held with industry experts to identify whether the proposed conceptual/mathematical model manages to capture the current practice for the ship energy systems selection, as well as the main challenges and future trends. Therefore, the usefulness of the developed model in real-life practice in the industry is explored. Semi-structured interviews were selected in order to investigate the model qualification because they allow a structured discussion along with giving the opportunity to explore further interesting topics (Russel, 1988) that will provide a better understanding of the model usefulness.

The participants' characteristics are presented in Table 5.2. The first participant is the Head of Projects in a shipping company consulting on ship repairs and conversion of merchant ships. The participant has 15 years of experience in marine consulting. The participant interacts with shipyards, class societies, designers and ship-owners due to the nature of the projects they engage. The participant is well accustomed to the current regulations and ship energy systems configuration trends in order to comply with the regulations. They have experience regarding the challenges the ship-owners face with the traditional configurations and support decisions for the retrofitting of alternative technologies on existing ships. As a result, they are aware of the difficulties and disadvantages of retrofitting instead of designing the ship from the beginning with the appropriate configurations to comply with the regulations. Finally, another aspect of the participant's work is the close interaction with the shipyards for the conversion and repair of merchant ships; therefore, they are up to date with the technologies provided by the shipyards.

The second participant is a technical manager of a shipping company that owns and operates bulk carrier ships. The participant has experience in the shipping industry for the last 18 years, currently from a ship-owner company and in the past from a shipbroker company. As a result, the participant has great experience both in the shipbuilding and operating of merchant ships and interacts with ship-owners, designers, class societies, charterers and shipyards. Therefore, the participant is recognised as suitable to provide input regarding the ship energy systems synthesis decision process and the current challenges the ship-owners face with the shipyards, the air pollution regulations and the class societies requirements. In addition, through the participants, past experience in a shipbrokers company, further information regarding the charterers' requirements for ship energy systems technologies and operation is provided.

Therefore, both participants were recognised as suitable for the conceptual/mathematical model qualification.

Table 5.2 Participants Characteristics

Interview	Date	Participant	Position	Years of experience	Company
#1	15/12/2017	P1	Head of Projects	15	Marine consulting company
#2	26/12/2017	P2	Technical Manager	18	Ship-owners company

Semi-structured interviews were held and the findings can be found in Appendix A.

The semi-structured interviews were held in order to get a better understanding of how to support decisions for the synthesis process. Therefore, understanding of the process would enhance the conceptual/mathematical model to represent reality and manage to facilitate the decision-making process. As a result, first, the current practice on the ship energy systems selection was discussed, including the indicators considered as well as the importance of the environmental objectives and the significance of the operating profile.

The second and third part of the interviews focused on the challenges due to the air pollution regulations and the technologies currently installed to comply with the regulations. The aim of these questions was to explore the current regulatory status, identify how the proposed model can address these challenges and which technologies should be included in the decision support method. The aim of the proposed method is to address the regulatory requirements and propose ship energy system configurations that can comply with current and future regulations. Therefore, this part of the interviewers was very important in order to understand the emerging technologies and trends from the industry perspective.

Finally, the usefulness of the proposed conceptual/mathematical model to support decisions on the ship energy systems according to the experience of the participants was discussed. At this stage of the semi-structured interviews, a preliminary version of the conceptual/mathematical model was presented to the participants in order to get an understanding of the concepts behind this research. The feedback the industry experts provided was used to improve the model.

The qualification of the conceptual/mathematical model aimed to evaluate the proposed model usefulness to support decisions for the ship energy systems synthesis. The findings from both interviews and their implications on the model development (highlighted in italics font) are discussed in the following section.

1. Current practices for selection of the ship energy systems machinery:

The current practice of ship energy systems selection was discussed and it was assessed how the model can be incorporated as well as facilitate this process. It was identified from the interviews that a systematic method to assess alternative configurations does not exist. In addition, during the selection of the ship energy systems, there is not great flexibility and the shipyards follow standardised designs. However, there is space for negotiation to introduce different technologies especially, with ‘high-value ships’ like cruise ships and large orders. These findings indicated that the proposed model can be employed by the ship-owner to support the decision process of selecting the shipyard depending on the technologies that are provided. Otherwise, the model can be used as support in the negotiation with the shipyard to modify the configuration. On the other hand, the shipyards could employ the proposed model to identify optimal standardised designs to propose to ship-owners.

As a result, there is a lack of methods to support the ship-owners during the configuration selection process, thus the usefulness of the proposed method is highlighted. In addition, it was inferred that in order for the proposed model to be useful it has to be flexible and modular to add different technologies. Therefore, be able to incorporate the technologies and configurations proposed by the shipyards. The input parameters for the performance of the energy systems should not be fixed but provided by the user, thus the performance parameters could be modified depending on the technology manufacturer suggestions each shipyard collaborates with. As a result, the systems approach was employed and the systems were modelled with a black box approach (more details were provided in Chapters 3 and 4), allowing flexibility to introduce technologies and change the performance parameters of the systems.

Moreover, the indicators employed to assess the configurations were discussed. Ship-owners are first interested in the capital cost and then on the operating expenditures, as well as the fuel consumption. However, in most merchant ships the charterers cover these expenses and therefore, have a great interest in the fuel efficiency. As a result, charterers have selection criteria that include fuel efficiency, thus indirectly the fuel efficiency affects the ship-owners. The participants mentioned that the internal rate of return and payback period are other economic performance indicators considered.

Findings from the interviews regarding the economic criteria used in the decision-making process indicate that the proposed model should include the investment cost, as it is a critical indicator for the ship-owners. The operating expenditures and specifically the fuel consumption are also of interest for the ship-owners. Therefore, it was an accurate assumption to consider both the capital and operational expenditures in the model. In this work, the aforementioned indicators are not considered separately, instead, the life cycle cost indicator is optimised, as it was identified in the literature as an accurate tool for sustainable investment decisions. However, according to the interview findings, further analysis of the life cycle cost to the capital and operational expenditure is included. The internal rate of return and payback period were not considered. The developed conceptual model aims to support decisions for configurations that improve the environmental and economic sustainability of the ship energy *systems, rather than just identifying the profitable ones. Some of the technologies examined offer currently no financial benefit but only environmental; these technologies would be overlooked by a traditional profitability analysis. Therefore, these indicators were excluded. In addition, the model could be also a useful tool for policymakers, who are not necessarily interested in the profitability of technologies but rather on their performance.*

In addition, the environmental impact of the ship energy systems is gaining great attention from charterers and ship passengers, especially in the cruise ship sector. Even though it is not currently one of the criteria used in the decision-making process of the ship energy systems synthesis, it is inferred from the discussion with the participants that incorporating greener technologies and improving the ship energy systems environmental impact has also economic incentives. The social awareness of the ship passengers and clients for more environmental impact influences the ship economic lifetime. Finally, the greener technologies are 'an asset' for gaining bank loan with better terms. Both participants supported that the ship energy systems configuration should comply with the current regulations; however, there are also concerns especially from the clients for the future regulatory environment. One participant mentioned that 'they expect for the regulations to be implemented before they act on them', whereas the other that they take the future regulations into consideration and 'future proof' the ship for potential retrofitting.

As a result, it was identified that in order to enhance the usefulness of the proposed model in supporting decisions for the ship energy systems, the model should have as constraints the current regulatory requirements and should be able to adapt to include future regulations. Finally, it was an accurate assumption to consider as an objective the environmental impact of ship energy systems according to the recent interest and the economic benefits derived from the greener configurations.

During the selection process, both participants supported that the focus is on the design speed and the variable operating profile is disregarded.

However, in this work, the systems are evaluated according to an operating profile and not just one design speed. The importance of including the operating profile for the synthesis process, in order to improve the fuel efficiency and environmental impact of the ship energy systems was discussed in the critical review in Section 2.3. Therefore, the proposed model bridges the gap between the industry current practice and the academic perspective.

Regarding the ship voyage and the percentage of time the ship sails in the ECA waters, the participants mentioned that it depends on the vessel type, the client and even though it is not always known, it has a significant impact.

As a result, the percentage that the ship sails in ECA waters should be considered as an input parameter on the model that the user can provide. The fact that the percentage of the voyage depends on the ship type was incorporated in this work as it is presented in the case studies, where different percentage was employed for the tanker and cruise ship (see Sections 6.3 and 7.3).

2. Environmental concerns

From the discussion, regarding the gas emissions concerns, it was inferred that the most important gas emissions are the NOx and SOx. In addition, the low sulphur fuel availability and infrastructures arose as a challenge. Finally, both participants supported that in the imminent future carbon policy scenarios are going to be implemented.

The significance of the NOx and SOx emissions is aligned with the model assumptions. The limitation of the infrastructures and availability of low sulphur fuels were accounted in the model by including more mature fuels (See Sections 6.2 and 7.2) with existing infrastructures on the ports, therefore assuming that they will be available. Finally, according to the input of the participants regarding the carbon pricing scenarios, an investigation of the optimal configurations under different carbon policy scenarios was performed and presented in Chapter 7.

3. Technologies

The feedback of the participants regarding the discussion for the most promising technologies and fuels was incorporated in the model.

The findings for current and trending technologies used to comply with the regulations (SCR, scrubber, EGR, WHR) as well as the fuels (LSHFO, MGO, MDO, LNG, LPG, and methanol) are aligned with the critical review (Chapter 2). Therefore, these alternatives were considered in the model. On the other hand, the participants also mentioned hydrogen and ethanol, however, the challenges regarding safety reasons agree with the existing literature (Chapter 2), thus these fuels were not included in the model. Emerging technologies like the solar panels, even though the benefits of their operation were acknowledged, safety reasons lead to challenges so the solar panels were not considered herein.

4. Proposed model

Regarding the usefulness of the proposed model, first, it was addressed whether the evaluation of the economic and environmental performance of alternative ship energy system configurations in the design phase would be advantageous. Both participants supported that considering both objectives would be beneficial. In addition, regarding the inclusion of the gas emissions as an objective in the decision support process they supported that it would be useful for charterers, class societies, regulators, ship-owners and shipyards. Finally, they endorsed the fact that a set of optimal solutions is provided instead of only one optimal configuration as it offers more flexibility.

The key findings of the qualification process were used to assess the model usefulness in supporting decisions for the ship energy systems. The industry experts provided feedback for the model in order to accurately represent reality, which was incorporated as discussed in this section. Finally, they acknowledged the overall benefits of the proposed model for the shipping industry.

5.3.2 Model Verification

The aim of the verification is to assess the differences between the results derived from the mathematical model and the computational (Babuska and Oden, 2004). ‘Numerical algorithm verification is fundamentally empirical. Specifically, it is based on testing, observations, comparisons, and analyses of code results for individual executions of the code’ (Oberkampf and Roy, 2010). Accordingly, the verification of the conceptual and mathematical model was through testing, comparison and observation of numerical examples. Multiple numerical examples were performed, compared with the computational model output leading to continuous improvements and elimination of errors that were identified in the code.

‘Code verification involves exercising the computer program developed to implement the computational model to determine and correct coding errors or other deficiencies that affect the efficiency and quality of output’ (Babuska and Oden, 2004). An iterative process was followed for the code verification, in order to eliminate the errors of the code and as a result the differences between the computational and mathematical model. For each mathematical model developed for the technologies included, the same input parameters were employed by the mathematical and computational model and the outputs were compared. If the results of the computational model did not agree with the mathematical then the code was analysed, the errors were identified and finally, the code was modified.

During this process different type of errors were identified and eliminated. The most significant error that led to great diversion between the two models results were the wrong units of measurement of the parameters. Therefore, the right conversion factors were used. Another error was the wrong transfer of the parameters between the functions of the code, which was eliminated by observation and analysis of the code. Finally, other algorithmic errors were identified during the verification process that were leading to wrong results. As a result, comparing the results of the two models facilitated the identification and elimination of the errors.

5.3.3 Model Validation

The computational model for supporting decisions consists of the ship energy systems model and the ship energy systems synthesis optimisation model. Computational model validation was defined at the beginning of this chapter as the process of identifying the degree that the developed computational model represents the real world as it was intended. The actions taken for the decision support computational model validation are displayed in Figure 5.2. The actions taken for the validation are distinct for each developed model and are discussed in the following section.

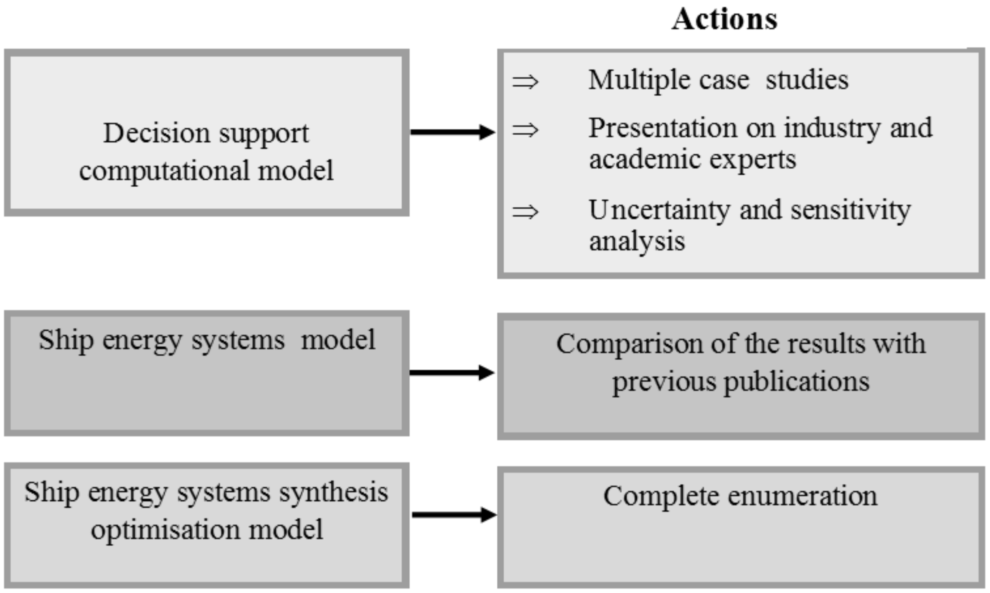

Figure 5.2 Validation of the computational model

a) Decision Support Computational model validation

The validation process to explore whether the decision support computational model results represent reality accurately consists of the application of the model on real case studies, therefore, particular instances are studied and analysed for the model validation (Duffy and O'Donnell, 1998). Case studies showcase the applicability of the model in a real situation (Yin, 2003). Applicability of the decision support computational model is interpreted as the degree to which the model is generic and it should be demonstrated with at least two distinct cases (Hay, 2015). The computational model was applied into two cases of different merchant ships and configurations. Applying the model in diverse cases and collecting data from different sources facilitates the validation process (Wang and Duffy, 2009).

The decision support computational model was applied on a tanker (Chapter 6) and a cruise ship (Chapter 7). The model had to be modified and different technologies were employed in order to accommodate the specific characteristics of each ship type. Different ship types were selected to validate that the model can effectively support decisions in diverse cases and the results are not subject to a specific ship type. In addition, the model was adapted for a multi-objective optimisation in the former case and bi-objective in the latter, in order to display the accuracy of the model results independently of the objectives considered.

The results from the decision support method are influenced by the input parameters, the sensitivity and uncertainty analysis of the influencing parameters is critical for the validation (Hamby, 1994). Not incorporating in the method the uncertainties leads to misleading results that do not accurately represented reality. Therefore, a sensitivity and uncertainty analysis were performed for both cases to investigate the solutions under different input parameters.

The results from the case studies were analysed and presented to industry and academic experts in order to investigate how accurately they represent the reality. First, the results were validated with previously published results and the level of agreement with them is discussed in the results section of the case studies chapters in this research (Chapter 6 & 7). Second, the model and the results of the case studies were presented and discussed with academic and industry experts during conferences and presentations to industrial collaborators of the university. In all the cases, the feedback regarding the model and the results was positive, validating that it manages to represent the reality. Finally, academic experts have appraised the computational model and the results through a peer-reviewed process, leading to the publication of the decision support method and the tanker ship case study results (Trivyza et al., 2018), as well as the cruise ship case study results (Trivyza et al., 2019b). In conclusion, academics, as well as industry experts, have positively assessed the accuracy of the computational model results to represent reality.

b) Ship energy systems model validation

The ship energy systems model estimates the economic and environmental performance of the ship energy systems configuration. The validation of the results derived from the model is performed by comparing the results with previous publications.

The environmental performance as derived from the developed model is compared with other publications in Table 5.3. The previous study of Chatzinikolaou and Ventikos (2015) on the life cycle exhaust emissions from ships served for the purposed of the ship energy systems model validation. This study was selected because the machinery life cycle emissions were investigated and allocated to different phases of the ship lifetime. In addition, similar emission models with the proposed method in this research were employed to estimate the emissions. In the literature, results on the exhaust gas emissions for the same type of ships investigated in this thesis could not be identified therefore the exhaust gas emissions of two different tanker ship sizes were compared. Chatzinikolaou and Ventikos (2015) performed a life cycle assessment on the exhaust gas emissions, however only the lifetime operation emissions of the machinery are displayed in the table because these operating phases were also considered in the developed model. The estimated values for the emissions belong to the same order of magnitude (10%-15% difference). Some variations are observed that are justified from the different ship size, operating profile, emission factors, engine size as well as emission reduction technologies and assumptions regarding the ECA waters. Despite these variations that are justified by the different cases and practices, the accuracy of the ship energy systems model to represent reality is demonstrated.

Table 5.3 Comparison of lifetime gas emissions estimation of the proposed model with previous publications

Study	This research	(Chatzinikolaou and Ventikos, 2015a)
Ship type	Aframax tanker (115,00 DWT)	Panamax tanker (74,296 DWT)
Engine type/ fuel type	Diesel/ HFO &MDO Auxiliaries	Diesel/ HFO &MDO Auxiliaries
Emissions estimated		
CO_2 (t)	1,189,000	1,069,620
SOx (t)	18,400	15,773
NOx (t)	28,435	30,492

The economic performance of the developed model in this research and previous publications is displayed in Table 5.4. Tzortzis and Frangopoulos (2018) study was selected, because in their work they estimate the economic performance of a merchant ship with mechanical propulsion system like the tanker case study (Chapter 6), whereas Sakalis and Frangopoulos (2018) present a case study on a ship with diesel electric propulsion like the cruise ship case study (Chapter 7). Both studies were selected because of similarities in the methodology with the model developed in this research. First, the present worth value of the capital and operating costs was considered, including the fuel and maintenance cost. Second, the main energy systems were considered except the exhaust emission reduction technologies and finally, different operating phases were employed to estimate the life cycle cost of the systems. The estimated total cost of the tanker is compared with Tzortzis and Frangopoulos (2018) and the cruise ship results with Sakalis and Frangopoulos (2018). The estimated values belong to the same order of magnitude (12%-40%) with some variations that depend on the operating profiles employed, the ship type, the nominal power of the technologies and especially the auxiliary boiler. For the cruise ship, the total life cycle cost is 40% higher compared to the considered merchant ship, which is justified by the higher installed power of the main engines as well as the thermal boilers. As a result, the accuracy of the ship energy systems model to represent reality is evaluated.

Table 5.4 Comparison of life cycle cost estimation of the proposed model with previous publications

Study	This research	(Tzortzis and Frangopoulos, 2018)	This research	(Sakalis and Frangopoulos, 2018)
Ship type	Aframax tanker	LNG-carrier	Cruise ship	Merchant ship
Nominal power installed				
Mechanical power (kW)	15,000	21,000	-	-
Electric power (kW)	2,560	3,000	72,000	20,000
Thermal boilers (kW)	2x23,000	1x4,000	2x15,000	1x150
Engine type/ fuel type	Diesel/ HFO &MDO Auxiliaries &WHR	Diesel/ HFO &MDO Auxiliaries &WHR	Diesel electric propulsion &WHR	Diesel electric propulsion &WHR
Life cycle cost (€)	63,589,000	55,894,772	173,090,000	103,183,676

c) Ship energy systems synthesis optimisation model validation

The third part of the validation process is to quantify the accuracy of the selected optimisation algorithm to identify the true Pareto front, therefore the efficiency of the algorithm for the specific problem. A method usually followed is the complete enumeration, in other words, the computation of the true non-dominated solutions of the problem (Wenzhong et al., 2007; Zhu et al., 2014). During the complete enumeration, the performance of all the potential combinations is estimated and the findings are evaluated according to the Pareto dominance principles in order to estimate the true Pareto front. However, it is impractical to estimate all the possible solutions when the problem is large (Wenzhong et al., 2007). For this reason, the approach of employing a smaller size optimisation problem is suggested in order to validate the optimisation algorithm results (Zhu et al., 2014). This approach is adopted in this research to identify the true Pareto front and evaluate the optimisation algorithm efficiency.

The application of the developed multi-objective decision support method presented in Chapter 4 is applied on a tanker ship. The extended optimisation problem is adapted to a smaller one in order to evaluate the algorithm. Therefore, the optimisation is formulated for 11 decision variables and 46,656 alternatives. The original application on the tanker vessel consisted of 14 variables and 3,379,200 alternatives, leading to a 73 times larger problem.

The validation was performed on an Intel(R) Core^{TM}8 i7-2600 CPU at 3.40GHz. The computational time for the complete enumeration of the scaled down problem was 25 minutes, whereas, for the optimisation was 1.5 minute. The results from the complete enumeration were compared with the optimisation results. The accuracy of the algorithm was investigated for both a multi-objective and a bi-objective problem since the method is applied in both ways.

A graphic representation of the results of the optimisation and the true Pareto front is presented in Figure 5.3. The results from the complete enumeration and the optimisation are depicted in the same figure. From the graphic representation is evident that the results from both methods agree.

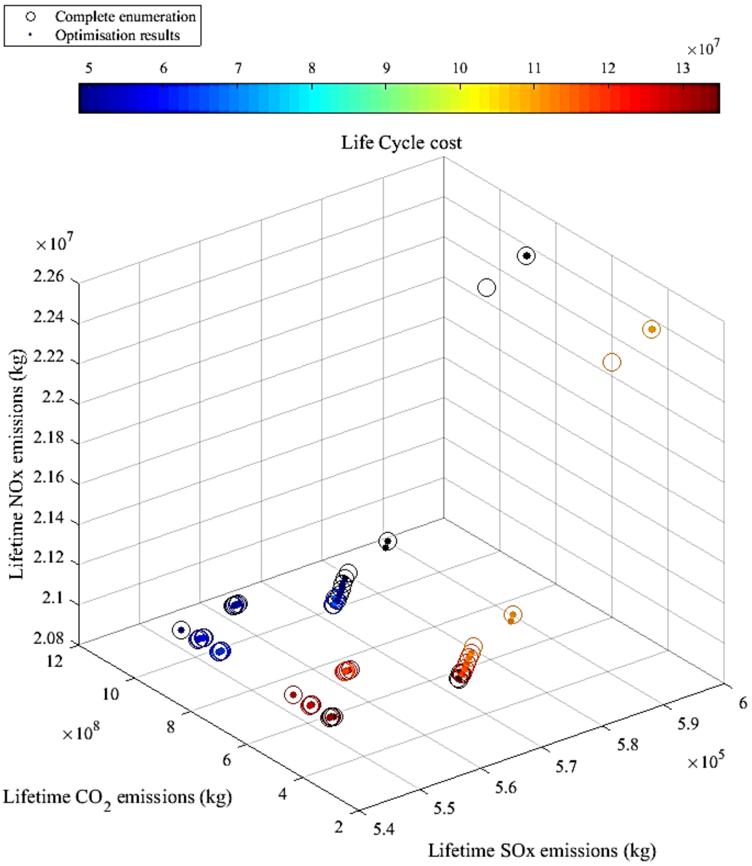

Figure 5.3 Multi-objective optimisation results

Furthermore, to complement the graphical representation and due to the complexity of the optimisation problem, three criteria were also investigated, in order to identify the efficiency of the algorithm:

- The first criterion investigates the percentage of the objective functions values of the solutions derived from the developed optimisation found in the complete enumeration results.
- The second criterion identifies the percentage of the configurations that appear on the solutions of both the optimisation and complete enumeration.
- The third criterion is similar to the second but it considers also the nominal power of the technologies of the solutions and not only the configurations.

The aforementioned criteria allow investigating the degree in which the true Pareto front from the complete enumeration agrees with the Pareto front from the developed optimisation. The last two criteria are investigated due to the multiple technological solutions and the possible range of nominal power for the technologies.

The results of the three criteria are displayed in Table 5.5. The results show high accuracy of the algorithm in identifying the true Pareto front, with a value higher than 85% which is considered a good approximation in the literature for multi-objective genetic algorithms (Wenzhong et al., 2007).

Table 5.5 Multi-objective optimisation accuracy

Criteria	Accuracy
CR1: Objective functions values	89%
CR2: Configurations	96%
CR3: Configurations with nominal power	89%

The first criterion is estimated focusing only on the value of the objective function. CR1 is included in the assessment, in case some different configurations have the same performance on the objective functions and therefore the algorithm identified the optimal performance but did not include all the optimal configurations.

Criterion CR2 estimates the number of times the same configuration appears in the two investigated Pareto front. This percentage appears the higher, indicating that the optimisation algorithm manages to identify 96% of the optimal configurations. Since the aim of the optimisation is the optimal synthesis this criterion is the most critical for this work, therefore it is inferred that the algorithm is successful in identifying the majority of the configurations.

On the other hand, the CR3 criterion considers also the nominal power of the main engine, which is a decision variable of the optimisation. It is evident that there is a lower percentage when the nominal power is considered. This indicates that the optimisation identifies the optimal configurations with higher accuracy than the nominal power. This is justified by the fact that a set of nominal power with a small step of 500 kW is considered in the optimisation; therefore, the algorithm identifies the optimal configuration and the near optimal nominal power.

Similarly, the results from the bi-objective optimisation and the complete enumeration are presented in Figure 5.4. It is evident that the algorithm accurately manages to identify a good approximation of the true Pareto front. From the figure, it is evident that only one solution of the true Pareto front is not identified from the algorithm.

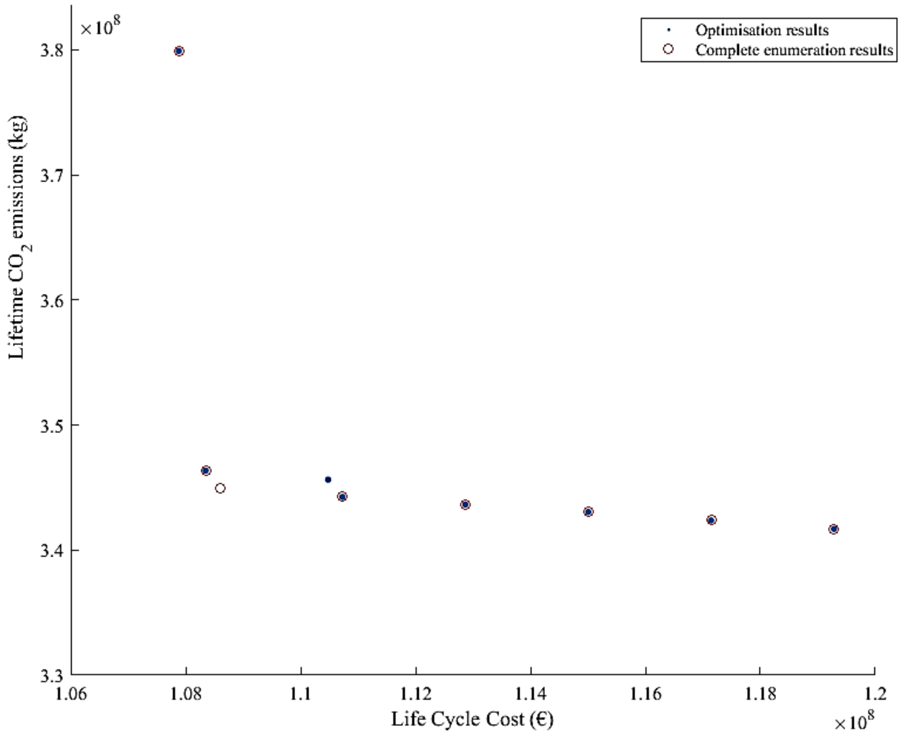

Figure 5.4 Bi-objective optimisation results

The three criteria discussed in the previous paragraphs were estimated for the bi-objective optimisation application and the results are displayed in Table 5.6. Again, in this case, all the criteria are higher than 85%, which is an acceptable threshold for the multi-objective genetic algorithms accuracy as it was mentioned in the preceding discussion.

From Table 5.6, the same conclusions with Figure 5.4 are derived and it is evident that only one solution from the Pareto front is not identified from the optimisation. According to CR2 criterion, there is a 100% accuracy on identifying the optimal configurations. On the other hand, for CR1 and CR3, it is inferred that even though the configuration is optimal, the nominal power is not.

Table 5.6 Bi-objective optimisation accuracy

Criteria	Accuracy
CR1: Objective functions values	88%
CR2: Configurations	100%
CR3: Configurations with nominal power	88%

In both cases, the algorithm manages to identify a significant percentage of the true Pareto front solutions that is above the acceptable threshold for multi-objective genetic algorithms. However, it was identified that the algorithm has greater accuracy in identifying only the optimal configuration without considering the nominal power. Finally, it is evident that increasing the objectives leads to decreasing the efficiency of the algorithm.

In this section, the performance of the algorithm was validated and it is evident that it accurately obtains a good approximation of the Pareto front.

5.4 Chapter Summary

In this chapter, the qualification, verification and validation of the developed method was presented. First, the procedure adopted in this research was introduced and the actions taken to assess the method were discussed. The conceptual model’s usefulness and ability to accurately represent reality were investigated through semi-structured interviews. The experts’ appraisal for the conceptual/mathematical model usefulness was presented and the findings from the interviews were discussed. The verification of the computational model was performed with a manual exploration of numerical examples providing an accurate representation of the conceptual model. The validation of the decision support computational model to accurately represent reality was investigated through multiple case studies that were appraised by academic and industry experts. The ship energy systems model was validated by comparing the results from previous publications. Finally, the accuracy of the optimisation algorithm to identify the true Pareto was investigated with the complete enumeration of a smaller scale example. In the next chapter, the method proposed in Chapter 4 and validated in this chapter is applied on an Aframax tanker ship and the results derived are discussed.

6 Tanker ship case study

6.1 Introduction to chapter

In Chapter 4, the proposed method to support decisions for the ship energy systems synthesis was demonstrated and it is applied herein on an Aframax crude oil tanker ship in order to showcase the applicability of the method and identify the near optimal configurations. In this chapter the term ‘optimal’ will be used to refer to the near optimal configurations derived from the multi-objective optimisation. First, the technologies and alternative fuels considered in the method are presented in Section 6.2. Then the case study is described along with the input parameters used. The multi-objective optimisation results are displayed and discussed in Section 6.4. Furthermore, the results of the uncertainty analysis as wells as the sensitivity analysis are demonstrated in Sections 6.5 and 6.7, respectively. The optimal configurations for different operating profiles are discussed in Section 6.6. In the end, some final remarks from the results are discussed.

6.2 Outlook of technologies included in the case study

For the investigated ship, the technologies in the grey cells presented in Table 6.1 were included in the proposed method application. The following alternatives selection was driven by the critical review in Chapter 2 and the industry experts input from the semi-structured interviews in Chapter 5.

The propulsion trends for the modern tankers were investigated and it was identified that for tankers larger than 10,000 DWT, the most prominent configuration is a mechanical direct drive transmission with a two-stroke engine (MAN Diesel & Turbo, 2005). The major marine technology providers, Wärtsilä (Thygesen and Santala, 2012) and MAN Diesel & Turbo (Petersen, 2013), propose designs with a two-stroke main engine for the modern Aframax tankers for more energy efficient, robust and reliable operation that satisfies the safety requirements.

Therefore, for the prime mover, only the two-stroke diesel and dual-fuel engines are considered. Gas engines are not included in the investigation because currently, only four-stroke gas engines exist. In addition, gas turbines and fuel cells are also not included for the propulsion, because only direct mechanical drive is considered prominent for Aframax tankers propulsion according to the marine technology providers.

On the other hand, MCFC are investigated for electric auxiliary engines along with diesel and dual fuel generators. Only MCFC are included in the synthesis optimisation, as it was justified in Chapter 2. For covering the ship thermal requirements, boilers of both the oil and gas fired type are considered in this investigation.

Regarding the fuel types, only mature fuels are investigated, therefore, hydrogen and biofuels are not included in this research due to the regulations regarding storage, safety as well as handling as it was discussed in Chapter 2. Methanol is not considered because due to the low energy density as well as the high prices that in the last years are even higher than MGO is not competitive with the LNG. LPG is not considered in the case study application, due to the higher historical prices compared to LNG and the barriers regarding the infrastructures as it was discussed in Chapter 2. Along with the fact that it has similar properties with LNG and the latter is in a great abundance, it is inferred that LPG is not as competitive as LNG.

All the prominent alternatives are investigated for the emission reduction technologies. In respect to the technologies that improve the energy efficiency of the ship energy systems, WHR with a turbogenerator and a shaft generator are considered. Furthermore, as it was discussed in the literature even though renewable sources improve the energy efficiency and environmental impact none of them is explored herein, due to the low efficiency, high cost as well as their weight and space limitations. Finally, thermal and electric energy storage was not studied in this thesis. The former is not considered as a prominent technology in marine applications. The latter is due to the need for a transient profile, as well as the fact that they are more appropriate for vessels with long dynamic periods as it was presented in Chapter 2.

Table 6.1 Technologies considered for the Aframax tanker energy systems

Prime Mover (2-stroke engine)							
diesel engine	*dual-fuel engine*	*gas engine*	*fuel cells*	*gas turbines*			
Electric auxiliary engine							
Diesel generators	*dual-fuel generators*	*fuel cells*					
Thermal boiler							
oil fired boiler	*gas fired boiler*						
Fuels							
HFO	*MDO*	*MGO*	*LSHFO*	*Natural gas/ LPG*	*methanol/ ethanol*	*hydrogen*	*biofuels*
Renewable energy sources							
solar panels	*wind turbines*						
SOx emissions abatement technologies							
scrubber							
NOx emissions abatement technologies							

SCR	*EGR*	
CO$_2$ emissions abatement technologies		
Carbon capture system		
Technologies to improve energy efficiency		
WHR	*shaft generator*	
Energy storage		
batteries	*thermal storage*	

Not all the potential combinations among the subsystems in Table 6.1 are possible; the compatibility of the various subsystems combinations is ensured through the technical constraints discussed in Section 4.7.

6.3 Case study description

The following sections describe the ship characteristics and case study application particulars.

6.3.1 Ship Characteristics

The characteristics of the investigated ship are presented in Table 6.2. The typical power plant configuration and energy systems particulars are displayed in Figure 6.1 and Table 6.3, respectively.

Table 6.2 Tanker ship characteristics

Characteristics	Value
Size	115,000 DWT
Displacement	140,000 MT
Length	250 m
Beam	45 m
Draft	15 m
Propulsor	Fixed Pitch Propeller

Table 6.3 Tanker energy systems particulars

Energy Systems Particulars	Value
Main engine	two stroke diesel
Maximum continuous rating	14,000 kW
Main engine fuel	HFO, MDO
Shaft Generator	1,200kW
Auxiliary Generator sets	3 diesel generator sets (800 kW)
Fuel auxiliary generator sets	MDO
Thermal boiler	Oil fired (HFO, LSHFO)
Thermal boiler capacity	2 sets of 30,000 kg/h

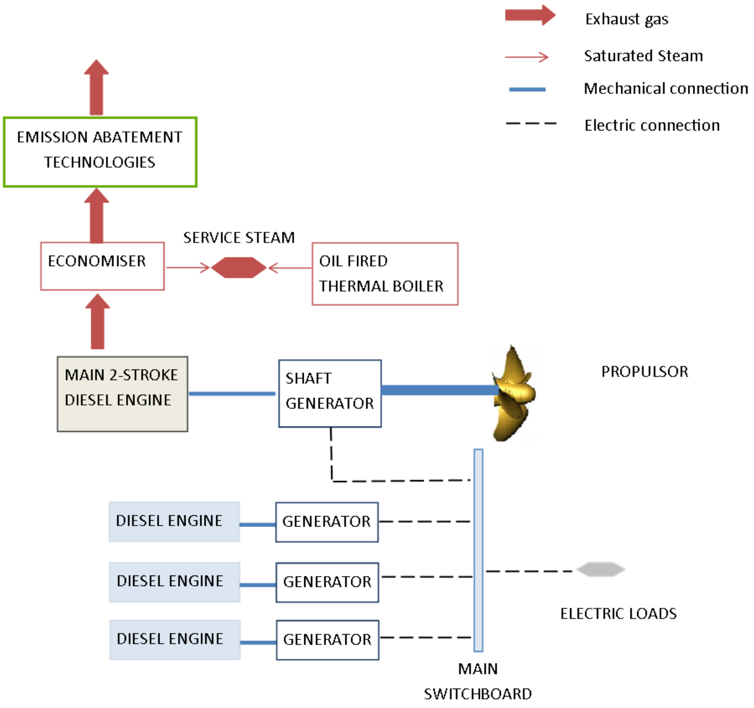

Figure 6.1 Aframax tanker ship typical power plant configuration

The ship energy systems configuration of the referenced Aframax tanker, which is presented in Figure 6.1, consists of a two-stroke diesel engine with a shaft generator that operates with HFO. The main engine switches to MDO and employs an SCR for the NOx emissions in order to comply with the Tier III regulation. In addition, the electric demand is provided by three diesel generators that operate with MDO and an SCR on the ECA waters. Finally, the saturated steam to cover the thermal demand is produced by the main engine exhaust gas heat with an economiser and by the two thermal oil fired boilers that operate with HFO.

6.3.2 Operating profile

The mechanical, thermal and electric energy demand of the ship is expressed as a function of time. As it was discussed in the literature review (Chapter 2), the assessment and optimisation of the ship energy systems is based on an assumed operating profile.

For this reason, the data for the operating profile (speed distribution, frequency of occurrence) in ballast and laden conditions for an Aframax tanker were taken from Banks et al. (2013). By using the speed distribution and the ship characteristics, the propulsion power was calculated according to empirical formulas provided in Man Diesel & Turbo (2011). Equations 6.1 and 6.2 express the thermal $P_{th,i}$ (kg/h) and electric $P_{el,i}$ (kW) power requirements as a function of the instantaneous propulsion engine power $P_{me,i}$ (kW) based on regression performed on measured operating data of the thermal and electric requirements for different operating phases of the Aframax tanker, as it was discussed in Chapter 4.

$$P_{el,i} = 244.8\ \ln(P_{me,i}) - 1200 \tag{6.1}$$

$$P_{th,i} = 238.11\ e^{(3.15\ 10^{-4}\ P_{me,i})} \tag{6.2}$$

The derived operating profiles for the investigated Aframax tanker propulsion, electric power and thermal power demands are shown in Figure 6.2. The mechanical and electric power is expressed in kW, whereas the thermal power demand is represented by the saturated steam mass flow (kg/h).

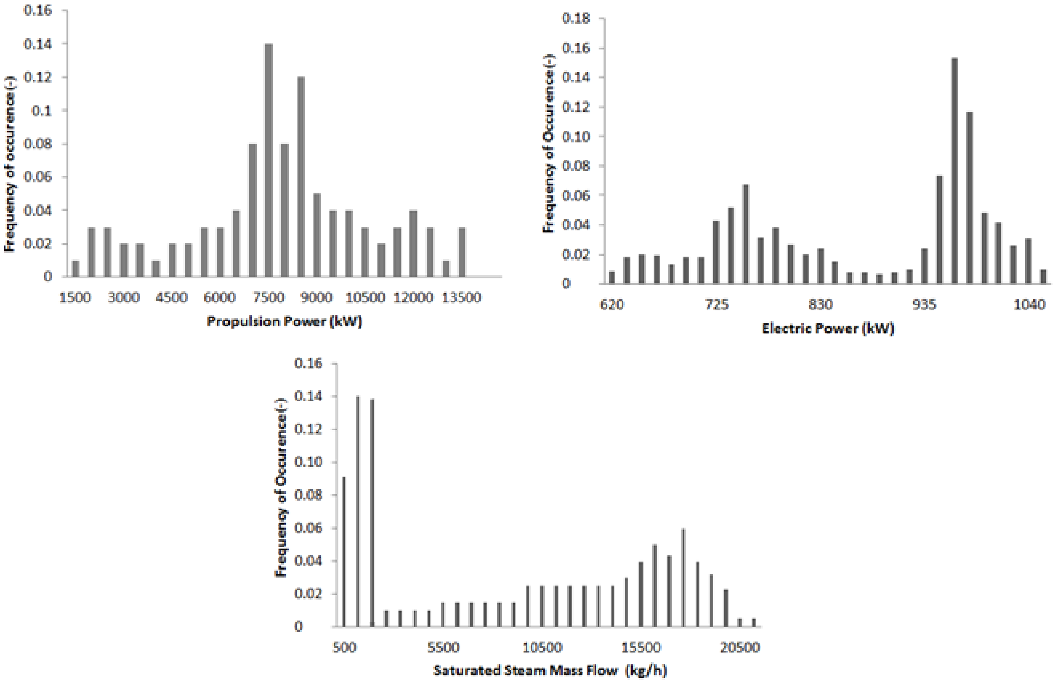

Figure 6.2 Typical operating profiles for an Aframax tanker

6.3.3 Case study assumptions

The following assumptions were considered for the developed method application for the Aframax tanker case study:

- This ship type is ocean-going and spends limited time close to the port (Buhaug et al., 2009). Previous studies show that it sails a limited amount of time in ECA waters (Burel et al., 2013). Therefore, it is assumed that the ship sails 10% of her time at ECA waters, where the Tier III and sulphur limit regulations are applicable.

- It is assumed that the ship spends 30% of her lifetime at port (Banks et al., 2013) and the power demand for loading and unloading for the auxiliaries is considered 75% of the installed auxiliary power (Chatzinikolaou and Ventikos, 2015a).
- The lifetime of the vessel is assumed 25 years, which is an average lifetime for tanker vessels, according to Chatzinikolaou and Ventikos (2015).
- Maintenance period was assumed to be 7% of her life (Turan et al., 2009).
- The nominal power for the WHR is assumed 3000 kW_e, which is appropriate to satisfy the electric demand of the vessel.
- The nominal power of the shaft generator and the thermal boiler is derived according to the current configuration.
- EGR technology is included in order for the dual fuel gas-injected engine to comply with the Tier III regulations, whereas SCR technology is considered for the diesel engine, as well as the oil fired boiler.
- It is assumed that the feeding and storage system for natural gas is included in the capital cost of the technologies that operate with natural gas.

6.4 Multi-objective optimisation Pareto front

Results from the optimisation of the investigated Aframax tanker energy systems are presented in this section and the optimal solutions are discussed. The findings of this section were presented in the J1 journal article (Trivyza et al., 2018). The Pareto front curves, where all four objectives were included in the optimisation process are displayed. All the presented solutions comply with the existing IMO Annex VI regulations for NOx and SOx emissions (IMO, 2005b, 2005a), as well as the EEDI regulations for energy efficiency. The life cycle cost of selected solutions is further analysed in order to get a better understanding of their performance. Finally, the EEDI values of the optimal solutions are compared with the estimated lifetime carbon emissions.

6.4.1 Multi-objective optimisation results for the Aframax tanker

The derived results from the multi-objective optimisation, with the four objective functions including the lifetime SOx, NOx, CO_2 emissions and the Life Cycle Cost are presented in Figure 6.3.

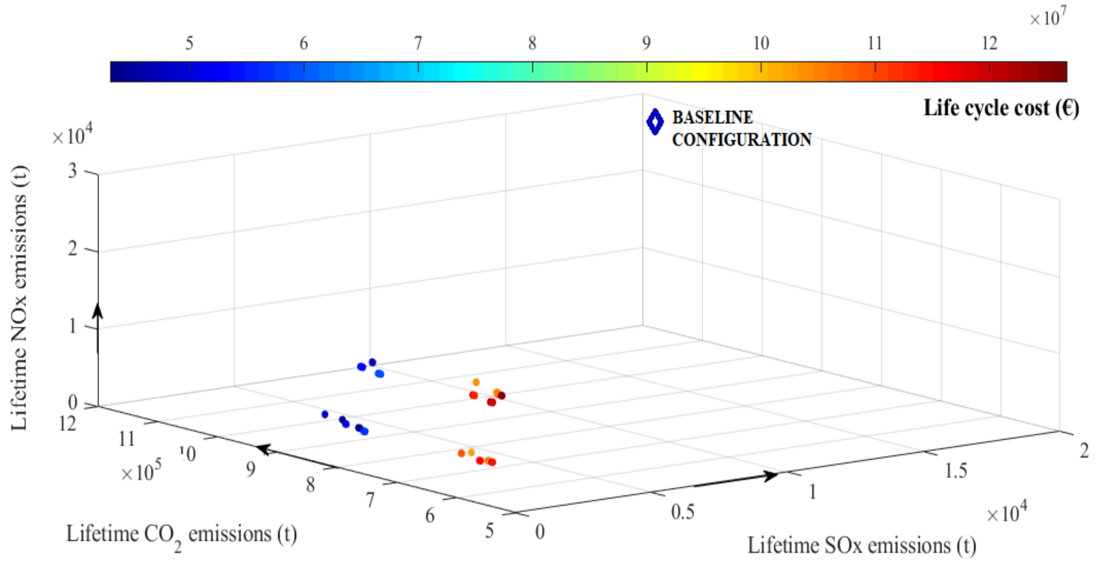

Figure 6.3 Multi-objective optimisation (SOx, NOx, CO$_2$, LCC)

The LCC is presented with a colour map and each point of the curve represents an optimal ship energy system configuration, according to the considered objectives. The performance of the baseline configuration of Table 6.3 is also presented. It is evident that the baseline does not belong in the Pareto front and performs worse than all the solutions in the environmental objectives. On the other hand, the baseline has a low life cycle cost, however from Figure 6.3 it is evident that other configurations exist that have similar LCC and at the same time manage to improve the environmental performance of the tanker ship energy systems.

It is inferred from Figure 6.3 that there is a variety of alternative configurations, which are all non-dominated and there is no solution that can perform better in any of the objectives without deteriorating the performance in another. Not a single solution can be recognised as the optimal, whereas a variety of environmental and cost-efficient solutions are generated, thus supporting the decision-making process and giving the opportunity to the decision maker to understand and manage the trade-offs among the objectives.

Furthermore, the results are displayed in four different views in Figure 6.4, in order to attain a better understanding of the performance of each solution. The three-dimensional view of the original Figure 6.3 is extracted and displayed in Figure 6.4 (a, b and c). In Figure 6.4, the two-dimensional views of the original figure are presented with the LCC objective in a colour map. In addition, from the analysis of the results, the optimal solutions of the Pareto front are clustered into categories; where each one consists of solutions that have a similar configuration but their performance on the objectives differ due to the nominal power of the main engine. The clustered solutions derived from the multi-objective optimisation of Figure 6.4 are displayed in detail in Table 6.4. It is also estimated and presented in the last columns of the table, the percentage difference of each grouped solution from the best performing case for each objective.

In total 13 groups of configurations were derived from the results of the multi-objective optimisation. Details regarding the main energy systems for propulsion, electric, thermal, energy efficiency as well as emission reduction technologies are presented in Table 6.4.

Solution 11 is the optimal for the economic objective and consists of a pre-mixed dual fuel engine for the ship propulsion that has the lowest capital cost and does not require after-treatment technology, therefore it exhibits no increase on the capital and operating costs of the energy systems. In addition, the electric energy is provided by dual fuel generator sets that operate with NG, which has the lowest price among the considered fuels. Finally, the SG is selected, which improves the energy efficiency of the systems, because the more efficient main engine drives the shaft generator that produces the required electric power.

Other solutions with low LCC are the alternatives 8 and 5 with an increase in the cost of less than 10% from solution 11. The rest of the solutions have a more significant increase in the LCC with alternative 6 being the least cost-efficient solution with an increase in the LCC around 190% of the most cost-efficient solution (solution 11). The reason this configuration is so expensive lies on the fact that it includes all the technologies that can improve the environmental performance and energy efficiency of the ship energy systems. In that respect, the trade-offs between the improved environmental performance and the high cost are demonstrated.

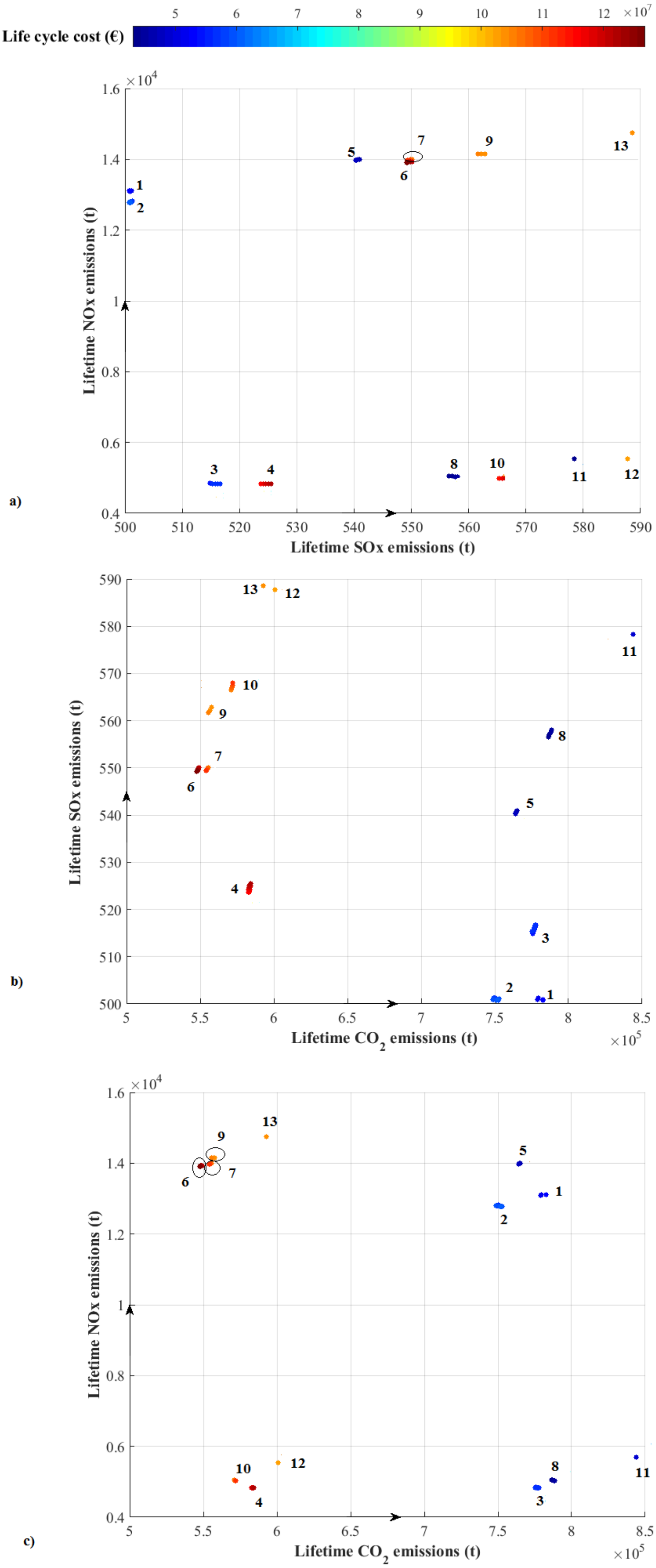

Figure 6.4 Multi-objective optimisation: a) SOx-NOx-LCC view, b) CO_2-SOx-LCC view, c) CO_2-NOx-LCC view

Table 6.4 Configurations of Figure 6.4

	Main Engine			**Emission reduction technology**	**Energy Efficiency technology**	**Auxiliary engines**			**Thermal Boiler**		**Percentage Difference from the best solution**			
	Type	**Fuel**	**MCR (MW)**			**Type**	**Fuel**	**Sets/Power (kW)**	**Type**	**Fuel**	**LCC**	**CO_2 emissions**	**SOx emissions**	**NOx emissions**
1	DF gas-injected	NG	14-15.5	EGR	WHR	DFG	NG	2x1280	GFB	NG	+(19% to 23%)	+42%	0%	+172%
2	DF gas-injected	NG	14-16	EGR	none	FC	NG	4x500	GFB	NG	+(32% to 39%)	+37%	0.5%	+165%
3	DF pre-mixed	NG	14-15.5	none	WHR	FC	NG	4x500	GFB	NG	+(26% to 33%)	+42%	+3%	0%
4	DF pre-mixed	NG	14-16	CC	WHR	FC	NG	4x500	GFB	NG	+(165% to 185%)	+7%	+5%	+1%
5	DF gas-injected	NG	14-15.5	EGR	SG	DFG	NG	2x 1280 &1x660	GFB	NG	+(8% to 10%)	+40%	+8%	+189%
6	DF gas-injected	NG	14.5-16	EGR & CC	WHR&SG	FC	NG	4x500	GFB	NG	+(180% to 190%)	0%	+10%	+189%
7	DF gas-injected	NG	14	EGR & CC	WHR&SG	FC	NG	4x500	GFB	NG	+177%	+1%	+10%	+193%
8	DF pre-mixed	NG	14-15.5	none	WHR&SG	DFG	NG	2x1280	GFB	NG	+(2% to 4%)	+44%	+11%	+5%
9	DF gas-injected	NG	14	EGR& CC	WHR&SG	DG	LSHFO	2x 1260 or 2x1260 &1x660	GFB	NG	+(142% to 145%)	+2%	+12%	+193%
10	DF pre-mixed	NG	14.5-16	CC	WHR&SG	DFG	NG	2x1280	GFB	NG	+(145% to 158%)	+4%	+13%	+5%
11	DF pre-mixed	NG	14	none	SG	DFG	NG	2x1280	GFB	NG	0%	+49%	+16%	+15%
12	DF pre-mixed	NG	14	CC	SG	DFG	NG	2x1280	GFB	NG	+138%	+10%	+17%	+15%
13	DF gas-injected	NG	14	EGR & CC	SG	DG	LSHFO	2x1260 &1x660	GFB	NG	+140%	+8%	+18%	+206%

The solution that manages to mitigate the most the carbon emissions (configuration 6) includes a carbon capture, fuel cells, WHR, SG, gas fired boiler and a gas-injected dual fuel engine. This configuration incorporates WHR and SG technologies that manage to improve the energy efficiency of the ship energy systems and as a result reduce the fuel consumption and the CO_2 emissions. In addition, the main energy systems operate with natural gas that has the lowest carbon coefficient factor. For the main engine, the gas-injected is selected due to the lower fuel consumption and as a consequence CO_2 emissions, whereas for the electric auxiliary the fuel cells that are the cleanest compared to the alternatives.

Other configurations with a very low carbon footprint impact are from groups 7, 9 and 10 with a small increase (less that 10%) in the carbon emissions objective compared to configuration 6. However, these solutions also experience a very high LCC. All the technologies that have a very low carbon footprint include a carbon capture technology. The solution that exhibits the highest lifetime CO_2 emissions belongs to group 11, which has low LCC and NOx emissions performance, whereas performs weakly on the SOx emissions objective. Therefore, trade-offs are observed between the low NOx and LCC objectives and the high SOx and CO_2 emissions for configuration 11.

Regarding the SOx emissions objective, it is evident that lifetime emissions range only from 500 to 590 t, this is due to the fact that all the presented configurations have a dual fuel prime mover that operates with natural gas, the sulphur fraction of which is almost zero. Configuration 1 and 2 with almost equal performance, have the optimal performance on the SOx objective, whereas 13 has the worst with an 18% increase from the best performing solution in the SOx objective. Solution 13 is one of the two configurations that includes diesel generator sets to provide the electric power demand, thus the high SOx emissions are derived from the higher sulphur content of the LSHFO compared to the natural gas.

For the SOx lifetime emissions, the optimal configuration (solution 1) consists of natural gas operating systems since it has the lowest sulphur content. The sulphur emissions are estimated based on the amount of fuel. This justifies the selected configuration. The main engine is gas-injected due to the lower fuel consumption and a WHR is selected that improves the fuel efficiency.

Finally, for the NOx emissions, the results indicate that the optimal solutions have either lifetime NOx emissions lower than 6000 t with best performing configuration 3 or emissions higher than 12000 t with worst performing group 13. This outcome is driven by the choice of the prime mover. In addition, the two configurations with the best performance on the NOx emissions include fuel cells, which is expected since fuel cells have the lowest NOx emissions factor compared to the other investigated technologies.

It is identified that the solution that manages to reduce the NOx emissions the most consists of a dual fuel pre-mixed engine for the propulsion, fuel cells for electricity and gas fired boiler for the thermal demand. This configuration was expected to be the optimal for the NOx emissions objective since it consists of technologies that have the lowest NOx emission factor.

It is evident from the results of Table 6.4 that the two-stroke dual fuel engine operating in natural gas is the dominant prime mover for the Aframax tanker. It is further observed that the prevailing technology for the thermal demand is the gas fired boiler. For the electric auxiliary engines, the alternatives operating with natural gas are dominating the solutions, however, there are few instances that diesel generators are selected. As a general comment of the results, it is inferred that gas operating energy systems are highly prefered.

The findings of Table 6.4 indicate that the configurations with premixed dual fuel engine reduce drastically the NOx emissions compared to the solutions with gas-injected technology. This is due to the lean burn combustion of the pre-mixed technology that manages to reduce the NOx emissions and reach the Tier III without an after treatment technology, whereas the gas-injected technology requires the EGR to comply with the Tier III regulation. On the other hand, the configurations that have the lowest SOx and CO_2 emissions, which are estimated as a function of the fuel consumed, consist of dual fuel gas-injected engine. This is due to the lower gas consumption of the gas-injected engines that leads to lower fuel consumed and as a consequence SOx and CO_2 emissions. For the economic objective, the premixed engine has the best performance with the gas-injected having an 8% higher life cycle cost. Even though the gas-injected has lower fuel consumption the overall LCC is higher than the other alternative due to the higher capital cost of the large compression equipment, the after-treatment capital and operating cost, as well as the consumables.

The main contributor in both the economic and environmental objective is the main engine; however, the electric auxiliary engines are an important system of the tanker energy systems. The impact of the electric auxiliaries on the NOx emissions objective is further discussed. First regarding the configurations with dual fuel gas-injected main engine it is evident that in the cases where diesel generator sets (9,13) are selected the NOx emissions are the highest. On the other hand, when the fuel cells (2,6,7) are selected the emissions are the lowest, whereas with the dual fuel generator sets (1,5) the values are intermediate. A similar outcome is derived when the configuration main engine is a premixed dual fuel engine and for the electric auxiliary dual fuel generator sets (8,10,11,12) are selected or fuel cells (3,4). However, this decrease of the NOx emissions has a negative impact on the LCC, with the cost increasing inversely to the NOx emissions.

Another observation derived from the results is that in some cases three sets of different nominal power instead of two sets for electricity production are considered, thus operating more efficiently in both high and low loads. Moreover, the benefits of the shaft generator on the overall emissions and life cycle cost are identified from the results of Table 6.4. The more efficient main engine operates to cover the ship electric power demand, thus the layout that includes a shaft generator is recognised as optimal in the majority of the solutions.

The WHR is highly selected on the optimal solutions and manages to improve the environmental impact of the ship energy systems, by employing the exhaust gas from the main engine to produce steam for the thermal requirements and furthermore to produce electricity through a steam generator. The benefits of the WHR are observed comparing the solutions 10 and 12 that have a similar configuration, however, solution 10 includes additionally a WHR. The configuration with the WHR exhibits a significant decrease in the NOx and CO_2 emissions that are almost half compared to solutions 12; in addition, the SOx emissions are reduced by 4%.

The carbon capture technology manages to reduce drastically the carbon emissions. It is estimated that the lifetime CO_2 emissions are reduced by around 35%, when the carbon capture system is employed. However, the cost is significantly increased and in some cases, it is almost two times higher. It is estimated that the carbon capture offers 250 €/t of CO_2 emissions, whereas, the last six months of 2018 EU ETS for CO_2 emissions average price was 5.93 €/t of CO_2. As a result, the technology seems prohibitive for real-life context applications, despite the incremental improvement on the carbon footprint.

In Table 6.5, the percentage of the technologies on the Pareto front solutions is estimated. In this analysis, all the solutions from the multi-objective optimisation were included considering also the different nominal power of the prime movers. It is evident that the dual fuel premixed and gas-injected engines are equally preferred by the optimisation, whereas there is no solution that consists of a diesel engine. In addition, the WHR system is included in the majority of the optimal configurations, and the shaft generator is selected by 70% of the solutions.

Table 6.5 Percentage of the technologies on the total solutions

Dual fuel gas-injected	52%
Dual fuel pre-mixed	48%
Diesel engines	0%
Shaft generator	70%
WHR	95%
CC	61%
Electric auxiliary	Diesel 5% Fuel cells 60% Dual fuel 35%
Electric auxiliary sets	2 sets 70% 3 sets 30%
Electric auxiliary fuel	LSHFO 5% NG 95%
Thermal boiler	NG 100%

The carbon capture technology for the reduction of the carbon emissions is selected by more than half of the solutions of the total Pareto front. Furthermore, regarding the electric power generation, the fuel cells are highly preferred along with the dual fuel generator sets and lastly in very few occasions the diesel generator sets. Finally, for the thermal boiler, as it was discussed previously the dominant solution is the gas fired boiler.

In Figure 6.5, the distribution of the optimal solutions main engine nominal power that were presented in Figure 6.3, is displayed. It is observed from the figure that there is a higher occurrence for 14.5 MW nominal power. There is also a lower but almost equal occurrence of main engines nominal power between 15 MW to 16 MW. The minimum required installed power for an Aframax tanker according to the regulations is 13.5 MW in order to satisfy the propulsion power requirements. However, in many instances higher nominal power is installed that combined with the shaft generator allows more efficient operation of the ship energy systems.

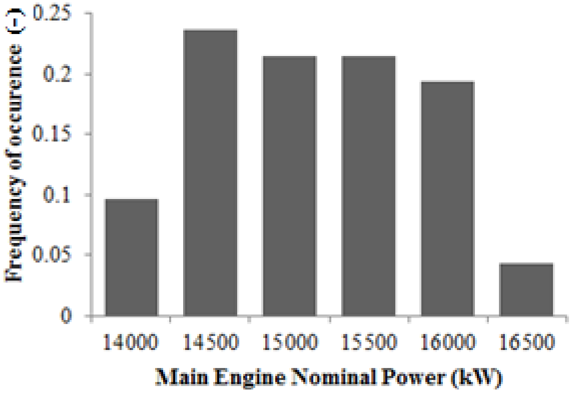

Figure 6.5 Main engine nominal power distribution of optimal solutions

6.4.2 Breakdown cost of selected solutions on the Pareto front

In this section, the life cycle cost of selected solutions is further analysed and broken down into capital and operating costs for each sub-system, this contributes in attaining a better understanding of the life cycle cost of the solutions. The configurations that are analysed are the best performing configurations for each objective, the current configuration (Table 6.3) and a solution of the Pareto front with similar LCC as the current configuration, according to Figure 6.3. The configurations that were discussed previously and are analysed in this section are presented in detail in Table 6.6.

The life cycle cost of the configurations from Table 6.6 is analysed in Figure 6.6 and Figure 6.7. In the former figure, the absolute values are presented, whereas in the latter the percentage values. The life cycle cost is analysed to the capital cost of the main engine, thermal boiler, electric auxiliary and other components, as well as the operating costs including maintenance and fuel cost of the main energy systems. Numbers were allocated to the configurations presented in Figure 6.6 in order to facilitate the discussion.

Table 6.6 Selected configurations of the Pareto front

	Optimal LCC (Group 11)	**Optimal SOx emissions (Group 1)**	**Optimal CO_2 emissions (Group 6)**	**Optimal NOx emissions (Group 3)**	**Pareto front solution with similar LCC with current (Group 2)**
Allocated number in Figures 6.6	1	3	2	4	6
Main engine	Dual fuel pre-mixed	Dual fuel gas-injected	Dual fuel gas-injected	Dual fuel pre-mixed	Dual fuel gas-injected
Nominal Power (kW)	14000	15500	16000	15500	15000
Energy efficiency technology	SG	WHR	SG &WHR	WHR	none
Emission reduction technology	none	EGR	EGR &CC	none	EGR
Electric auxiliary	2xDual fuel GS	2x Dual fuel GS	4x fuel cells	4x fuel cells	4x fuel cells
Thermal boiler	Gas fired boiler	Gas fired boiler	Gas fired boiler	Gas fired boiler	Gas fired boiler

From Figure 6.6, it is identified that the capital cost of the main engine is higher for configurations 2,3 and 6, which have a gas-injected engine installed that has a higher capital cost as it was discussed previously. On the other hand, the current configuration (5) exhibits the lowest main engine capital cost. The prime mover of the current configuration is a diesel engine that has the lowest capital cost factor. The thermal boiler has the same capital cost in all the cases since in all the alternatives a natural gas fired boiler is installed with the same nominal power.

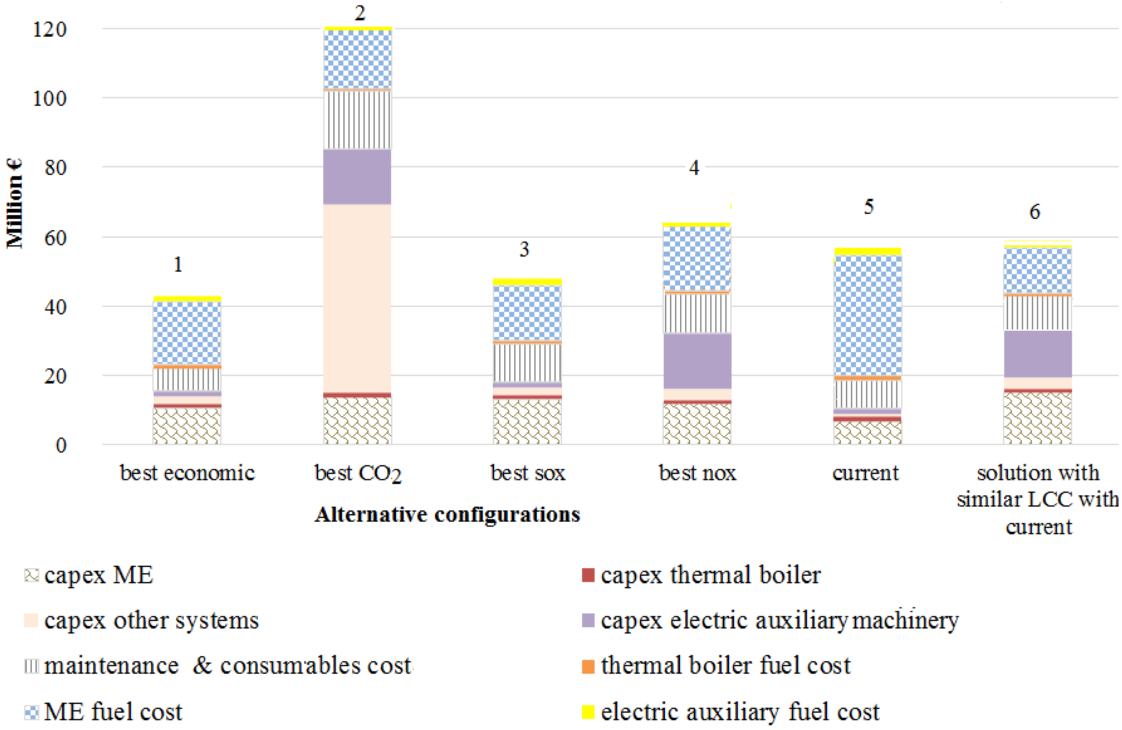

Figure 6.6 LCC breakdown analysis of selected solutions (absolute value)

The electricity power sub-systems capital cost varies dramatically among the configurations of Figure 6.6. The cost is very low for options 1 and 3 that consist of dual fuel generator sets, as well as for 5 that consists of diesel generator sets. The capital cost of the diesel generator set (solution 5) is the lowest compared to the considered alternatives. It is evident from Figure 6.6 that the fuel cells capital cost, including the stacks and the replacement of the stacks during the ship lifetime, is 10.8 times higher than the other alternatives. Finally, the capital cost of the other sub-systems is very low for the configurations 1, 3, 5 and 6 that include either only an after-treatment technology for the NOx emissions (SCR, EGR) or a technology that improves the energy efficiency (SG, WHR). Solution 2 has extremely high capital cost for the other sub-systems, reaching almost 16.3 times higher compared to the other alternatives, due to the excessive cost of the carbon capture technology.

Another observation from the results of Figure 6.6 is regarding the maintenance of the components and consumables cost for the emission reduction technologies. It is evident that configurations 2, 3,4 and 6 have the highest maintenance cost due to the requirements of the multiple configurations like the WHR, EGR, SG, CC and the fuel cells.

It is highlighted that the current configuration has the highest prime mover fuel cost, almost 1.9 times higher than the other alternatives. The sub-system that is the greatest contributor in the fuel consumed, is the main engine fuel cost, whereas the fuel cost for the thermal boiler as well as the electric machinery is quite low. It is identified from the figure that the thermal boiler fuel cost of the current configuration is slightly higher compared to the other alternatives, due to the higher cost price of the HFO. In addition, the fuel cost of the electric auxiliary sub-system of options 2, 4 and 6 is lower compared to the other alternatives due to the lowest fuel consumption of the fuel cells.

It is evident from the results of Figure 6.6 that the most expensive configurations are required to mitigate first the CO_2 emissions and second the NOx emissions. For the best CO_2 emissions configuration, the LCC is almost 120 M€, whereas, for the best NOx emissions, it is around 65 M€, almost half. The cost is high for these alternatives mostly due to the fuel cells and for the CO_2 objective is due to the economic impact of the carbon capture. On the other hand, regarding the SOx emissions objective, configuration 3 appears the most cost-efficient among the best performing solutions on the emissions objectives, with a cost comparable with configuration 1, which is the best performing for the economic objective. Therefore, it is inferred that reducing SOx emissions is not a preventive solution regarding LCC.

Finally, comparing the current configuration (5) with the most cost-efficient solution (1) and a solution from the optimisation with similar cost (6), it is evident that it is possible to have configurations with low life cycle cost even lower than the current configuration and at the same time improve the environmental impact of the energy systems. It is observed that the current configuration is optimal regarding the capital cost of the energy systems and it is estimated that it is almost 3.2 times lower, whereas, the other alternatives perform better regarding the operating expenditures. The increase in the capital cost of the more environmental solutions is due to the more environmentally friendly technologies, like the fuel cells and dual fuel engines, compared to the more cost-efficient diesel engines. However, the gas operating technologies due to the low price of natural gas have a lower fuel cost during the vessel lifetime. In the end, it is demonstrated that it is possible to achieve a lower life cycle cost of the current configuration while improving the environmental impact of the ship energy systems and complying with the current regulations.

The percentage of each significant cost that contributes to the overall life cycle cost of the ship energy system is presented in Figure 6.7. This is useful to identify in each alternative configuration the cost that contributes the most. It is observed from the results of Figure 6.7 that the most significant cost for the LCC differs in each configuration. The main engine fuel cost along with the capital cost of the electric machinery have the greatest contribution on the LCC of the configuration with the optimal NOx emissions performance. Furthermore, the maintenance and consumable are high, therefore, it is evident that the fuel cells due to the high capital cost and maintenance requirements have a great impact on the LCC of the configuration. For the alternative with the best carbon emissions, the greatest contribution comes from the capital cost of the other sub-systems, in specific the high cost of the carbon capture system. Finally, for the best performing SOx emissions configuration, the main engine has the most significant impact on the life cycle cost with the fuel cost and the main engine capital cost.

Similarly, for the best LCC alternative, the main contributor to the cost is by far the prime mover fuel and capital cost. In the current configuration, the same results are observed, however, in that case, the fuel cost consists the 64% of the LCC compared to the best economic alternative that it was only 43%. For the configuration with similar cost as the current solutions, it is observed that the greatest impact on the LCC is due to the electric auxiliary machinery capital cost as well as the main engines capital and fuel cost. Finally, it is evident that the fuel expenditures of the current configuration are almost 40% higher than the solution with similar LCC, which denotes that the lifetime fuel cost of the diesel engine operating with HFO is dramatically higher than the natural gas.

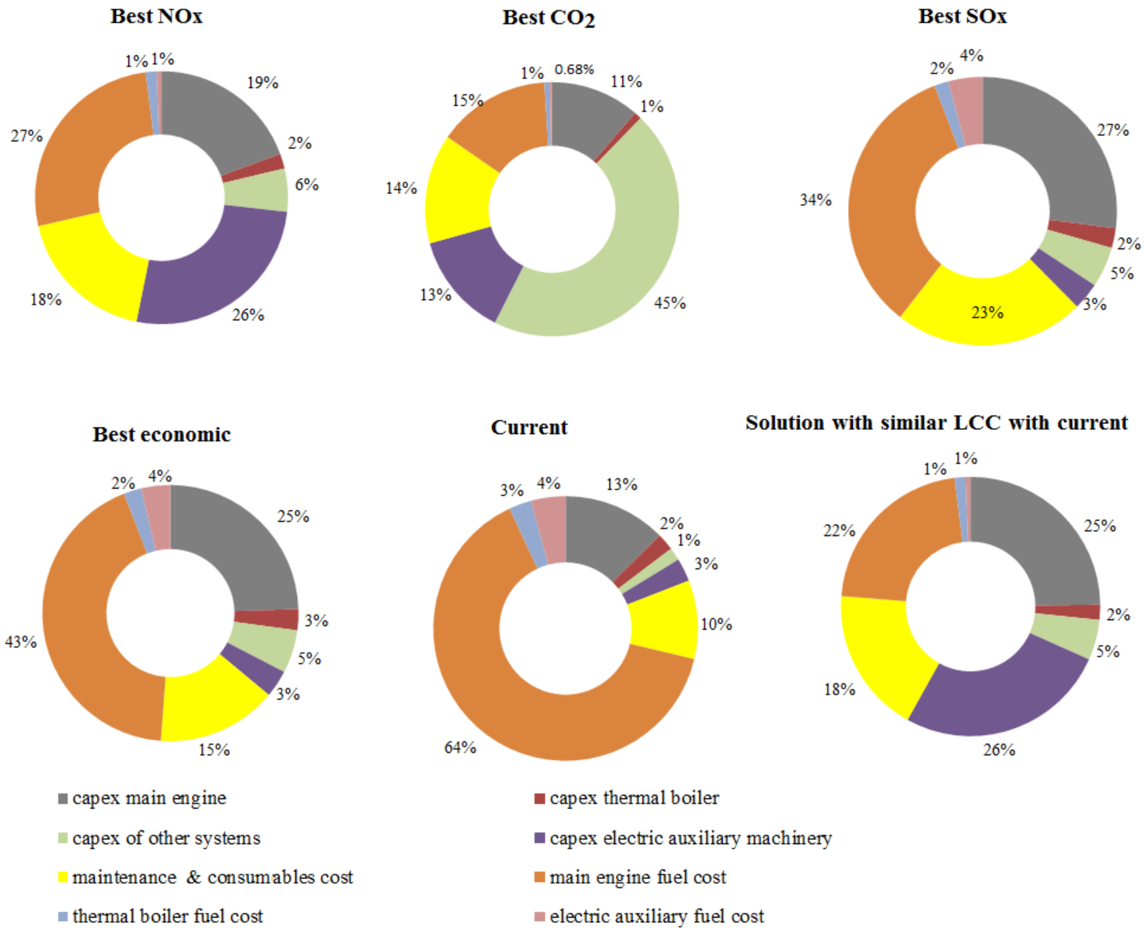

Figure 6.7 LCC breakdown analysis of selected solutions (percentage values)

6.4.3 Comparison of solutions EEDI and lifetime CO_2 emissions

In this section, the EEDI for every optimal solution derived from the multi-objective optimisation is estimated and presented. The results of the EEDI for each solution are compared with the lifetime CO_2 emissions. The EEDI reference value for Phase 0 for an Aframax tanker is estimated as it was indicated by IMO (IMO, 2014), according to Appendix C.

The reference value for Phase 1 until 2019, for Phase 2 until 2024 and for Phase 3 from 2025 and onwards is estimated according to the regulations (IMO, 2016b) and presented in Table 6.7. It is noted that these values correspond to newly built ships.

Table 6.7 Reference values for EEDI regulation for an Aframax tanker

Phase	Reference value (gr CO^2/t NM)
1	3.72
2	3.3
3	2.89

The EEDI is estimated for each solution according to IMO guidelines (IMO, 2014) (see Appendix C). The carbon capture is also considered in the calculation of the EEDI since it is directly related to the CO_2 emissions. In Table 6.8, the attained EEDI for each solution of the Pareto front is displayed and compared with the lifetime CO_2 emissions. The solutions are ranked according to the EEDI values in ascending order. In addition, the last two columns present the percentage difference of the EEDI and lifetime emissions corresponding with the EEDI values and the lifetime carbon emissions of the current configuration. The respective values for the current configuration for the EEDI value and for the lifetime carbon emissions are also displayed on the table.

It is evident from the table that all the solutions comply with the EEDI Phase 1 and 2 and as a result, they are considered green alternative configurations according to the imposed IMO EEDI regulation until 2019. However not all solutions can comply with the EEDI Phase 3 value, in specific the solutions of group 3 are above the reference value. Therefore, it is evident that after 2024, there are configurations derived from the optimisation that cannot comply with the EEDI Phase 3.

Table 6.8 EEDI values and lifetime CO_2 emissions of the optimal solutions

Group	EEDI (gr CO^2/t NM)	Lifetime CO_2 emissions (1000 t)	Percentage difference from baseline EEDI	Percentage difference from baseline CO_2 emissions
9	2.11	555-558	-29%	-53.5% to -53.8%
7	2.15	552	-28%	-54%
13	2.18	592	-27%	-51%
12	2.29	600	-24%	-50%
11	2.31	816	-23%	-32%
6	2.23-2.31	547-555	-23% to -26%	-54% to 55%
5	2.34-2.43	764	-19% to -22%	-36%
10	2.4-2.58	572	-14% to -20%	-52%
8	2.33-2.6	787	-13% to -22%	-34%
1	2.41-2.7	780	-10% to -20%	-35%
2	2.5-2.73	750	-9% to -17%	-38%
4	2.55-2.75	583	-8% to -15%	-51%
3	2.6-2.9	776	-4% to -13%	-36%
Current configuration	3	1201.1	(-)	(-)

From the results presented in Table 6.8, it is evident that the EEDI and the lifetime CO_2 emissions indicate different solutions as optimal and worst performing. According to the EEDI regulation, the greener solutions belong to the groups 9, 7 and 13; however, the CO_2 lifetime emissions indicate that the solutions, which have the lowest carbon footprint, belong to the clusters 6, 7 and 9. On the other hand, the solutions with the higher EEDI value are from groups 3, 4 and 2, whereas, for lifetime CO_2 emissions from 11, 8 and 1. In addition, it is observed that there is a variation on the EEDI on some group of solutions, whereas the lifetime emissions have very small variations. This is mainly due to the fact that the EEDI is highly dependent on the nominal power, however the lifetime carbon emissions are estimated according to the real power requirements. Thus, for the same configuration with different nominal power, there is a great range on the EEDI, whereas for the lifetime carbon emissions the value is almost the same.

Differences are observed also for the values of the percentage difference from the current for the EEDI and the lifetime carbon emissions. From group 9, it is identified that the performance of the solution regarding the EEDI is improved 29% from the baseline, whereas for the carbon emissions it is 53.5%. Therefore, even though the lifetime CO_2 emissions are reduced by half compared to the current configuration, the EEDI has a much lower improvement. Another observation comes from comparing solution 11 and 12. For the EEDI the two solutions have only a 1% difference whereas the lifetime carbon emissions have 18%. Furthermore, it is evident that solution 3 has a minor improvement comparing to the current regarding the EEDI, in some cases it is only 4%. On the other hand, the lifetime emissions manage to reduce 36% compared to the current configuration.

The EEDI values are greatly affected by the installed power, whereas for the lifetime carbon emissions the most significant factor is the type of the technologies and the lifetime operating requirements. As a result, the EEDI promotes configurations that have lower installed nominal power, whereas it does not support solutions that manage to have a beneficial impact on the lifetime carbon footprint of the energy systems. A great misalignment is identified between the results of the two indicators and the solutions that are identified from the optimisation. The solutions that manage to reduce greatly the CO_2 emissions, according the EEDI, they have only a marginal improvement from the current configuration. Therefore, it is inferred that the EEDI underestimates the effect of technologies for reducing the carbon emissions.

6.5 Results from the uncertainty analysis of the tanker ship

An uncertainty analysis according to Chapter 4 is performed in order to investigate the influence of the input parameters on the results and evaluate the robustness of the optimal configurations. The results of the uncertainty analysis are presented and discussed in this section. The term original case used herein refers to optimal configurations of the former section.

First, the solutions that are mostly identified on the Pareto front of the uncertainty analysis are demonstrated (6.5.1). Then the best performing configurations on each objective are presented (6.5.2). For the original case solutions robustness, the frequency of appearance of the original case best-performing configurations on the uncertainty analysis Pareto front is displayed (6.5.3). Finally, the number of the uncertainty analysis Pareto fronts that the optimal configurations of the original case appear in are presented (6.5.4).

6.5.1 Solutions identified on the tanker ship uncertainty analysis Pareto fronts

In this section, the percentage that each technology appears on all the Pareto fronts of the uncertainty analysis is estimated and displayed in Table 6.9. The results from this table are compared with Table 6.5 that presents the percentage of the technologies that appear on the Pareto front of the original case. This analysis is performed in order to identify the solutions robustness in an uncertain environment. The inputs for the parameters ranges were discussed in Chapter 4.

From the results of Table 6.9, it is inferred that the greatest percentage of the solutions consists of dual fuel engines, with the gas-injected having an advantage compared with the pre-mixed. There is also a small percentage of solutions that have a diesel engine for the main propulsion operating with HFO. Similar results are observed from the original case with dominant solutions the dual fuel engines and predominant the gas-injected, however, in the original case, there were not any solutions with diesel main engine. The fact that solutions with diesel engines appear on the uncertainty analysis results is highly related with the fuel prices influence on the ship energy systems performance. Thus, it is evident that if the prices are altered, configurations with diesel main engine will constitute a small percentage of the optimal solutions. However, the dual fuel engines remain the most robust solution.

Regarding the energy efficiency technologies similarities are identified with the original case study results from Table 6.5. A high percentage of solutions, around 70% of the optimal configurations includes a shaft generator. Additionally, the WHR is selected in almost 90% of the solutions on the Pareto front; in align with the original case where the percentage of the configurations with WHR technology was around 95%. The carbon capture technology appears in 51% of the solutions derived from the Pareto fronts of the uncertainty analysis, whereas in the original case a percentage of 61% was observed. Therefore, it is inferred that the emission reduction technologies and the energy efficiency are robust and the alterations on the capital cost of the technologies do not influence the results.

Table 6.9 Technologies identified on the Pareto fronts from the uncertainty analysis and original case

	Pareto fronts of uncertainty analysis	Original case (Table 6.5)
Dual fuel engines gas-injected	56%	52%
Dual fuel engine pre-mixed	39%	48%
Diesel engines	5% HFO	0%
SOx reduction for diesel	fuel switch LSHFO 71% scrubber 29%	-
CC	51%	61%
Shaft generator	68%	70%
WHR	89%	95%
Electric auxiliary	Diesel 34%	5%
	Fuel cells 51%	60%
	Dual fuel 15%	35%
Electric auxiliary sets	2 sets 65%	70%
	3 sets 35%	30%
Electric auxiliary fuel	MDO 2%	-
	LSHFO 32%	5%
	NG 66%	95%
Thermal boiler	HFO 0.2%	-
	LSHFO 20%	-
	NG 79.8%	100%

Furthermore, the percentage of fuel cells on the solutions is high in line with the original case; however, in the original case, it was 60%, whereas, in the results from the uncertainty analysis it is decreased by 9%. A high increase of 19% is observed for the diesel generator sets, around 29% compared to the original case. Along these lines, there is a 20% decrease in the dual fuel generator sets. Therefore, the results for the electric auxiliary machinery are not as robust as the other sub-systems. This is mostly related to the fact that the overall contribution of the auxiliary electric sub-systems on the emissions and the LCC is small compared to the other sub-systems. In addition, their performance on the objectives is highly dependent on the fuel prices and technologies capital cost; therefore, this sub-system is sensitive to the input parameters uncertainty.

Finally, regarding the thermal boiler, the greatest percentage of the results has as optimal technology the gas fired boiler. However, compared to the original case there is a 20% of solutions with an oil fired boiler operating with LSHFO, indicating a relative robustness of the solution.

The solutions from the uncertainty analysis are clustered into 206 groups, when the nominal power is not considered. Therefore, 206 different combinations of the included technologies and fuels appear on the Pareto fronts from the uncertainty analysis. However, not all solutions appear frequently, the more frequent configurations on the Pareto front that constitute 90% of the overall solutions are displayed in Figure 6.8. The thickness of the lines in this figure demonstrates the percentage each configuration appears on the solutions in the Pareto fronts of the uncertainty analysis.

The figure allows a better understanding of the identified configurations. It is evident that the number of configurations increases significantly due to the electric auxiliary engine alternatives. Therefore, it is observed that there are some configurations that appear only in a frequency of 0.3%. The graphic representation of the configurations supports the findings of Table 6.9.

From the preceding analysis, it is evident that some sub-systems are very robust, whereas others are sensitive to the input parameters uncertainty.

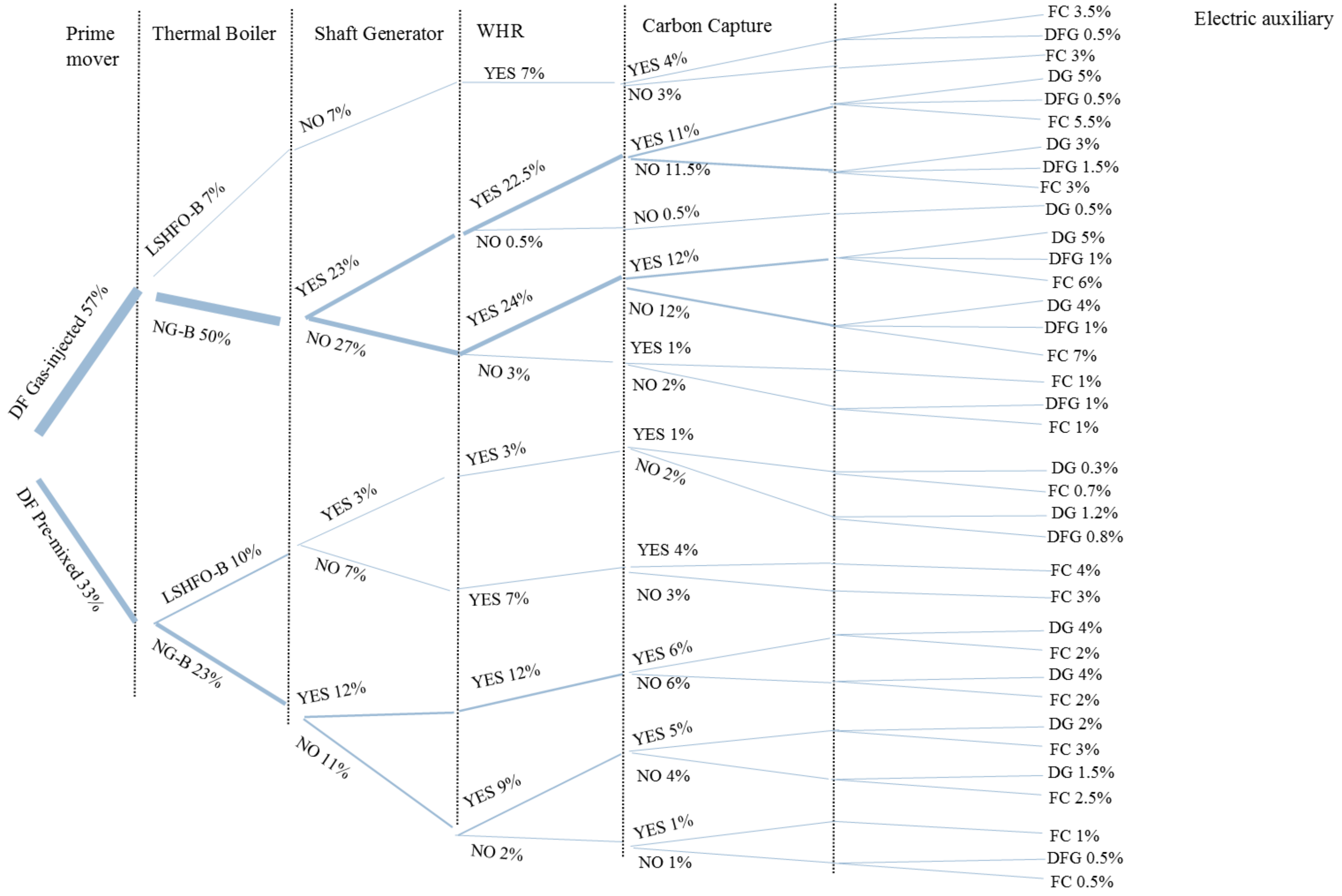

Figure 6.8 Graphic representation of uncertainty analysis solutions (90% of the solutions)

The distribution of the nominal power as it was identified on the Pareto fronts of the uncertainty analysis is investigated. The nominal power distribution of the prime mover of the solutions derived from the uncertainty analysis is depicted in Figure 6.9, along with the results from the original case shown in Figure 6.5. Similar results with the original case are observed, it is identified that there is a high occurrence in the nominal power of 15 MW and in approximately 50% it was recognised as the main engine power of the optimal solution. Finally, the distribution has the same range for both the uncertainty analysis and original case.

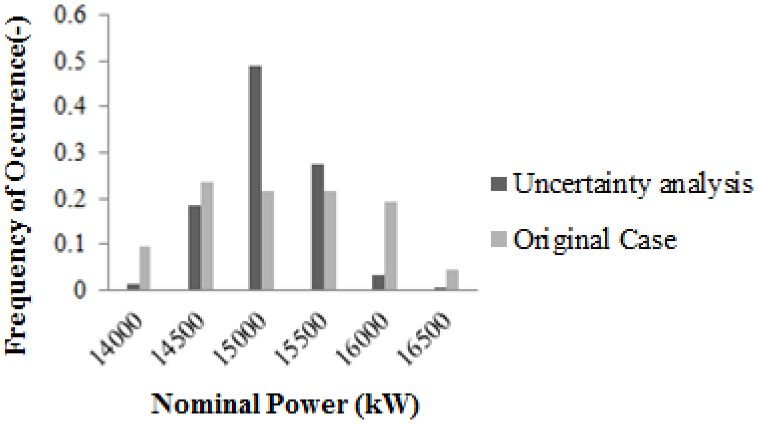

Figure 6.9 Nominal power distribution of uncertainty analysis and original case solutions

6.5.2 Optimal configurations for each objective robustness

In this section, the configurations from the uncertainty analysis that are mostly identified as optimal for each of the four objectives are presented. The results are depicted on four tables, Tables 6.10, 6.11, 6.12 and 6.13, where the percentage that each technology appears as the optimal configuration of each objective, LCC, CO_2, SOx and NOx, respectively is displayed. In addition, in order to facilitate the discussion, the best solution for each objective as it was identified from the optimisation of the original case (Table 6.4) is displayed. This analysis investigates whether the configurations that perform best on each objective are robust.

From the results of Table 6.10, it is identified that the greatest percentage of the best performing solutions in respect to the economic objective from the uncertainty analysis has as main engine the dual fuel pre-mixed and gas-injected. This is aligned with the results presented in Table 6.4 from the original case study, were the most cost-efficient solution had a pre-mixed followed by configurations that had a gas-injected engine. However, from the uncertainty analysis, it is evident that there are limited occasions, where the diesel engine is selected in the optimal configurations. When the diesel engine is selected an SCR technology is considered in order to comply with the Tier III regulations and for the sulphur emissions, in

64% of the cases LSHFO switch and in fewer instances a scrubber. The selection between scrubber and LSHFO switch is quite dependent on the relevant prices of the fuels, however, it is highlighted that LSHFO switch is more cost efficient than the scrubber in most cases. However, still, the pre-mixed dual fuel engine is robust as the prime mover with the best performance in the economic objective.

In addition, the SG is employed in the greatest percentage of the most economic solutions similar with the original case, whereas the WHR system is only on half the solutions, which agrees with the most cost-efficient solutions of Table 6.4. On the other hand, the carbon capture was not identified in any of the uncertainty analysis solutions, which is reasonable since the capital cost of the technology is very high. Furthermore, the greatest percentage of the solutions consists of gas fired boilers similar to the original case, whilst there is a small number of solutions that have an oil fired boiler. Therefore, the impact of the fuel prices uncertainty is highlighted; however, the gas boiler is quite robust as it is evident from the comparison of the original case and uncertainty analysis results.

Table 6.10 Solutions that perform best on LCC objective

	Results from the uncertainty analysis	**Best performing solution of the original case**
Dual fuel engines gas-injected	28%	-
Dual fuel engines pre-mixed	69%	✓
Diesel engines	3% with HFO	-
SOx reduction for diesel	fuel switch LSHFO 64%	-
	scrubber 36%	-
Carbon Capture	0%	-
Shaft generator	99%	✓
WHR	45%	-
Electric auxiliary	Diesel 57%	-
	Dual fuel 43%	✓
Electric auxiliary sets	2 sets 57%	✓
	3 sets 43%	-
Electric auxiliary fuel	LSHFO 57%	-
	NG 43%	✓
Thermal boiler	HFO 4%	-
	NG 96%	✓

Finally, for the electric auxiliary engines, there is a misalignment with the original case study regarding the type of the engine. In Table 6.4, the most cost-efficient solutions consist of dual fuel generator sets, similar to Table 6.10, where the dual fuel generators are identified in almost half of the cases. In addition, it is observed that there is also a great percentage of configurations with diesel generator sets. This finding is aligned with the previous analysis and it is derived that further investigation on this sub-system is required.

In Table 6.11, the best performing configurations for the CO_2 emissions consist of a dual fuel gas-injected engine as it was also identified in the original case, followed by few occasions that the pre-mixed was selected as the optimal solution. Therefore, the selection of the prime mover appears to be robust. In all the cases along with the original, the carbon capture technology was included, which is justified by the fact that this technology manages to reduce drastically the emissions. The inclusion of the shaft generator and WHR is in high occurrence on the optimal solutions. This fact agrees with the results of the original case and is supported from the literature since these technologies manage to improve the energy performance of the ship energy systems and as a result reduce the carbon emissions.

Table 6.11 Solutions that perform best on CO_2 emissions objective

	Results from the uncertainty analysis	Best performing solution of the original case
Dual fuel engines gas-injected	93%	✓
Dual fuel engine pre-mixed	7%	-
Diesel engines	0%	-
Shaft generator	85%	✓
WHR	96%	✓
CC	100%	✓
Electric auxiliary	Diesel 25%	-
	Fuel cells 69%	✓
	Dual fuel 6%	-
Electric auxiliary sets	2 sets 51%	-
	3 sets 49%	✓
Electric auxiliary fuel	LSHFO 25%	-
	NG 75%	✓
Thermal boiler	NG 100%	✓

Regarding the electric auxiliary, it is evident that the fuel cells appear in the majority of the solutions similar to the original case. Therefore, it is a dominant technology for the best CO_2 emissions objective. The gas fired boiler is the selected technology of the optimal configurations in the original case and is also dominant among the alternatives in the uncertainty analysis results.

In Table 6.12, the optimal solutions regarding the SOx emissions objective are presented. It is inferred from the results that the majority of the configurations that perform optimally in this objective consist of a dual fuel gas-injected engine, similar to the original case. In addition, a great percentage of the solutions includes a WHR, whereas the SG percentage is not as high. Both conclusions were identified in the results of the original case, rendering the original best performing configuration for the SOx emissions robust. Only a small percentage of solutions includes CC, this result is derived due to the multi-objective nature of the optimisation since the CC technology has no impact on the SOx emissions. For the thermal boiler, similar to the results of the original optimisation, most of the configurations consist of a gas fired boiler. Finally, for the electric auxiliary sub-systems, there is equal sharing for the fuel cells and dual fuel generator sets. Both technologies manage to reduce the SOx emissions drastically, thus it is justified that they are selected among the optimal solutions. In the original case, dual fuel generators were selected for the electric auxiliary, herein the technology appears in almost 50% of the optimal configurations. The other 50% of configurations consists of fuel cells, which were identified from Table 6.4, in solutions of Group 2 that have almost zero percentage difference on the SOx emissions. Therefore, the electric auxiliary sub-system appears robust.

Table 6.12 Solutions that perform best on SOx emissions objective

	Results from the uncertainty analysis	Best performing solution of the original case
Dual fuel engines gas-injected	93%	✓
Dual fuel engine pre-mixed	7%	-
Diesel engines	0%	-
CC	3%	-
Shaft generator	50%	-
WHR	85%	✓
Electric auxiliary	Diesel 0%	-
	Fuel cells 51%	-
	Dual fuel 49%	✓
Electric auxiliary sets	2 sets 59%	✓
	3 sets 41%	-
Electric auxiliary fuel	NG 100%	✓
Thermal boiler	LSHFO 9%	-
	NG 91%	✓

Table 6.13 provides the uncertainty analysis results regarding the NOx emissions objective best performing configurations. The dominant main engine technology is the dual fuel pre-mixed, similar to the original case. Therefore, this technology is the predominant for the NOx emissions mitigation. The electric auxiliary fuel cells is also the most dominant solution followed by the dual fuel generator sets. However, the greatest percentage of configurations includes fuel cells, the same with the original case. The gas fired boiler is a prevailing technology for the optimal configurations of the uncertainty analysis and the original case. The carbon capture is selected in very few cases, which is expected since it does not have an impact on the NOx emissions.

Table 6.13 Solutions that perform best on NOx emissions objective

	Results from the uncertainty analysis	Best performing solution of the original case
Dual fuel engines gas-injected	0%	-
Dual fuel engine pre-mixed	100%	✓
Diesel engines	0%	-
CC	4%	-
Shaft generator	69%	-
WHR	90%	✓
Electric auxiliary	2% Diesel	-
	72% Fuel cells	✓
	26% Dual fuel	-
Electric auxiliary sets	2 sets 45%	-
	3 sets 55%	✓
Electric auxiliary fuel	2% LSHFO	-
	95% NG	✓
Thermal boiler	1% LSHFO	-
	99% NG	✓

Finally, the WHR system appears in the majority of the optimal solutions in Table 6.13. The original case configuration also includes a WHR, therefore, this technology is considered robust. On the other hand, the SG has a high percentage on the best performing configurations; however, it was not identified in the optimal configuration of the nominal case. Both technologies are beneficial for the mitigation of NOx emissions; however, the WHR is more robust.

6.5.3 Appearance of the original case best performing configurations on the uncertainty analysis solutions

In the previous section, the configurations that appear more frequently as best performing for the objectives were presented. In this section, the frequency that the optimal configurations of the original case for each objective appear on the optimal solution of the uncertainty analysis results is investigated. The reason for this analysis is to investigate, whether the optimal configurations are robust under the uncertain input parameters.

The frequency of appearance of the best performing solutions as optimal on the results of the uncertainty analysis on each objective is presented in Table 6.14. The optimal configurations for each objective of the original case were presented in Table 6.6.

Table 6.14 Appearance of original case optimal configurations on the uncertainty analysis results

Objective	Percentage of the best performing solutions
LCC	5%
CO_2	32%
SOx	45%
NOx	28%

It is evident from the results of Table 6.14 that the best-performing solutions for each objective of the base case, except of the economic objective, are robust and appear in a great percentage of the Pareto fronts of the uncertainty analysis. In addition, it is derived from the results that they are the most frequent configurations for the optimal solution for each objective. The LCC configuration is the least robust and appears in a very low percentage on the uncertainty analysis results, whereas the configuration that is derived with a frequency of 46% as the most promising for the economic objective from the uncertainty analysis results is displayed in Table 6.15.

Table 6.15 Configuration that appears more frequently as best performing on the economic objective

Sub-system	Most frequent configuration
Main engine	Dual fuel pre-mixed
Energy efficiency technology	SG
Emission reduction technology	none
Electric auxiliary	2xDiesel Gen (LSHFO)
Thermal boiler	Gas fired boiler

The configuration of Table 6.15 is a solution identified also on the original case solutions of Table 6.6 with only exception the electric auxiliary machinery. In the uncertainty analysis, the optimal configuration consists of diesel auxiliary generators, whereas, in the original case it consists of dual fuel generators. As a result, it is evident that the best-performing solution for the economic objective is robust in respect of all the sub-systems except the electric auxiliary engine. Great diversity is observed regarding the electric auxiliary systems, as it was identified from the discussion in Section 6.5.1.

6.5.4 Appearance of original case configurations on the uncertainty analysis Pareto fronts

In this section, the total times each group of solutions of the original case presented in Table 6.4 appears on the different Pareto fronts of the uncertainty analysis is discussed. In the previous section, the frequency of the configurations on the total Pareto fronts of the uncertainty analysis was discussed, however, it is possible due to the different nominal powers that one configuration might appear multiple times on one Pareto. Therefore, in this section, another aspect of the robustness of the solutions is explored.

The uncertainty analysis was repeated 1000 times and in Table 6.16 it is displayed in how many Pareto fronts of the uncertainty analysis, the solutions of the original case Pareto were identified. It is evident that some configurations where more dominant and appeared in many Pareto fronts, for example, solutions 6, 7 and 9. Therefore, these configurations and technologies appear more dominant and not affected by the uncertain factors of the environment. The solutions that appear the least on the uncertainty analysis Pareto fronts are from the groups 12 and 13. The lower frequency of appearance of these solutions denotes the impact of the input parameters changes on the optimal configurations.

Table 6.16 Number of Pareto fronts the original case optimal solutions appear

Group	Number of Pareto fronts (of total 1000 Pareto fronts)
1	110
2	109
3	125
4	130
5	98
6	155
7	153
8	98
9	139
10	99
11	97
12	73
13	79

The results of this analysis indicate the influence of the input parameters on the optimal configurations and demonstrate the significance of the uncertainty analysis in order to identify the whole envelope of optimal solutions.

6.6 The effect of the operating profile on the optimal solutions

In this work, an expected operating profile derived from real operating data for an Aframax tanker was used for the original case. In order, to study the effect of the operating profile on the optimal solutions, different operating profiles are considered, while the other parameters are kept the same as the original case. The three operating profiles scenarios including the one for the original case are presented in Figure 6.10. The purpose of this analysis is to investigate, whether alternative operating profiles indicate different optimal configurations and examine the influence the profile has on the results.

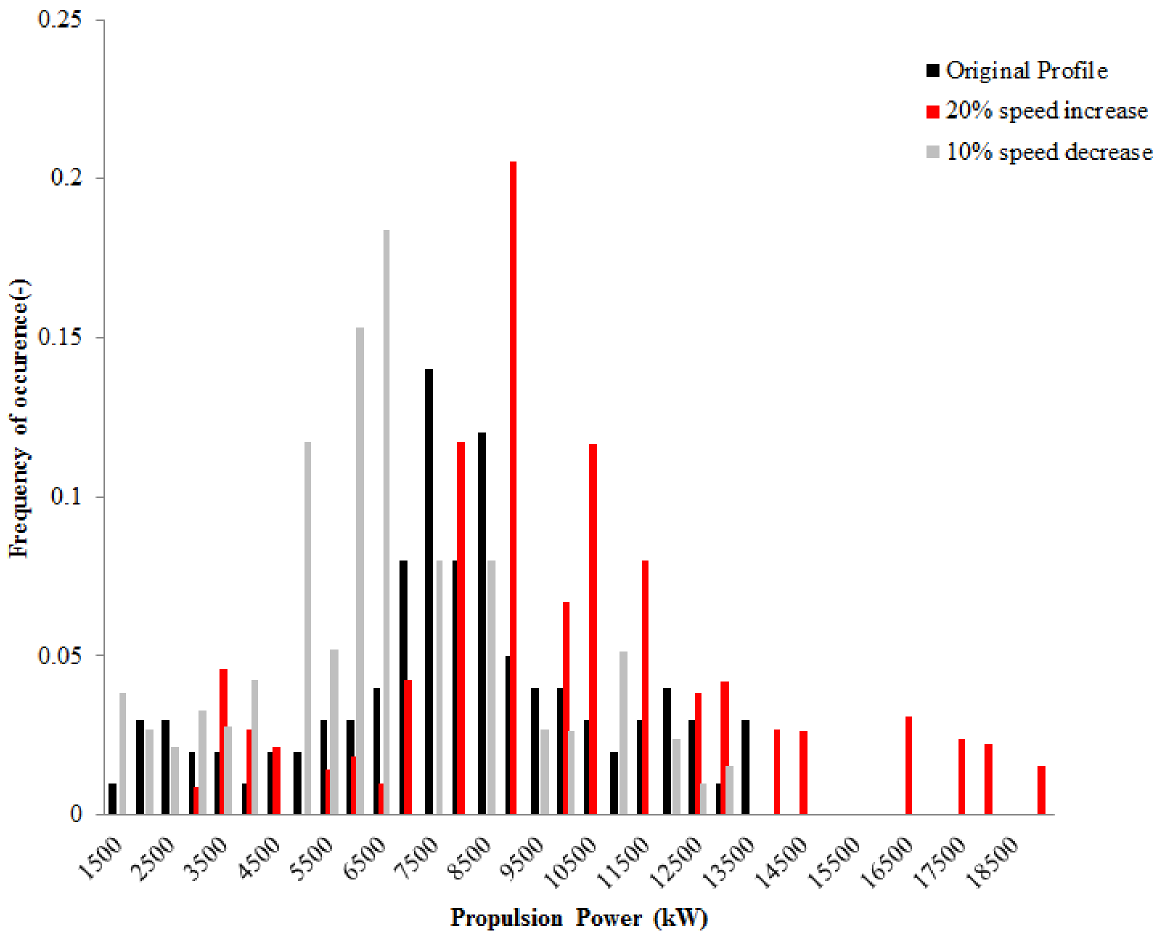

Figure 6.10 Operating profile scenarios

The two operating profiles investigated herein are derived by increasing by 20% and decreasing by 10% the speed profile of the original case from Banks et al. (2013). The 10% decrease is imposed as the original profile presented in Banks et al. (2013) was already in a slow steaming mode compared to speed profiles from previous years. The optimal configurations derived from the different profiles are presented in Tables 6.17 and 6.18, for the profile with the higher speeds and lower speeds respectively. It is evident from the tables that the performance on the four objectives of the similar configurations varies, due to the different power requirements derived from the operating profile.

Table 6.17 Optimal configurations for profile with +20% speed shift

	Main Engine			Emission reduction technology	Energy Efficiency technology	Auxiliary engines			Thermal Boiler		Percentage Difference from the best solution			
	Type	**Fuel**	**MCR (MW)**			**Type**	**Fuel**	**Sets/Power (kW)**	**Type**	**Fuel**	**LCC**	**CO_2 emissions**	**SOx emission**	**NOx emissions**
1	DF gas-injected	NG	19.5-21	EGR	WHR	DFG	NG	2x 1280 &1x660	GFB	NG	+(20% to 25%)	+(35% to36%)	0%	+169%
2	DF pre-mixed	NG	19.5-21	CC	WHR	DFG	NG	2x1280	GFB	NG	+(174% to 190%)	+(10% to11%)	+2.8%	+3
3	DF gas-injected	NG	19.5-21	EGR	WHR&SG	FC	NG	4x500	GFB	NG	+(43% to 46%)	+(28% to29%)	+3.6%	+119%
4	DF gas-injected	NG	19-20.5	EGR	WHR&SG	DFG	NG	2x 1280 or 2x 1280 &1x660	GFB	NG	+(10% to14%)	+(30% to32%)	+3.7%	+120%
5	DF gas-injected	NG	20-20.5	EGR&CC	SG&WHR	FC	NG	4x500	GFB	NG	+(209% to 214%)	+(0 to0.1%)	+5%	+119%
6	DF gas-injected	NG	19.5-21	EGR & CC	WHR&SG	DFG	NG	2x 1280 or 2x 1280 &1x660	GFB	NG	+(172% to 187%)	+(0.2% to1.5%)	+5.2%	+120%
7	DF pre-mixed	NG	19.5	CC	WHR	FC	NG	4x500	GFB	NG	+195%	+2.5%	+7.6%	0%
8	DF pre-mixed	NG	19-21	none	SG	DFG	NG	2x1280	GFB	NG	+(0 to 3%)	+(38% to 39%)	+9.5%	+7%
9	DF gas-injected	NG	19.5	EGR& CC	SG	DG	LSHFO	2x 1260	GFB	NG	+172%	+7%	+12.2%	+131%
10	DF pre-mixed	NG	19.5-21	CC	SG	DG	LSHFO	2x 1260	GFB	NG	+(164% to178%)	+(7% to 8%)	+13.8%	+10%

Table 6.18 Optimal configurations for profile with -10% speed shift

	Main Engine			Emission reduction technology	Energy Efficiency technology	Auxiliary engines			Thermal Boiler		Percentage Difference from the best solution			
	Type	**Fuel**	**MCR (MW)**			**Type**	**Fuel**	**Sets/Power (kW)**	**Type**	**Fuel**	**LCC**	**CO_2 emissions**	**SOx emissions**	**NOx emissions**
1	DF gas-injected	NG	15-16	EGR	WHR	DFG	NG	2x 1280 &1x660	GFB	NG	+(17% to 19%)	+32	0%	+116%
2	DF pre-mixed	NG	14	none	WHR	FC	NG	4x500	GFB	NG	+39%	+30%	+1%	0%
3	DF gas-injected	NG	14.5-15	EGR&CC	WHR	FC	NG	4x500	GFB	NG	+(210% to217%)	+3%	+1%	+111%
4	DF pre-mixed	NG	14	CC	SG	FC	NG	4x500	GFB	NG	+186%	+3%	+2%	0%
5	DF gas-injected	NG	14.5-15	EGR	WHR&SG	FC	NG	4x500	GFB	NG	+(48% to 49%)	+29%	+7%	+127%
6	DF pre-mixed	NG	14.5	none	SG	DFG	NG	2x 1280 &1x660	GFB	NG	0%	+38%	+8%	+7%
7	DF gas-injected	NG	14-16	EGR&CC	WHR&SG	FC	NG	4x500	GFB	NG	+(193to 213%)	0%	+8%	+127%
8	DF gas-injected	NG	14.5-15	EGR& CC	WHR&SG	DFG	NG	2x 1280 &1x660	GFB	NG	+(159% to172%)	+1.5%	+8%	+129%
9	DF pre-mixed	NG	14.5	CC	WHR&SG	DFG	NG	2x 1280 &1x660	GFB	NG	+152%	+2%	+10%	+3%
10	DF gas-injected	NG	16	EGR	WHR&SG	DG	LSHFO	2x 1260 & 1x660	GFB	NG	+20%	+31%	+10%	+133%
11	DF pre-mixed	NG	14.5	CC	SG	DFG	NG	2x1280	GFB	NG	+149%	+8%	+14%	+11%

The main difference identified comparing the configurations in Table 6.4 and Table 6.17 is the nominal power of the main engine, as it was expected since the power requirements increase with the profile with higher speed. Therefore, the nominal power of the main engine should be higher to satisfy the power demand. On the other hand, for the profile with the lower speed, it is observed that the nominal power of the main engine remains in the same ranges as in Table 6.4. This is expected since the required power of both profiles is similar and the main difference is the frequency of occurrence, according to Figure 6.10. However, the nominal power cannot be lower than 14 MW, according to the regulations for minimum power requirements of an Aframax tanker.

It is observed from the tables that the optimal solutions are similar for the three operating profiles. A differentiation is identified on the number of sets of the auxiliary engine. For the profile with the lower speeds in the majority of the solutions, there are three sets of electric auxiliary engines installed, two with higher power and one with lower. This is justified by the fact that the electric demand is lower since it is estimated as a function of the propulsion power demand. As a result, it is more efficient to be provided by an engine with lower nominal power that operates in loads that are more efficient.

It is inferred comparing the results of the original cases (Table 6.4) with Tables 6.17 and 6.18 that the optimal configurations for each objective are the same for the different operating profiles except the nominal power that was discussed previously. For the lowest NOx emissions, the premixed dual fuel engine, with fuel cells, a natural gas boiler and a WHR is the optimal solutions in all three profiles. Therefore, this configuration is robust regarding the alterations of the operating profile. The only differentiation in Table 6.17 is that the solution has also a carbon capture technology, however, this has no impact on the NOx emissions and it is selected in the configuration due to the multiple objectives nature of the optimisation. The gas-injected dual fuel engine with dual fuel generator sets, gas boiler and a WHR is the configuration that performs optimally regarding the SOx emissions for all the potential changes on the operating profiles.

For the carbon emission objective, the three Pareto fronts for the different operating profiles exhibit the same configuration that includes a gas-injected dual fuel engine with fuel cells, gas boiler, a shaft generator, WHR and a carbon capture technology. Finally, for the solution with the best life cycle cost in all the investigated cases, the optimal configuration consists of a pre-mixed dual fuel engine with a shaft generator, dual fuel generators and a gas fired boiler. These findings support the fact that the configurations originally presented are robust and perform optimally in the carbon and economic objectives for all the investigated profiles.

The main finding of this analysis is that the optimal configurations are robust regarding the variations of the operating profile. However, it is important for the decision maker to be provided with the solutions of the optimisation for different profiles in order to identify the optimal nominal power for the ship energy systems. Especially, since the operating management for the vessel is not standard and regarding the policy of the operator, it is possible to be operated in higher or lower speeds. Therefore, this analysis provides support for the decision maker to select the optimal configuration along with the nominal power.

6.7 Sensitivity analysis of the optimal solutions

In this section, according to Section 3.4.9 it is investigated how the variations of the fuel prices and the capital cost of specific technologies affect the performance of the optimal configurations of the original optimisation (Table 6.4). In that way, the alterations of the investigated parameters lead to the projected results for the life cycle cost of the optimal solutions. As a result, the decision maker can have a better understanding of the ranges of the life cycle cost of the configurations in an uncertain environment, as well as the impact of the most significant economic parameters on the optimal solutions life cycle cost.

First, the variations of the fuel prices are investigated and the results are discussed. The natural gas is the dominant fuel for the optimal configurations; thus, the life cycle cost of the optimal configurations is estimated for a range of the natural gas prices. A range from -60% to +160% of the current price used in the original application is examined. This range was selected according to the historical prices of the natural gas for the last 10 years (2008-2018) (YCharts, 2018).

In Figure 6.11, the life cycle cost of the 13 optimal configurations for the respective variations of the natural gas prices is presented. It is evident from the figure that an increase in the natural gas price leads to the increase of the life cycle cost. In some cases, it is inferred that the life cycle cost is almost doubled, when the natural gas price increases by 160%. The deviations on the fuel prices have a significant impact on the life cycle cost of the ship energy systems and play a critical role, especially since it is a very uncertain parameter that is affected by exogenous factors. Therefore, the decision maker should investigate the potential impact of the fuel prices on the configurations.

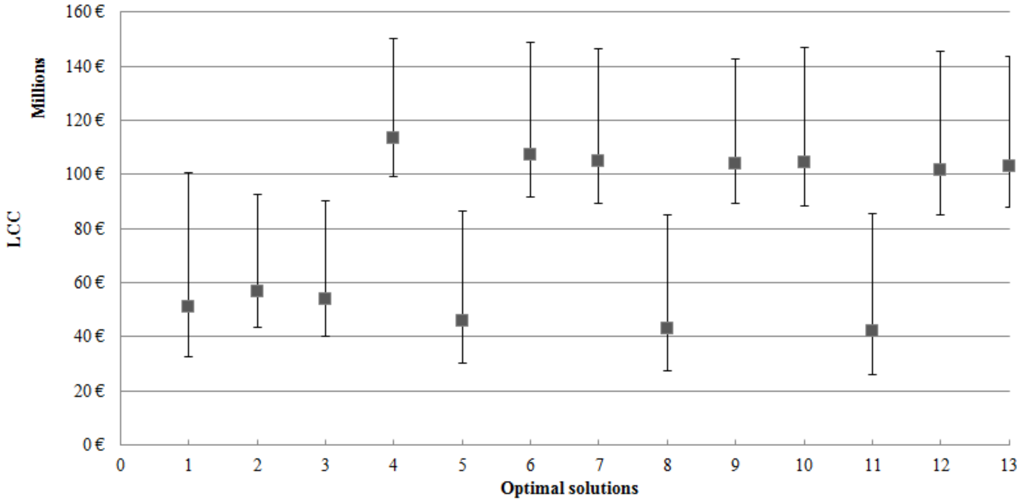

Figure 6.11 Natural Gas prices variation: -60% to +160%

In the following part of this section, the impact of the alteration of the capital cost on the optimal configurations is examined. The scope of this section is to investigate the impact of the uncertain parameters, for this reason only the capital cost of emerging technologies for the ship energy systems, as the carbon capture and fuel cells are explored. On the other hand, the traditional technologies that have been used in the marine industry for many years and have an established price are not considered.

The life cycle cost ranges of the optimal configurations due to the respective variations of the capital cost of the carbon capture are presented in Figure 6.12. It should be noted from the figure that the changes in this parameter affect only the configurations that include the carbon capture technology, whereas for the other solutions the cost remains unchanged. It is observed that a 50% decrease in the carbon capture capital cost has a much higher impact than a 60% decrease in the natural gas price. This is justified by the fact that for the configurations, which include a carbon capture technology the latter constitutes the greatest percentage of the life cycle cost, as it was presented in Figure 6.7. Therefore, the decision maker should focus on determining with accuracy the investment cost of the carbon capture, since the cost of the technology affects significantly the life cycle cost of the energy systems.

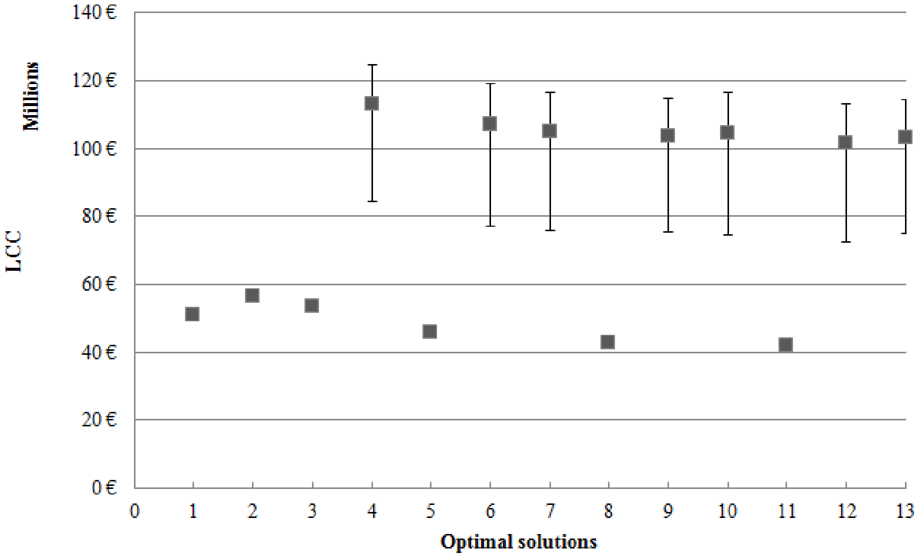

Figure 6.12 Carbon Capture capital cost variation: -50% to +20%

The life cycle cost of the optimal configurations along with the range of the cost according to the variations of the fuel cells capital cost are displayed in Figure 6.13. It is noted that the changes in this parameter affect only the configurations that include fuel cells technology. It is identified from the figure that the changes in the fuel cells capital cost prices do not have a great impact on the life cycle cost. The greatest variation on the total cost is a 13% decrease, when the fuel cells cost decreases by 50%. Therefore, the alterations on the fuel cells investment cost do not affect significantly the life cycle cost compared to the other investigated parameters.

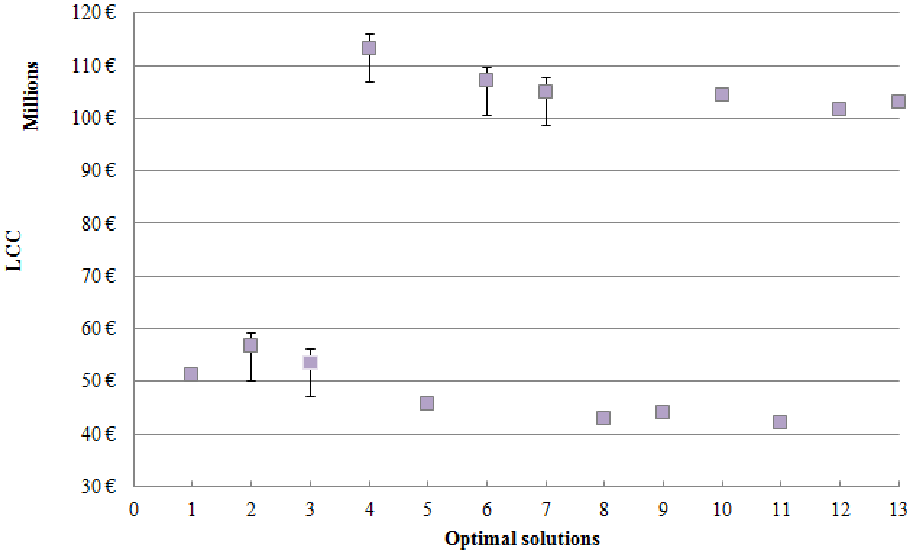

Figure 6.13 Fuel Cells capital cost variation: -50% to +20%

Compared to Figure 6.12, the 50% decrease in the carbon capture technology leads to a 26% decrease on the LCC, whereas the similar decrease of the fuel cells reduces the life cycle cost only by 13%. Therefore, for the decision maker regarding the emerging technologies, the capital cost of the carbon capture should have the greatest priority instead of the fuel cells investment cost.

6.8 Discussion of results

The aim of this section is to summarise and discuss the most significant outcomes derived from this case study application. A real operating profile was employed for the case study and the multi-objective optimisation was performed first for the original input parameters and then for uncertain parameters.

In total it can be inferred that the predominant ship energy systems configuration that manages to improve both the environmental and economic performance of tanker ship energy systems consists of natural gas operating sub-systems, compared to the current configuration, which uses HFO. This solutions was also identified as robust under an uncertain environment. It is identified that the prime mover selected from the optimiser is the dual fuel engine despite the higher capital cost, due to the engine's higher cost as well as the required feeding and storage systems. The LCC is still lower than the diesel engine due to the low price of natural gas, as well as, the lower consumption and higher efficiency of the dual fuel engines. These results also confirm the findings reported in previous studies (Baldi et al., 2013; Livanos et al., 2014) according to which, configurations with dual fuel engine outperform both on environmental and economic objectives the diesel engine configurations. However, in this analysis, the life cycle cost considers only the capital cost of the engines including the storage and feeding system, whereas the cost of the ship structural changes to accommodate the natural gas storage is not incorporated.

From the comparison of the life cycle cost of the selected solutions and the LCC of the current configuration, it was inferred that there is an increase in the capital cost of the more environmentally friendly solutions. This is due to the greener technologies, for example, the fuel cells and dual fuel engines included in the solutions, compared to the more cost-efficient traditional diesel engines. Nonetheless, gas operating technologies contribute to lower operating costs due to the low price of natural gas. Therefore, it is demonstrated that it is possible to achieve a lower environmental impact and at the same time lower life cycle cost than the current practice.

In this work, two different types of marine two stroke dual fuel engines were considered, one with direct gas injecting and one of pre-mixed combustion. There are trade-offs among the technologies that were demonstrated in the results of the case study. The low-pressure concept of the pre-mixed engine is advantageous regarding the cost-efficient gas supply technology without the need for large compression equipment. Therefore, the capital cost of this technology is lower. In addition, it manages to reduce the NOx emissions to Tier III level without the need of an after-treatment technology due to the usage of the lean combustion concept. Therefore, avoiding the after-treatment capital and operating cost including the consumables. However, the gas-injected engine has a lower gas consumption, thus lower fuel consumption and therefore lower SOx and CO_2 emissions. Therefore, a trade-off is identified between the pre-mixed and gas injected dual fuel engines.

The very attractive price of the natural gas promotes these solutions, however, the market is volatile and it is affected by various exogenous factors. Accordingly, from the uncertainty analysis, it was demonstrated that a small percentage of optimal solutions has as prime mover the diesel engine for the main propulsion operating with HFO. Regardless, the solution with a dual fuel natural gas engine remains the most promising. However, in the cases that the diesel engine is among the optimal solutions, it is more preferable to operate with HFO and switch to low sulphur fuel in order to comply with the SOx regulations, rather than employing a scrubber. Despite the fact that the scrubber is the after-treatment technology that is currently used for SOx emissions reduction. In previous case studies on deterministic optimisation of optimal emission reduction alternatives, the same results were identified; however, the results vary when the stochasticity of the input parameters is included (Balland et al., 2013). In addition, in other studies in the literature, the results were affected by the percentage of time the ship spends in ECA waters (Gu and Wallace, 2017) and by the operating profile (Lloyd’s Register, 2015).

The findings for the electric auxiliary sub-system indicate that the most promising technologies among the investigated ones to improve the environmental and economic impact of the ship energy systems are the fuel cells and the dual fuel generator sets. In limited cases, the diesel generators operating with LSHFO were identified among the optimal solutions. Natural gas operating technologies manage to provide low emissions and operating costs. However, the fuel cells have a very high economic impact and in the configurations that they were selected to provide electric energy, they contributed more than 20% of the life cycle cost of the configuration. On the other hand, the dual fuel generator sets manage to reduce the environmental impact of the energy systems without increasing the cost dramatically. The results are confirmed by previous studies, in which compared to the current technologies, fuel cells showed improved energy efficiency and considerable reduction on the environmental footprint (Welaya et al., 2011). In addition, in the literature, it was identified that four stroke dual fuel engines demonstrate low environmental impact (Stoumpos et al., 2018), which is aligned with the findings from the presented case study.

On the other hand, even though there was a high preference for the fuel cells and dual fuel generator sets, the results were not as robust as the other solutions denoting that they are highly affected by the changes of the fuel prices. Another interpretation of the results is that the contribution on the emissions and life cycle cost of the electric auxiliary machinery is not as high as the other systems and therefore, the model is not as sensitive to identify the optimal technology for the electric system.

From the results, it is indicated that the shaft generator and WHR are selected in the majority of the optimal solutions derived from the multi-objective optimisation. They offer a cost-effective and more environmentally friendly performance for the investigated system, according to the relevant literature (Baldi and Gabrielii, 2015). Similar conclusions were obtained from the uncertainty analysis; both technologies appeared robust, having the same high percentage on the solutions of the uncertainty analysis despite the changes on the capital cost.

Carbon Capture systems demonstrate a great potential and is a robust solution to improve the environmental performance of the ship energy systems; however, they exhibit a very high capital cost and a great impact on the overall life cycle cost. Even though the technology is investigated, a detailed analysis of the impact of the technology on the ship design and stability, due to the extra weight and space occupation is not included. The Carbon Capture technology was successfully implemented for onshore applications; however, there are challenges regarding the storage of CO_2, for ship applications. Nonetheless, there is still a great interest in the application of Carbon Capture on ships (DNV and PSE, 2013; Wang et al., 2017; Zhou and Wang, 2014). Carbon capture is a promising technology in order to mitigate the carbon emissions despite the high cost that constitutes a great percentage of the overall life cycle cost, as it was demonstrated herein.

The gas fired boiler is a dominant technology for the thermal power production, the low emission factors of the natural gas and the lean combustion of the gas boilers makes the technology promising for the mitigation of the emissions, along with the low, competitive price of natural gas. The boiler performance has an important impact on the life cycle cost and lifetime emissions of a tanker that has a high thermal power demand. In the existing literature, there is no evidence of studies that investigated the thermal boiler alternative technologies.

The results derived from the EEDI regulation investigation indicated that after 2024, there are some solutions derived from the optimisation that cannot comply with the reference value of EEDI Phase 3. In addition, the current technology will not be able to comply with the future EEDI phases. Therefore, the need for greener technologies was demonstrated. In addition, there is a misalignment with the estimations of the lifetime carbon emissions and the EEDI of the solutions of the optimisation. It was evident that the EEDI underestimates the effect of the optimal configurations proposed to reduce the CO_2 emissions. This is due to the fact that it is highly dependent on the nominal power of the engine installed (Plessas et al., 2018), as well as it is estimated according to a design speed, and not the real operation of the ship. However, the real mitigation of the emissions is highly dependent on the type of technologies and the ship operating profile. From the analysis, it is evident that the EEDI does not manage to capture the real carbon impact of the Aframax tanker ship energy systems and as a result, as a policy it cannot have a significant impact in improving the carbon footprint of the tanker ship energy systems.

The optimal configurations were also investigated for different operating profiles indicating that for a reasonable range of the profile variation the optimal configurations remain robust. However, the nominal power of the main engine and the electric auxiliary machinery are affected by the operating profile. Therefore, a realistic operating profile, sufficiently representing the investigated vessel lifetime is required in order to optimise the nominal power of the engines. Finally, the life cycle cost of the optimal solutions was presented according to variations of the most important cost parameters of the ship energy systems. It was evident that the changes in the fuel prices, as well as the carbon capture technology capital cost, have a very high impact on the overall life cycle cost of the configurations.

6.9 Chapter summary

In this chapter, the natural gas operating systems were identified as the optimal configuration regarding environmental and economic objectives for the Aframax tanker energy systems. This solution is preferred due to the low price of natural gas; however, from the uncertainty analysis a small percentage of optimal solutions had as prime mover the diesel operating with HFO. The traditional SOx emissions abatement technology for the diesel engine was not identified as optimal and the switch to low sulphur fuel was preferred. The carbon capture technology manages to reduce the carbon footprint of the tanker ship energy systems, nonetheless, it has a prohibitive cost in real life applications. It was also inferred that the current configuration will not comply with the next EEDI phase, therefore emphasising the need for the proposed method. Finally, the fuel price and the capital cost of the carbon capture technology are the most influential cost factors over the ship life cycle.

7 Cruise ship case study

7.1 Introduction to chapter

In this chapter, the applicability of the proposed method is demonstrated on a cruise ship. A bi-objective optimisation of the cruise ship energy systems is performed focusing on the life cycle cost and the CO_2 emissions. The term 'optimal' will be used in this chapter when introducing the near optimal configurations derived from the bi-objective optimisation of the cruise ship energy systems. This investigation is critical for cruise ships, due to the continuous growth of the sector, the significant contribution to the global carbon emissions, and the current target of IMO on the CO_2 emissions. First, the case study characteristics are described and the assumptions employed are discussed. Then, the results from the bi-objective optimisation are discussed in Section 7.4. Furthermore, the findings of the uncertainty analysis and the sensitivity analysis are presented. Finally, the results and remarks from the application of the method on the specific cruise ship are discussed.

7.2 Outlook of the technologies included

In this chapter, a cruise ship with a 140,000 GT is employed to showcase the developed method and identify the optimal cruise ship energy systems. For the investigated vessel, the alternatives for the sub-systems are displayed in Table 7.1 and the investigated technologies are highlighted. The selection of these technologies for the case study is driven from the related literature presented in Chapter 2.

A common configuration for the cruise ship power plant is the 'fully electric' type with four stroke engines driving generators in order to produce the required electric demand (Baldi et al., 2017). This configuration benefits the cruise ships in terms of safety, reliability, flexibility and comfort due to the low noise and vibration levels necessary on a vessel with passengers (MAN, 2014). Therefore, the investigated ship power plant in this case study is of the fully electric type and the most promising technologies are the four-stroke diesel and dual-fuel engines, as well as the fuel cells.

The rest of the alternatives were selected similarly with the previous case study, however, in the application presented in this chapter, methanol is additionally considered as a fuel option type. This is justified from the current trends in the industry regarding methanol fuelled cruise ships (Sahnen, 2018).

It is highlighted that not all the potential combinations among the technologies presented in Table 7.1 are feasible as it was discussed in Chapter 4.

Table 7.1 Technologies considered for the cruise ship energy systems

Engines							
diesel generator	*dual-fuel generator*	*gas generator*	*fuel cells*	*gas turbines*			
Thermal boiler							
oil fired boiler	*gas fired boiler*						
Fuels							
HFO	*MDO*	*MGO*	*LSHFO*	*natural gas/ LPG*	*methanol/ ethanol*	*hydrogen*	*biofuels*
Renewable energy sources							
solar panels	*wind turbines*						
SOx emissions abatement technologies							
scrubber							
NOx emissions abatement technologies							
SCR	*EGR*						
CO_2 emissions abatement technologies							
Carbon capture system							
Technologies to improve energy efficiency							
WHR	*shaft generator*						
Energy storage							
batteries	*thermal storage*						

7.3 Case study description

In this section, the ship characteristics and the case study application particulars are presented.

7.3.1 Ship Characteristics

The investigated ship characteristics are displayed in Table 7.2 and the typical power plant configuration and energy systems particulars are presented in Table 7.3.

Table 7.2 Cruise ship characteristics

Characteristics	Value
Size	140,000 GT
Length	300 m
Beam	40 m
Draft	10 m
Propulsor	Azipods and Bow thrusters

Table 7.3 Cruise ship energy systems particulars

Energy Systems Particulars	Value
Generator sets	6x four stroke diesel
Sets/Maximum continuous rating	6x12000 kW
Generator sets fuel	HFO/LSHFO
Thermal boiler	Oil fired (HFO)
Thermal boiler capacity	2 sets of 20,000 kg/h

The typical configuration for a fully electric cruise ship is depicted in Figure 7.1. In a fully electric configuration, the electric power is distributed to the electric system switchboards to cover the electric power requirements and provide power for the electric motors to drive the ship propellers. Thermal boilers along with the economiser provide the saturated steam for the ship heating services. In addition, emission reduction technologies are installed in order for the ship to comply with the emission regulations. For the NOx emissions, an SCR is employed, whereas for the SOx emissions the operators switch to a lower sulphur fuel.

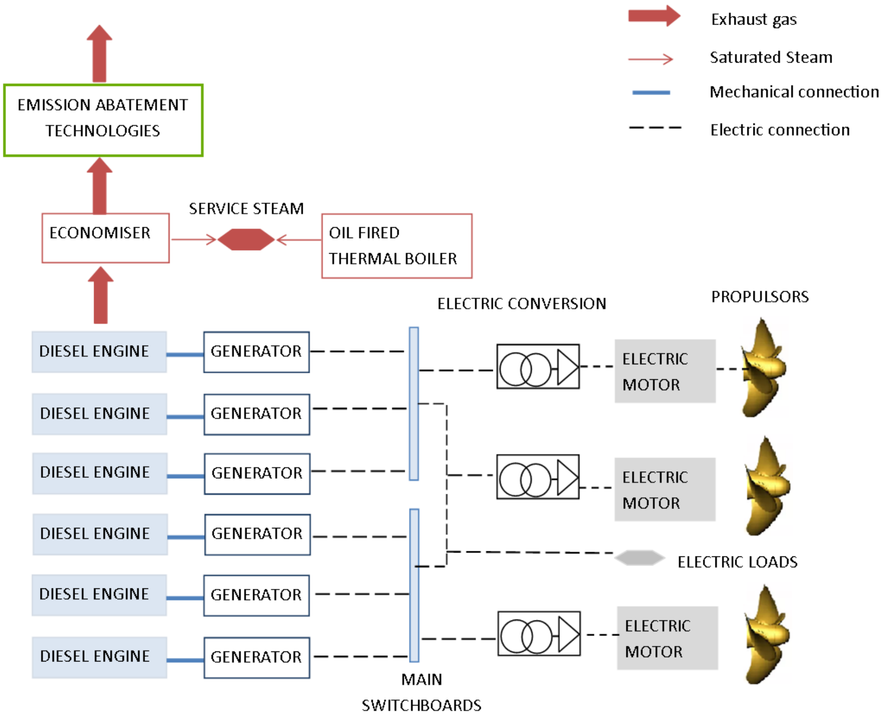

Figure 7.1 Typical configuration for a 140,000 GT cruise ship

7.3.2 Operating profile

As discussed in Chapter 4, expected operating profiles were used as inputs to the method in order to estimate the ship energy systems lifetime performance.

The operating profile that expresses the total electric power to satisfy the propulsion and electric demand for the hotel load and auxiliary machinery is presented in Figure 7.2. The profile was derived by analysing of actual operating data measurements collected shipboard a cruise ship for 5 years of operation.

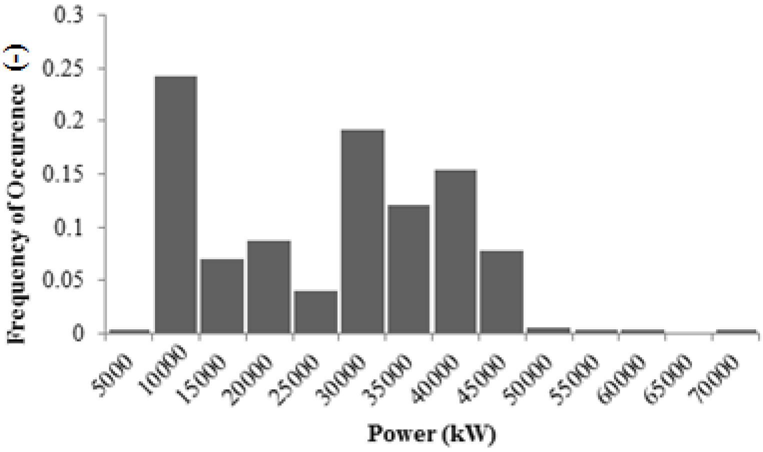

Figure 7.2 Typical operating profile of a 140,000 GT cruise ship[4]

A regression analysis was performed on the actual operating data, according to Equation 7.1 and the thermal requirements are expressed as a function of the instantaneous power of the engines. The operating profile for the thermal requirements of the cruise ship is displayed in Figure 7.3.

$$m_{ss}\left[\frac{kg}{h}\right] = 4527\, e^{2\,10^{-5} P_i(kW)} \tag{7.1}$$

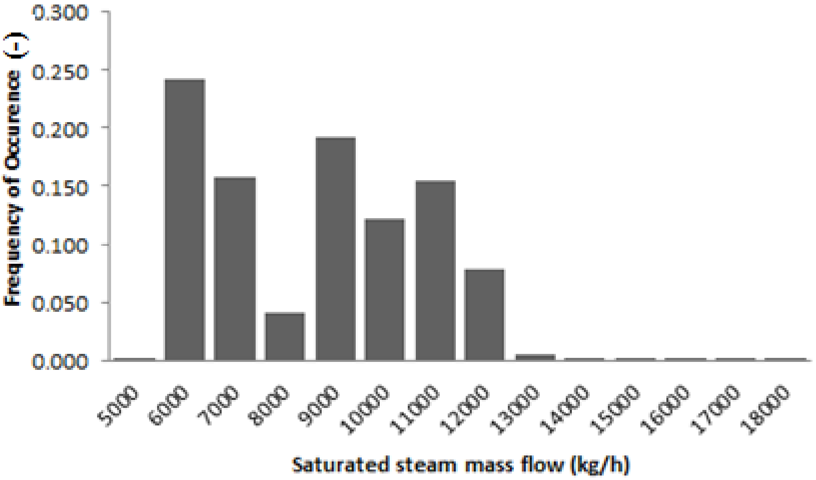

Figure 7.3 Typical saturated steam demand for a 140,000 GT cruise ship[4]

7.3.3 Case study assumptions

The following assumptions have been considered for the application of the case study:

---

[4] The data could not be provided for anonymity reasons.

- According to the cruise ships typical routes and the fact that cruise ships spend a great percentage of their life near ports (as discussed in Chapter 3), it is considered that the vessel sails the majority of her life inside ECA waters. Therefore, it is assumed that the ship needs to satisfy for 100% of her time the Tier III and sulphur limit regulations.
- The lifetime of the vessel is assumed 25 years, an average lifetime for ships.
- Maintenance of cruise ship life is assumed 7% (Turan et al., 2009).
- It is assumed that only two different types of engines can simultaneously be used in a configuration since multiple engine types have adverse effects in complexity and maintenance cost, especially due to the multiple spare parts requirements, and it is avoided in practice (Baldi et al., 2017).
- The engines may have different nominal power, whereas the number and nominal power of engines is selected to satisfy the minimum power requirements, according to the regulations. In specific, it is assumed that the total power installed needs to cover the power demand in the most demanding operating phase with one engine out of operation and the rest running at 90% load of their nominal power (Baldi et al., 2017).
    - The nominal power for the WHR is assumed 3000 kW_e, which can provide both electric energy and saturated steam for the thermal requirements. When the WHR is included in the configuration, the contribution of the turbogenerator power is considered for the selection of the engines nominal power and size.
    - The nominal power of the thermal boiler is derived according to the current configuration, as in this application, only the type of the technologies is investigated.

In the investigated cruise ship energy systems, the load allocation (sharing) between the system components in each discrete operating point of the considered operating profile takes place according to the following procedure:

- The energy systems components are considered to operate with the following sequence: first, the FCs will be used; in subsequence, the DF generator sets will be used until to operate at 90% of their nominal power and finally, the diesel sets will be used until to operate at 90% of their nominal power.
- For solutions that include components of different size, it is assumed that first the components of the smaller power will be operated (each one operating up to 90% of their nominal power) and then the components of the larger size (also each one operating up to 90% of their nominal power) until the total power demand is covered.
- For the cases where more than one engines of the same type need to operate for covering the ship power demand, even load sharing approach is assumed.

- It is assumed that the generator sets do not operate lower than 10% of the engines MCR, as operating in so low loads may cause various operational issues.

7.4 Bi-objective optimisation results for the cruise ship

In this section, first, the bi-objective optimisation results of the investigated cruise ship energy systems are presented and the optimal configurations are discussed. Then the cost breakdown of selected solutions is performed and the most significant cost factors for each configuration on the ship energy systems life cycle cost are identified. Finally, the EEDI value is estimated for the optimal solutions and compared with the lifetime carbon emissions.

7.4.1 Pareto front derived by the bi-objective optimisation

In Figure 7.4, the solutions of the bi-objective optimisation are presented, where each point of the curve describes one optimal configuration according to the set objectives. All the presented solutions comply with the IMO regulations for SOx, NOx emissions inside ECA waters and the EEDI regulations for energy efficiency. It is evident from the results that there is a variety of alternative configurations and a single optimal solution does not exist. A variety of cost-efficient configurations that can improve the carbon footprint are generated, thus giving to the decision maker the opportunity to manage the trade-offs among the investigated objectives.

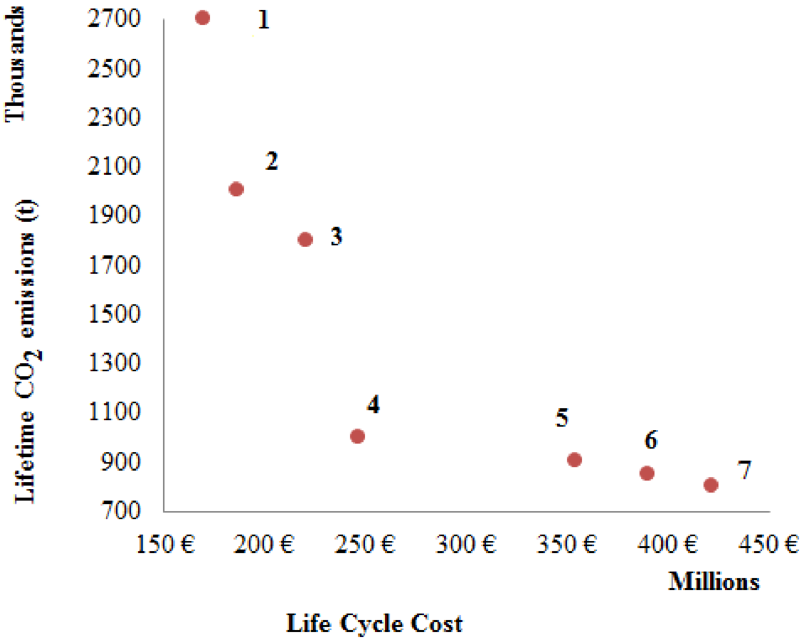

Figure 7.4 CO_2 & LCC optimal solutions

The configurations of the seven solutions of Figure 7.4 are displayed in detail in Table 7.4. In the last column of the table, the percentage difference of the performance of each configuration solution from the best case for each objective is presented. It is evident from the figure that the carbon emissions range between the best and worst performing solution is approximately 2000 thousands CO_2 emissions, thus a great range of improvement can be achieved. At the same time, the range of the LCC of the best performing to the worst performing configuration is almost 300 million €. There are numerous configurations between these ranges and the trade-offs of the two objectives are evident.

A variety of combinations of a set of engines with different nominal power is displayed in Table 7.4. In the majority of the solutions (1,2,3,4,5) the engines have similar nominal power as the current configuration. Therefore, the nominal power of the generator sets in the current design is identified among the optimal solutions. However, in almost all the cases (1,3,4,5) one set of engines has lower nominal power and the other higher. There is a number of solutions in Table 7.4 that have seven (1,2) sets of engines comparing to the traditional six sets of the current configuration, which appears only in one solution (solution 2). In the case that the configuration consists of six engines, higher nominal powers are selected for the generators. This is expected since there are fewer engines to satisfy the power requirements. On the other hand, when more than six engines are identified then there is a set of engines with higher nominal power and a set with lower. As a result, these configurations manage to operate efficiently both in higher and lower power requirements.

The best performing solution regarding the economic objective is a combination of diesel generators with dual fuel gas engines. The diesel generators operate with LSHFO and SCR as an after treatment technology in order to comply with the strict regulations inside ECA waters. In addition, a gas fired boiler is included as well as a WHR with a turbogenerator that employs the wasted energy from the exhaust gas of the engines to produce electric energy. It is evident from the table that the diesel generator sets constitute only the 30% of the total installed power, whereas the greatest part of the installed power capacity is provided by the dual fuel generator sets.

The next best performing solution regarding the LCC (solution 2) has similar configurations with the previous one; however, it consists only of dual fuel generator sets. Both configurations have a similar economic impact, whereas they have a significant difference in the CO_2 emissions, almost 28% increase is observed in the case that a diesel generator set is included.

Table 7.4 Configurations of Figure 7.4

	Main Engine	**Carbon**	**Energy**	**Thermal Boiler**		**Percentage Difference from the best solution**	
	Sets / MCR /Type/ Fuel	**Capture technology**	**Efficiency technology**	**Type**	**Fuel**	**LCC**	**CO_2 emissions**
1	3x7000 kW D (LSHFO) & 4x12000 kW DF (NG)	-	WHR	GFB	NG	0%	+235%
2	3x12000 kW DF (NG) & 3x11000 kW DF (NG)	-	WHR	GFB	NG	+1%	+139%
3	3x11000 kW DF (NG) & 4x9000 kW DF (NG)	✓	WHR	GFB	NG	+30%	+112%
4	42x500 kW FC (NG) & 4x12000 kW DF (NG)	✓	WHR	GFB	NG	+43%	+21%
5	66x500 kW FC (NG) & 3x12000 kW DF (NG)	✓	WHR	GFB	NG	+98%	+12%
6	96x500 kW FC (NG) & 3x7000 kW DF (NG)	✓	WHR	GFB	NG	+115%	+0.5%
7	138x500 kW FC (NG)	✓	WHR	GFB	NG	+142%	0%

As a result, the replacement of the diesel generator set with a dual fuel operating with natural gas indicates a cost increase of 2.1 €/t of CO_2 emissions. Therefore, in the case that carbon taxation is implemented the full gas operating energy system is a profitable solution, in comparison with the EU ETS for CO_2 emissions which average price was 5.93 €/t of CO_2 the last six months of 2018.

The next solution (3) has dual fuel generator sets as prime movers and a gas fired boiler for the thermal requirements. In addition, a WHR and a carbon capture technology are included. It is evident that the operation of the CC technology manages to reduce 11% the lifetime carbon emissions, however, a 27% increase on the LCC is observed. Therefore, the carbon capture technology operation comes at a cost of 180 €/t of CO_2 emissions reduced. As a result, the inclusion of the carbon capture is not an economically feasible solution unless a carbon taxation policy is enforced with a significantly higher carbon price.

The next group of solutions (4,5,6) has a similar configuration and consists of a combination of dual fuel generator sets with fuel cells. The rest of the energy systems are the gas fired boiler, the WHR and carbon capture. It is estimated that the improvement on the carbon footprint by replacing some dual fuel generator sets with fuel cells is 43%, whereas the increase on the LCC is 20%. As a result, it is estimated that the technology comes at a cost of 35 €/t of CO_2 emissions, which is still higher compared to the last six months average price of the EU ETS for CO_2 emissions.

In this group of solutions with the same configuration and different number and nominal power of a set of engines, it is observed that while the installed power of fuel cells increases at the same time the LCC is increased, whereas the carbon emissions are decreased. The fuel cells have the highest capital cost, therefore, when higher nominal power of fuel cells is installed then the LCC increases. On the other hand, they have a lower carbon footprint and as a result, the CO_2 emissions are reduced.

The solution (7) with the best performance regarding the CO_2 emissions consists of fuel cells with a gas thermal boiler, WHR and carbon capture technology. This configuration has the highest life cycle cost due to the high capital cost of the fuel cells and carbon capture technology. Compared to solution 6 that combines dual fuel generator sets with fuel cells, solution 7 that consists only of fuel cells manages to reduce the CO_2 emissions around 6%. At the same time, the cost is increased by approximately 15%, therefore a 1000 €/t of CO_2 emissions is estimated. As a result, the current high capital cost of the fuel cells and the low environmental improvement makes this solution economically prohibitive.

Some final observations are that the WHR technology with turbo-generator is selected in all the optimal solutions, offering both lifetime economic and environmental benefits; despite the increase in the capital cost. The gas fired boiler dominates the optimal solutions, due to the fact that the natural gas has lower carbon content and a lower price in comparison with the HFO. Finally, methanol is not selected as an alternative fuel in any of the solutions even though, it has a very low carbon content. This is due to the fact that methanol has a lower heating value that is almost half of the natural gas and higher price, as a result, the fuel amount required is double and therefore, the fuel cost and the overall carbon emissions are increased compared to the natural gas.

In Table 7.5, the percentage of the technologies on solutions of the Pareto front is estimated. It is identified that the dual fuel generator sets are more dominant on the results of the optimisation, whereas there is a small percentage of solutions that consists of diesel generator sets. In addition, it is inferred from the results that it is optimal regarding both the carbon footprint and the economic objective to operate with the LSHFO comparing to the scrubber for the diesel generators, according to the prices considered for the fuels in this application. The fuel cells constitute approximately 34% of the technologies for propulsion on the cruise ship, despite the high economic cost. On the other hand, there are no solutions that consist of engines that operate with methanol fuel. In addition, the WHR system is included in all of the optimal configurations demonstrating the beneficial impact of the WHR for the fuel efficiency and consequently the carbon emissions mitigation. The carbon capture is selected in a great percentage of the solutions of the Pareto front, even though it has a high economic impact. Finally, the gas fired boiler is the dominant solution for the thermal power requirements.

Table 7.5 Percentage of the technologies on the total solutions

Dual fuel engines (NG)	60%
Diesel engines	6%
Fuel Cells	34%
Dual fuel engines (methanol)	0%
SOx reduction for diesel	fuel LSHFO 100% scrubber 0%
Carbon Capture	75%
WHR	100%
Thermal boiler	HFO 0% LSHFO 0% NG 100%

In Figure 7.5, the distribution of the nominal power of the diesel and dual fuel generator sets of the optimal solutions presented in Figure 7.4 is displayed. The fuel cells are not included in the distribution since they consists of small modules of 500 kW.

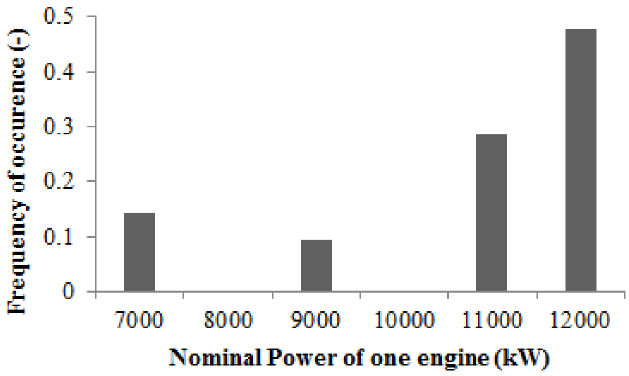

Figure 7.5 Nominal power distribution

It is observed from the figure that there is a higher occurrence for 12 MW nominal power and the second best is 11 MW, whereas the frequency of the other nominal power values is very low. The typical nominal power for the generator sets of a cruise ship of the investigated size is 12 MW, thus the optimisation identifies that this size of generator sets are among the most cost and carbon efficient solutions. Therefore, the results agree with the current practise, even though combinations of other nominal sizes are introduced that can sufficiently improve the LCC and the emissions as it was presented in Table 7.4.

7.4.2 Cost Breakdown of selected solutions on the Pareto front

In this section, the life cycle cost of selected solutions is further analysed and broken down into capital and operating costs of each sub-system. The display of the capital cost separately from the operational is meaningfully especially since the ship-owners place emphasis on the capital cost. In that respect, a better understanding of the life cycle cost of the solutions on the Pareto front is attained. The analysis is presented for both the absolute values in Figure 7.6 and the percentages in Figure 7.7.

In Figure 7.6, the best performing configurations for the two objectives and the current configuration provided in Table 7.3 as well as one configuration that belongs at the Pareto front and has the closest LCC with the current configuration are analysed. The configurations of the optimal solutions presented in Figure 7.4 correspond to the respective numbers in Figure 7.6.

From Figure 7.6 it is identified that the current configuration has the lowest capital cost of the number of engines installed, whereas solution 7 has by far the highest. This is justified by the fact that the former configuration consists of diesel generator sets that have the lowest cost factors, whereas the latter from fuel cells which have the highest. The other alternatives consist either of a combination of dual fuel and diesel generator sets or just dual fuel, therefore they have a moderate value for the capital cost of the number of engines installed.

On the other hand, the capital cost of the other sub-systems varies among the solutions. Solutions 4 and 7 include a carbon capture technology and as a result exhibit a significant increase in the capital cost. The capital cost of other systems includes the thermal boiler, which has the same capital cost in all the cases, since in all the alternatives a boiler is installed with the same nominal power. Furthermore, the maintenance and consumables cost in solution 7 is exceptionally high, almost three times greater than the other alternatives due to the fuel cells stacks replacement cost during the ship lifetime.

Another observation from Figure 7.6 is that the fuel cost of solution 7 is the lowest, due to the lowest fuel consumption of the fuel cells and the low price of the natural gas. On the other hand, the current configuration has the highest fuel cost due to the diesel generator sets higher fuel consumption and the LSHFO higher price. The thermal boiler fuel cost is very low comparing to the engines, especially since the thermal demand is partially covered by the thermal energy of the engines exhaust gas. It is therefore inferred that the greatest energy consumer and emissions producer are the engines installed to cover the propulsion and electric demand. Finally, the boiler fuel cost is similar in all the alternatives.

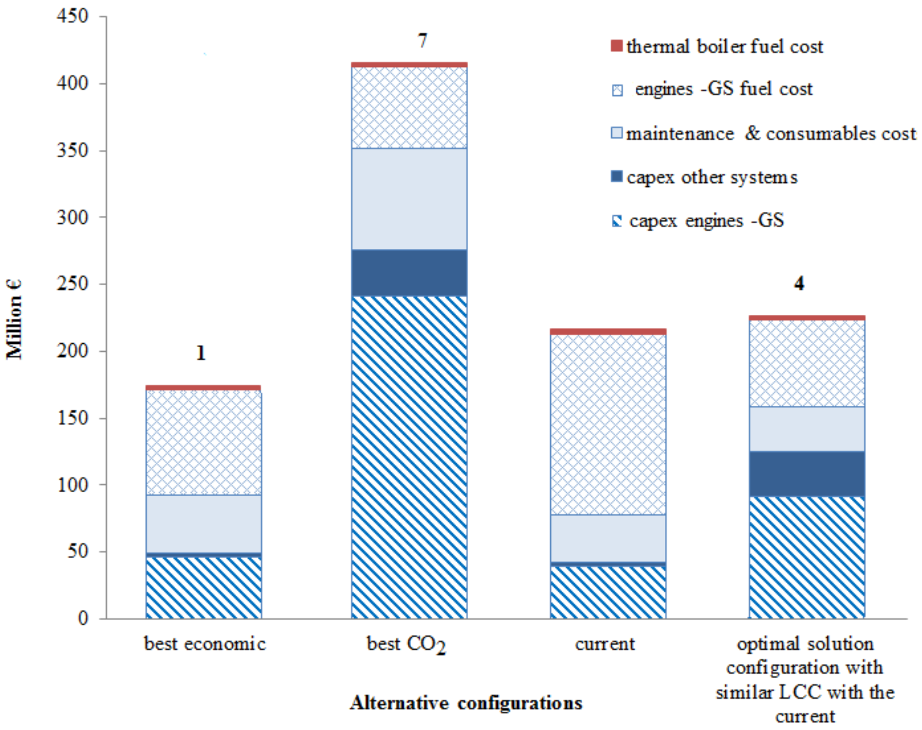

Figure 7.6 Breakdown of Pareto front solutions (absolute value)

Moreover, comparing the current configuration with the solution with the best LCC and a solution from the optimisation with similar cost, it is evident that it is possible to have configurations with lower life cycle cost than the current, almost 25% for solution 1 and similar life cycle cost for solution 4, while improving the carbon footprint of the energy systems by 16% and 65% respectively. It is observed that the current configuration exhibits the lowest capital cost of the ship energy systems, whereas the other alternatives have a better performance regarding the operating lifetime expenses. The increase in the capital cost of the more environmentally friendly alternatives is attributed to the use of carbon capture technology and dual fuel engines, compared to the more cost efficient diesel engines. On the other hand, the gas operating technologies have lower fuel operating cost due to the low price of natural gas.

From Figure 7.7, it can be further inferred that the greatest percentage of the LCC comes from the fuel cost, except for the best CO_2 configuration (solution 7) and solution 4. In the latter solutions, the capital cost is very high due to the high cost of the fuel cells and corresponds for more than 40% of the life cycle cost. In all of the cases, it is evident that the boiler fuel cost has a very low contribution to the overall LCC. It is highlighted from the results of Figure 7.7 that the capital cost of the other sub-systems is a significant contribution on the total cost 8% and 13%, respectively for the best CO_2 emissions performing solution as well as the configuration with similar LCC as the current. This is because these configurations include a carbon capture technology.

Finally, comparing the optimal solution with similar LCC as the current with the current configuration it is identified that the fuel cost of the diesel generator sets of the latter alternative consists of almost 70% of the total cost, compared with the former alternative that is 32%. On the other hand, the capital cost of the other sub-systems is only 1% for the current, whereas for the other configuration it is 13%. This great increase is owing to the capital cost of the carbon capture technology. Therefore, it is inferred that by replacing the traditional diesel generator sets with dual fuel that have lower operating expenditures offers the same life cycle cost, while improving the lifetime carbon emissions.

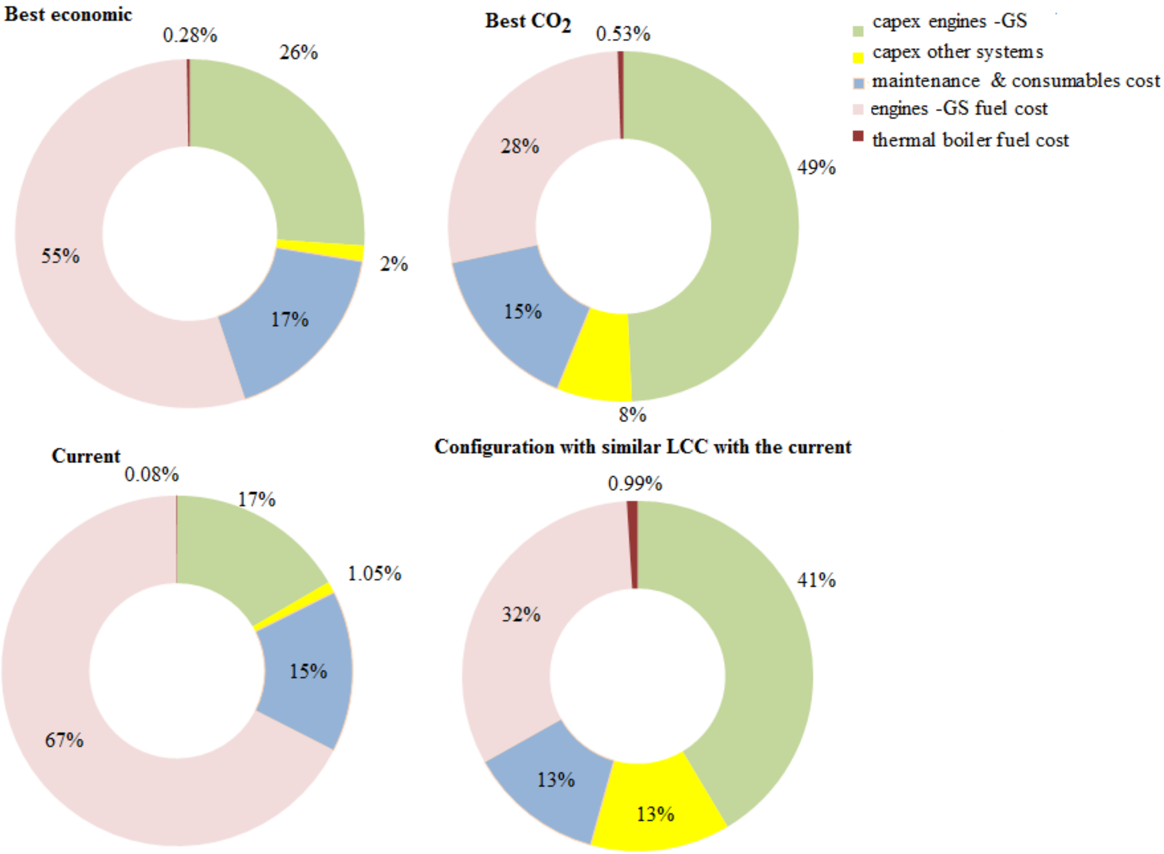

Figure 7.7 Breakdown of Pareto front solutions (percentages)

7.4.3 Comparison of solutions EEDI and lifetime CO_2 emissions

In this section, the EEDI value is estimated for the optimal solution derived from the bi-objective optimisation, in order to investigate whether the proposed configurations comply with the EEDI. In addition, the results of the EEDI for each optimal configuration are compared with the lifetime CO_2 emissions.

The EEDI reference values are estimated according to the Appendix C. The reference value for Phase 1 until 2019, for Phase 2 until 2024 and for Phase 3 from 2025 and onwards are estimated according to the regulations (IMO, 2016b) and presented in Table 7.6.

Table 7.6 Reference values for EEDI regulation for a 140,000GT cruise ship

Phase	**Reference value (gr CO^2/t NM)**
1	12.85
2	10.82
3	9.47

The EEDI is estimated for each optimal configuration according to Appendix C for non-conventional propulsion systems; in addition, the carbon capture is included in the calculation of the EEDI since it is directly related with the CO_2 emissions. The EEDI indicators along with the lifetime carbon emissions of the Pareto front solutions are displayed in Table 7.7. The solutions are ranked according to the EEDI values in ascending order.

Table 7.7 EEDI value of the optimal solutions

Configuration	EEDI (gr CO^2/t NM)	Lifetime CO_2 emissions (1000t)	Percentage difference from baseline EEDI	Percentage difference from baseline CO_2 emissions
7	6.46	828	-45%	-75%
6	7.12	832	-40%	-74%
5	7.45	930	-37%	-72%
4	7.80	1003	-34%	-69%
3	8.45	1374	-28%	-58%
2	8.80	1976	-25%	-40%
1	9.13	2031	-23%	-38%
Current configuration	11.8	3284.1	(-)	(-)

The percentage difference of the EEDI and lifetime emissions corresponding with the EEDI values and the lifetime carbon emissions of the current configuration is displayed in the last two columns of the table. The EEDI and the lifetime carbon emissions for the current configuration are also presented. The results indicate that the current configuration complies only with Phase 1 and in order to attain Phases 2 and 3, a different solution is required.

Table 7.7 shows that all the proposed solutions from the optimisation comply with the three phases of the EEDI. As a result, they are considered green alternatives according to the imposed EEDI regulations until 2024. The estimated EEDI and lifetime carbon emissions values propose the same order for the configurations. Therefore, both indicators agree with the potential of the configurations to improve the carbon footprint of the ship energy systems.

However, differences are observed for the solutions values of the percentage difference from the current configuration of the EEDI and the lifetime carbon emissions. The percentage improvement of solution 7 from the current configuration according to the EEDI is 45%, whereas for the lifetime emissions is 75%, almost two times higher. Generally, the EEDI range of improvement from the current configuration is very narrow, comparing to the lifetime carbon emissions range. The range from solution 1 to 7 is only 22% according to EEDI, whereas for the lifetime emissions it is 37%, which corresponds to a 70% difference between the two values. Therefore, even though the lifetime emissions are reduced significantly the EEDI indicates a much lower improvement and as a result, does not manage to accurately capture the benefits of the configurations.

The EEDI is highly affected by the installed power and it is estimated based on the design speed, comparing to the lifetime carbon emissions that consider an operating profile. The carbon emissions depend on the type of fuel and the operation of the engines; however, the EEDI does not include the real operation of the ship energy systems. Therefore, a misalignment is identified between the two values, which corresponds to the inability of the EEDI to accurately capture the real carbon emissions that are emitted from the configurations during the ship energy systems lifetime operation.

7.5 Results from the uncertainty analysis on the cruise ship

An uncertainty analysis is performed in this section in order to investigate the influence of the input parameters on the robustness of the solutions. The uncertainty analysis was performed according to Monte Carlo simulation and the probability density functions used for the input parameters were presented in Chapter 4. The results from the uncertainty analysis are presented and discussed in the following sub-sections.

First, the uncertainty analysis solutions robustness is investigated and the solutions that are mostly identified on the uncertainty analysis Pareto fronts are presented (7.5.1). In addition, the configurations that appear more frequently as best performing on each objective are discussed (7.5.2). Then the robustness of the original case is explored and the frequency of appearance of the original case best performing configurations on the uncertainty analysis Pareto fronts is displayed, in order to investigate the robustness of the configurations (7.5.3). Finally, the number the optimal configurations of the original case appear on the uncertainty analysis Pareto fronts is demonstrated (7.5.3).

7.5.1 Solutions identified on the cruise ship uncertainty analysis Pareto fronts

In this section, it is investigated whether the solutions that appear on the Pareto front of the original case are robust with the alterations of the input parameters and the percentage the solutions appear on the total Pareto fronts of the uncertainty analysis is discussed. The results are presented in Table 7.8 and are compared with the results from the original case from Table 7.5, in order to facilitate the discussion.

From Table 7.8, it is inferred that dual fuel generator sets operating with natural gas constitute the greatest percentage of engines of the cruise ship energy system. Similar results with a small decrease of 6% on the total dual fuel engines were observed on the original case findings, therefore it is evident that the natural gas operating dual fuel engines are robust solutions and the high preference of this alternative is not affected by changes on the fuel prices or technologies capital costs.

Regarding the diesel generator sets, it is evident that in both cases the technology corresponds to a small percentage on the solutions, independently from the input parameters alterations. However, it is important to highlight that the SOx emissions abatement alternative is affected by the variations on the fuel prices. It is evident that in the original case the diesel generator sets were operating with LSHFO in order to comply with the sulphur content regulations, whereas from the solutions of the uncertainty analysis it is identified that 25% of the solutions operate with HFO and employ a scrubber to satisfy the SOx regulations. This denotes that the sulphur reduction technology for the diesel engines is affected by the relative difference between the prices of the HFO and LSHFO and a further investigation is required to identify which alternative is the optimal.

Table 7.8 Solutions identified on the Pareto fronts from the uncertainty analysis and original case

	Results from the uncertainty analysis	**Original case (Table 7.5)**
Dual fuel engines (NG)	66%	60%
Diesel engines	4%	6%
Fuel Cells	29%	34%
Dual fuel engines (methanol)	1%	0%
SOx reduction for diesel	fuel switch LSHFO 75% scrubber 25%	fuel LSHFO 100% scrubber 0%
Carbon Capture	78%	75%
WHR	90%	100%
Thermal boiler	HFO 8% LSHFO 32% NG 60%	HFO 0% LSHFO 0% NG 100%

From Table 7.8 results, it is evident that the fuel cells constitute a high percentage of the optimal solutions for the cruise ships. A percentage of 29% and 34% of fuel cells among the optimal solutions is identified for both the uncertainty analysis and original case results, respectively. Therefore, despite the high cost of the fuel cells, it is inferred that the solution is robust. Another observation that derives from the solutions of the uncertainty analysis is that a very small percentage of generator sets that operate with methanol is identified. Compared to the original case where there were no solutions with methanol, it is inferred that the lower prices of methanol benefit this alternative. However, the percentage is still very low to consider methanol as a prominent solution compared to the other alternatives.

Carbon capture technology is a very robust solution as it is identified in both the results of the uncertainty analysis and the nominal case in a high percentage of 75% to 78%. Therefore, despite the high cost, it remains a promising solution in improving the carbon footprint of the configurations independent of potential increase on the capital cost of the technology. Furthermore, the WHR is selected in almost 90% of the solutions on the Pareto front of the uncertainty analysis and 100% on the original case. As a result, the solution is quite robust and the high percentage estimated in both cases indicates that it is a solution that considerably improves the energy efficiency of the cruise ship configurations.

Finally, regarding the thermal boiler, it is evident from the results of Table 7.8 that the dominant technology is the gas fired boiler with a percentage of 60% and 100% for the uncertainty analysis Pareto fronts and the original case, respectively. However, it is observed from the results that variations on the fuel prices identify other fuels like the LSHFO and the HFO as optimal for the thermal boiler. This denotes that the solution is not as robust. In addition, as it was identified from Figure 7.7 the contribution of the boiler in the overall fuel amount and as a result on the carbon emissions is very low, therefore the optimisation is not so sensitive for the selection of the specific sub-system.

The solutions derived from the uncertainty analysis are clustered into 47 groups without considering the number and sizes of the generator sets. As a result, 47 different combinations of the configurations are identified on the Pareto fronts from the uncertainty analysis. However, it was estimated that not all solutions appear as frequently. The ship energy system configurations that are the most frequent on the Pareto front correspond to the 91.5% of the total solutions identified from the uncertainty analysis. Overall, 12 different configurations are the most frequent and are graphically presented in Figure 7.8. The thickness of the lines indicates the percentage that each technology appears on the uncertainty analysis results.

The figure helps to attain a better understanding of the optimal configurations identified on the Pareto fronts of the uncertainty analysis. It is evident that the greatest percentage of the solutions consists of a combination of dual fuel generators, whereas only 1.5% of alternatives has as engines only fuel cells. The rest of the solutions includes a combination of fuel cells and dual fuel generators. Similar results were identified from Figure 7.4, therefore the solutions for the cruise ship engines appear robust.

In addition, it is evident that the number of alternatives increases significantly due to the different fuel types of the boiler. Therefore, there are some configurations that appear only in 1% of the frequent solutions. Similar findings were identified in the preceding discussion demonstrating the high influence of the fuel prices on the thermal boiler fuel type.

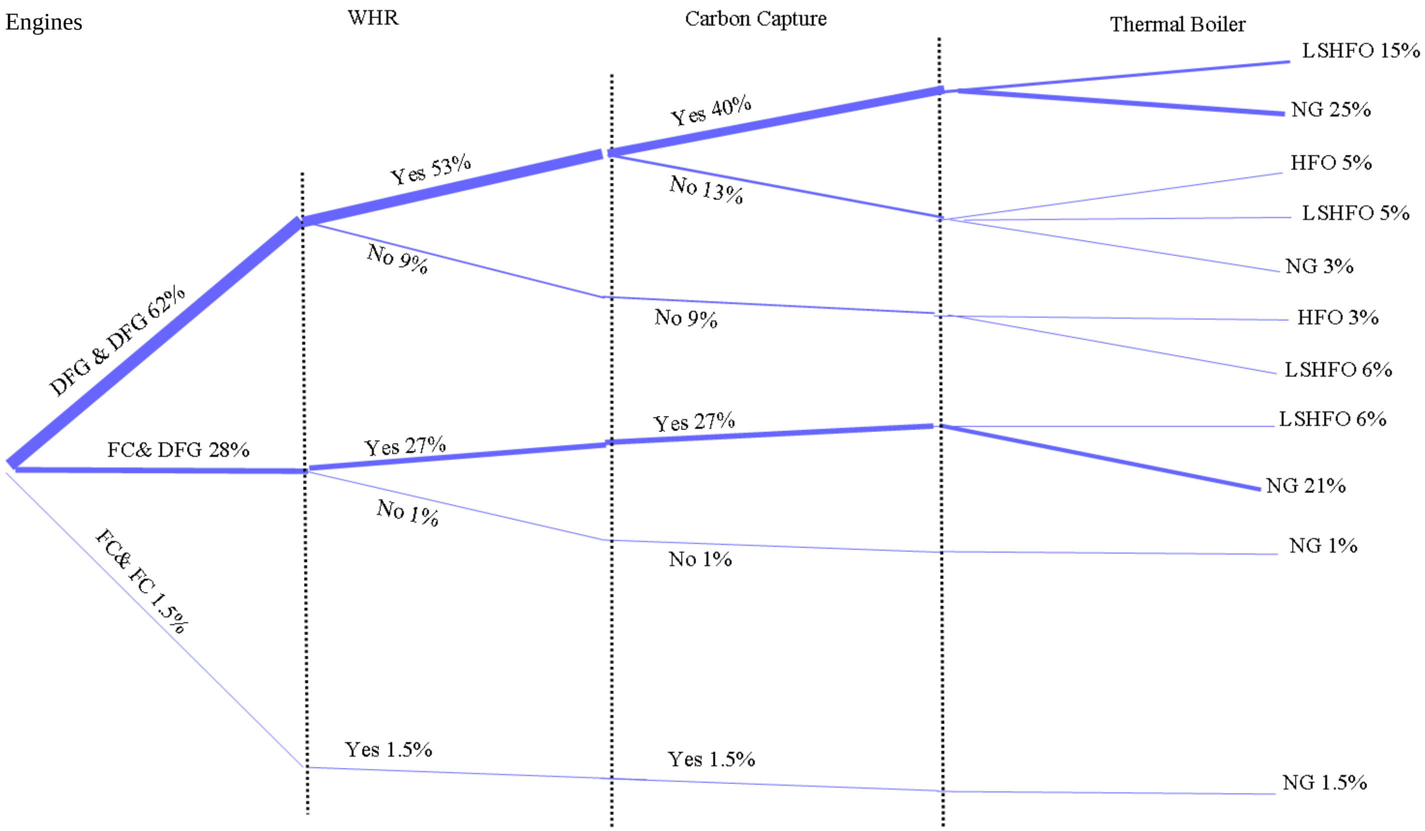

Figure 7.8 Graphic representation of uncertainty analysis solutions (91.5 % of the solutions)

From the analysis, it was identified which solutions are robust and which are affected by changes in the input parameters. Furthermore, in the optimisation, the nominal power and number of the generators sets were investigated. Therefore, the distribution of the nominal power of each generator set (dual fuel and diesel) as it was derived from the Pareto fronts of the uncertainty analysis is presented in Figure 7.9.

The nominal power distribution of the solutions generator sets derived from the uncertainty analysis is depicted along with the results from the original case that were presented in Figure 7.5. From this figure, it is identified that in both cases of the uncertainty analysis and the original case the most frequent nominal power for the generators is 12 MW per unit. This is the nominal power installed on the generators of the current configuration, thus it appears that for the specific ship and operating profile the generators sets with 12 MW nominal power, efficiently cover the power requirements.

Finally, it is identified from the figure that the distribution of the nominal power of the original case and the uncertainty analysis is quite similar. Therefore, the nominal power of the generators suggested is robust.

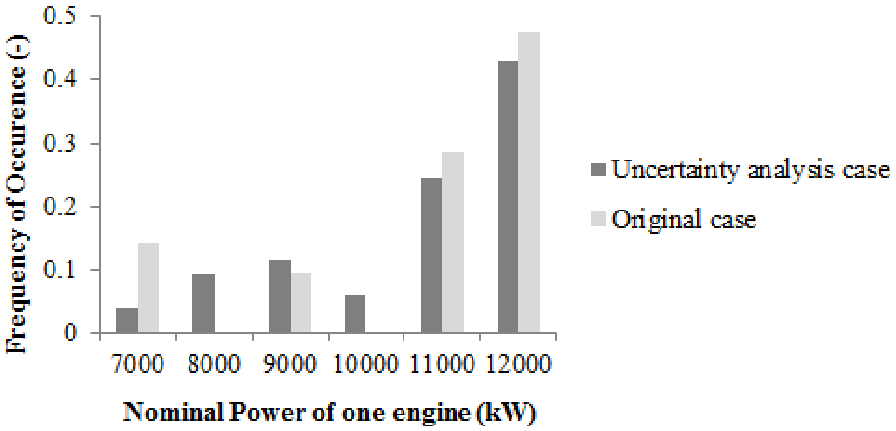

Figure 7.9 Nominal power distribution of uncertainty analysis solutions

7.5.2 Optimal configurations for each objective robustness

In this section, the configurations that appear more frequently as optimal for the two objectives from the results of the uncertainty analysis are displayed. This analysis is performed in order to investigate the robustness of the configurations specifically on the best solutions for each objective. The results are depicted for the LCC and lifetime CO_2 emissions objectives in Table 7.9 and Table 7.10, respectively. In order to facilitate the results discussion, a second column is added with the best performing solutions for the two objectives as they were identified from the original case in Table 7.4.

The technologies for the best performing solutions regarding the economic objective are presented in Table 7.9. It is evident from the results that the most promising technology for the engines is the dual fuel generator sets in a percentage of 94% with few alternatives that combine dual fuel generator sets with diesel. On the other hand, there are no solutions with fuel cells or engines operating with methanol. The results agree with the findings from the original case indicating that the solution for the engines for the economic objective is robust.

In addition, it is observed that there are no solutions with CC technology similar to the original case, which is expected since it has a very high capital cost. On the other hand, as it was identified from the original case, almost all of the solutions include a WHR; therefore, it is evident that it is a robust solution and manages to efficiently improve the economic and carbon footprint of the cruise ship energy systems.

Table 7.9 Solutions that perform best on the LCC objective

	Results from the uncertainty analysis	Best performing solution of the original case
Dual fuel (NG)	94%	-
Dual fuel (NG) & Diesel	6%	✓
SOx reduction for diesel	fuel switch LSHFO 100%	✓
	scrubber 0%	-
Carbon Capture	0%	-
WHR	99%	✓
Thermal boiler	HFO 10%	-
	LSHFO 25%	-
	NG 65%	✓

Regarding the thermal boiler, the findings of the uncertainty analysis indicate that the gas fired boiler is a promising alternative for the best performing solutions of the economic objective. However, changes on the fuel prices affect this sub-system and other fuel types indicating most dominant the oil fired boiler with LSHFO as optimal in 25% of the cases. Therefore, the boiler fuel type is influenced by fuel price changes.

The technologies that appear on the optimal solutions regarding the carbon emissions objective are presented in Table 7.10. The most dominant solution with an 80% of appearance for the engines are the fuel cells, which is aligned with the original case results. However, the changes on the input parameters indicate that in some cases the optimal solution consists of a combination of fuel cells with dual fuel engines operating with natural gas and in a small percentage with methanol.

Table 7.10 Solutions that perform best on the CO_2 emissions objective

	Results from the uncertainty analysis	Best performing solution of the original case
Dual fuel (NG) & Fuel cells	19%	-
Fuel Cells	80%	✓
Dual fuel engines (methanol) & Fuel cells	1%	-
Carbon Capture	100%	✓
WHR	98%	✓
Thermal boiler	HFO 0%	-
	LSHFO 1%	-
	NG 99%	✓

The carbon capture technology is identified in all of the configurations that perform best on the carbon emissions objective. This agrees with the original case results and it is justified since this technology has a beneficial impact in reducing the CO_2 emissions. Similarly, WHR is a robust alternative that improves the energy efficiency of the cruise ship systems.

Finally, regarding the thermal boiler, it is inferred from the results that the gas fired boiler is the dominant solution for the carbon emissions objective.

7.5.3 Appearance of the original case best performing configurations on the uncertainty analysis solutions

The frequency of appearance of the best performing optimal configurations of the original case for each objective on the uncertainty analysis Pareto fronts are presented. This section contributes to identifying the robustness of the identified configurations on the original case.

In Table 7.11, the findings from the analysis are presented. The optimal configurations of the original case were displayed in Table 7.4. It is evident from the results that the configurations identified from the original case appear in a great percentage of the Pareto fronts as optimal solutions. However, it is evident that the configuration for the carbon emission objective has a higher appearance and it is the most robust. Regarding the configuration for the LCC objective, it is inferred considering also the findings in Table 7.9 that the configuration with the highest appearance on the Pareto fronts consists completely from dual fuel generators and not a combination of dual fuel and diesel.

Table 7.11 Appearance of original case optimal configurations on the uncertainty analysis results

Objective	Percentage of the best performing solutions
LCC	28%
CO_2	55%

7.5.4 Appearance of original base case configurations on the uncertainty analysis solutions

In the final section of the uncertainty analysis results, the total number of Pareto fronts of the uncertainty analysis each optimal solution from the original case appears on are presented in Table 7.12. It is possible due to the different nominal powers and sets of engines that one configuration might appear multiple times on one Pareto front. Therefore, this analysis complements the robustness of the original case configuration by considering only once the appearance of the configuration on the Pareto front.

The uncertainty analysis was repeated for 1000 times and the number of Pareto fronts each solution appeared is presented. From the results, it is inferred that some solutions are more dominant and robust than others and therefore appear in more Pareto front of the uncertainty analysis. The configurations with the highest appearance are the solution with the combination of fuel cells with dual fuel generators with the carbon capture, WHR and natural gas boiler (solutions 4-6) as well as the alternative with the dual fuel generators, the carbon capture, WHR and natural gas boiler (solution 3). Both solutions appear in more than 25% of the Pareto fronts, therefore these configurations appear robust against the changes of the input parameters.

On the other hand, the other solutions appear in more than 10% of the Pareto fronts, however, are not as robust as solutions 3 to 6. This is due to the thermal boiler, as it was demonstrated from Figure 7.8 with the graphic representation of the configurations. There is a great percentage of configurations similar to the original case with the only difference the fuel type of the thermal boiler.

Table 7.12 Number of Pareto fronts the base case optimal solutions appear

Group	Number of Pareto fronts they appear (of total 1000 Pareto fronts)
1	98
2	90
3	270
4-6	290
7	150

7.6 Investigation of the optimal cruise ship energy systems under different carbon policy scenarios

In this section the optimal cruise ship energy systems configuration are investigated for potential carbon pricing policy scenarios, this work was presented on J2 article (Trivyza et al., 2019). Recently, it has been discussed to introduce shipping operations into the European Emission Trading Market Scheme for CO_2 emissions (Koesler et al., 2015; Shi, 2016) as well as to tax the carbon emissions, according to the land-based power plants. Potential carbon policies would have significant cost implications on the marine industry, leading to necessary changes on the ship design and operations. Improvements towards technologies and fuels with reduced carbon emissions would be an essential step in order for the shipping companies to reduce the impending costs. Therefore, this investigation is critical for cruise ships, due to the significant cost implication of the high level of CO_2 emissions under potential carbon pricing policies.

Four scenarios are considered, the non-taxation scenario (NT) which is the original case presented in Section 7.4 and three carbon pricing policy scenarios (CP, NP, SD) derived from the World Energy Outlook study (International Energy Agency, 2017). The optimal cruise ship configurations are investigated for the three carbon policy scenarios in order to assess their potential impact on the optimal ship energy systems configuration.

The adopted scenarios are displayed in Figure 7.10. The three scenarios CP, NP and SD are derived from interpolation of the values forecasted for the region of European Union on the years 2025 and 2040 for the power, industry and aviation sector and it is assumed that the marine industry will follow. On the year 2018, the carbon policy price is set zero since in the shipping industry no carbon policy has yet been implemented. The scenarios are as follows:

1. No tax (NT) scenario: assuming that carbon pricing is not going to be implemented and therefore there is no cost for CO_2 emissions, which is the current situation in the marine industry.
2. Current policies (CP) scenario: considering only the momentum of the policies that have been implemented in the energy sector by the mid of the year 2017.
3. New policies (NP) scenario: includes the existing policies as well as incorporates the ambitions of the policymakers in the energy sector.
4. Sustainable development (SD) scenario: entails policy scenarios required in order to comply with the 2030 agenda of the United Nations for Sustainable Development, representing the vision of the energy sector.

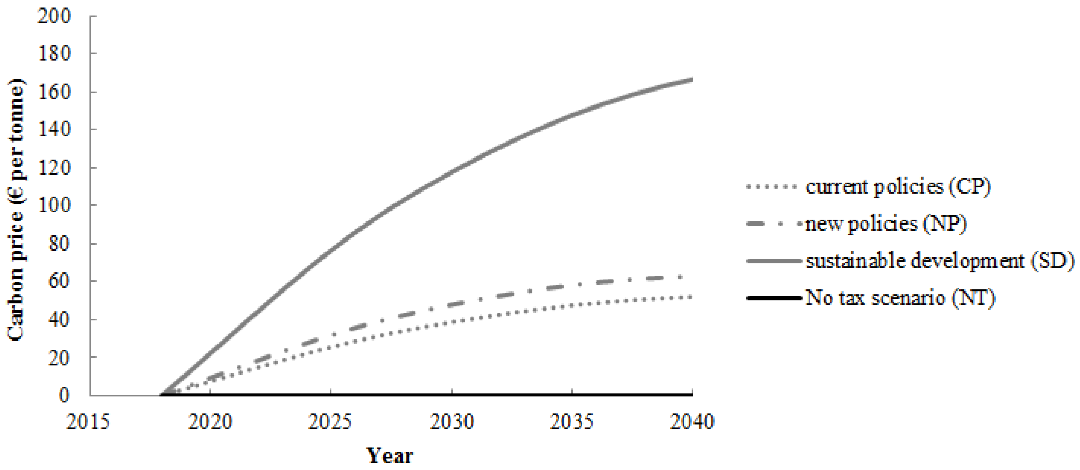

Figure 7.10 Carbon pricing policy scenarios adapted from International Energy Agency (2017)

The performance of the Pareto front solutions along with the current configuration (marked as a red x) are presented for all the scenarios in Figure 7.11. It is interesting to note that the current configuration is not included in the Pareto front of the optimal solutions in any of the scenarios. In addition, a number of optimal configurations can reduce the LCC and at the same time decrease the lifetime CO_2 emissions more than 40% comparing to the current configuration.

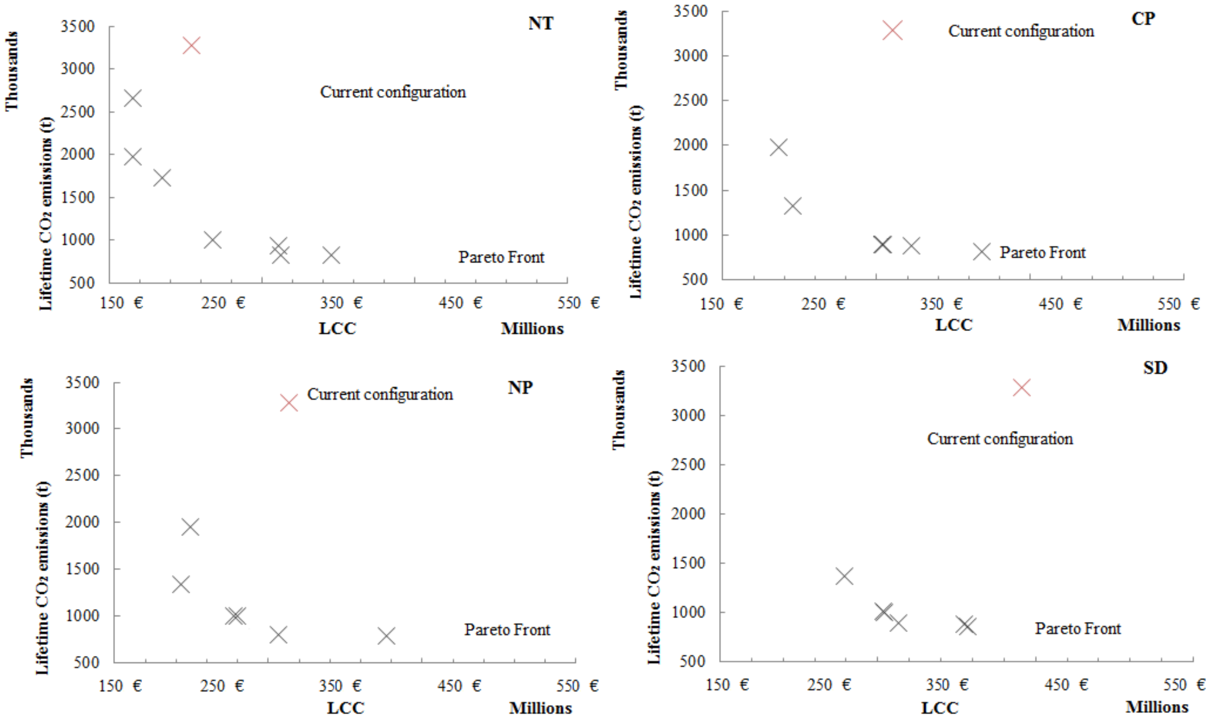

Figure 7.11 CO_2 & LCC optimisation of ship energy systems under the four carbon scenarios

Comparing the three first graphs (NT, CP, NP) of Figure 7.11, it is identified that the solutions of the Pareto front have a similar shape. Their performance on the lifetime CO_2 emissions objective varies on a range between 700-2700 thousand tonnes of CO_2 emissions. The solutions of the four figures differ significantly on the LCC, due to the carbon cost induced by the pricing policies. In addition, in the first three scenarios, even though the current configuration does not belong to the Pareto front, there are still solutions that perform better than the baseline regarding the CO_2 emissions objective but have a much higher LCC. However, in the SD scenario, all the solutions identified have better economic and carbon footprint than the current configuration.

To provide a deeper insight into the performance of the current configuration under every carbon pricing policy scenario the percentage increase of the life cycle cost is presented in Table 7.13. As it was expected there is a significant cost increase due to the carbon price and in the extreme situation of the SD scenario, the cost is almost 2 times higher than the NT option. This finding signifies the importance of identifying alternative technological configurations to avoid the potentially extreme future high life cycle cost impact from the carbon policies.

Table 7.13 Current cruise ship energy systems configuration LCC

Scenario	LCC
NT	-
CP	+50%
NP	+62%
SD	+110%

In the following figures of this section, the Pareto fronts of the four investigated scenarios are presented. Numbers are allocated on the selected solutions to facilitate the discussion: the best performing solution regarding the economic objective (1), the lifetime carbon emissions (2) and a solution that has similar LCC with the current configuration (3) are marked on the figures.

In Figure 7.12, the solutions on the Pareto front are presented for the CP carbon pricing scenario and the broken down cost of selected solutions. The configurations are similar to the Pareto front of NT scenario. One main difference is that due to the carbon cost the LCC increased for all solutions. In addition, in this case, the solution with the best economic performance consists only of dual fuel generator sets and not a combination of dual fuel with diesel sets like in the NT scenario. This change is identified on the trade-off between the lower capital cost of the diesel engine and the higher cost of the carbon price. Comparing the most

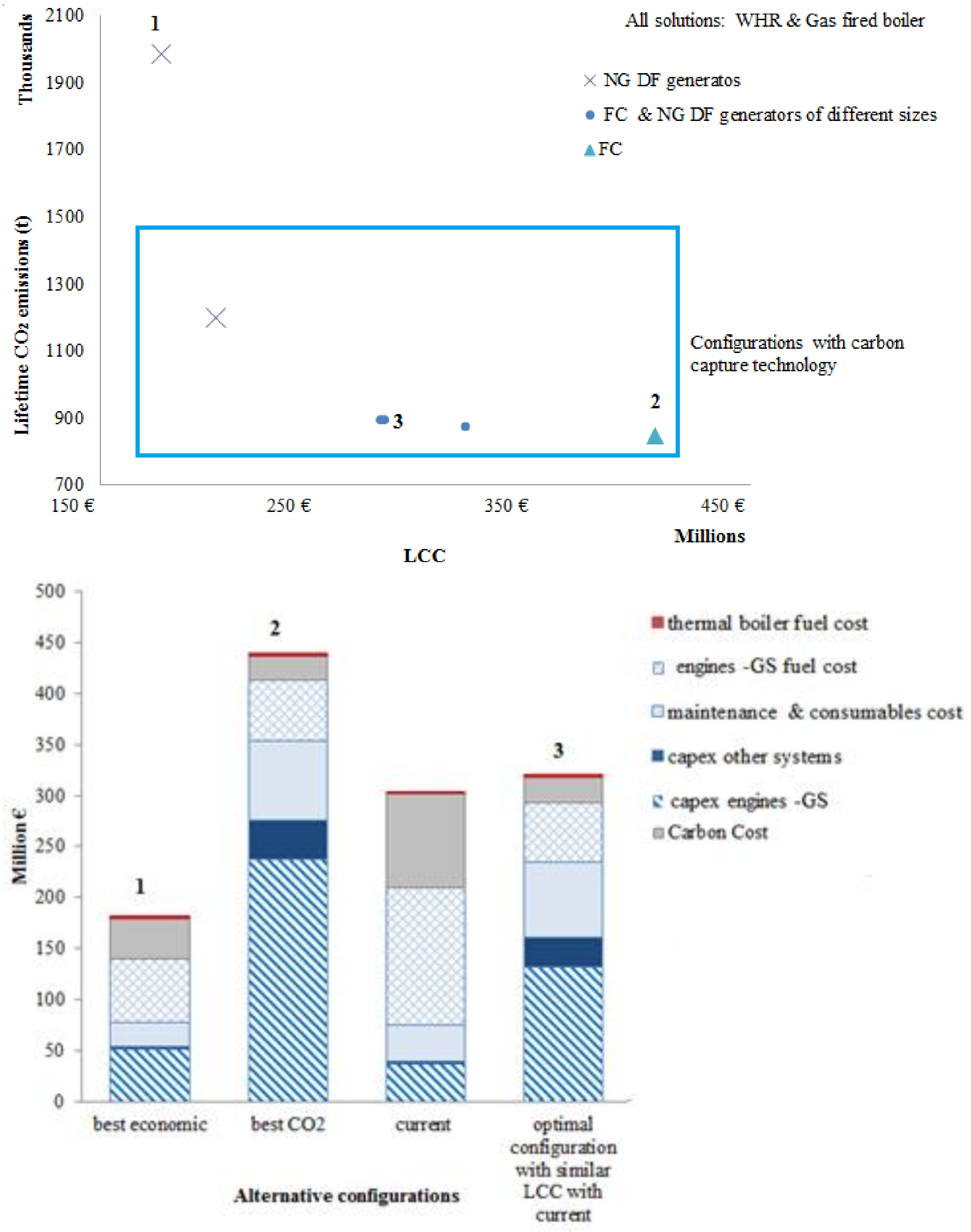

Figure 7.12 CO$_2$ & LCC optimal solutions of CP scenario

cost-efficient solution with NG with the most cost-efficient with NG and CC, there is a 30% increase on the LCC and a 40% decrease on the CO$_2$ emissions.

It is estimated that the carbon cost for the current solution is two times the carbon cost of solution 1 and four times of solutions 2 and 3. Solutions 2 and 3 consist of fuel cells and carbon capture technology, so this significant reduction of CO$_2$ emissions was expected. However, from the comparison of solution 3 with 1, it is inferred that the replacement of diesel with dual fuel generator sets reduces the carbon cost almost to half. It can also be concluded for the current configuration that even in the CP scenario, which models the momentum from the already announced policies, the carbon cost over the lifetime of a cruise ship can constitute 25% of the total LCC.

In Figure 7.13, the solutions from the bi-objective optimisation for the NP carbon pricing scenario along with their cost analysis are displayed. The solutions follow a similar pattern with the CP scenario, which is justified as the carbon prices for the NP and CP are very close (see Figure 7.10). An increase in the LCC is observed compared to the CP and it is identified that the number of solutions with the carbon capture technology is higher. This is a result of the trade-off between the higher capital investment for advanced CC technologies and the lifetime carbon cost. Comparing again the most cost-efficient solutions with NG dual fuel generators with or without CC, it is observed a 7% increase on the cost and a 28% decrease on the carbon footprint. As a result, higher carbon price scenarios make the CC technology more favourable, thus achieve a great reduction on the CO_2 emissions with a small increase on the LCC.

It is interesting to compare solutions 2 and 3, the former consist of fuel cells and the latter is a combination of fuel cells and dual fuel generator sets operating with natural gas. It is identified that the decrease in the CO_2 emissions and as a result the CO_2 cost reduction is very small; however, the great difference between these configurations is the capital cost, which is almost double for the fuel cells. On this scenario, where the cost of the carbon is increasing compared to the CP scenario but still is moderate it is observed that the carbon cost of the current configuration is 30% of the LCC. As a result, a slight increase in the carbon price leads to 20 M€ increase on the LCC.

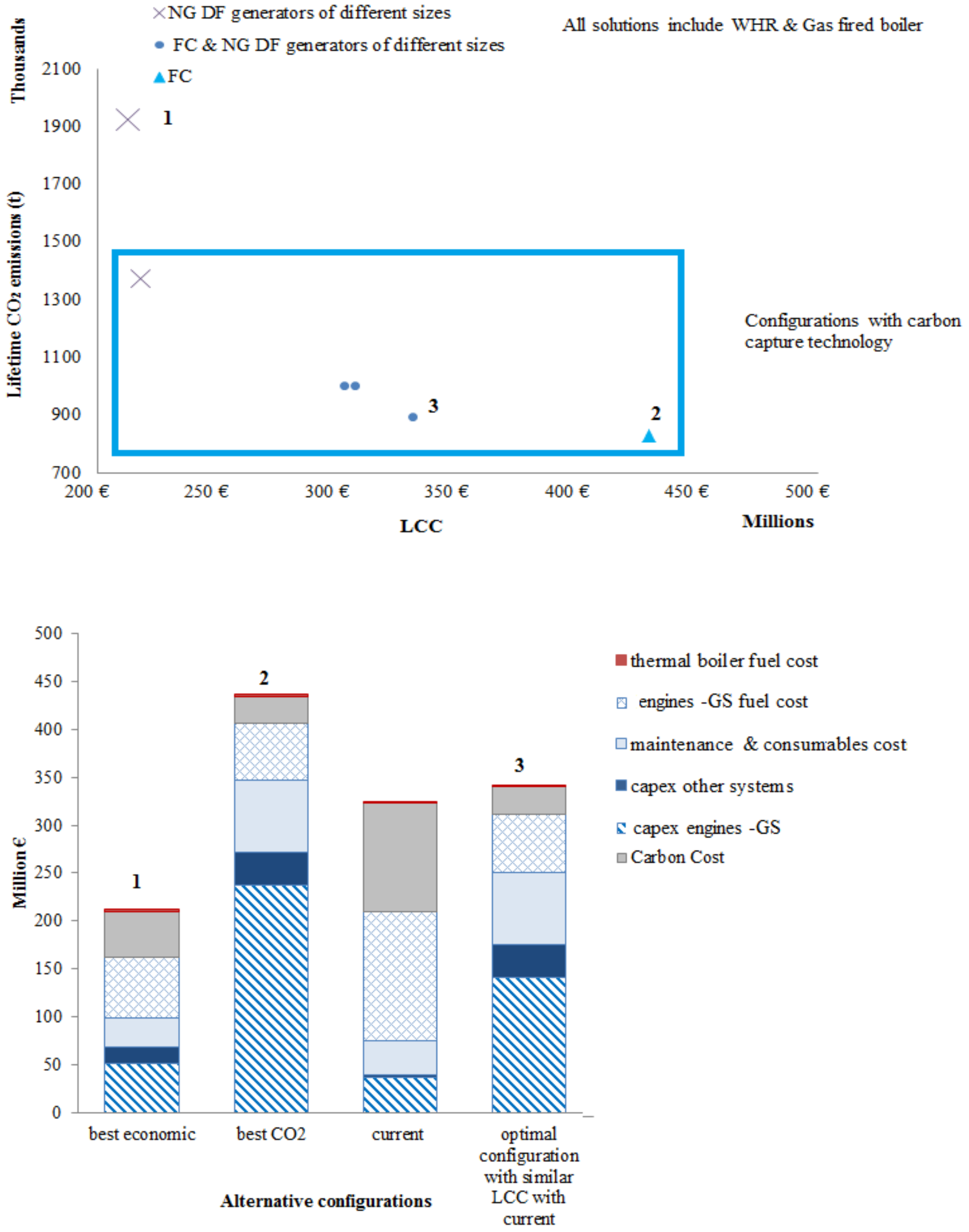

Figure 7.13 CO$_2$ & LCC optimal solutions of NP scenario

Finally, in Figure 7.14, the optimal solutions for the SD scenario are displayed. In this scenario, all the optimal solutions include carbon capture. This is due to the fact that the carbon price is very high and the configurations with the lower capital cost in the previous scenarios are no longer optimal due to the higher CO$_2$ emissions levels and consequently carbon cost. On this scenario the percentage of solutions with a combination of fuel cells with dual fuel engines increased, comparing to the previous scenarios.

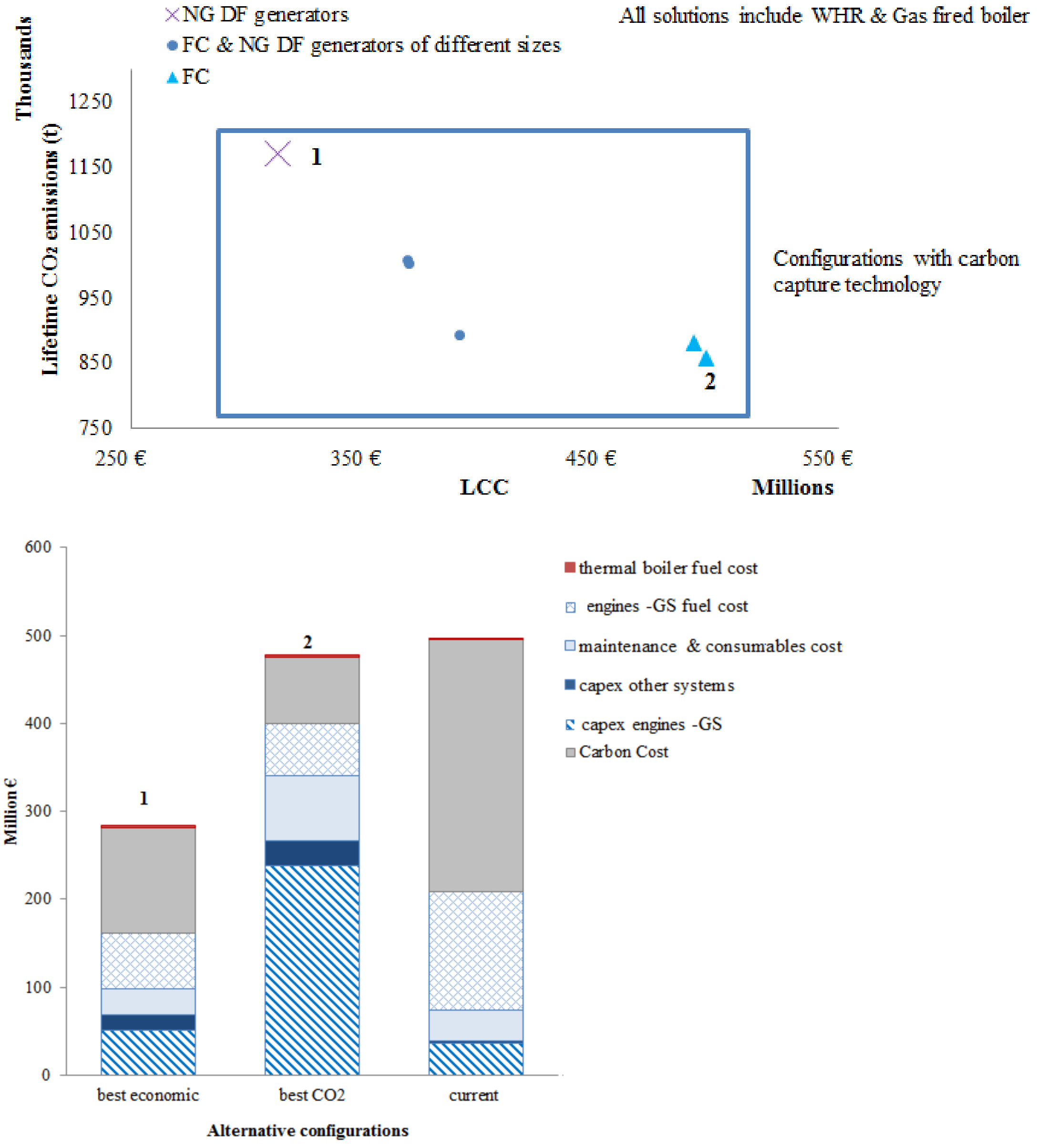

Figure 7.14 CO_2 & LCC optimal solutions of SD scenario

In this scenario, there is no solution that has similar cost as the current configuration. The solution with the closest LCC is solution 2, with the best CO_2 performance. Due to the very high CO_2 price, the carbon cost corresponds to 55% of the life cycle costs for the current configuration. Comparing with the solutions 1 and 2 the carbon cost of the current configuration is approximately three and four times greater, respectively.

From the analysis, it is inferred that when the carbon policy scenarios become stricter then there are no solutions that consist of diesel generators, in addition, the majority of the optimal configurations include fuel cells. Furthermore, in the extremely high carbon policy scenario, all the solutions include a carbon capture technology. Finally, it is identified that with the increase of the carbon prices, the carbon cost of the current configuration becomes economically prohibitive.

7.7 The effect of the operating profile on the optimal solutions

The effect of the operating profile on the optimal configurations is investigated in this section, in order to explore the influence it has on the optimal configurations and identify the solutions under alternative operational policies. As a result, the optimisation is performed for different operating profiles while the other parameters are kept the same as the original case. The two operating profile scenarios considered in this section including the one for the original case are presented in Figure 7.15. The two operating profiles investigated herein are derived by increasing and decreasing the speed profile from the original case by 20%.

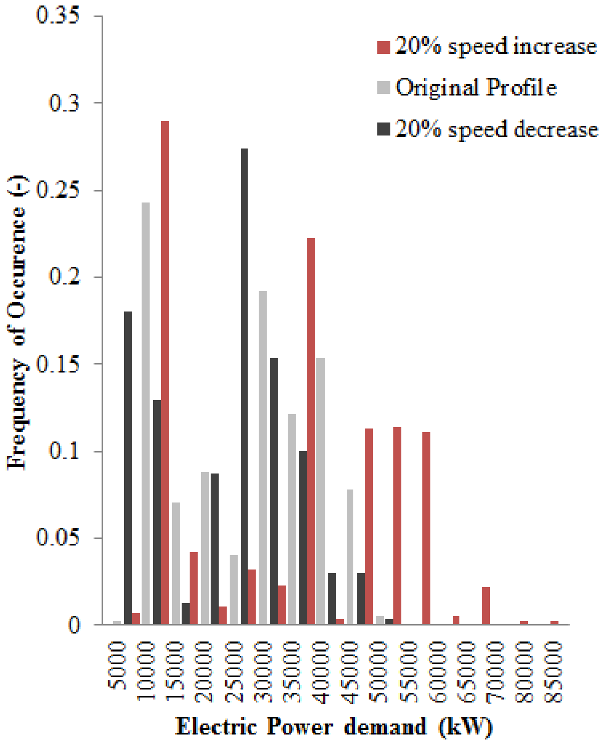

Figure 7.15 Operating profile scenarios

The solutions of the optimisation for the two operating profiles are displayed in Table 7.14 and 7.15 for the profile with the higher speeds and lower speeds, respectively. Comparing the solutions derived in this section with the optimal configurations from the original case in Table 7.4, it is evident that the optimal energy systems are similar. The majority of the configurations consist of dual fuel generator sets operating with natural gas and in some cases fuel cells or diesel engines. For both operating profiles, the best performing solutions include fuel cells. In addition, all the configurations have a gas fired boiler and a WHR, whereas a considerable number of solutions include a carbon capture technology. Therefore, these configurations exhibit robustness regarding the changes in the operational profile.

It is observed that the total nominal power installed varies between the different profiles. This is justified because the nominal power installed depends on the operating requirements. Another observation from the two tables similar to the original case is that none of the solutions has all the generator sets with the same size, compared to the current configuration. Therefore, solutions with engines with higher and lower nominal power lead to more cost and carbon efficient operation.

In Table 7.14 for the operating profile with higher speeds, it is identified that there is no configuration that consists of diesel engines and the most economic solution is a combination of dual fuel generator sets. It is inferred that in order to satisfy the operational requirements of the profile with the higher speed, the engines operation and consequently the fuel consumption increases. This result in higher operating cost and carbon emissions, therefore the diesel engines are not optimal anymore.

In Table 7.15, a great number of solutions consists of a combination of engines with lower and higher nominal power. The operating profile with lower speeds consists of a high period of the ship operating in low loads; therefore, the engines with the lower nominal power manage to satisfy the lower power requirements more efficiently.

The main findings of this analysis are that the optimal configurations regarding the two investigated objectives are robust according to variations of the operating profile. The only exception is the configuration with the lowest LCC, whereas in the case of higher speed profile the solution with diesel generators is not optimal anymore. As a result, it can be inferred that a combination of dual fuel generators offers the lowest LCC in most of the cases overall, including the uncertainty analysis results. In addition, it was identified that the optimal nominal power and number of sets varies for different speed profiles, therefore it is important for the decision maker to be provided with the optimal configurations for different operating profiles. As a result, this analysis supports decisions for both the optimal configuration and the nominal power.

Table 7.14 Optimal configurations of operating profile with a 20% increase of the speed

	Main Engine Sets / MCR /Type/ Fuel	Carbon Capture technology	Energy Efficiency technology	Thermal Boiler		Percentage Difference from the best solution	
				Type	Fuel	LCC	CO$_2$ emissions
1	4x13000 kW DF (NG) & 3x10000 kW DF (NG)	-	WHR	GFB	NG	0%	+132%
2	4x13000 kW DF (NG) & 3x10000 kW DF (NG)	✓	WHR	GFB	NG	+31%	+58%
3	60x500 kW FC (NG) & 4x13000 kW DF (NG)	✓	WHR	GFB	NG	+100%	+32%
4	104x500 kW FC (NG) & 3x10000 kW DF (NG)	✓	WHR	GFB	NG	+103%	+11%
5	164x500 kW FC (NG)	✓	WHR	GFB	NG	+215%	0%

Table 7.15 Optimal configurations of operating profile with a 20% decrease of the speed

	Main Engine Sets / MCR /Type/ Fuel	Carbon Capture technology	Energy Efficiency technology	Thermal Boiler		Percentage Difference from the best solution	
				Type	Fuel	LCC	CO$_2$ emissions
1	2x8000 kW D (LSHFO) & 3x12000 kW DF (NG)	-	WHR	GFB	NG	0%	+200%
2	2x11000 kW DF (NG) & 3x10000 kW DF (NG)	-	WHR	GFB	NG	+14%	+83%
3	2x11000 kW DF (NG) & 3x10000 kW DF (NG)	✓	WHR	GFB	NG	+31%	+36%
4	66x500 kW FC (NG) & 3x12000 kW DF (NG)	✓	WHR	GFB	NG	+87%	+7%
5	60x500 kW FC (NG) & 2x11000 kW DF (NG)	✓	WHR	GFB	NG	+114%	+6%
6	80x500 kW FC (NG) & 2x6000 kW DF (NG)	✓	WHR	GFB	NG	+118%	+2%
7	104x500 kW FC (NG)	✓	WHR	GFB	NG	+142%	0%

7.8 Sensitivity analysis of the optimal solutions

In this section, the impact of the variations of the fuel prices and the capital cost of specific technologies on the optimal configurations of the original optimisation life cycle cost is presented. The fuel prices and capital cost are the parameters that have the most significant impact for the ship energy system LCC therefore, this analysis supports the decision maker to attain a better understanding of the configurations LCC in an uncertain environment.

In Figure 7.16, the variations of the fuel prices are investigated. The range from -60% to +160% of the fuel price used in the original case is examined. It is observed that the increase in the price leads to a significant increase in the life cycle cost. It is evident that in all the cases when the price is increased by 160% then the life cycle cost is also higher by more than 30%, whereas when the price is decreased the LCC has a maximum 8% decrease.

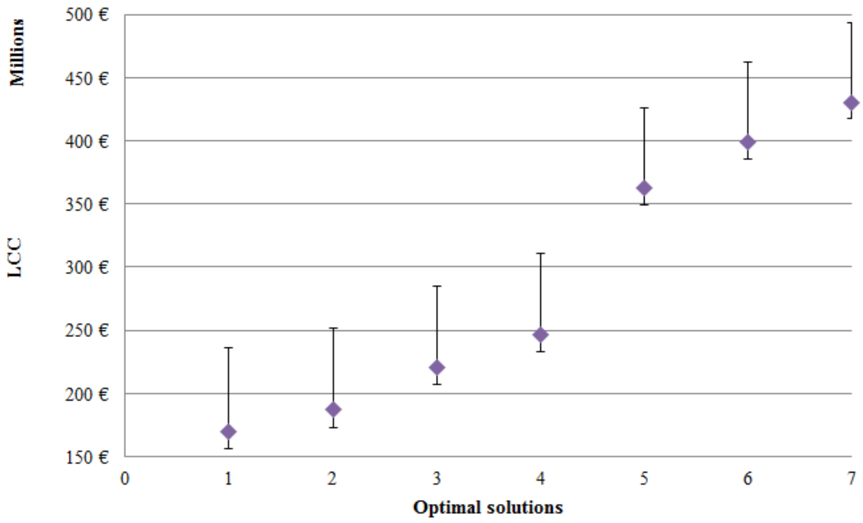

Figure 7.16 Fuel prices variation: -60% to +160%

Therefore, it is evident that the fuel prices have a great impact on the life cycle cost of the cruise ship energy systems. As a result, it is critical for the decision maker to investigate the potential impact of the uncertain parameters on the configurations.

In subsequence, the impact of the fuel cells capital cost on the optimal solutions is investigated by varying its price from -50% to +20% of the nominal value employed in the original case study. Fuel cells are a promising technology to mitigate the CO_2 emissions, however, it is an emerging technology and the prices are not yet established. The derived results are displayed in Figure 7.17. As it was expected the changes in this parameter affects only the configurations that include fuel cells.

The most significant impact of the price variation is observed in solutions 7, which consists totally of fuel cells. In this case, the variations of the price lead to a range of the LCC from +10% to -30% from the respective value of the original case. On the other cases that the engines consist of a combination of fuel cells and dual fuel engines, the variation of the cost is not so pronounced. In the latter cases, the maximum increase is 7% whereas the decrease is 20%. From the previous figure, it is identified that a 50% decrease of the fuel cells price has a greatest impact on the LCC comparing to the 60% decrease in the fuel price. Therefore, the decision maker should focus on determining the capital cost of the fuel cells with the greatest possible accuracy, since deviations from the nominal cost greatly affect the life cycle cost of the energy systems.

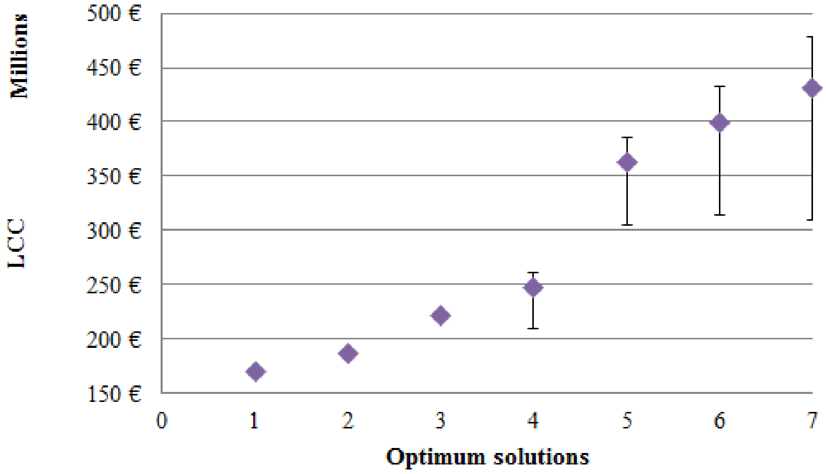

Figure 7.17 Fuel cells capital cost prices variation: -50% to +20%

The life cycle cost ranges of the optimal configurations due to the respective variations of the carbon capture capital cost are presented in Figure 7.18. This technology was investigated as it is not mature yet for the ship energy systems, therefore, the investment price is still uncertain. In addition, it is a technology that has a very high cost and consequently high impact on the LCC of the ship energy systems. It is evident from the figure that the changes in this parameter affect only the configurations that include the carbon capture technology.

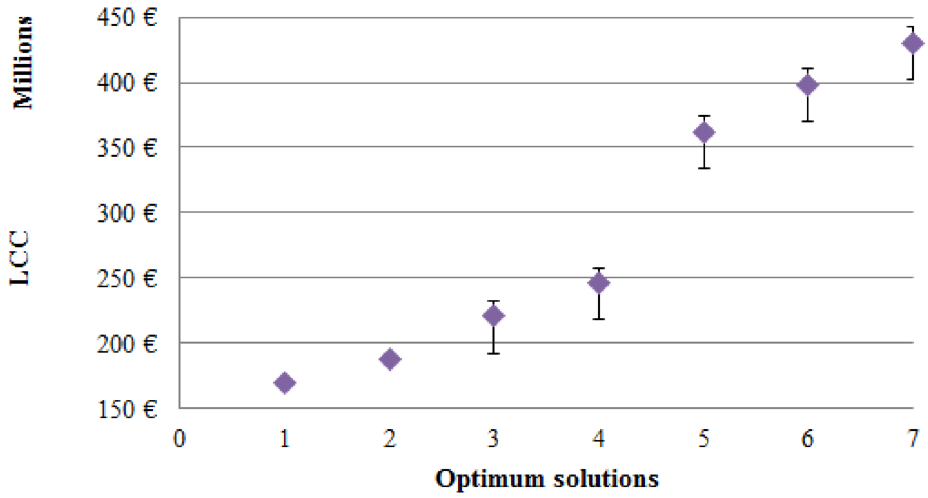

Figure 7.18 Carbon Capture system capital cost prices variation: -50% to +20%

It is identified that a 50% decrease of the carbon capture capital cost leads to a 6% reduction of the LCC, whereas the 20% increase of the technology's cost influences only by a 2% increase the total cost. Compared to the previous cases it is evident that the impact of the carbon capture price on the life cycle cost is less significant. Therefore, for the decision maker regarding the emerging technologies, the capital cost of the fuel cells should have the greatest priority.

7.9 Discussion of results

In this section, the most significant findings derived from this case study are discussed, whereas the results from the application of the method are displayed in Chapter 8. In this chapter, the developed method was applied on a cruise ship with 140,000 GT. A bi-objective application of the method was presented considering as objectives the life cycle cost and the lifetime carbon emissions.

Comparing the performance of the bi-objective optimisation results with the current configuration it is identified that the latter does not belong in the Pareto front of the optimal solutions. It can be inferred from the presented results that the technologies that are most prominent to mitigate the CO_2 emissions whilst reducing the life cycle cost are the technologies operating with natural gas compared to the traditional configuration that consists of systems operating with HFO. On the contrary, it was estimated that natural gas operating configurations manage to reduce the carbon emissions 20% while lowering the life cycle cost by 25% for the best performing solution for the economic objective. Therefore, it is evident that the bi-objective optimisation method generates a variety of alternative solutions that perform better than the current configuration both by improving the carbon footprint of cruise ship energy systems and at the same time reducing the life cycle cost.

The current configuration was identified even less competitive when different carbon policy scenarios were investigated. In specific, for the strictest policy scenario, the current configuration was recognised as economically prohibitive, with the carbon cost constituting 55% of the total life cycle cost. As a result, the importance of identifying solutions that improve the carbon footprint performance of the cruise ship energy systems was highlighted, in order to avoid in the future extreme expenses for the carbon policy costs.

It was identified that the most dominant technology for the electric power generation that improves both the environmental and economic performance of the ship energy systems is the dual fuel generator sets operating with natural gas. Despite the fact that the dual fuel engines have a higher capital cost, these configurations prove to be dominant on the optimal solutions due to the low carbon content and the low price of the natural gas. However, the life cycle cost includes only the capital cost of the machinery, whereas the cost of the ship structural changes to accommodate the natural gas storage is not incorporated. The beneficial impact of the dual fuel engines on the cruise ships identified in this work regarding the cost savings agrees with the literature (Wik, 2016). Finally, the positive impact of the installation of dual fuel generator sets on vessels regarding both the environment and the operating cost was indicated by previous studies (Livanos et al., 2012; Tzannatos et al., 2015).

Furthermore, the engines operating with methanol manage to reduce the CO_2 emissions and seem to be a prominent alternative for the CO_2 emissions reduction for the cruise ships according to the literature (Andersson and Márquez Salazar, 2015), due to the very low carbon content. However, due to the lower heating value of methanol that is almost half of the HFO and the natural gas, the fuel storage requirements are almost double compared to HFO and NG. In addition, despite the lower carbon content than the natural gas, which is two times lower, the total carbon emissions are higher for methanol due to the lower heating value that is 2.4 times lower than the natural gas. Along with the higher methanol price compared with natural gas, this solution was not identified among the optimal. However, from the uncertainty analysis, solutions with methanol were identified in a small percentage of the results when the relative difference of the fuel prices benefits methanol.

The solution with the optimal economic performance is a combination of diesel generator sets with dual fuel operating with natural gas. However, the robustness of this solution is not very high, as it was discussed in the uncertainty analysis results and in many cases; the optimal solution regarding the economic objective was a combination of dual fuel generators. It should be noted that on the original case Pareto front, a configuration with a combination of dual fuel generator sets is identified with only 1% higher life cycle cost comparing to the best performing in the economic objective and at the same time with a 30% reduction on the carbon emissions. Therefore, the configuration with a combination of dual fuel generator sets is recognised as a more robust solution performing best on the LCC objective.

In addition, it was identified that it is more efficient to operate the diesel generators with LSHFO rather than the current approach with a scrubber in order to mitigate the SOx emissions. From previous studies, it was identified that the latter configuration with scrubber for cruise ship has a high investment cost (Wik, 2016). However compared to low sulphur fuel solution and the relative prices of fuels the scrubber is a solution more suitable for the mid-term future, whereas the low sulphur fuel is for the short term future (Armellini et al., 2018). This was inferred also by the uncertainty analysis results, where changes on the fuel prices benefit the configuration with a scrubber.

From the preceding analysis, it was denoted that fuel cells are the most promising technology to mitigate the CO_2 emissions, despite their high capital cost, which in some cases consists the 49% of the LCC of the ship energy systems. The environmental benefits of the fuel cells on passenger ships are supported by the literature (Bassam et al., 2016; De-Troya et al., 2016). In this analysis, only the capital and operational costs of fuel cells were considered, whereas, the structural changes to incorporate the fuel cells additional weight and size were excluded. A great percentage of solutions was identified that consisted of a combination of dual fuel generator sets with fuel cells or only fuel cells. It was evident that the partial replacement of dual fuel generator sets with fuel cells increased the life cycle cost by 20% but on the other hand, managed to mitigate the carbon emissions by 43%. On the other hand, the total replacement of dual fuel generators with fuel cells increased the LCC by 15% with only decreasing the CO_2 emissions by 0.5%. Therefore, fuel cells are suitable to improve the carbon footprint of the cruise ship energy systems; however, in combination with dual fuel generator sets they are more economically viable.

Carbon Capture technology has great potential in reducing the emissions for compliance to the future CO_2 emissions reduction targets, even though the carbon capture does not operate to its full capabilities due to the space restriction assumption made in this model. Still, it is evident that it manages to reduce drastically the CO_2 emissions, nonetheless with the trade-off of increasing the capital cost. As it was discussed in the previous chapter, the carbon capture technology has great potential for offshore applications even though it is not yet established. From the results, it was indicated that this technology currently has a very high cost for marine applications and a 180 €/t of CO_2 emissions is estimated due to the technology, thus making it prohibitive in the real world. However, from the analysis of the carbon policy scenarios it was evident that if high carbon prices were forced then the carbon capture would be apparent in order to cope with the high carbon costs.

The gas fired boiler is a dominating technology among the optimal configurations, the low carbon coefficient of the natural gas makes the technology promising for the mitigation of the emissions. However, the uncertainty analysis results indicate that the fuel type for the thermal boiler is affected by the fuel prices and in some cases, there is a great percentage of optimal solutions that includes oil fired boiler operating with LSHFO. Therefore, this solution is not so robust to the fuel prices changes.

Finally, it is highlighted from the results that the waste heat recovery technology improves the efficiency of the cruise ship energy systems and its benefits surpass the increase on the capital cost since this technology was present in every solution of the Pareto front. In addition, the uncertainty analysis results indicate that this solution is robust. Therefore, the WHR technology has good potential to be included in the future cruise ship energy systems, this is aligned with previous studies that presented the environmental and economic benefits of WHR on cruise ships (Baldi et al., 2018).

The optimal solutions and the current configuration EEDI values were estimated. It was inferred that the current configuration complies only with Phase 1 of the EEDI regulations, thus new greener alternatives need to be identified in order to attain the reference EEDI values. The configurations proposed in this work manage to comply with all the EEDI phases. It is evident from the results, that the EEDI is highly affected by the design speed compared to the lifetime carbon emissions that are estimated according to an expected operating profile. Therefore, even though both the EEDI and the lifetime carbon emissions rank the configurations in the same order of preference, there is a misalignment in the improvement of the configurations compared to the current configuration. As a result, the EEDI does not manage to capture the real carbon impact of the cruise ship energy systems as well as the great benefits of the greener technologies, thus as a policy that aims to mitigate the carbon emissions, the EEDI cannot have a significant impact in improving the carbon footprint of the ship.

The optimal configurations under different operating profiles as well as the impact of the parameters that influence most significantly the ship energy systems performance were investigated, in order to support the decision maker on the cruise ship energy systems synthesis. It was indicated that the optimal configurations remain robust, for a reasonable range of variation of the operating profile, whereas, the nominal power installed is affected. As a result, further investigation of the expected operating profile is required in order to support the decision maker. Finally, the impact of the fuel prices and emerging technologies capital cost variations on the life cycle cost was examined. It was evident that the changes in the fuel prices, as well as the fuel cells capital cost, have a very high impact on the overall life cycle cost of the cruise ship energy systems. Therefore, the decision maker has to take into consideration the impact of these parameters in the final decision of the cruise ship energy systems synthesis.

7.10 Chapter summary

In this chapter, it was identified that the current configuration does not belong in the Pareto front of the cruise ship energy systems optimal solutions, whereas, the technologies operating with natural gas manage to reduce the carbon emissions 20% while lowering the life cycle cost by 25% for the best performing solution for the economic objective. The environmental benefits of the fuel cells were demonstrated and they were identified as the most promising technology to reduce the ship carbon footprint. However, fuel cells have a very high cost and it was inferred from the findings that a combination of dual fuel generator sets with fuel cells mitigates the carbon emissions without increasing dramatically the life cycle cost. The carbon capture technology has a high impact on the life cycle cost despite reducing the carbon emissions for the cruise ship energy systems. However, the carbon policy scenarios analysis indicated that the carbon capture would be an economically viable solution in the future if the carbon prices become high. Furthermore, it was presented that the EEDI does not manage to capture the real carbon impact of the cruise ship energy systems neither promotes the benefits of the greener technologies. Finally, the fuel prices and the capital cost of fuel cells have the most significant impact on the cruise ship energy systems overall life cycle cost.

8 Discussion and Conclusions

8.1 Introduction to chapter

In this chapter, first the accomplishment of the aim and objectives of this research are discussed. Then, the novelty of this research is summarised and reflections on the developed method and the findings are presented. The implications of this work for academia and industry are demonstrated, as well as recommendations for future work are outlined. Finally, the concluding remarks are summarised.

8.2 Review of research objectives

As it was stated in Chapter 1, the question that drove this research is the following.

How can the environmental and economic performance of the ship energy systems synthesis be optimised over the ship lifetime during the early design stage?

The research question is answered by the development of the presented decision support method that contributes in improving the ship energy systems sustainability over the ship lifetime. The developed method supports decisions for the ship energy systems synthesis with respect to environmental and economic sustainability objectives, whilst considering the systems lifetime operating requirements.

This work was intended to address the following literature gaps identified in the critical review reported in Chapter 2:

- *a lack of approaches that optimise the environmental objective, along with the traditional economic objective in order to support decisions for the ship energy systems synthesis, whilst evaluating the ship energy systems, according to a varying expected operating profile*
- *a lack of a more general approach that supports decisions and optimises the integrated ship energy systems synthesis, allowing the technology and fuel type selection of the main energy systems, as well as other components significant for the sustainability of the systems.*

The research aim was accomplished through the research objectives that were discussed in Chapter 1 and in this section, it is outlined how these objectives were achieved.

Objective 1: Investigate, map and analyse the existing decision support methods for optimal ship energy systems synthesis.

This objective was achieved by identifying and analysing the basic principles for sustainable ship energy systems and the methods to support decisions for sustainable energy systems synthesis in Chapter 2. First, the sustainability in shipping and specifically in ship energy systems was addressed. The basic characteristics and technologies that have potential to improve the ship energy systems sustainability were identified. Then the methods to support decisions for sustainable energy systems were outlined, due to their similarities with to the ship energy systems. The key findings from the decision support methods for sustainable energy systems regarding the indicators and the methods employed were identified and used as a guideline, in order to develop the decision support method for the ship energy systems synthesis. In subsequence, the most significant part of the critical literature review, regarding the state-of-the-art methods to support decisions for sustainable ship energy systems and in specific support decisions for the synthesis was presented in Section 2.5. This analysis led to the gaps identification that were presented in the beginning of this section.

Objective 2: Identify the key environmental and economic indicators for the ship energy systems sustainability and formulate mathematical expressions to describe them.

The first part of this objective was attained by the critical review reported in Chapter 2, where the key environmental and economic indicators employed to express the sustainability of energy systems and ship energy systems were identified. As a result, for the environmental aspect the lifetime exhaust gas emissions were considered as the most important set of indicators, whereas for the economic objective the life cycle cost. The formulation of the mathematical expressions for the indicators was performed according to the literature and technical reports; the equations developed and employed in this method were presented in Section 4.4, where the economic and environmental ship energy systems performance analysis was discussed.

Objective 3: Identify and analyse the ship energy systems that have the greatest impact on the ship sustainability.

The systems identified to have the greatest impact on the ship energy systems sustainability, include the main ship energy systems and related components that are responsible for the energy conversion shipboard. Therefore, they have the greatest impact on the operating expenditure and lifetime exhaust gas emissions. The reasoning of the systems selection was discussed in the scope of this research, in Chapter 1.

In Chapters 3 and 4, the ship energy systems were analysed, according to the systems approach, which was recognised as an approach that manages to tackle the complexity and addresses the interactions of the integrated ship energy systems. The systems approach was followed and the ship energy systems were decomposed into sub-systems as reported in Chapter 4. For each sub-system the input and output parameters were identified, as well as the interconnections among the sub-systems.

Objective 4: Investigate the established and emerging technologies to improve the ship energy systems sustainability and develop models to describe their performance.

First in Chapter 2, a review on the traditional and emerging technologies that are currently used or they have potential to be used in the future was reported. As a second step, the list of the considered technologies was discussed in the semi-structured interviews with experts and the results were presented in Chapter 5. Mathematical models were developed to estimate the performance of the technologies included in this method. The mathematical models presented in Chapter 4, were derived from the literature and technical reports and the models constants were found by regression analysis. The developed mathematical models were validated in Chapter 5, where results from previous publications were compared with the outputs of the developed models. The results indicated that the estimated values are within the same order of magnitude with the published data.

Objective 5: Formulate the optimisation problem of the ship energy systems synthesis, identify the optimisation algorithm that suitably addresses the complex problem, and evaluate the efficacy of the selected optimisation algorithm.

This objective was achieved in two parts of this thesis. First, according to literature presented in Chapter 3 on the section regarding the multi-objective optimisation of the ship energy systems synthesis, it was identified that NSGA-II is the most prominent algorithm for multi-objective combinatorial problems, as well as manages to address the optimisation of complex energy systems. Then, NSGA-II algorithm efficacy on providing the near optimal solutions for the ship energy systems synthesis problem was validated, by comparing the algorithm outputs with those from the complete enumeration.

The formulation of the optimisation problem including the objective functions that were developed according to the key indicators to express sustainability of ship energy systems, the constraints, as well as the decision variables, were presented in Chapter 4. In addition, the optimal algorithm parameters were selected according to the Taguchi Design of Experiments method. The results from the algorithm validation were presented in Chapter 5, indicating a sufficient approximation of the true Pareto front.

Objective 6: Develop the computational model of the proposed decision support method for the ship energy systems synthesis.

The mathematical models and the objective functions developed and presented in Chapter 4 were transformed into a computational model in Matlab programming language. The verification that the computational model accurately represents the developed mathematical models was discussed in Chapter 5. The verification of the computational model was investigated through manual explorations, comparing the results of the two models facilitated the identification and elimination of the errors.

Objective 7: Evaluate the applicability of the proposed method.

Two case studies were performed on different ship types in order to evaluate the applicability of the decision support method as it was discussed in Chapter 5. The first case study was the multi-objective optimisation of the ship energy systems of an Aframax tanker ship in Chapter 6, whereas the second case study presented the bi-objective optimisation of a cruise ship energy systems in Chapter 7. The justification for selecting the specific ship types was discussed in Chapter 3. In both cases, the findings from the method application were displayed and discussed. The derived results were compared with results from previous publications in order to investigate their accuracy.

Objective 8: Validate the derived results from the method application under different conditions.

This objective was achieved by performing an uncertainty and sensitivity analysis on the input parameters in Chapters 6 and 7, which is critical for the validation of the results. The uncertainty analysis explored the robustness of the solutions under an uncertain environment, whereas the sensitivity investigated the impact of the most significant uncertain parameters on the near optimal configurations. The uncertainty analysis was performed with the Monte Carlo simulation and by employing probability density functions for the most significant input parameters, as were presented in Chapter 4. Then the robustness of the results was discussed for each case study. The near optimal configurations were investigated under different operating profiles and carbon scenarios for the cruise ship case study. Finally, a sensitivity analysis on the most significant parameters was performed on the near optimal configurations of both case studies.

8.3 Research novelty

The novelty of this research lies in the decision support method developed to optimise the ship energy systems synthesis at the early design phase with respect of both environmental and economic objectives, as well as considerations of the ship lifetime operating requirements.

The proposed method is the first to introduce the optimisation of both the life cycle cost and the exhaust gas emissions from the ship energy systems, while considering as constraints the environmental regulations. Thus, it evaluates at the same time the two objectives and proposes configurations that improve both the environmental and economic sustainability of the ship energy systems, in comparison with the existing literature of ship energy systems synthesis optimisation, where only the economic objective was considered. As it was identified from the Critical review in Chapter 2, supporting decisions to improve the sustainability of energy systems requires adopting an approach that integrates both the economic and environmental aspects.

In addition, the proposed method supports decisions for the type of the integrated energy systems, the main engine, auxiliary electric machinery and thermal boiler system type, or their fuel type. The existing studies in the synthesis optimisation of ship energy systems, compared to the proposed method in this thesis, considered a predefined ship energy systems configuration and focused on the optimisation of the heat recovery system and the number of units, or in few cases on the emission control technologies selection.

Finally, an expected operating profile was employed to evaluate the performance of the systems compared to the existing literature that considers some representative operating phases for the ship energy systems synthesis.

8.4 Reflections

In this section, reflection on the method boundaries, the proposed method, the data challenges and finally on the findings and the cross-case comparison of the case study findings is presented.

8.4.1 Method boundaries

According to the boundaries and assumptions of this work that confined the research, the method presented in this thesis supports decisions on the ship energy systems synthesis at the early design phase, but it cannot be employed for a detailed design of the ship energy systems for the following reasons. First, only the main energy systems that are involved to produce the energy required shipboard and after-treatment, as well as energy efficiency technologies were considered, excluding other energy systems. These systems have the greatest contribution on the lifetime operational cost and gas emissions according to the literature. Second, the interactions between the ship energy systems with the propellers and the hull were excluded from the presented analysis. Third, the detailed analysis of the emerging energy systems performance and the structural changes on the ship required to include them, was not considered. Finally, the optimisation on the proposed systems design and operation was not performed.

Furthermore, this work cannot be employed for the assessment of the ship energy systems sustainability. First, only environmental and economic aspects of sustainability were considered, excluding the social due to the existing methods limitations. In addition, the environmental aspect of sustainability was accounted regarding the operational lifetime exhaust gas emissions, since it was derived from the literature as the most significant impact of the systems. Therefore, other environmental impacts like the resources depletion, or the waste were not reported. Finally, the cost of the ship energy systems end of life was disregarded due to the limited contribution to the life cycle cost.

These assumptions and boundaries were selected according to the aim and scope of this research, which is to provide a set of near optimal configurations for the main ship energy systems in the design phase that can contribute towards the improvement of the environmental and economic sustainability of ship energy systems. Even though these boundaries were derived from the literature review, it is possible that they limit this research and in general every extension of the boundaries is considered to enhance the systems assessment (Baldi, 2016). However, the proposed method is modular with respect to multiple aspects such as inclusion of indicators, systems and technologies. Therefore, further investigation is essential to explore, whether the boundaries and assumptions considered herein need to be extended and what impact this will have on the sustainability indicators and the near optimal configurations.

8.4.2 Proposed method

An advantage of the presented method is that both established and emerging technologies can be included in the optimisation, thus providing the decision maker an insight of the current and future optimal ship energy systems. Therefore, mathematical models were developed for established and emerging technologies. However, challenges arise from the inclusion of the emerging technologies. First, there is an uncertainty regarding their performance due to the limited available evidence of their operation. In addition, it is not yet certain that these technologies, namely the fuel cells and carbon capture system can be integrated in the ship energy systems. In both cases, further analysis on their impact on the ship structure and general arrangement is required. For example, in the cruise ship case study, it was derived from the optimisation that the best performing solution regarding the carbon emissions objective includes only fuel cells for the energy production. This is a configuration that could be promising in the future; however, an analysis should be performed in order to provide further insight, whether this configuration is possible to provide the total electric energy demand for a cruise ship.

In this work, the ship energy systems are optimised according to an operating profile derived from yearly operational data of the particular ships. The results are highly affected by the chosen operating profiles. Even though, the operating profiles were developed from shipboard measurements, as it was presented in Banks et al. (2013), the speed distribution and as a consequence the power demand varies through the years. The profile is strongly influenced by the marine fuel prices, as well as the ship freight rates. In addition, in general the operating profile cannot be predetermined for a future ship, thus the uncertainty for the profile is inevitable. However, the value of evaluating the ship energy systems performance according to an operating profile instead of limited design points was demonstrated in the critical literature review. Therefore, in order to reduce the uncertainty stemming from the operating profile dependency on external conditions the near optimal configurations were investigated for different operating profiles. Three different operating profiles were considered for each case study and the findings from the method application were discussed.

Furthermore, the cost factors of the technologies were considered proportional to the nominal power, which is a common practice in the literature (Balland et al., 2014; Livanos et al., 2014; Theotokatos and Livanos, 2013b; Tzannatos et al., 2015). It could be considered a limitation that the economy of scale is not included and further investigation could provide an insight on the impact of the cost factors on the results.

A multi-objective optimisation method was employed in order to optimise the ship energy systems synthesis. NSGA-II was selected for the ship energy systems synthesis problem according to the method characteristics and from previous successful application of the algorithm in relevant problems, as it was presented in Chapter 3. In addition, the ship energy systems synthesis optimisation algorithm validation was performed in Chapter 5. A complete enumeration of a smaller size problem was performed, as it is a common approach to evaluate the accuracy of the genetic algorithm to identify the true Pareto front according to the literature. The results indicated an acceptable accuracy, which can be viewed as an advantage of the algorithm selection. Nevertheless, further investigation of potential other multi-objective evolutionary algorithms could provide more information of whether NSGA-II is the best performing algorithm for the problem.

It was identified on the optimisation algorithm efficiency validation (Chapter 5) that despite the good approximation of the Pareto front solutions, the algorithm does not manage to provide all the optimal solutions. This has a negative impact on the decision support method; however, it is an inevitable disadvantage of the genetic algorithms nature. Therefore, it is possible to provide to the decision maker a limited set of near optimal solutions and not the extensive Pareto front. In this work, in order to balance this disadvantage, the optimisation was repeated for each case for ten times, in order to allow the NSGA-II to identify all the near optimal solutions. Finally, an uncertainty analysis was performed and an extensive discussion was provided on the robustness of the solutions and the potential optimal configurations under uncertainty.

A practical aspect that has an impact on the method application is the computational time required to derive the Pareto front of the optimal solutions. Both case studies were demonstrated in an Intel(R) Core$^{\text{TM}}$8 i7-2600 CPU at 3.40GHz and the average computational time for each case study was 6.5 minutes. For the uncertainty analysis (1000 simulations) of each case study, the average time was 7,298 minutes. The computational time increases with the number of objectives and the alternatives considered. As a result, this can have a negative impact on the application of the method in a real life context, when more objectives or technologies are included.

The optimisation can be performed for different number of objectives depending on the decision maker preferences, as it was demonstrated in this thesis. In the first case study, a multi-objective application was presented considering three gaseous emissions and the economic objective, whereas in the second case study a bi-objective optimisation was formulated considering only the carbon emissions along with the economic objective. However, increasing the number of objectives affects negatively the computational time and might affect the accuracy of the method. This was evident from the optimisation algorithm validation in Chapter 5, where the accuracy of identifying the optimal configurations for the bi-objective optimisation was 100% and the computational time 1.5 minutes, whereas the accuracy was 96% and the computational time 2.1 minutes for the multi-objective problem.

To gain further insight into the potential of the optimisation algorithm to identify the optimal solutions, future investigation could be performed with different number of objectives.

Two case studies were carried out to evaluate the developed decision support method; these include the tanker ship presented in Chapter 6 and the cruise ship presented in Chapter 7. The case studies were discussed in depth in the aforementioned chapters. The applicability of the method is a key consideration; therefore, the two case studies were performed into two diverse types of merchant vessels with differences on the configuration. One is a typical direct driven propulsion of an ocean going vessel, whereas the other is an electric driven propulsion of a cruise ship vessel. In addition, they have differences on the power demand; on one hand, the tanker has high thermal demand, on the other hand, the cruise ship has a high electric load. Furthermore, differences are observed on the typical journey of the two vessels; the tanker is an ocean going vessel sailing for a short time within ECA waters, whereas the cruise ship spends a high percentage of time within ports coastal areas and ECA waters. Therefore, it is demonstrated that the method is generic and can be applied in different merchant ship types.

In addition, different technologies were included in the two case studies according to the literature and the industry trends. From the two applications, it is evident that various technologies and power plant arrangements can be considered according to the decision maker preferences, thus the method is modular and flexible.

The overall method presented in this thesis supports decisions for the integrated ship energy systems taking into consideration the power plant for the propulsion, electric and thermal power along with emission control and energy efficiency technologies. It was evident from the uncertainty analysis results for the tanker ship that the electric sub-system was not as robust as the other sub-systems. The contribution of the tanker electric sub-system to the life cycle cost and lifetime emissions was not significant due to the limited operation of the sub-system, driven from the low electric demand and the coverage of the demand from the WHR system or shaft generator. Therefore, despite the fact that the method is generic and can be applied to different ship types, it is possible that it is not as sensitive regarding energy sub-systems that have a small contribution to the objectives. For instance, in some ship types like the containerships, which have very low thermal demand it is possible that the thermal sub-system will not be as robust. This is a potential limitation of the proposed method. However, in order to address this issue, an uncertainty analysis was performed for the most significant input parameters and the robustness of the solutions was investigated. Investigation of other ship types could provide further insight on this issue.

The findings from the two case studies results were analysed and interpreted only by the author and the academic supervisors, which can be considered a disadvantage. The interpretation of the case study results by industry experts may have offered additional insight regarding the method and the findings. However, the results were compared with previous publications, as it was discussed in the method qualification, verification and validation, exhibiting a convergence with the existing literature. Therefore, it was indicated that the findings sufficiently represent reality. In the future, industry experts with greater knowledge could be involved to provide an evaluation of the findings.

8.4.3 Data challenges

Modelling and optimising the ship energy systems required access to relevant input data, whose accuracy was of great importance due to their influence on the results. Different sources of data were used including online sources, the existing literature, technical reports and shipboard measurements. It is evident though that the inclusion of technical reports and shipboard measurements was crucial.

The mathematical models that are used to estimate the performance of the ship energy systems affect strongly the optimisation of the configurations. In the marine industry, several engine manufacturers offer a great number of products with different performance. In order for the mathematical models to accurately represent reality the available engines and sizes of engines should be considered. Access and documentation of all the available engines was out of the scope of this work. However, products from two main marine engine manufacturers were included with a wide range of engines sizes for the specific case studies. It is concluded that further investigation is required to understand, whether the involvement of additional engine manufacturers would lead to more representative mathematical models.

Furthermore, emerging technologies were considered including the fuel cells and carbon capture system. The technologies were modelled according to data found in the literature, however there were limited resources regarding their performance, especially technical reports. In the uncertainty analysis performed, the technical parameters were included, therefore handling the uncertainty of the input parameters. However, a further exploration on the performance of the emerging technologies would provide a better insight on the findings.

8.4.4 Discussion of the case studies findings

Another reflection on the findings from the two case studies stems from the cross comparison of the two presented case studies and similarities identified on the optimal technologies. A question that arises is whether the results generated from the case studies can be generalised to other ship types, therefore in the proceeding discussion the findings are compared to the existing literature.

It was evident from the results that the most promising configurations operate with natural gas, indicating that this fuel will be dominant. Similar results were identified in the literature (see section 2.3), where it was also observed that the natural gas will be dominant also for other ship types like containerships and passenger ferries.

The waste heat recovery technology was dominant in the near optimal configurations for both ship case studies, illustrating the potential of this technology to improve the ship energy systems sustainability. Similar results were identified in the literature (see Section 2.5), where the benefits of the WHR on different ship types including bulk carriers, passenger, tankers and cruise ships were highlighted.

Fuel cells have gained great attention for ships. In this work, they were identified as near optimal to support electric power both for the tanker and the cruise ships, however for the tanker their power contribution was significantly lower compared to the cruise ship. From both case studies, it was evident that fuel cells manage to improve the ship environmental impact but the accompanied life cycle cost and specifically capital cost increase is significant. In the case of the cruise ship, this was more evident. The positive impact of fuel cells in shipping is recognised and their application on different ship types in investigated and considered as a potential solution in order to mitigate the ship emissions. This is highlighted in Tronstad et al. (2017), where the various projects on fuel cells applications on commercial, passenger, cruise and service vessels are discussed.

The carbon capture technology, even though has high capital cost, was recognised on the near optimal solutions for both case studies, where the carbon emissions is the key objective, indicating the benefits of this technology to improve the ship energy systems carbon footprint. However, it is a novel technology for ships compared to land based power plants and more research is needed for various issues, including the installation and space constraints, as well as the technology high cost. Few occasions are identified in the literature on cargo ships (Wang et al., 2017; Zhou and Wang, 2014), whereas DNV with PSE are working on a project to promote carbon capture on ships (PSE Ltd, 2013).

Therefore, the findings confirm other literature outputs, which is a strong indication that the aforementioned technologies in to some extend can be considered to be representative for different ship types. However, this needs to be confirmed by performing more investigations for ships with significantly different characteristics.

Comparing the findings from the sensitivity analysis of the two case studies, it is evident that the changes on the fuel prices and emerging technologies have different implications on the two investigated ships. For the tanker ship, the variations on the fuel prices along with the carbon capture cost affect significantly the life cycle cost. On the other hand, for the cruise ship the fuel cells and fuel prices are the most important costs. This differentiation is justified by the solutions break down cost presented for the two case studies. As a result, the findings from this section depend on the ship type and cannot be generalised.

8.5 Research contribution

In this section, the significant contribution of the undertaken research in this thesis as well as the contribution to the academia and the industry is discussed.

8.5.1 Theoretical implications

The significant contribution of this work to knowledge is the decision support method for ship energy systems that considers both environmental and economic objectives and optimises the ship energy systems performance over the ship lifetime according to a real operating profile.

This is the first study that introduces the environmental objective, while performing multi-objective optimisation for the ship energy systems synthesis. It was identified from the critical review that considering the integrated environmental and economic dimension of sustainability is critical in order to improve sustainability. Specifically, decision support methods for sustainable energy systems demonstrated the importance of integrating the environmental objective along with the economic. However, the state-of-the-art studies on ship energy systems synthesis optimisation (see Section 2.5) consider only the economic objective (Balland et al., 2014; Dimopoulos et al., 2008b; Kalikatzarakis and Frangopoulos, 2016; Sakalis and Frangopoulos, 2018; Tzortzis and Frangopoulos, 2018). Even though, several studies aimed at improving the environmental impact of ship energy systems by introducing greener technologies or fuels, there was a lack in including the environmental objectives in the optimisation process. Therefore, this work advances the state-of-the-art in the field of sustainable ship energy systems synthesis.

In specific, this is the first work on ship energy synthesis optimisation that introduces the exhaust gas emissions as an objective in the synthesis optimisation of the ship energy systems. The significance of optimising the exhaust gas emissions of the energy systems was demonstrated in the pertinent literature review of energy systems. In the existing literature on ship energy systems decision support, there are very few studies where authors considered the exhaust gas emissions when assessing the ship energy systems performance. In the majority of the cases presented in Section 2.5, the exhaust gas emissions of few alternative ship energy systems components were estimated and their performance was used to compare the alternatives (Ahn et al., 2017; Ammar and Seddiek, 2018; Armellini et al., 2018; Baldi et al., 2013; Burel et al., 2013; Corbett, Lack, et al., 2010; Gaspar et al., 2014; Jiang et al., 2014; Mavrelos and Theotokatos, 2018; Yang et al., 2012). This indicates that the ship energy systems emissions are an essential criterion when selecting the ship energy systems components. Optimisation methods that included the exhaust gas emissions as objectives were limited and the optimisation was on the operation or design of the ship energy systems (Ancona et al., 2018; Jianyun et al., 2018; Kalikatzarakis and Frangopoulos, 2015; Lan et al., 2015) with focus on the carbon emissions but none addressed the systems synthesis. As a result, the proposed method introduces the exhaust gas emissions objective, considering the most significant exhaust gas emissions from ships, in the synthesis optimisation.

Other researchers could build on this method by adding more objectives and performing a holistic analysis of the ship energy systems configuration. The proposed method is flexible and could be adapted to include more objectives in the optimisation process, including other emissions, reliability or social indicators. In addition, the results could be used in different applications for a more detailed analysis of the proposed configurations. The design and operational optimisation of the proposed configuration could be performed, in order to identify in more detail, the ship energy systems components and their optimal operating point. Moreover, the optimal configurations could be employed by energy and exergy, as well as safety and reliability analyses.

In this thesis, typical operating profiles presented in Chapters 6 and 7 were used to evaluate the performance of the ship energy systems. The pertinent literature in Section 2.3.2, indicated the importance of considering the ship expected operating profile, when evaluating the ship energy systems performance in the design phase (Ahlgren et al., 2015). Especially, since the real operating profile differs from the design conditions (Coraddu et al., 2014) and the fluctuations of the variable ship operating profile of different merchant ships was presented by Banks et al. (2013). Most of the work related to the ship energy systems synthesis optimisation (see Section 2.5) focuses on limited well defined operating phases with an assumption of the time spend in each operation and the required power (Balland et al., 2014; Dimopoulos et al., 2008b; Kalikatzarakis and Frangopoulos, 2016; Sakalis and Frangopoulos, 2018; Tzortzis and

Frangopoulos, 2018). However, this approach with the typical operating phases partially represents the ship operation and fluctuations of the operating profile (Baldi, 2016). Therefore, this method indicates a way to take into consideration the real ship operation in the synthesis optimisation.

Other researchers could build on this method and different technologies, alternative fuels and even future technologies can be investigated for the current or imminent regulations. The optimisation problem in this thesis is formulated as a multi-objective combinatorial optimisation; therefore, the proposed method manages to support decisions regarding the synthesis of integrated energy systems. This allows to consider multiple alternative technologies for the ship energy systems, compared to the current studies on ship energy systems synthesis optimisation (see Table 2.4 of Section 2.5) that considered a specific technology for the main engine, thermal boiler and electric auxiliary machinery, as well as their fuel type. Therefore, the formulation of the problem as a combinatorial allows to introduce more than one technological options for the ship energy systems.

A final contribution to the theory stems from the carbon pricing scenarios analysis. The investigation of the near optimal configurations under different scenarios indicated the impact of the carbon price on the configurations. In addition, it helped to identify the carbon price, at which the high cost technologies, like the carbon capture technology become competitive. Other emerging technologies and alternative fuels could be introduced and the proposed method could be employed to identify the ‘tipping point’ that the investigated technologies become a viable economically option.

8.5.2 Implications to shipping industry

The method of the undertaken research offers extensive applications for the shipping industry, the ship-owners, manufacturers as well as policymakers. In the following paragraphs, the implications of the developed method to shipping stakeholders are demonstrated.

8.5.2.1 Implications for policymakers

The presented method can provide decision support to regulatory bodies in order to test existing tools and future policies. The regulations could be introduced as a constraint in the method to identify whether they manage to reduce the gas emissions and if the existing ship energy systems configurations can comply with the regulations. The usefulness of the method for the policy makers was evident from the valuable information regarding the EEDI regulation. First, it was identified that the operating profile should not be overlooked in the future regulations. Considering only one design speed, like the EEDI is inaccurate and does not manage to capture the real carbon footprint of the configurations. As a result, it does not provide incentives for the ship-owners to adopt greener technologies, whereas the lifetime emissions is a more representative metric. Therefore, adopting the lifetime CO_2 emissions metric leads to the promotion of green solutions and decarbonisation of the shipping industry. As a result, the method also proposes metrics that could be used in the future from the policy makers to regulate the ship energy systems.

As it was discussed in Chapter 1, ship emissions policy is an imminent regulation in the shipping industry and the method could support the policymakers introduce future emission policies. Similar with the analysis presented in this thesis, where the impact of the carbon policy scenarios on the ship energy systems synthesis was investigated for a cruise ship. In specific, the method could be beneficial in identifying potential optimal configurations with the current and emerging technologies for future policy scenarios. As a result, inform the policymakers first for the prospective technologies to cope with the policies and second answering the question whether the existing technologies can cope with the potential regulations. Moreover, the economic impact of the future regulations on the ship energy systems life cycle cost could be quantified with the presented method, offering a better insight on the development of the regulations.

Furthermore, introduction of taxation on the bunker fuels is considered recently to be introduced by the regulatory bodies (Hemmings, 2011), in order to promote more sustainable fuels. The proposed method could be employed to support the policymakers decide the potential fuel taxation. Different fuel taxation scenarios could be simulated and the life cycle cost of the solutions could be estimated in order to identify the impact of the fuels taxation on the ship life cycle cost. In addition the solutions identified in the Pareto front could provide an indication of the optimal potential fuel mix. The future fuel mix identification could guide also the required infrastructures for bunker fuels.

Finally, the presented method was applied on two different merchant ship types that constitute a great volume of the merchant fleet and have a high impact on the global emissions and ship fuel consumption. The lifetime emissions were estimated for different established and emerging ship energy systems technologies that are not extensively employed yet. If the representative results for the tanker and cruise ship fleet were multiplied by the number of existing ships on the fleet this could provide a rough estimation of the whole tanker and cruise ship lifetime emissions magnitude. Therefore, the results could be beneficial for policymakers providing an indicative projection of the tanker and cruise ship fleet emissions for the state-of-the-art and future technologies. Considering that these ships are dominant in the global fleet, these estimations provide an understanding of the magnitude of the global emissions from ships and whether with the emerging technologies the emissions targets can be met.

8.5.2.2 Implications for ship-owners and operators

Subsequently, the implications of the proposed method to ship-owners and operators are discussed. The method could be beneficial for the ship-owners and operators to make more sustainable decisions that will allow improving on the ship energy systems environmental impact, compliance with the regulations while reducing the ship life cycle cost. This could be done by applying the method for different ship types and technologies therefore identifying a range of alternative optimal configurations by the optimisation. This is very useful during the decision making process especially for investments that have 25 years lifetime, rather than presenting just one single solution. Therefore, the visualisation of those near optimal alternatives allows the ship-owners to understand and manage the trade-offs of the conflicting objectives. The analysis indicated that the current configuration does not belong to the near optimal solutions and configurations with natural gas operating systems perform better in both economic and environmental objectives. Specifically, in the case of potential carbon policies scenarios, the significant carbon cost on the current configuration life cycle cost renders it prohibitive. Moreover, the presented method can be applied for different policy scenarios providing an insight on the near optimal configurations according to the future regulations. By providing both the economic and environmental objectives it can be quantified how much it needs to be spent in order to achieve a lower environmental footprint.

The method was applied into two ship types, an Aframax tanker and a cruise ship. The derived results can be found in Chapters 6 and 7, providing the ship-owners a detailed analysis and discussion of the near optimal configurations for the specific ship types. However, the method is modular and flexible therefore can provide the near optimal configurations of other merchant ship types. The mathematical models need to be adapted and the specific characteristics and operating requirements should be provided. As a result, it can be employed in different types of ship by ship-owners and operators and with some adaptations identify the near optimal ship energy systems configurations.

The proposed method can support the ship-owners with handling the input parameters uncertainty by applying the method for different probability density functions of the uncertain parameters. Therefore, the method can identify the dominant solutions in an uncertain environment, which is critical for long-term investments. In addition, the impact of the most critical economic parameters on the near optimal solutions life cycle cost is provided by the sensitivity analysis, supporting the ship-owner understand the investment risks.

Furthermore, the inclusion of the operating profile and the degradation factors in the synthesis process leads into selecting the ship energy systems configurations based on the operational lifetime. This proposed approach is more realistic compared to the current status in the industry, where one design point is used, providing more accurate estimations of the ship energy systems performance. As a result, the method can be employed for different ship types to simulate the lifetime performance of a specific configuration and therefore the ship-owners and operators can have a more accurate estimation of the ship lifetime emissions and operating cost. This is significant for the operators, providing support in selecting to charter the ship with the optimal lifetime economic and environmental performance.

The method could support the ship-owner and operators to get a better understanding regarding the near optimal configuration for different operational management practices after running the computational model for various operating profiles. As a result, it would be identified how the near optimal configurations are affected by the operation of the vessel.

The method could also be adapted to support decisions for ship retrofitting. The mathematical models could be used to estimate the performance of different retrofitting design options; making sure that the interactions between the ship energy systems components are investigated and the behaviour of the new design is estimated according to the operating requirements. Therefore, help identify the near optimal retrofitting design.

It was derived from the semi-structured interviews that the ship energy systems selection depends heavily on the standardised designs of the shipyards. The developed method is flexible and therefore it is possible to add more technologies and fuel choices according to the ship-owners preferences or the proposed designs from the shipyards they collaborate. As a result, the method could be employed to identify the shipyard that offers the most environmental and economic sustainable solutions.

Alternative future policy scenarios could be investigated by the proposed method enabling ship-owners and operators to identify optimal configurations for the different policy scenarios. As a result, help them have a better understanding on the challenges they may face in the future. In specific have an insight on the economic impact of policy scenarios, as well as the challenges to cope with the future regulations with the established technologies. Furthermore, the proposed method could be employed to identify the future optimal fuel mix according to the potential fuels taxation.

In addition, the estimation of the EEDI provided beneficial information for the ship-owners. The current configurations did not comply with the future phases of EEDI; therefore, it appears obligatory to identify alternative configurations. The decision support method could be employed to propose near optimal configurations for the new design in order to comply with the future EEDI phases.

8.5.2.3 Implications for marine technology manufacturers

The section 8.5.3 that discusses the implication to shipping industry was amended to include discussion on how the outputs of the tool can be used to support the different stakeholders (see section 8.5.3). Focus was placed on the manufacturers as it was discussed during the viva examination as follows:

8.5.2.4 Implications for policymakers

The presented method can provide decision support to regulatory bodies in order to test existing tools and future policies. The regulations could be introduced as a constraint in the method to identify whether they manage to reduce the gas emissions and if the existing ship energy systems configurations can comply with the regulations. The usefulness of the method for the policy makers was evident from the valuable information regarding the EEDI regulation. First, it was identified that the operating profile should not be overlooked in the future regulations. Considering only one design speed, like the EEDI is inaccurate and does not manage to capture the real carbon footprint of the configurations. As a result, it does not provide incentives for the ship-owners to adopt greener technologies, whereas the lifetime emissions is a more representative metric. Therefore, adopting the lifetime CO_2 emissions metric leads to the promotion of green solutions and decarbonisation of the shipping industry. As a result, the method also proposes metrics that could be used in the future from the policy makers to regulate the ship energy systems.

As it was discussed in Chapter 1, ship emissions policy is an imminent regulation in the shipping industry and the method could support the policymakers introduce future emission policies. Similar with the analysis presented in this thesis, where the impact of the carbon policy scenarios on the ship energy systems synthesis was investigated for a cruise ship. In specific, the method could be beneficial in identifying potential optimal configurations with the current and emerging technologies for future policy scenarios. As a result, inform the policymakers first for the prospective technologies to cope with the policies and second answering the question whether the existing technologies can cope with the potential regulations. Moreover, the economic impact of the future regulations on the ship energy systems life cycle cost could be quantified with the presented method, offering a better insight on the development of the regulations.

Furthermore, introduction of taxation on the bunker fuels is considered recently to be introduced by the regulatory bodies (Hemmings, 2011), in order to promote more sustainable fuels. The proposed method could be employed to support the policymakers decide the potential fuel taxation. Different fuel taxation scenarios could be simulated and the life cycle cost of the solutions could be estimated in order to identify the impact of the fuels taxation on the ship life cycle cost. In addition the solutions identified in the Pareto front could provide an indication of the optimal potential fuel mix. The future fuel mix identification could guide also the required infrastructures for bunker fuels.

Finally, the presented method was applied on two different merchant ship types that constitute a great volume of the merchant fleet and have a high impact on the global emissions and ship fuel consumption. The lifetime emissions were estimated for different established and emerging ship energy systems technologies that are not extensively employed yet. If the representative results for the tanker and cruise ship fleet were multiplied by the number of existing ships on the fleet this could provide a rough estimation of the whole tanker and cruise ship lifetime emissions magnitude. Therefore, the results could be beneficial for policymakers providing an indicative projection of the tanker and cruise ship fleet emissions for the state-of-the-art and future technologies. Considering that these ships are dominant in the global fleet, these estimations provide an understanding of the magnitude of the global emissions from ships and whether with the emerging technologies the emissions targets can be met.

8.5.2.5 Implications for ship-owners and operators

Subsequently, the implications of the proposed method to ship-owners and operators are discussed. The method could be beneficial for the ship-owners and operators to make more sustainable decisions that will allow improving on the ship energy systems environmental impact, compliance with the regulations while reducing the ship life cycle cost. This could be done by applying the method for different ship types and technologies therefore identifying a range of alternative optimal configurations by the optimisation. This is very useful during the decision making process especially for investments that have 25 years lifetime, rather than presenting just one single solution. Therefore, the visualisation of those near optimal alternatives allows the ship-owners to understand and manage the trade-offs of the conflicting objectives. The analysis indicated that the current configuration does not belong to the near optimal solutions and configurations with natural gas operating systems perform better in both economic and environmental objectives. Specifically, in the case of potential carbon policies scenarios, the significant carbon cost on the current configuration life cycle cost renders it prohibitive. Moreover, the presented method can be applied for different policy scenarios providing an insight on the near optimal configurations according to the future regulations. By providing both the economic and environmental objectives it can be quantified how much it needs to be spent in order to achieve a lower environmental footprint.

The method was applied into two ship types, an Aframax tanker and a cruise ship. The derived results can be found in Chapters 6 and 7, providing the ship-owners a detailed analysis and discussion of the near optimal configurations for the specific ship types. However, the method is modular and flexible therefore can provide the near optimal configurations of other merchant ship types. The mathematical models need to be adapted and the specific characteristics and operating requirements should be provided. As a result, it can be employed in different types of ship by ship-owners and operators and with some adaptations identify the near optimal ship energy systems configurations.

The proposed method can support the ship-owners with handling the input parameters uncertainty by applying the method for different probability density functions of the uncertain parameters. Therefore, the method can identify the dominant solutions in an uncertain environment, which is critical for long-term investments. In addition, the impact of the most critical economic parameters on the near optimal solutions life cycle cost is provided by the sensitivity analysis, supporting the ship-owner understand the investment risks.

Furthermore, the inclusion of the operating profile and the degradation factors in the synthesis process leads into selecting the ship energy systems configurations based on the operational lifetime. This proposed approach is more realistic compared to the current status in the industry, where one design point is used, providing more accurate estimations of the ship energy systems performance. As a result, the method can be employed for different ship types to simulate the lifetime performance of a specific configuration and therefore the ship-owners and operators can have a more accurate estimation of the ship lifetime emissions and operating cost. This is significant for the operators, providing support in selecting to charter the ship with the optimal lifetime economic and environmental performance.

The method could support the ship-owner and operators to get a better understanding regarding the near optimal configuration for different operational management practices after running the computational model for various operating profiles. As a result, it would be identified how the near optimal configurations are affected by the operation of the vessel.

The method could also be adapted to support decisions for ship retrofitting. The mathematical models could be used to estimate the performance of different retrofitting design options; making sure that the interactions between the ship energy systems components are investigated and the behaviour of the new design is estimated according to the operating requirements. Therefore, help identify the near optimal retrofitting design.

It was derived from the semi-structured interviews that the ship energy systems selection depends heavily on the standardised designs of the shipyards. The developed method is flexible and therefore it is possible to add more technologies and fuel choices according to the ship-owners preferences or the proposed designs from the shipyards they collaborate. As a result, the method could be employed to identify the shipyard that offers the most environmental and economic sustainable solutions.

Alternative future policy scenarios could be investigated by the proposed method enabling ship-owners and operators to identify optimal configurations for the different policy scenarios. As a result, help them have a better understanding on the challenges they may face in the future. In specific have an insight on the economic impact of policy scenarios, as well as the challenges to cope with the future regulations with the established technologies. Furthermore, the proposed method could be employed to identify the future optimal fuel mix according to the potential fuels taxation.

In addition, the estimation of the EEDI provided beneficial information for the ship-owners. The current configurations did not comply with the future phases of EEDI; therefore, it appears obligatory to identify alternative configurations. The decision support method could be employed to propose near optimal configurations for the new design in order to comply with the future EEDI phases.

8.5.2.6 Implications for marine technology manufacturers

The method could be beneficial for marine technology manufacturers. Mathematical models were developed for the different available technologies for the ship energy systems. As a result, the method could be employed to compare the competitive technologies regarding their environmental and economic lifetime performance on the ship energy systems. The outputs of this comparison could be used from the manufacturers first to improve the performance of their technologies or second as a promotion against their competitors.

In addition, the method could be useful for manufacturers to help them identify the technologies they should invest on. The method is flexible to include different mature and emerging technologies, therefore the results indicate which of the considered technologies have the best performance regarding economic and environmental objectives. In specific, by applying the method for future potential regulations it can help identify, which emerging technologies can comply with these regulations. The results, from the cruise ship application for different policy scenarios contributed in identifying that carbon capture technology and fuel cells will be the most economically viable solutions in an extreme scenario. This could be used as an indication for which emerging technologies will be most promising in the future and therefore it is worth investing on.

The method could be adapted to identify the near optimal configurations for different cost scenarios of specific technologies. This could be useful for the manufacturers to investigate for which capital cost the specific technologies are identified as optimal, as a result support them in recognising the pricing of the technologies. In addition, for emerging technologies as it was indicated for the carbon capture, when extreme carbon policy scenarios were investigated then this technology regardless of the high capital cost was identified as optimal. Therefore, this method could support the manufacturers for the pricing of emerging technologies according to the regulatory status.

Furthermore, the method proposes optimal configurations that include the integrated ship energy systems, however the majority of the manufacturers produce specific subsystems. Therefore, the findings of the optimal configurations could be used as an indication of potential collaboration with manufacturers of other subsystems in order to propose optimal integrated ship energy systems.

8.6 Future research recommendations

Through this research, a number of points for improvement and future investigations were identified. The following areas are recommended for future research:

- In future studies it would be important to develop a set of typical operating profiles for different ship types. In this work, the synthesis of the ship energy systems was performed according to expected operating profiles. However, the data in academic sources are limited and from industry sources, it is not easy to access them. Moreover, in the limited cases that the operational data are recorded shipboard they need extensive analysis, as there is a great part of inaccurate data.

- In future research, additional technologies and fuels that seem prominent but are currently at very early maturity stages can be considered, like hydrogen fuel, other types of fuel cells, as well as different power plant configurations, like hybrids etc. In the case studies presented in this thesis, the technologies and the configurations considered were driven from the literature and interviews with industry experts. However, specific technological requirements from a designer or ship-owner could be included in a customised application.
- In future work, methods that can optimise the configuration considering both steady-state and transient conditions should be identified. In that respect batteries could be included in the alternative technologies.
- In future studies, the method could be extended to provide a set of near optimal solutions regarding the whole ship systems. The developed method herein was focused on the main ship energy systems excluding for example other energy systems like the ventilation or navigation system or the hull and propeller. However, the challenge in optimising holistically the ship systems, lies in the fact that the problem becomes very complex and the algorithm might not be able to identify the near optimal ship systems.
- The decision support method was developed to provide a set of near optimal solutions, giving the decision maker the opportunity to manage the trade-offs among the solutions and select among them. As a future work, the results from the Pareto front could be employed by a multi-criteria analysis method and a single optimal solution could be derived. However, in that case the decision maker is required to provide subjective weights for each objective.
- In this work, the optimisation of the ship energy systems is according to sustainability objectives, however the social aspect was not considered. As it was discussed in previous chapters, there are limited resources of data to assess the social impact of energy systems and especially ship energy systems due to their offshore nature. In future studies, the social aspect of ship energy systems sustainability impact could be investigated and potentially be combined with the other dimensions of sustainability.

8.7 Concluding remarks

In the past few years, there has been a growing interest to enhance the sustainability of shipping operations due to their significant economic and environmental impact. Ship energy systems have the most significant impact on the energy consumption and emissions, as well as the operational cost of the ship lifetime. Therefore, interest has been placed to the development of technologies, as well as investigation of alternative fuels and configurations aiming to improve the environmental and economic performance of the ship energy systems. The great number of established and emerging technologies, alternative fuels and the possible combinations among them renders the technology selection for the ship energy systems challenging.

The proposed method supports decisions for the ship energy systems synthesis with respect to environmental and economic sustainability objectives, whilst considering the systems lifetime operating requirements. Mathematical models of both established and emerging technologies were developed to estimate the energy systems performance during the ship lifetime. The ship energy systems technical, environmental and economic performance was assessed and optimised according to an expected operating profile. The genetic algorithm NSGA-II was employed to solve the multi-objective combinatorial optimisation problem of selecting the integrated ship energy systems configuration. The derived results were visualised to reveal the Pareto front of optimal solutions.

The developed method was implemented in two case studies, an Aframax oil tanker and a cruise ship vessel. The visualisation of the near optimal configurations allows the decision makers to understand and manage the trade-offs of the conflicting objectives. In both case studies, it was identified that the current configuration does not belong to the near optimal solutions and the most promising configurations consist of natural gas operating sub-systems. The potential benefits of emerging technologies like fuel cells and carbon capture system were demonstrated.

The EEDI value was estimated for the solutions derived from the optimisation. The results indicated the benefits of the proposed method to propose solutions to mitigate the carbon emissions compared to the EEDI, which does not manage to capture the real carbon impact of the configurations. Uncertainty analysis on the parameters of the model was performed demonstrating the robustness of the solutions under different circumstances. The sensitivity analysis of the most critical economic parameters on the optimal solutions was explored and the estimated ranges of the configurations life cycle cost support the decision maker mitigate the uncertainty of a long-term investment. Different operating profiles were investigated indicating how the near optimal configurations are affected by the ship operation. Finally, the near optimal configurations were explored under alternative future carbon policy scenarios, in order to attain a better understanding on the most prominent future configurations under each scenario.

References

Abadie, L.M., Goicoechea, N. and Galarraga, I. (2017), “Adapting the shipping sector to stricter emissions regulations: Fuel switching or installing a scrubber?”, *Transportation Research Part D: Transport and Environment*, Elsevier, Vol. 57 No. October, pp. 237–250.

Abul’Wafa, A.R. (2013), “Optimization of economic/emission load dispatch for hybrid generating systems using controlled Elitist NSGA-II”, *Electric Power Systems Research*, Elsevier B.V., Vol. 105, pp. 142–151.

Afgan, N.H., Carvalho, M.G. and Hovanov, N. V. (2000), “Energy system assessment with sustainability indicators”, *Energy Policy*, Vol. 28 No. 9, pp. 603–612.

Ahlgren, F., Mondejar, M.E., Genrup, M. and Thern, M. (2015), “Waste Heat Recovery in a Cruise Vessel in the Baltic Sea by Using an Organic Rankine Cycle: A Case Study”, *Journal of Engineering for Gas Turbines and Power*, Vol. 138 No. 1, p. 011702.

Ahn, J., Park, S.H., Lee, S., Noh, Y. and Chang, D. (2018), “Molten carbonate fuel cell (MCFC)-based hybrid propulsion systems for a liquefied hydrogen tanker”, *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 43 No. 15, pp. 7525–7537.

Ahn, J., You, H., Ryu, J. and Chang, D. (2017), “Strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker”, *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 42 No. 8, pp. 5366–5380.

AIAA. (1998), *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*.

Alibaba.com. (2018), “Global trade starts here”, available at: https://www.alibaba.com/?spm=a2700.7724857.scGlobalHomeHeader.6.179f4935PBhocC.

Alkaner, S. and Zhou, P. (2006), “A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application”, *Journal of Power Sources*, Vol. 158 No. 1, pp. 188–199.

Alvik, S., Eide, M.S., Endresen, O., Hoffmann, P. and Longva, T. (2009), *Pathways to Low Carbon Shipping - Abatement Potential towards 2030*.

Ammar, N.R. and Seddiek, I.S. (2018), “Thermodynamic, environmental and economic analysis of absorption air conditioning unit for emissions reduction onboard passenger ships”, *Transportation Research Part D: Transport and Environment*, Elsevier, Vol. 62, pp. 726–738.

Ancona, M.A., Baldi, F., Bianchi, M., Branchini, L., Melino, F., Peretto, A. and Rosati, J. (2018), “Efficiency improvement on a cruise ship: Load allocation optimization”, *Energy Conversion and Management*, Vol. 164 No. February, pp. 42–58.

Anderson, K. and Bows, A. (2012), “Executing a Scharnow turn: reconciling shipping emissions with international commitments on climate change”, *Carbon Management*, Vol. 3 No. 6, pp. 615–628.

Andersson, K., Brynolf, S., Lindgren, F.J. and Wilewska, M. (2016), *Shipping and the Environment: Improving Environmental Performance in Marine Transportation*, *New York*, 1st ed., Springer, Berlin, available at:https://doi.org/10.1007/978-3-662-49045-7.

Andersson, K. and Márquez Salazar, M. (2015), *Methanol as a Marine Fuel*.

Angelakoglou, K. and Gaidajis, G. (2015), “A review of methods contributing to the assessment of the environmental sustainability of industrial systems”, *Journal of Cleaner Production*, Elsevier Ltd, available at:https://doi.org/10.1016/j.jclepro.2015.06.094.

Armellini, A., Daniotti, S., Pinamonti, P. and Reini, M. (2018), “Analysis of alternative energy production systems for a large cruise ship to meet new IMO regulations. Part A: GTs as prime movers”, *Applied Energy*, Elsevier, Vol. 211 No. October 2017, pp. 306–317.

Armstrong, V.N. and Banks, C. (2015), “Integrated approach to vessel energy efficiency”, *Ocean Engineering*, Vol. 110, pp. 39–48.

Asariotis, R. and Benamara, H. (2012), “Review of Maritime Transport, 2012”, *UNCTAD Report*, available at:https://doi.org/10.1017/CBO9781107415324.004.

Atkinson, G.M. (2016), “Analysis of marine solar power trials on Blue Star Delos”, *Journal of Marine Engineering & Technology*, Vol. 15 No. 3, pp. 115–123.

Azapagic, A. (1999), “Life cycle assessment and its application to process selection, design and optimisation”, *Chemical Engineering Journal*, Vol. 73 No. 1, pp. 1–21.

Babuska, I. and Oden, J.T. (2004), “Verification and validation in computational engineering and science: basic concepts”, *Computer Methods in Applied Mechanics and Engineering*, Vol. 193

No. 36–38, pp. 4057–4066.

Bader, J., Deb, K. and Zitzler, E. (2010), "Faster Hypervolume-Based Search Using Monte Carlo Sampling.", in Ehrgott, M., Naujoks, B., Stewart, T. and Wallenius, J. (Eds.), *Multiple Criteria Decision Making for Sustainable Energy and Transportation Systems. Lecture Notes in Economics and Mathematical Systems*, Vol. 634, Springer Berlin Heidelberg, available at:https://doi.org/https://doi.org/10.1007/978-3-642-04045-0_27.

Bagchi, T.P. (1999), *Multiobjective Scheduling by Genetic Algorithms*, available at:https://doi.org/10.1007/978-1-4615-5237-6_6.

Baldi, F. (2013), *Improving Ship Energy Efficiency through a Systems Perspective*, Chalmers University of Technology.

Baldi, F. (2016), *Modelling , Analysis and Optimisation of Ship Energy Systems PhD Thesis*, Chalmers University of Technology.

Baldi, F., Ahlgren, F., Melino, F., Gabrielii, C. and Andersson, K. (2016), "Optimal load allocation of complex ship power plants", *Energy Conversion and Management*, Vol. 124, pp. 344–356.

Baldi, F., Ahlgren, F., Nguyen, T. Van, Thern, M. and Andersson, K. (2018), "Energy and exergy analysis of a cruise ship", *Energies*, Vol. 11 No. 10, available at:https://doi.org/10.3390/en11102508.

Baldi, F., Ahlgren, F., Nguyen, T.V., Gabrielii, C. and Andersson, K. (2015), "Energy and exergy analysis of a cruise ship", *Efficiency Cost Optimisation Simulation and Environmental Impact of Energy Systems*, France.

Baldi, F., Bengtsson, S. and Andersson, K. (2013), "The influence of propulsion system design on the carbon footprint of different marine fuels", *Low Carbon Shipping Conference*, pp. 1–12.

Baldi, F. and Gabrielii, C. (2015), "A feasibility analysis of waste heat recovery systems for marine applications", *Energy*, Elsevier Ltd, Vol. 80, pp. 654–665.

Baldi, F., Gabrielii, C., Melino, F. and Bianchi, M. (2015), "A preliminary study on the application of thermal storage to merchant ships", *Proceedings of the International Conference on Applied Energy*, Vol. 75, Elsevier B.V., pp. 2169–2174.

Baldi, F., Johnson, H., Gabrielii, C. and Andersson, K. (2015), "Energy and exergy analysis of ship energy systems – the case study of a chemical tanker", *International Journal of Thermodynamics*, Vol. 18, available at:https://doi.org/10.5541/ijot.5000070299.

Baldi, F., Marechal, F. and Tammi, K. (2017), "Process integration as a tool for the improvement of cruise ships energy efficiency", *Conference: Shipping in Changing Climates*, London, UK.

Baldi, F., Nguyen, T.V. and Ahlgren, F. (2016), "The application of process integration to the optimisation of cruise ship energy systems : a case study", *Internatiomal Conference on Efficiency Cost Optimisation Simulation and Environmental Impact of Energy Systems*.

Baldi, F., Wang, L., Pérez-Fortes, M. and Maréchal, F. (2019), "A Cogeneration System Based on Solid Oxide and Proton Exchange Membrane Fuel Cells With Hybrid Storage for Off-Grid Applications", *Frontiers in Energy Research*, Vol. 6 No. January, available at:https://doi.org/10.3389/fenrg.2018.00139.

Balland, O., Erikstad, S.O. and Fagerholt, K. (2014), "Concurrent design of vessel machinery system and air emission controls to meet future air emissions regulations", *Ocean Engineering*, Elsevier, Vol. 84, pp. 283–292.

Balland, O., Erikstad, S.O., Fagerholt, K. and Wallace, S.W. (2013), "Planning vessel air emission regulations compliance under uncertainty", *Journal of Marine Science and Technology (Japan)*, Vol. 18 No. 3, pp. 349–357.

Balland, O., Ove Erikstad, S. and Fagerholt, K. (2012), "Optimized selection of air emission controls for vessels", *Maritime Policy & Management*, Vol. 39 No. 4, pp. 387–400.

Balsamo, F., Capasso, C., Miccione, G. and Veneri, O. (2017), "Hybrid Storage System Control Strategy for All-Electric Powered Ships", *Energy Procedia*, Elsevier B.V., Vol. 126, pp. 1083–1090.

Banawan, A.A., El Gohary, M.M. and Sadek, I.S. (2010), "Environmental and economical benefits of changing from marine diesel oil to natural-gas fuel for short-voyage high-power passenger ships", *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, Vol. 224 No. 2, pp. 103–113.

Banks, C., Turan, O., Incecik, A., Theotokatos, G., Izkan, S., Shewell, C. and Tian, X. (2013), "Understanding Ship Operating Profiles with an Aim to Improve Energy Efficient Ship Operations", *Low Carbon Shipping Conference*, pp. 1–11.

Bassam, A.M., Phillips, A.B., Turnock, S.R. and Wilson, P.A. (2016), "An improved energy management strategy for a hybrid fuel cell/battery passenger vessel", *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 41 No. 47, pp. 22453–22464.

Basurko, O.C. and Mesbahi, E. (2014), "Methodology for the sustainability assessment of marine technologies", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 68, pp. 155–164.

Bazmi, A.A. and Zahedi, G. (2011), "Sustainable energy systems: Role of optimization modeling techniques in power generation and supply - A review", *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, Vol. 15 No. 8, pp. 3480–3500.

Bejan, A., Tsatsaronis, G. and Moran, M. (1996), *Thermal & Design Optimization*, John Wiley and Sons, New York.

Bengtsson, S., Andersson, K. and Fridell, E. (2011), "A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels", *Journal of Engineering for the Maritime Environment*, Vol. 225, pp. 97–110.

Bensaid, S., Specchia, S., Federici, F., Saracco, G. and Specchia, V. (2009), "MCFC-based marine APU: Comparison between conventional ATR and cracking coupled with SR integrated inside the stack pressurized vessel", *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 34 No. 4, pp. 2026–2042.

Benvenuto, G., Campora, U. and Trucco, A. (2014), "Comparison of ship plant layouts for power and propulsion systems with energy recovery", *Journal of Marine Engineering and Technology*, Vol. 13 No. 3, pp. 3–15.

Benvenuto, G. and Figari, M. (2011), "Dynamic simulation techniques for the evaluation of the propulsion system behavior", *Marine Technology and Engineering*, Vol. 1, pp. 321–348.

Biert, L. van, Godjevac, M., Visser, K. and Aravind, P. V. (2016), "A review of fuel cell systems for maritime applications", *Journal of Power Sources*, Elsevier B.V, Vol. 327 No. X, pp. 345–364.

BIX. (2018), "Bunker Index", available at: http://www.bunkerindex.com/prices/bix.php?priceindex_id=2.

Blanchard, B. and Fabrycky, W. (2014), *System Engineering and Analysis*, 5th ed., Pearson Prentice Hall, US.

Blanchard, B.S. and Fabrycky, W.J. (1981), *Systems Engineering and Analysis*, Prentice Hall.

Boersema, J.J. and Reijnders, L. (2009), *Principles of Environmental Sciences*, Springer.

Boonstra, H., Cho, K.H., Besse, P.A., Birmingham, R., Moore, W. and Zanic, V. (2006), "Design Principles and Criteria", *17th International Ship and Offshore Structures Congress*, Vol. 1, Seoul, Korea, pp. 521–599.

Del Borghi, A., Gallo, M., Strazza, C. and Del Borghi, M. (2014), "An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: The case study of tomato products supply chain", *Journal of Cleaner Production*, Elsevier Ltd, Vol. 78, pp. 121–130.

Brinks, H.W. and Chryssakis, C. (2017), *LPG as a Marine Fule*.

Brynolf, S., Baldi, F. and Johnson, H. (2016), "Energy Efficiency and Fuel Changes to Reduce Environmental Impacts", in Andersson, K., Brynolf, S., Lindgren, J.F. and Wilewska-Bien, M. (Eds.), *Shipping and the Environment : Improving Environmental Performance in Marine Transportation*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 295–339.

Brynolf, S., Fridell, E. and Andersson, K. (2014), "Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol", *Journal of Cleaner Production*, Vol. 74 No. X, pp. 86–95.

Brynolf, S., Magnusson, M., Fridell, E. and Andersson, K. (2014), "Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels", *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 28 No. X, pp. 6–18.

Buhaug, Ø., Corbett, J.., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.., et al. (2009), "Second IMO GHG Study2009", *International Maritime Organization (IMO)*, p. 240.

Burel, F., Taccani, R. and Zuliani, N. (2013), "Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion", *Energy*, Elsevier Ltd, Vol. 57 No. December 2005, pp. 412–420.

Burhenne, S., Tsvetkova, O., Jacob, D., Henze, G.P. and Wagner, A. (2013), "Uncertainty quantification for combined building performance and cost-benefit analyses", *Building and Environment*, Vol. 62, pp. 143–154.

Cabezas-Basurko, O. (2010), *Methodologies for Sustainability Assessment of Marine Technologies*, Newcastle University.

Cabezas-Basurko, O., Mesbahi, E. and Moloney, S.R. (2008), "Methodology for sustainability analysis of ships", *Ships and Offshore Structures*, Vol. 3 No. February 2015, pp. 1–11.

Carley, K.M., Kamneva, N.Y. and Reminga, J. (2004), *Response Surface Methodology*, available at:https://doi.org/10.1002/wics.73.

Carlton, J., Aldwinkle, J., Anderson, J., Arcoumanis, C., Balston, D., Bardot, A., Beall, C., et al. (2013), "Future Ship Powering Options: Exploring alternative methods of ship propulsion", *Royal Academy of Engineering*, No. July, p. 95.

Cavazzuti, M. (2013), *Optimization Methods: From Theory to Design Scientific and Technological Aspects in Mechanics*, *Optimization Methods: From Theory to Design Scientific and Technological Aspects in Mechanics*, available at:https://doi.org/10.1007/978-3-642-31187-1.

Cebrucean, D., Cebrucean, V. and Ionel, I. (2014), "CO2capture and storage from fossil fuel power plants", *Energy Procedia*, Elsevier B.V., Vol. 63 No. ii, pp. 18–26.

Chang, K.Y. (2011), "The optimal design for PEMFC modeling based on Taguchi method and genetic algorithm neural networks", *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 36 No. 21, pp. 13683–13694.

Chapman, L. and Day, A. (2012), "Hybrid system for handling premature convergence in GA – Case of grammar induction", *Applied Soft Computing Journal*, Elsevier B.V., Vol. 13 No. 5, pp. 2923–2931.

Chatzimouratidis, A.I. and Pilavachi, P. a. (2009), "Sensitivity analysis of technological, economic and sustainability evaluation of power plants using the analytic hierarchy process", *Energy Policy*, Vol. 37 No. 3, pp. 788–798.

Chatzinikolaou, S. and Ventikos, N.P. (2014), "Applications of Life Cycle Assessment in Shipping Industry", available at:https://doi.org/10.5593/SGEM2014/B42/S19.038.

Chatzinikolaou, S.D. and Ventikos, N.P. (2015a), "Holistic framework for studying ship air emissions in a life cycle perspective", *Ocean Engineering*, Elsevier, Vol. 110, pp. 113–122.

Chatzinikolaou, S.D. and Ventikos, N.P. (2015b), "Critical Analysis of Air Emissions from Ships: Lifecycle Thinking and Results", *Green Transportation Logistics: The Quest for Win-Win Solutions*, available at:https://doi.org/10.1007/978-3-319-17175-3.

Chaudhari, P., Dharaskar, R. and Thakare, V.M. (2010), "Computing the Most Significant Solution from Pareto Front obtained in Multi-objective Evolutionary", *Ijacsa*, Vol. 1 No. 4, pp. 63–68.

Churchill, F. (2018), "Shippers agree first ever climate change target", *Supply Management*, available at: https://www.cips.org/en-GB/supply-management/news/2018/april/shipping-industry-agree-emissions-reduction-targets/?utm_source=Adestra&utm_medium=email&utm_term=&utm_content=Shippers agree first ever climate change target&utm_campaign=SM Daily 17.4.18.

Cichowicz, J., Theotokatos, G. and Vassalos, D. (2015), "Dynamic energy modelling for ship life-cycle performance assessment", *Ocean Engineering*, Elsevier, Vol. 110, pp. 1–13.

CIN. (2018), "Cruise Ship Orderbook", *Cruise Ship Industry News*, available at: https://www.cruiseindustrynews.com/cruise-news/cruise-ship-orderbook.html.

ClassNK. (2018), *Alternative Fuels and Energy Efficiency for the Shipping Industry: An Overview of LNG, LPG and Methanol Fuelled Ships*.

Clausen, N.B. (2015), *Tier III NO x Emission Reduction Technologies EGR and SCR*.

CLIA. (2013), *Energy Efficiency for Cruise Passenger Ships, MEPC 65/4/6*.

CLIA. (2017), *2018 Cruise Industry Outlook*, available at: https://cruising.org/docs/default-source/research/clia-2018-state-of-the-industry.pdf?sfvrsn=2.

Coello Coello, C.A., Dhaenens, C. and Jourdan, L. (2010), "Multi-objective combinatorial optimization: Problematic and context", *Advances in Multi-Objective Nature Inspired Computing*, Vol. 272, pp. 1–21.

Coello Coello, C.A., Lamont, G.. and VanVeldhuizen, D.A. (2007), *Evolutionary Algorithms for Solving Multi-Objective Problems*, 2nd ed., Springer.

Coello Coello, C.A., Lamont, G.B. and Veldhuizen, D.A. V. (2007), *Evolutionary Algorithms for Solving Multi-Objective Problems*, *Evolutionary Algorithms for Solving Multi-Objective Problems*, 2nd ed., Springer, available at:https://doi.org/10.1007/978-0-387-36797-2.

Cohen, J. (1988), *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed., Academic Press, New York.

Collin, R.M. and Collins, W., J. (2010), *Encyclopedia of Sustainability*, Press, Greenwood, Santa Barbara, California.

Collis, J. and Hussey, R. (2003), *Business Research: A Practical Guide for Undergraduate and Postgraduate Students,* 2nd ed., Basingstoke: Palgrave Macmillan.

Conejo, A.J., Carrion, M. and Morales, J.M. (2010), *Decision Making under Uncertainty in Electricity Markets*, Springer, New York, available at:https://doi.org/10.1057/jors.2014.93.

Cooper, H. (1989), *Integrating Research: A Guide for Literature Reviews (Applied Social Research Methods)*, 2nd ed., Sage Publications, Inc., Thousand Oaks, CA, US.

Coraddu, A., Figari, M. and Savio, S. (2014), "Numerical investigation on ship energy efficiency by Monte Carlo simulation", *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 228 No. 3, pp. 220–234.

Corbett, J., Winebrake, J. and Green, E. (2010), "An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping", *Carbon Management*, Vol. 1 No. April, pp. 207–225.

Corbett, J.J. and Fischbeck, P. (1997), "Emissions from Ships", *Science*, Vol. 278 No. 5339, pp. 823 LP – 824.

Corbett, J.J., Lack, D.A., Winebrake, J.J., Harder, S., Silberman, J.A. and Gold, M. (2010), "Arctic shipping emissions inventories and future scenarios", *Atmospheric Chemistry and Physics*, Vol. 10 No. 19, pp. 9689–9704.

Corbett, J.J. and Winebrake, J.J. (2008), "Emissions Tradeoffs among Alternative Marine Fuels: Total Fuel Cycle Analysis of Residual Oil, Marine Gas Oil, and Marine Diesel Oil", *Journal of the Air & Waste Management Association*, Vol. 58 No. 4, pp. 538–542.

Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V. and Lauer, A. (2007), "Mortality from ship emissions: A global assessment", *Environmental Science and Technology*, Vol. 41 No. 24, pp. 8512–8518.

Creswell, J.W. (2009), *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 3rd ed., Sage Publications.

Cwilewicz, R. and Górski, Z. (2014), "Coges As a Future of Marine Propulsion", *Gdynia Maritime University*, Vol. 84, pp. 5–13.

Daskalakis, I., Chatzinikolaou, S. and Ventikos, N.P. (2015), "Platform for Assessing Ship Emissions From a Life Cycle Perspective", *Shipping in Changing Climates Conference*.

De-Troya, J.J., Álvarez, C., Fernández-Garrido, C. and Carral, L. (2016), "Analysing the possibilities of using fuel cells in ships", *International Journal of Hydrogen Energy*, Vol. 41 No. 4, pp. 2853–2866.

Deb, K. (2008), "Introduction to Evolutionary Multiobjective Optimization", in Branke, J., Deb, K., Miettinen, K. and Słowiński, R. (Eds.), *Multiobjective Optimization: Interactive and Evolutionary Approaches*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 59–96.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002), "A fast and elitist multiobjective genetic algorithm: NSGA-II", *IEEE Transactions on Evolutionary Computation*, Vol. 6 No. 2, pp. 182–197.

Deb, M., Debbarma, B., Majumder, A. and Banerjee, R. (2016), "Performance –emission optimization of a diesel-hydrogen dual fuel operation: A NSGA II coupled TOPSIS MADM approach", *Energy*, Elsevier Ltd, Vol. 117, pp. 281–290.

Dedes, E.K., Hudson, D.A. and Turnock, S.R. (2016), "Investigation of Diesel Hybrid systems for fuel oil reduction in slow speed ocean going ships", *Energy*, Elsevier Ltd, Vol. 114, pp. 444–456.

Depuis, R. and Neilson, J.J. (1997), "Dynamic Analysis : Sail the Ship Before it's Built", *Naval Engineers*.

Devuyst, D., Hens, L. and Lannoy, W.D. (2001), *How Green Is the City? Sustainability Assessment and the Management of Urban Environmenta*, Columbia University Press, New York.

Dimopoulos, G., Kougioufas, A. and Frangopoulos, C. (2008a), *Synthesis , Design and Operation Optimization of a Marine Energy System*, National Technical University of Athens, available at:https://doi.org/10.1016/j.energy.2007.09.004.

Dimopoulos, G.G. (2009), *Synthesis, Design and Operation of Marine Energy Systems*, National Technical University of Athens.

Dimopoulos, G.G., Georgopoulou, C.A., Stefanatos, I.C., Zymaris, A.S. and Kakalis, N.M.P. (2014), "A general-purpose process modelling framework for marine energy systems", *Energy Conversion and Management*, Elsevier Ltd, Vol. 86, pp. 325–339.

Dimopoulos, G.G. and Kakalis, N.M.P. (2010), "An integrated modelling framework for the design , operation and control of marine energy systems", *CIMAC Congress 2010*.

Dimopoulos, G.G., Kougioufas, A. V. and Frangopoulos, C.A. (2008b), "Synthesis, design and operation optimization of a marine energy system", *Energy*, Vol. 33 No. 2, pp. 180–188.

Dimopoulos, G.G., Stefanatos, I.C. and Kakalis, N.M.P. (2016), "Exergy analysis and optimisation of a marine molten carbonate fuel cell system in simple and combined cycle configuration", *Energy Conversion and Management*, Elsevier Ltd, Vol. 107, pp. 10–21.

DNV-GL. (2016), "USE OF METHANOL AS F UEL Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility", available at: http://www.imo.org/fr/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Report Methanol 21.01.2016.pdf.

DNV-GL. (2018), *Current Price Development Oil and Gas*, available at: https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html.

DNV and PSE. (2013), *Report on Ship Carbon Capture and Storage*, Vol. 37, available at:https://doi.org/10.1017/S0165070X00006744.

Duffy, A.H.B. and O'Donnell, F.J. (1998), "A design research approach", *Aid*, Vol. 98 No. July, pp. 20–27.

Dzida, M. and Olszewski, W. (2011), "Comparing combined gas tubrine/steam turbine and marine low speed piston engine/steam turbine systems in naval applications", *Polish Maritime Research*, Vol. 18 No. 4, pp. 43–48.

Easterby-Smith, M., Thorpe, R. and Jackson, P. (2012), *Management Research*, 4th ed., Sage Publications, London, UK.

EDUCOGEN. (2001), *The European Educational Tool on Cogeneration*, 2nd ed., The European Association for the Promotion of Cogeneration, Brussels, Belgium.

Edwards, A. (2005), *The Sustainability Revolution: Portrait of a Paradigm Shift*, New Society Publishers, Canada.

EGCSA. (2018), "Scrubber orders full ahead", available at: https://www.egcsa.com/scrubber-orders-full-ahead/ (accessed 20 July 2018).

Ehrgott, M. and Gandibleux, X. (2000), "A survey and annotated bibliography of multiobjective combinatorial optimization Multikriterielle Kombinatorische Optimierung Ubersicht und Kommentierte Bibliographie", *OR Spektrum*, Vol. 22, pp. 425–460.

Ehrgott, M. and Gandibleux, X. (2008), "Hybrid Metaheuristics for Multi-objective Combinatorial Optimization", *Hybrid Metaheuristics. Studies in Computational Intelligence*, Springer Berlin Heidelberg, available at:https://doi.org/10.1007/978-3-319-30883-8.

Ehrgott, M. and Ruzika, S. (2008), "Improved ε-constraint method for multiobjective programming", *Journal of Optimization Theory and Applications*, Vol. 138 No. 3, pp. 375–396.

EIA. (2013), *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, US Department of Energy*, available at:https://doi.org/10.2172/784669.

EIA. (2016), *Combined Heat and Power Technology Fact Sheets Series*, available at:https://doi.org/10.1097/01.mat.0000169120.48527.87.

Ekins, P., Simon, S., Deutsch, L., Folke, C. and DeGroot, R. (2003), "A framework for the practical application of the concepts of critical natural capital and strong sustainability", *Ecological Economics*, Vol. 44, pp. 165–185.

Elkington, J. (2001), "Enter the Triple Bottom Line", *The Triple Bottom Line: Does It All Add Up?*, Vol. 1 No. 1986, pp. 1–16.

Ellingsen, H., Fet, A.M. and Aanondsen, S. (2002), *Tool for Environmental Efficient Ship Design, ENSUS*, Newcastle, UK.

Entec. (2002), "Ship Emissions Final Report - Quantification of Ship Emissions", *Ship Emissions Final Reeport*, No. July, pp. 3–48.

Entec. (2005), *Service Contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments. Task 2c- SO2 Abatement*, UK, London.

Environmental Protection Agency. (1998), "Natural Gas Combustion", *AP 42 External Combustion Sources*, Fifth., US, available at: https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf.

Environmental Protection Agency. (1999), *Emissions Factors, External Combustion Sources*, Vol. I, US, available at: https://www3.epa.gov/ttn/chief/ap42/ch01/index.html.

EPA. (2016), *Sources of Greenhouse Gas Emissions*, available at: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

EPA and CHP. (2015), *Catalog of CHP Technologies*.

Etghani, M.M., Shojaeefard, M.H., Khalkhali, A. and Akbari, M. (2013), "A hybrid method of modified NSGA-II and TOPSIS to optimize performance and emissions of a diesel engine using biodiesel", *Applied Thermal Engineering*, Elsevier Ltd, Vol. 59 No. 1–2, pp. 309–315.

EU. (2014), *Proposal for a Regulation of the European Parliament and of the Council on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions From Maritime Transport* *and Amending Regulation (EU) No. 525/2013 – Political Agreement*.

Eurostat. (2018), "Producer price index, Total EU-28", available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Industrial_producer_price_index_overview.

Eyring, V., Isaksen, I., S., A., Berntsen, T., Collins, W., J., Corbett, J., J., Endresen, O., Grainger, R., G., et al. (2010), "Transport impacts on atmosphere and climate: Shipping", *Atmospheric Environment*, Vol. 44, available at:https://doi.org/10.1016/j.atmosenv.2009.04.059.

Eyring, V., Köhler, H.W., Van Aardenne, J. and Lauer, A. (2005), "Emissions from international shipping: 1. The last 50 years", *Journal of Geophysical Research D: Atmospheres*, Vol. 110 No. 17, pp. 171–182.

Fagerholt, K. and Psaraftis, H.N. (2015), "On two speed optimization problems for ships that sail in and out of emission control areas", *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 39 No. x, pp. 56–64.

Fet, A.M. (2002), "Environmental reporting in marine transport based on LCA", *Journal of Marine Design and Operations*, pp. 1476–1556.

Fet, A.M., Aspen, D.M. and Ellingsen, H. (2013), "Systems engineering as a holistic approach to life cycle designs", *Ocean Engineering*, Vol. 62 No. APRIL, pp. 1–9.

Fet, A.M. and Sorgard, E. (1999), *Life Cycle Evaluation of Ship Transportation - Development of Methodology and Testing*.

Figueira, J., Greco, S. and Ehrgott, M. (2005), *Multiple Criteria Decision Analysis: State of the Art Surveys, Challenges*, 2nd ed., Vol. 78, Springer, New York, available at:https://doi.org/10.1007/b100605.

Flood, R.. and Carson, E.R. (1988), *Dealing with Complexity*, Plenum Press, New York and London.

Frangopoulos, C. a. and Caralis, Y.C. (1997), "A method for taking into account environmental impacts in the economic evaluation of energy systems", *Energy Conversion and Management*, Vol. 38 No. 15–17, pp. 1751–1763.

Frangopoulos, C. a., Spakovsky, M.R. Von and Sciubba, E. (2002), "A Brief Review of Methods for the Design and Synthesis Optimization of Energy Systems", *International Journal of Thermodynamics*, Vol. 5 No. 4, pp. 151–160.

Frangopoulos, C.A. (2018), "Recent developments and trends in optimization of energy systems", *Energy*, Elsevier Ltd, Vol. 164, pp. 1011–1020.

Frangopoulos, C.A. and Keramioti, D.E. (2010), "Multi-Criteria evaluation of energy systems with sustainability considerations", *Entropy*, Vol. 12 No. 5, pp. 1006–1020.

Frangopoulos, C.A. and Sciubba, E. (2009), "Modeling, Simulation and Optimization in Energy Systems", *Exergy, Energy System Analysis and Optimization*, 1st ed., Vol. II.

Frangopoulos, C.A., Spakovsky, M.R. Von and Sciubba, E. (2009), "Design and Synthesis optimization of energy systems", *Exergy, Energy System Analysis and Optimization*, Vol. II.

FuelTrade. (2014), "Low sulphur bunker fuels to meet 2015 ECA requirements", available at: https://ft-maritime.com/index.php?story=17 (accessed 1 September 2018).

Ganapathy, T., Gakkhar, R.P. and Murugesan, K. (2011), "Optimization of performance parameters of diesel engine with Jatropha biodiesel using response surface methodology", *International Journal of Sustainable Energy*, Vol. 30 No. SUPPL. 1, available at:https://doi.org/10.1080/14786451.2011.594889.

Gaspar-Cunha, A. and Covas, J.A. (2008), "Robustness in multi-objective optimization using evolutionary algorithms", *Computational Optimization and Applications*, Vol. 39 No. 1, pp. 75–96.

Gaspar-Cunha, A., Ferreira, J. and Recio, G. (2014), "Evolutionary robustness analysis for multi-objective optimization: Benchmark problems", *Structural and Multidisciplinary Optimization*, Vol. 49 No. 5, pp. 771–793.

Gaspar, H.M., Balland, O., Aspen, D.M., Ross, A.M. and Erikstad, S.O. (2014), "Assessing air emissions for uncertain lifecycle scenarios via responsive systems comparison method", *Proc IMechE Part M: J Engineering for the Maritime Environment*, Vol. 229 No. 4, pp. 1–15.

Gaspar, H.M., Ross, A.M., Rhodes, D.H. and Erikstad, S.O. (2012), "Handling Complexity Aspects in Conceptual Ship Design", *International Marine Design Conference*, Glasgow, UK, pp. 1–14.

Gasparators, A. and Scolobig, A. (2012), "Choosing the most appropriate sustainability assessment tool", *Ecological Economics*, Elsevier B.V., Vol. 80, pp. 1–7.

Gasparatos, A., El-Haram, M. and Horner, M. (2008), "A critical review of reductionist approaches for assessing the progress towards sustainability", *Environmental Impact Assessment Review*, Vol.

28 No. 4–5, pp. 286–311.

El Geneidy, R., Otto, K., Ahtila, P., Kujala, P., Sillanpää, K. and Mäki-Jouppila, T. (2017), “Increasing energy efficiency in passenger ships by novel energy conservation measures”, *Journal of Marine Engineering & Technology*, Vol. 4177 No. May 2017, pp. 1–14.

Gerber, L., Fazlollahi, S. and Maréchal, F. (2013), “A systematic methodology for the environomic design and synthesis of energy systems combining process integration, Life Cycle Assessment and industrial ecology”, *Computers and Chemical Engineering*, Vol. 59, pp. 2–16.

Ghauri, P. and Gronhaug, K. (2005), *Research Methods in Business Studies –A Practical Guide.*, 3rd ed., Prentice Hall.

Giannakoudis, G., Papadopoulos, A.I., Seferlis, P. and Voutetakis, S. (2010), “Optimum design and operation under uncertainty of power systems using renewable energy sources and hydrogen storage”, *International Journal of Hydrogen Energy*, Elsevier Ltd, Vol. 35 No. 3, pp. 872–891.

Giannantoni, C., Lazzaretto, A., Macor, A., Mirandola, A., Stoppato, A., Tonon, S. and Ulgiati, S. (2005), “Multicriteria approach for the improvement of energy systems design”, *Energy*, Vol. 30 No. 10, pp. 1989–2016.

Gibson, R.B. (2006), “Sustainability assessment”, *Impact Assessment and Project Appraisal*, Vol. 24 No. 3, pp. 170–182.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K. and Murphy, A. (2018), “Assessment of full life-cycle air emissions of alternative shipping fuels”, *Journal of Cleaner Production*, The Authors, Vol. 172, pp. 855–866.

GlobalCruiseShip. (2018), “List of Cruise Ships”, available at: http://www.globalcruiseship.com/list-of-cruise-ships/ship.html.

Goglio, P., Smith, W.N., Grant, B.B., Desjardins, R.L., Mcconkey, B.G., Campbell, C.A. and Nemecek, T. (2015), “Accounting for soil carbon changes in agricultural life cycle assessment (LCA): a review”, *Journal of Cleaner Production*, Elsevier Ltd, Vol. 104, pp. 23–39.

Gong, J. and You, F. (2015), “Sustainable design and synthesis of energy systems”, *Current Opinion in Chemical Engineering*, Elsevier Ltd, Vol. 10, pp. 77–86.

Gratsos, G.A., Psaraftis, H.N. and Zachariadis, P. (2010), “Life- Cycle CO2 emissions of bulk carriers: A comparative study”, *International Journal of Maritime Engineering*, Vol. 53 No. 9, pp. 1689–1699.

Grljušić, M., Medica, V. and Radica, G. (2015), “Calculation of efficiencies of a ship power plant operating with waste heat recovery through combined heat and power production”, *Energies*, Vol. 8 No. 5, pp. 4273–4299.

Gu, Y. and Wallace, S.W. (2017), “Scrubber: A potentially overestimated compliance method for the Emission Control Areas: The importance of involving a ship’s sailing pattern in the evaluation”, *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 55, pp. 51–66.

Guba, E.G. and Lincoln, Y.S. (1994), *Competing Paradigms in Qualitative Research*, Sage Publications, London, UK.

Hacking, T. and Guthrie, P. (2008), “A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment”, *Environmental Impact Assessment Review*, Vol. 28 No. 2–3, pp. 73–89.

Hair, J.F., Ringle, C.M. and Sarstedt, M. (2011), “PLS-SEM: Indeed a Silver Bullet”, *Journal of Marketing Theory and Practice*, Vol. 19 No. 2, pp. 139–152.

Hair, J.F.J.., William, B.C.., Babin, B.J. and Anderson, R.E. (2014), *Multivariate Data Analysis*, 7nth ed., Pearson, available at:https://doi.org/10.1038/259433b0.

Hamby, D.M. (1994), “A review of techniques for parameter sensitivity analysis of environmental models”, *Environmental Monitoring and Assessement*, Vol. 32 No. c, pp. 135–154.

Han, J., Charpentier, J.F. and Tang, T. (2012), “State of the art of fuel cells for ship applications”, *IEEE International Symposium on Industrial Electronics*, No. April, pp. 1456–1461.

Hansen, J.P., Kaltoft, J., Bak, F., Gortz, J., Pedersen, M. and Underwood, C. (2014), *Reduction of SO2, NOx and Particulate Matter from Ships with Diesel Engines*, Miljøstyrelsen, available at: http://www.alfalaval.com/microsites/puresox/documents/978-87-93026-57-5.pdf.

Harrington, R.L. (1992), *Marine Engineering*, 1934th ed., Society of Naval Architects and Marine Engineers, Jersey City.

Harrould-Kolieb, E. (2008), *Shipping Impacts on Climate: A Source with Solution, Oceana*.

Hart, D., Lehner, F., Rose, R. and Lewis, J. (2018), “The Fuel Cell Industry Review 2015”, *E4tech*, pp. 1–52.

Hasegawa, K. and Iqbal, K.S. (2000), “Inland transportation system planning by life cycle impact assessment: a case study", *Journal of Marine Science and Technology*, Vol. 5 No. 1, pp. 1–8.

Hassan Pour, A., Safieddin Ardebili, S.M. and Sheikhdavoodi, M.J. (2018), "Multi-objective optimization of diesel engine performance and emissions fueled with diesel-biodiesel-fusel oil blends using response surface method", *Environmental Science and Pollution Research*, Environmental Science and Pollution Research, Vol. 25 No. 35, pp. 35429–35439.

Hay, L. (2015), *Generic Models of Technical Systems Sustainability*, Strathclyde.

Hay, L., Duffy, A. and Whitfield, R.I. (2014), "The Sustainability Cycle and Loop: Models for a more unified understanding of sustainability", *Journal of Environmental Management*, Vol. 133, pp. 232–257.

Hemmings, B. (2011), *The CO2 Taxation Option for an EU Shipping Measure*.

Henggeler, A. and Henriques, C.O. (2005), "Multi-Objective Optimization and Multi-Criteria Analysis Models and Methods for Problems in the Energy Sector", in 2nd (Ed.), *Multiple Criteria Decision Analysis: State of the Art Surveys*, Springer.

Hestad, K. and Aarskog, K.J. (2010), *LCA of Fuel Cells Onboard Ships*, Norwegian University of Science and Technology, available at: https://brage.bibsys.no/xmlui/bitstream/handle/11250/237857/378128_FULLTEXT01.pdf?sequence=1.

Hirst, E. and Schweitzer, M. (1990), "Electric-Utility Resource Planning and Decision-Making: The Importance of Uncertainty", *Risk Analysis*, Vol. 10, pp. 23–28.

Holland, M., Hunt, A., Hurley, F., Navrud, S. and Watkiss, P. (2005), *Methodology for the Cost-Benefit Analysis for CAFE - Volume 1: Overview of Methodology*, Didcot, UK.

Horváth, I. (2004), "on Methodological Characteristics of Engineering Design Research", *Design*, pp. 1–8.

Horvath, S., Fasihi, M. and Breyer, C. (2018), "Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040", *Energy Conversion and Management*, Vol. 164 No. November 2017, pp. 230–241.

Hountalas, D.T., Katsanos, C. and Mavropoulos, G.C. (2012), "Efficiency Improvement of Large Scale 2-Stroke Diesel Engines Through the Recovery of Exhaust Gas Using a Rankine Cycle", *Procedia - Social and Behavioral Sciences*, Vol. 48, pp. 1444–1453.

Howitt, O.J.A., Revol, V.G.N., Smith, I.J. and Rodger, C.J. (2010), "Carbon emissions from international cruise ship passengers' travel to and from New Zealand", *Energy Policy*, Elsevier, Vol. 38 No. 5, pp. 2552–2560.

Hsieh, C.C. and Felby, C. (2017), *Biofuels for the Marine Shipping Sector*.

IEA. (2012), *Energy Technology Perspectives 2012*, *International Energy Agency*, available at:https://doi.org/10.1787/energy_tech-2012-en.

IMO. (2005a), "Annex VI-Regulations for the prevention of Air Pollution from Ships. Sulphur Oxides (SOx)-Regulation 14".

IMO. (2005b), "Annex VI, Regulations for the prevention of Air Pollution from Ships. Nitrogen Oxides (NOx), Regulation 13".

IMO. (2011), *Annex 19-Resolution MEPC.203(62), Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto*.

IMO. (2012), *Annex 9, Resolution MEPC.213(63), 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP)*.

IMO. (2013), *Annex 16, Resolution MEPC. 232(65)-2013 Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions*, *Annex 16, Resolution MEPC. 232(65)*, Vol. 232.

IMO. (2014), *Annex 5, Resolution MEPC.245(66), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships*.

IMO. (2016a), *Methanol as Marine Fuel: Environmenal Benefits, Technology Readiness and Economic Feasibility*, London, UK.

IMO. (2016b), *Ship Energy Efficiency Regulations and Related Guidelines*, London, UK, available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air pollution/M2 EE regulations and guidelines final.pdf.

INCOSE. (2015), *Systems Engineering Handbook*, 4th ed., John Wiley & Sons, Inc., Hoboken, New Jersey.

International Energy Agency. (2017), "World Energy Outlook", p. 32.

IRENA. (2012), *Renewable Energy Technologies: Cost Analysis Series: Wind Power*, *Power*

Generation Technologies, Vol. 1, available at:https://doi.org/10.1016/B978-0-08-098330-1.00011-9.

IUCN. (1980), *World Conservation Strategy: Living Resource Conservation for Sustainable Development. Gland: International Union Conservation of Nature and Natural Resources*.

Jain, V. and Sachdeva, G. (2017), “Energy, exergy, economic (3E) analyses and multi-objective optimization of vapor absorption heat transformer using NSGA-II technique”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 148, pp. 1096–1113.

Jeong, B., Wang, H., Oguz, E. and Zhou, P. (2018), “An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems”, *Journal of Cleaner Production*, Elsevier Ltd, Vol. 187, pp. 111–130.

Jiang, L., Kronbak, J. and Christensen, L.P. (2014), “The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil”, *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 28, pp. 19–27.

Jianyun, Z., Li, C., Bin, W. and Lijuan, X. (2018), “Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel”, *Applied Energy*, Vol. 226 No. September 2017, pp. 423–436.

Johnson, J. (2018), “IMO strikes shipping’s first carbon emissions agreement”, *The Marine Professional*, available at: https://www.imarest.org/themarineprofessional/item/4169-imo-strikes-shipping-s-first-carbon-emissions-agreement.

Kalikatzarakis, M. and Frangopoulos, C.A. (2015), “Multi-criteria selection and thermo-economic optimization of Organic Rankine Cycle system for a marine application”, *International Journal of Thermodynamics*, Vol. 18 No. 2, p. 133.

Kalikatzarakis, M. and Frangopoulos, C.A. (2016), “Thermo-economic optimization of synthesis, design and operation of a marine organic Rankine cycle system”, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* , Vol. 231 No. 1, pp. 137–152.

Kameyama, M., Hiraoka, K. and Tauchi, H. (2007), “Study on Life Cycle Impact Assessment for Ships”, *Relatório Geral Instituto de Pesquisa Marítima*, Vol. 7 No. 3, pp. 133–143.

Kates, R.W., Clark, W.C., Corell, R., Hall, M.J., Jaeger, C.C., Lowe, I., McCarthy, J.J. Schellnhuber, H.J., et al. (2001), “Sustainability science”, *Science*, Vol. 292, pp. 641–642.

Kizielewicz, J. (2017), “Methods of Raising Funds for Purchasing of New Cruise Ships by International Corporations”, *International Journal of Management and Economics*, Vol. 53 No. 2, pp. 69–83.

Kleijnen, J.P.C. (2011), “Sensitivity Analysis Versus Uncertainty Analysis: When to Use What?”, *Predictability and Nonlinear Modelling in Natural Sciences and Economics*, pp. 322–333.

Ko, M., Kim, Y., Chung, M. and Jeon, H. (2015), “Multi-Objective Optimization Design for a Hybrid Energy System Using the Genetic Algorithm”, *Energies*, Vol. 8 No. 4, pp. 2924–2949.

Koch, T., Zhou, P. and Blanco Davis, E. (2013), *Analysis of Economic and Environmental Performance of Retrofits Using Simulation*.

Koesler, S., Achtnicht, M. and Köhler, J. (2015), “Course set for a cap? A case study among ship operators on a maritime ETS”, *Transport Policy*, Elsevier, Vol. 37, pp. 20–30.

Kong, D.-S., Jang, Y.-S. and Huh, J.-H. (2015), “Method and Case Study of Multiobjective Optimization-Based Energy System Design to Minimize the Primary Energy Use and Initial Investment Cost”, *Energies*, Vol. 8 No. 6, pp. 6114–6134.

Krajnc, D. and Glavic, P. (2005), “A model for integrated assessment of sustainable development”, *Resources, Conservation and Recycling*, Vol. 43 No. 2, pp. 189–208.

Kristensen, H.O. (2012), *Energy Demand And Exhaust Gas Emissions of Marine Engines*, Denmark, available at: http://www.skibstekniskselskab.dk/public/dokumenter/Skibsteknisk/Foraar 2013/25.02.2013/WP 2 - Report 5 - Energy demand and emissions of marine engines - December 2012.pdf.

Kucukkoc, I., Karaoglan, A.D. and Yaman, R. (2013), “Using response surface design to determine the optimal parameters of genetic algorithm and a case study”, *International Journal of Production Research*, Vol. 51 No. 17, pp. 5039–5054.

Kulkarni, O., Kulkarni, N., Kulkarni, A.J. and Kakandikar, G. (2018), “Constrained cohort intelligence using static and dynamic penalty function approach for mechanical components design”, *International Journal of Parallel, Emergent and Distributed Systems*, Vol. 33 No. 6, pp. 570–588.

Kumar, A., Sah, B., Singh, A.R., Deng, Y., He, X., Kumar, P. and Bansal, R.C. (2017), “A review of multi criteria decision making (MCDM) towards sustainable renewable energy development”, *Renewable and Sustainable Energy Reviews*, Elsevier, Vol. 69 No. November 2016, pp. 596–609.

Kumar, R. (2011), *Research Methodology: A Step-by-Step Guide for Beginners*, 3rd ed., Sage Publications, London, UK.

Kyriakidis, F., Sørensen, K., Singh, S. and Condra, T. (2017), “Modeling and optimization of integrated exhaust gas recirculation and multi-stage waste heat recovery in marine engines”, *Energy Conversion and Management*, Elsevier, Vol. 151 No. March, pp. 286–295.

Lan, H., Wen, S., Hong, Y.Y., Yu, D.C. and Zhang, L. (2015), “Optimal sizing of hybrid PV/diesel/battery in ship power system”, *Applied Energy*, Elsevier Ltd, Vol. 158, pp. 26–34.

Landamore, M., Birmingham, R. and Downie, M. (2007), “Establishing the Economic and Environmental Life-Cycle Costs of Marine Systems: A Case Study from the Recreational Craft Sector”, *Marine Technology*, Vol. 44, pp. 106–117.

Larsen, U., Pierobon, L., Haglind, F. and Gabrielii, C. (2013), “Design and optimisation of organic Rankine cycles for waste heat recovery in marine applications using the principles of natural selection”, *Energy*, Elsevier Ltd, Vol. 55, pp. 803–812.

Lazzaretto, A., Manente, G. and Toffolo, A. (2018), “SYNTHSEP: A general methodology for the synthesis of energy system configurations beyond superstructures”, *Energy*, Elsevier Ltd, Vol. 147, pp. 924–949.

Lazzaretto, A. and Toffolo, A. (2004), “Energy, economy and environment as objectives in multi-criterion optimization of thermal systems design”, *Energy*, Vol. 29 No. 8, pp. 1139–1157.

Lee, J., Shin, S. and Kim, S. (2014), “An optimal design of marine systems based on neuro- response surface method”, *International Journal of Naval Architecture and Ocean Engineering*, Elsevier Masson SAS, Vol. 7 No. 2011, pp. 58–66.

Li, X., Hu, Y., Zhou, J., Li, X. and Kang, R. (2018), “Bayesian step stress accelerated degradation testing design: A multi-objective Pareto-optimal approach”, *Reliability Engineering and System Safety*, Elsevier Ltd, Vol. 171 No. April 2017, pp. 9–17.

Ling-Chin, J. and Roskilly, A.P. (2016), “Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective – A life cycle assessment case study”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 117, pp. 305–318.

Lior, N. (2006), *About Sustainability Metrics for Energy Development*, available at: http://www.seas.upenn.edu/~lior/documents/LiorAboutsustainabilitymetrics.pdf.

Lior, N. (2015), “Quantifying sustainability for energy development”, *Energy Bulletin*, Vol. 19, pp. 8–24.

Listewnik, J. (1995), “Feasibility Analysis Of Shaft Generators Application For Optimum Electric Power Generation At Sea In New Built Ships”, *WIT Transactions on The Built Environment*, Vol. 12, pp. 407–415.

Livanos, G.A., Theotokatos, G. and Pagonis, D.-N. (2014), “Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 79, pp. 640–651.

Livanos, G.A., Theotokatos, G. and Pagonis, D.N. (2012), “Techno-Economical Investigation of Alternative Propulsion Concepts of Ferries Operating in Mediterranean Sea – Introduction of Lng As”, *3nd International Conference on Contemporary Problems of Thermal Engineering*, Poland, pp. 18–20.

Lloyd’s Register. (1995), *Marine Exhaust Emissions Research Programme*, London, UK.

Lloyd’s Register. (2015), “Your options for emissions compliance”, p. 60.

Lloyd’s Register and UCL. (2014), *Global Marine Fuel Trends 2030*, *Lloyd’s Register*, available at: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwimkJvr2tzYAhWMsxQKHbzgBSEQFggnMAA&url=http%3A%2F%2Fwww.lr.org%2Fen%2Fprojects%2Fglobal-marine-trends-2030.aspx&usg=AOvVaw0Ldi1AFD25CHbaDj6m0w88.

Lövblad, G., Fridell, E. (2006), “Experiences from use of some techniques to reduce emissions from ships”, *Swedish Maritime Administration, Göteborg*, No. 10.1109/FormSERA.2012.6229785.

Lu, J., Zhang, G., Ruan, D. and Wu, F. (2007), *Multi-Objective Group Decision Making*, Imperial College Press, London, UK.

Luo, X. and Wang, M. (2017), “Study of solvent-based carbon capture for cargo ships through process modelling and simulation”, *Applied Energy*, Elsevier Ltd, Vol. 195, pp. 402–413.

Majumdar, A. and Ghosh, D. (2015), “Genetic Algorithm Parameter Optimization using Taguchi Robust Design for Multi-response Optimization of Experimental and Historical Data”, *International Journal of Computer Applications*, Vol. 127 No. 5, pp. 26–32.

MAN. (2014), *Diesel-Electric Drives*.

MAN Diesel. (2013), "ME-GI Dual Fuel MAN B & W Engines", pp. 1–32.

Man Diesel & Turbo. (2011), *Basic Principles of Ship Propulsion*, *Man Diesel & Turbo*, available at: http://www.mandieselturbo.com/files/news/filesof5405/5510_004_02 low.pdf.

Man Diesel & Turbo. (2017), *CEAS Engine Calculations*, available at: http://marine.man.eu/.

MAN Diesel & Turbo. (2005), "Propulsion Trends in Tankers", *MAN Diesel*, pp. 1–15.

MAN Diesel & Turbo. (2016), *MAN L32/44 GenSet Project Guide – Marine Four-Stroke Diesel Engine Compliant with IMO Tier II*, available at: http://marine.mandieselturbo.com/docs/librariesprovider6/4-stroke-project-guides/man-l32-44-genset-imo-tier-ii-marine.pdf?sfvrsn=5.

MAN Diesel &Turbo. (2017), *MAN L35/44DF Project Guide – Marine Four-Stroke Dual Fuel Engines Compliant with IMO Tier II*.

Mansouri, S.A., Lee, H. and Aluko, O. (2015), "Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions", *Transportation Research Part E: Logistics and Transportation Review*, Elsevier Ltd, Vol. 78, pp. 3–18.

Maragkogianni, A. and Papaefthimiou, S. (2015), "Evaluating the social cost of cruise ships air emissions in major ports of Greece", *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 36, pp. 10–17.

Mardani, A., Jusoh, A., Nor, K.M.D., Khalifah, Z., Zakwan, N. and Valipour, A. (2015), "Multiple criteria decision-making techniques and their applications - A review of the literature from 2000 to 2014", *Economic Research-Ekonomska Istrazivanja*, Routledge, Vol. 28 No. 1, pp. 516–571.

Maritime Knowledge Center; TNO; TU Delft. (2018), *Public Final Report – Methanol as an Alternative Fuel for Vessels*.

Martínez-Vega, D., Sanchez, P., Castilla, G., Fernandez, E., Cruz-Reyes, L., Gomez, C. and Martinez, E. (2017), "Evaluation of the Evolutionary Algorithms Performance in Many-Objective Optimization Problems Using Quality Indicators", *Nature-Inspired Design of Hybrid Intelligent Systems*, Springer.

Marty, P., Corrignan, P., Gondet, A., Chenouard, R. and Hétet, J. (2012), "Modelling of energy flows and fuel consumption on board ships : application to a large modern cruise vessel and comparison with sea monitoring data", *Proceedings of the International Marine Design Conference*, No. November.

Mateo, J.R.S.C. (2012), "Multi Criteria Analysis", *Multi-Criteria Analysis in the Renewable Energy Industry, Green Energy and Technology*, Springer-Verlag, London, UK, available at:https://doi.org/10.1007/978-1-4471-2346-0.

Matlab. (2018), *MATLAB Programming Fundamentals*, MathWorks Inc.

Mavrelos, C. and Theotokatos, G. (2018), "Numerical investigation of a premixed combustion large marine two-stroke dual fuel engine for optimising engine settings via parametric runs", *Energy Conversion and Management*, Elsevier, Vol. 160 No. November 2017, pp. 48–59.

Mavromatidis, G., Orehounig, K. and Carmeliet, J. (2018), "Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems", *Applied Energy*, Elsevier, Vol. 214 No. February, pp. 219–238.

Mavrotas, G. (2009), "Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems", *Applied Mathematics and Computation*, Vol. 213 No. 2, pp. 455–465.

Mavrotas, G. and Diakoulaki, D. (2005), "Solving Multi-objective MILP Problems in Process Synthesis using the Multi-Criteria Branch and Bound Algorithm", *Chemical Engineering & Technology*, Vol. 28 No. 12, pp. 1500–1510.

Mavrotas, G., Figueira, J.R. and Siskos, E. (2015), "Robustness analysis methodology for multi-objective combinatorial optimization problems and application to project selection", *Omega (United Kingdom)*, Elsevier, Vol. 52, pp. 142–155.

Mavrotas, G., Georgopoulou, E., Mirasgedis, S., Sarafidis, Y., Lalas, D., Hontou, V. and Gakis, N. (2007), "An integrated approach for the selection of Best Available Techniques (BAT) for the industries in the greater Athens area using multi-objective combinatorial optimization", *Energy Economics*, Vol. 29 No. 4, pp. 953–973.

Mavrotas, G., Pechak, O., Siskos, E., Doukas, H. and Psarras, J. (2015), "Robustness analysis in multi-objective mathematical programming using Monte Carlo simulation", *European Journal of Operational Research*, Elsevier B.V., Vol. 240 No. 1, pp. 193–201.

Mcphail, S.J., Leto, L., Della Pietra, M., Cigolotti, V. and Moreno, A. (2015), "International Status of

Molten Carbonate Fuel Cells 2015”, *Advanced Fuel Cells Implementing Agreement Annex 23 - MCFC*, pp. 1–34.

Mehmeti, A., Santoni, F., Della Pietra, M. and McPhail, S.J. (2016), “Life cycle assessment of molten carbonate fuel cells: State of the art and strategies for the future”, *Journal of Power Sources*, Elsevier B.V, Vol. 308 No. October 2017, pp. 97–108.

Meredith, J.R., Raturi, A., Amoako-Gyampah, K. and Kaplan, B. (1989), “Alternative research paradigms in operations”, *Journal of Operations Management*, Vol. 8 No. 4, pp. 297–326.

Methanex. (2018), “Methanol Prices”, available at: https://www.methanex.com/.

Milewski, J. and Budzianowski, W. (2014), “Recent key technical barriers in solid oxide fuel cell technology”, *Archives of Thermodynamics*, Vol. 35 No. 1, pp. 17–41.

Minella, G., Ruiz, R., Ciavotta, M., Minella, G., Ruiz, R. and Ciavotta, M. (2008), “A review and evaluation of multi-objective algorithmsfor the flowshop scheduling problem”, No. April 2016, pp. 1–44.

Miola, A.A., Paccagnan, V., Massarutto, A., Perujo, A. and Turvani, M. (2009), *External Costs of Transportation Case Study : Maritime Transport*, available at:https://doi.org/10.2788/18349.

Misra, K.B. (2008), “Engineering Design: A Systems Approach”, *Handbook of Performability Engineering*, pp. 13–24.

Mondejar, M.E., Ahlgren, F., Thern, M. and Genrup, M. (2017), “Quasi-steady state simulation of an organic Rankine cycle for waste heat recovery in a passenger vessel”, *Applied Energy*, Elsevier Ltd, Vol. 185, pp. 1324–1335.

Moreno-Gutiérrez, J., Calderay, F., Saborido, N., Boile, M., Rodríguez Valero, R. and Durán-Grados, V. (2015), “Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods”, *Energy*, Vol. 86, pp. 603–616.

Morris, M.D. (1991), “Factorial Sampling Plans for Prelim inary Computational Experiments”, *Technometrics*, Vol. 33 No. 2, pp. 161–174.

Motley, M.R., Nelson, M. and Young, Y.L. (2012), “Integrated probabilistic design of marine propulsors to minimize lifetime fuel consumption”, *Ocean Engineering*, Vol. 45, available at:https://doi.org/10.1016/j.oceaneng.2012.01.032.

Mrzljak, V. (2016), “Comparison of COGES and Diesel-Electric Ship Propulsion Systems”, *Annals of Maritime Studies*, pp. 131–148.

Murphy, A., Landamore, M., Pazouki, K. and Gibson, M. (2013), “Modelling ship emission factors and emission indices”, *Low Carbon Shipping Conference*, p. 18.

Narula, K. (2014), “Emerging Trends in the Shipping Industry –Transitioning Towards Sustainability”, *Maritime Affairs: Journal of the National Maritime Foundation of India*, Taylor & Francis, Vol. 10 No. 1, pp. 113–138.

Ness, B., Urbel-Piirsalu, E., Anderberg, S. and Olsson, L. (2007), “Categorising tools for sustainability assessment”, *Ecological Economics*, Vol. 60 No. 3, pp. 498–508.

Niccolucci, V., Galli, A., Kitzes, J., Pulselli, R., Borsa, S. and Marchettini, N. (2008), “Ecological Footprint analysis applied to the production of two Italian wines”, *Agriculture, Ecosystems & Environment*, Vol. 128 No. 3, pp. 162–166.

Nikolaisen, S.R. (2014), *Life Cycle Cost Comparison Study*, Norwegian University of Science and Technology.

Nilsen, O.. (2018), *LNG Regulatory Update: Best Fuel of the Futurem Conference & Study Tour*.

Niu, X., Wang, H., Hu, S., Yang, C. and Wang, Y. (2018), “Multi-objective online optimization of a marine diesel engine using NSGA-II coupled with enhancing trained support vector machine”, *Applied Thermal Engineering*, Elsevier, Vol. 137 No. March, pp. 218–227.

Norgaard, R.. (1994), *Development Betrayed: The End of Progress and a Coevolutionary Revisioning of the Future*, Routledge, Canada.

Norris, G.A. (2001), “Integrating life cycle cost analysis and LCA”, *International Journal of Life Cycle Assessment*, Vol. 6 No. 2, pp. 118–120.

Oberkampf, W.. and Roy, C.J. (2010), *VerificatiOberkampf, W.. and Roy, C.J. (2010), Verification and Validation in Scientific Computing, Cambridge University Press, Available at:Https://Doi.Org/Http://Dx.Doi.Org/10.1017/CBO9780511760396.on and Validation in Scientific Computing*, Cambridge University Press, available at:https://doi.org/http://dx.doi.org/10.1017/CBO9780511760396.

Ovrum, E. and Bergh, T.F. (2015), “Modelling lithium-ion battery hybrid ship crane operation”, *Applied Energy*, Elsevier Ltd, Vol. 152, pp. 162–172.

Ovrum, E. and Dimopoulos, G. (2012), “A validated dynamic model of the first marine molten carbonate fuel cell", *Applied Thermal Engineering*, Elsevier Ltd, Vol. 35 No. 1, pp. 15–28.

Packalén, S. and Karlsson Nord, N. (2017), *Combined Gas-and Steam Turbine as Prime Mover in Marine Applications*, Chalmers University, available at: http://publications.lib.chalmers.se/records/fulltext/250183/250183.pdf.

Pathirage, C.P., Amaratunga, R.D.G. and Haigh, R.P. (2008), "The Role of Philosophical Context in the Development of Theory : Towards Methodological Pluralism", *The Built & Human Environment Review*, Vol. 1, pp. 1–10.

Pearce, D.W., Markandya, A. and Barbier, E.B. (1989), *Blueprint for a Green Economy*, Earthscan, UK:London.

Pelet, X., Favrat, D. and Leyland, G. (2005), "Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO2 emissions", *International Journal of Thermal Sciences*, Vol. 44 No. 12, pp. 1180–1189.

Penjic, E. (2018), "In Depth: Methanol is ready for use as marine fuel", *World Maritime News*, 16 April, available at: https://worldmaritimenews.com/archives/249601/interview-methanol-is-ready-for-use-as-marine-fuel/.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quéré, C., Marland, G., et al. (2012), "The challenge to keep global warming below 2 °C", *Nature Climate Change*, Nature Publishing Group, a division of Macmillan Publishers Limited. All Rights Reserved., Vol. 3, p. 4.

Petersen, P.D. (2013), "Tanker Major Chooses G-type Engine", *MAN Global Corporate Website*, available at: https://www.corporate.man.eu/en/press-and-media/presscenter/Tanker-Major-Chooses-G-type-Engine-61760.html (accessed 1 November 2018).

Phillips, D. (1987), *Philosophy, Science, and Social Inquiry: Contemporary Methodological Controversies in Social Science and Related Applied Fields of Research*, Pergamon Press, Oxford, England.

Piacentino, A. and Cardona, F. (2008), "EABOT - Energetic analysis as a basis for robust optimization of trigeneration systems by linear programming", *Energy Conversion and Management*, Vol. 49 No. 11, pp. 3006–3016.

Plessas, T., Kanellopoulou, A., Zaraphonitis, G., Papanikolaou, A. and Shigunov, V. (2018), "Exploration of design space and optimisation of RoPax vessels and containerships in view of EEDI and safe operation in adverse sea conditions", *Ocean Engineering*, Elsevier Ltd, Vol. 162 No. May, pp. 1–20.

Pohekar, S.D. and Ramachandran, M. (2004), "Application of multi-criteria decision making to sustainable energy planning—A review", *Renewable and Sustainable Energy Reviews*, Vol. 8 No. 4, pp. 365–381.

Pope, J., Annandale, D. and Morrison-Saunders, A. (2004), "Conceptualising sustainability assessment", *Environmental Impact Assessment Review*, Vol. 24 No. 6, pp. 595–616.

Poveda, C. a and Lipsett, M. (2011), "A Review of Sustainability Assessment and Sustainability/Environmental Rating Systems and Credit Weighting Tools", *Journal of Sustainable Development*, Vol. 4 No. 6, pp. 36–55.

Princaud, M., Cornier, A. and Froelich, D. (2010), "Developing a tool for environmental impact assessment and eco-design for ships", *Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for the Maritime Environment*, Vol. 224 No. M3, pp. 207–224.

PSE Ltd. (2013), "DNV and PSE report on ship carbon capture & storage", February, available at: https://www.psenterprise.com/news/news-press-releases-dnv-pse-ccs-report.

Quariguasi Frota Neto, J., Walther, G., Bloemhof, J., van Nunen, J.A.E.E. and Spengler, T. (2009), "A methodology for assessing eco-efficiency in logistics networks", *European Journal of Operational Research*, Elsevier B.V., Vol. 193 No. 3, pp. 670–682.

Radan, D., Southall, M., Fiet, C., Benatmane, M., Ceng, P., Fiet, F., Butcher, M., et al. (2016), "Integration, optimisation and benefits of energy storage for marine applications", *13th IIternational Naval Engineering Conference*, Bristol, UK, pp. 1–13.

Rao, S.S. (2009), *Engineering Optimization: Theory and Practice*, 4th ed., John Wiley & Sons Ltd., Hoboken, New Jersey.

Raptotasios, S.I., Sakellaridis, N.F., Papagiannakis, R.G. and Hountalas, D.T. (2015), "Application of a multi-zone combustion model to investigate the NOx reduction potential of two-stroke marine diesel engines using EGR", *Applied Energy*, Elsevier Ltd, Vol. 157, pp. 814–823.

Reber, M. (2011), *A Theory of Value in Design*, Glasgow, UK.

Rech, S., Zandarin, S., Lazzaretto, A. and Frangopoulos, C.A. (2017), "Design and off-design models of single and two-stage ORC systems on board a LNG carrier for the search of the optimal performance and control strategy”, *Applied Energy*, Elsevier Ltd, Vol. 204, pp. 221–241.

Reich, Y. (1994), “Layered models of research methodologies”, *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing*, Vol. 8 No. 4, pp. 263–274.

Reinikainen, K. (2018), “Shipbuilding activity picks up in early 2018”, *Fairplay*, 28 March, available at: https://fairplay.ihs.com/markets/article/4299416/shipbuilding-activity-picks-up-in-early-2018.

Remenyi, D., Williams, B., Money, A. and Swartz, E. (1998), *Doing Research in Business and Management: An Introduction to Process and Method.*, Sage Publications, London, UK.

Ren, J. and Lützen, M. (2015), “Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties”, *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 40, pp. 43–60.

Ren, J. and Lützen, M. (2017), “Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information”, *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, Vol. 74 No. January 2016, pp. 1003–1019.

Ridley, D. (2012), *The Literature Review A Step-by-Step Guide for Students*, 2nd ed., SAGE Publications Ltd, Sheffield University, UK.

Rodrigue, J.-P. and Notteboom, T. (2013), “The Geography of Cruise Shipping: Itineraries, not Destinations”, *Applied Geography*, Vol. 38 No. 2006, pp. 31–42.

Roland, J., de Smet, Y. and Figueira, J.R. (2012), “On the calculation of stability radius for multi-objective combinatorial optimization problems by inverse optimization”, *4or*, Vol. 10 No. 4, pp. 379–389.

Rolls Royce Plc. (2017), *Marine Products and Systems*.

Roy, B. (2005), “Paradigms and Challenges”, *Multiple Criteria Decision Analysis: State of the Art Surveys*, 2nd ed., Springer.

Russel, B.H. (1988), *Research Methods in Cultural Anthropology*, Sage Publications, California, USA.

SA Risk -Sea. (2010), “Air pollution from ships”, pp. 1–3.

Sahnen, D. (2018), “MethaShip: Renewable Methanol Is ‘Fuel with a Future’”, *World Maritime News*, available at: https://worldmaritimenews.com/archives/263017/methaship-renewable-methanol-is-fuel-with-a-future/.

Sakalis, G.N. and Frangopoulos, C.A. (2018), “Intertemporal optimization of synthesis, design and operation of integrated energy systems of ships: General method and application on a system with Diesel main engines”, *Applied Energy*, Elsevier, Vol. 226 No. February, pp. 991–1008.

Sala, S., Ciuffo, B. and Nijkamp, P. (2015), “A systemic framework for sustainability assessment”, *Ecological Economics*, The Authors, Vol. 119, pp. 314–325.

Santoyo-Castelazo, E. and Azapagic, A. (2014), “Sustainability assessment of energy systems: Integrating environmental, economic and social aspects”, *Journal of Cleaner Production*, Elsevier Ltd, Vol. 80, pp. 119–138.

Saunders, M., Lewis, P. and Thornhill, A. (2008), *Research Methods for Business Students*, *Research Methods for Business Students*, available at:https://doi.org/10.1007/s13398-014-0173-7.2.

Saunders, M., Lewis, P. and Thornhill, A. (2009), *Research Methods for Business Students*, 5th ed., Harlow, Pearson Education Limited.

Schinas, O. and Stefanakos, C.N. (2014), “Selecting technologies towards compliance with MARPOL Annex VI: The perspective of operators”, *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 28, pp. 28–40.

Schlesinger, S. (1979), “Terminology for Model Credibility”, *Simulation*, Vol. 32 No. 3.

Sciberras, E.A. and Norman, R.A. (2012), “Multi-objective design of a hybrid propulsion system for marine vessels”, *IET Electrical Systems in Transportation*, Vol. 2 No. 3, p. 148.

Semioshkina, N. and Voigt, G. (2006), “An overview on Taguchi Method”, *Journal Of Radiation Research*, Vol. 47 Suppl A No. 2, pp. A95–A100.

Sen, P. and Yangi, J. (1995), “Multiple-criteria Decision-making in Design Selection and Synthesis”, *Journal of Engineering Design*, Taylor & Francis, Vol. 6 No. 3, pp. 207–230.

Shang, C., Srinivasan, D. and Reindl, T. (2016), “Generation-scheduling-coupled battery sizing of stand-alone hybrid power systems”, *Energy*, Elsevier Ltd, Vol. 114, pp. 671–682.

Sharaf, O.Z. and Orhan, M.F. (2014), “An overview of fuel cell technology: Fundamentals and applications”, *Renewable and Sustainable Energy Reviews*, Elsevier, Vol. 32, pp. 810–853.

Sharafi, M. and ELMekkawy, T.Y. (2014), “Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach”, *Renewable Energy*, Vol. 68, pp. 67–79.

Sheikholeslami, M. and Ganji, D.D. (2016), “Heat transfer improvement in a double pipe heat exchanger by means of perforated turbulators", *Energy Conversion and Management*, Elsevier Ltd, Vol. 127, pp. 112–123.

Shi, Y. (2016), "Reducing greenhouse gas emissions from international shipping: Is it time to consider market-based measures?", *Marine Policy*, Elsevier, Vol. 64, pp. 123–134.

Ship & Bunker. (2018), "World Bunker Prices".

Shu, G., Liu, P., Tian, H., Wang, X. and Jing, D. (2017), "Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine's exhaust waste heat", *Energy Conversion and Management*, Elsevier Ltd, Vol. 146, pp. 107–123.

Silveira, J.L., Martins Leal, E. and Ragonha, L.F. (2001), "Analysis of a molten carbonate fuel cell: Cogeneration to produce electricity and cold water", *Energy*, Vol. 26 No. 10, pp. 891–904.

Singh, D.V. and Pedersen, E. (2016), "A review of waste heat recovery technologies for maritime applications", *Energy Conversion and Management*, Elsevier Ltd, Vol. 111 No. X, pp. 315–328.

Singh, R.K., Murty, H.R., Gupta, S.K. and Dikshit, A.K. (2009), "An overview of sustainability assessment methodologies", *Ecological Indicators*, Vol. 9 No. 2, pp. 189–212.

Smith, D.J. (2004), "Design and Operational Changes are Reducing the Cost of Reciprocating Engine Maintenance", *Power Engineering*, available at: http://www.power-eng.com/articles/print/volume-108/issue-6/features/design-and-operational-changes-are-reducing-the-cost-of-reciprocating-engine-maintenance.html.

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., et al. (2014), "Third IMO Greenhouse Gas Study 2014", *International Maritime Organization (IMO)*, p. 327.

SNAME. (1990), *Marine Diesel Power Plant Practises, T&R Bulletin 3-49*.

Soffiato, M., Frangopoulos, C.A., Manente, G., Rech, S. and Lazzaretto, A. (2015), "Design optimization of ORC systems for waste heat recovery on board a LNG carrier", *Energy Conversion and Management*, Elsevier Ltd, Vol. 92, pp. 523–534.

Solem, S., Fagerholt, K., Erikstad, S.O. and Patricksson, Ø. (2015), "Optimization of diesel electric machinery system configuration in conceptual ship design", *Journal of Marine Science and Technology*, Springer Japan, pp. 406–416.

Di Somma, M., Yan, B., Bianco, N., Graditi, G., Luh, P.B., Mongibello, L. and Naso, V. (2017), "Multi-objective design optimization of distributed energy systems through cost and exergy assessments", *Applied Energy*, Elsevier Ltd, Vol. 204, pp. 1299–1316.

Song, J., Song, Y. and Gu, C. (2015), "Thermodynamic analysis and performance optimization of an Organic Rankine Cycle (ORC) waste heat recovery system for marine diesel engines", *Energy*, Elsevier Ltd, Vol. 82, pp. 976–985.

Soroudi, A. and Amraee, T. (2013), "Decision making under uncertainty in energy systems: State of the art", *Renewable and Sustainable Energy Reviews*, Elsevier, Vol. 28, pp. 376–384.

Soyster, A.L. (1973), "Convex programming with set-inclusive constraints and applications to inexact linear programming.", *Operations Research*, Vol. 21.

Srinivas, N. and Deb, K. (1994), "Multiobjective optimization using nondominated sorting in genetic algorithms", *Evolutionary Computation*, Vol. 2, pp. 221–248.

Stasinopoulos, P., Smith, M.H., Hargroves, K. and Desha, C. (2009), *Whole System Design: An Integrated Approach to Sustainable Engineering Design*, Earthscan, London, UK.

Steen, B. (1999), *A Systematic Approach to Environmental Priority Strategies in Product Development (EPS). Version 2000 – General System Characteristics*.

Stenersen, D. and Thonstad, O. (2017), *GHG and NOx Emissions from Gas Fuelled Engines*, available at: www.sintef.no/ocean.

Stewardson, D.J. and Whitfield, R.I. (2004), "A demonstration of the utility of fractional experimental design for finding optimal genetic algorithm parameter settings", *Journal of the Operational Research Society*, Vol. 55 No. 2, pp. 132–138.

Stojiljković, M.M., Stojiljković, M.M. and Blagojević, B.D. (2014), "Multi-objective combinatorial optimization of trigeneration plants based on metaheuristics", *Energies*, Vol. 7 No. 12, pp. 8554–8581.

Stoumpos, S., Theotokatos, G., Boulougouris, E., Vassalos, D., Lazakis, I. and Livanos, G. (2018), "Marine dual fuel engine modelling and parametric investigation of engine settings effect on performance-emissions trade-offs", *Ocean Engineering*, Elsevier Ltd, Vol. 157 No. February, pp. 376–386.

Streimikiene, D. (2010), "Comparative assessment of future power generation technologies based on carbon price development", *Renewable and Sustainable Energy Reviews*, Elsevier Ltd, Vol. 14

No. 4, pp. 1283–1292.

Sun, X., Jiao, Y. and Tian, P. (2011), “Marketing research and revenue optimization for the cruise industry: A concise review”, *International Journal of Hospitality Management*, Elsevier Ltd, Vol. 30 No. 3, pp. 746–755.

Tadros, M., Ventura, M. and Guedes Soares, C. (2019), “Optimization procedure to minimize fuel consumption of a four-stroke marine turbocharged diesel engine”, *Energy*, Elsevier Ltd, Vol. 168, pp. 897–908.

Taguchi, G. and Wu, Y. (1980), *Introduction to Off-Line Quality Control*.

Taljegård, M. (2012), “Cost-effective choices of marine fuel under stringent carbon dioxide targets Results from the Global Energy Transition (GET) model”.

Tarabella, A. and Burchi, B. (2011), “Sustainability of Food Products Applying Integrated Life Cycle Tools by”, *International Journal of Economic Practices and Theories*, Vol. 1 No. 1, pp. 28–33.

Thacker, B.H., Doebling, S.W., Hemez, F.M., Anderson, M.C., Pepin, J.E. and Rodriguez, E. a. (2004), *Concepts of Model Verification and Validation*, *Los Alamos National Laboratory*, available at:https://doi.org/10.2172/835920.

Theotokatos, G. and Livanos, G. (2013a), “Techno-economical analysis of single pressure exhaust gas waste heat recovery systems in marine propulsion plants”, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 227 No. 2, pp. 83–97.

Theotokatos, G. and Livanos, G. a. (2013b), “Modern Concepts of Ferries Propulsion Plant for Reducing Fuel Consumption Cost and CO 2 Emissions”, *Low Carbon Shipping Conference*, London, pp. 1–12.

Thygesen, J. and Santala, M.M. (2012), “Wärtsilä launches efficient new Aframax tanker design”, *Wärtsilä Web Side*, available at: https://www.wartsila.com/media/news/22-10-2012-wartsila-launches-efficient-new-aframax-tanker-design (accessed 30 October 2018).

Tillig, F., Ringsberg, J., Mao, W. and Ramne, B. (2016), “A generic energy systems model for efficient ship design and operation”, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 231 No. 2, pp. 649–666.

Tincelin, T., Mermier, L., Pierson, Y., Pelerin, E. and Jouanne, G. (2010), “A Life Cycle Approach To Shipbuilding and Ship Operation”, *Ship Design and Operation for Environmental Sustainability*.

Todd, D. (1997), *Newcastle Multiple Criteria Genetic Algorithms in Engineering Design and Operation*, University of Newcastle.

Trautmann, H., Wagner, T., Naujoks, B., Preuss, M. and Mehnen, J. (2009), “Statistical Methods for Convergence Detection of Multi-Objective Evolutionary Algorithms”, *Evolutionary Computation*, Vol. 17 No. 4, pp. 493–509.

Tremuli, P. (2008), “Developments and Perspectives of Marine Engines”, *Clean Combustion and Greenhouse Gases*.

Triantaphyllou, E. (2010), *Multi-Criteria Decision Making Methods: A Comparative Study.*, Springer.

Trivyza, N.L., Rentizelas, A. and Theotokatos, G. (2018), “A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability”, *Energy Conversion and Management*, Vol. 168, pp. 128–149.

Trivyza, N.L., Rentizelas, A. and Theotokatos, G. (2019a), “Impact of carbon pricing on the cruise ship energy systems optimal configuration”, *Energy*, available at:https://doi.org/https://doi.org/10.1016/j.energy.2019.03.139.

Trivyza, N.L., Rentizelas, A. and Theotokatos, G. (2019b), “Impact of carbon pricing on the cruise ship energy systems optimal configuration”, *Energy*, Elsevier Ltd, Vol. 175, pp. 952–966.

Tronstad, T., Åstrand, H.H., Haugom, G.P. and Langfeldt, L. (2017), *Study on the Use of Fuel Cells in Shipping*.

Trozzi, C., Consulting, T., Gregorio, V., Curbastro, R. and Roma, I. (2006), *Emission Estimate Methodology for Maritime Navigation*, available at: http://www.epa.gov/ttnchie1/conference/ei19/session10/trozzi.pdf.

Tsoutsos, T., Drandaki, M., Frantzeskaki, N., Iosifidis, E. and Kiosses, I. (2009), “Sustainable energy planning by using multi-criteria analysis application in the island of Crete”, *Energy Policy*, Vol. 37 No. 5, pp. 1587–1600.

Turan, O., Ölçer, A.İ., Lazakis, I., Rigo, P. and Caprace, J.D. (2009), “Maintenance/repair and production oriented life-cycle cost/earning model for ship structural optimisation during conceptual design stage O. TURAN*”, *Ships and Offshore Structures*, Vol. 4 No. 911061310, pp. 107–125.

Turco, M., Ausiello, A. and Micoli, L. (2016), “Fuel Cells Operating and Structural Features of MCFCs and SOFCs”, *Treatment of Biogas for Feeding High Temperature Fuel Cells: Removal of Harmful Compounds by Adsorption Processes*, Springer International Publishing, Cham, pp. 31–76.

Turkmen, B.S. and Turan, O. (2007), “A new integrated multi-objective optimisation algorithm and its application to ship design”, *Ships and Offshore Structures*, Vol. 2 No. August 2014, pp. 21–37.

Tzannatos, E., Papadimitriou, S. and Koliousis, I. (2015), “A Techno-Economic Analysis of Oil vs. Natural Gas Operation for Greek Island Ferries”, *International Journal of Sustainable Transportation*, Vol. 9 No. 4, pp. 272–281.

Tzortzis, G.J. and Frangopoulos, C.A. (2018), “Dynamic optimization of synthesis, design and operation of marine energy systems”, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, available at:https://doi.org/10.1177/1475090217749370.

U.S. Energy Information Administration. (2013), *Annual Energy Outlook*.

Ulungu, E.L. and Teghem, J. (1994), “Multi-objective combinatorial optimization problems: A survey”, *Journal of Multi-Criteria Decision Analysis*, Vol. 3 No. 2, pp. 83–104.

UN. (2015), *Transforming Our World: The 2030 Agenda for Sustainable Development*, available at: https://sustainabledevelopment.un.org/post2015/transformingourworld.

UNCED. (1992), *Earth Summit 92 (Agenda 21)*, Regency Press, London.

Utne, I.B. (2009), “Life cycle cost (LCC) as a tool for improving sustainability in the Norwegian fishing fleet”, *Journal of Cleaner Production*, Vol. 17 No. 3, pp. 335–344.

Uusitalo, L., Lehikoinen, A., Helle, I. and Myrberg, K. (2015), “An overview of methods to evaluate uncertainty of deterministic models in decision support”, *Environmental Modelling and Software*, Elsevier Ltd, Vol. 63, pp. 24–31.

Vanek, F.. and Albright, L.D. (2008), *Energy Systems Engineering Evaluation & Implementation*, McGraw Hill.

Vanwortswinkel, L. and Nijs, W. (2010), *Industrial Combustion Boilers*, available at:https://doi.org/10.1201/EBK1420085280.

Vasudevan, S., Farooq, S., Karimi, I.A., Saeys, M., Quah, M.C.G. and Agrawal, R. (2016), “Energy penalty estimates for CO2capture: Comparison between fuel types and capture-combustion modes”, *Energy*, Elsevier Ltd, Vol. 103, pp. 709–714.

Walsh, C. and Bows, A. (2011), “Incorporating lifecycle elements into the energy efficiency design index.”, *Low Carbon Shipping International Conference on Technologies, Operations, Logistics and Modelling*, Glasgow, UK.

Wang, C., Martinac, I. and Magny, A. (2015), “Multi-objective robust optimization of energy systems for a sustainable district in stockholm”, *Building Simulation Conference*, pp. 2010–2017.

Wang, H., Zhou, P. and Wang, Z. (2017), “Reviews on current carbon emission reduction technologies and projects and their feasibilities on ships”, *Journal of Marine Science and Application*, Vol. 16 No. 2, pp. 129–136.

Wang, J., Yan, Z., Wang, M., Li, M. and Dai, Y. (2013), “Multi-objective optimization of an organic Rankine cycle (ORC) for low grade waste heat recovery using evolutionary algorithm”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 71, pp. 146–158.

Wang, J.J., Jing, Y.Y., Zhang, C.F. and Zhao, J.H. (2009), “Review on multi-criteria decision analysis aid in sustainable energy decision-making”, *Renewable and Sustainable Energy Reviews*, Vol. 13 No. 9, pp. 2263–2278.

Wang, M., Lawal, A., Stephenson, P., Sidders, J. and Ramshaw, C. (2011), “Post-combustion CO2 capture with chemical absorption: A state-of-the-art review”, *Chemical Engineering Research and Design*, Institution of Chemical Engineers, Vol. 89 No. 9, pp. 1609–1624.

Wang, W. and Duffy, A.H.B. (2009), “A triangulation approach for design research”, *International Conference on Engineering Design, ICED’09*, No. August, pp. 275–286.

Wang, X. and Teo, C.-C. (2013), “Integrated hedging and network planning for container shipping’s bunker fuel management”, *Maritime Economics & Logistics*, Vol. 15, available at:https://doi.org/10.1057/mel.2013.5.

Wang, X., Yang, C., Huang, M. and Ma, X. (2018), “Multi-objective optimization of a gas turbine-based CCHP combined with solar and compressed air energy storage system”, *Energy Conversion and Management*, Elsevier, Vol. 164 No. 30, pp. 93–101.

Wärtsilä. (2009), *Boosting Energy Efficiency*.

Wärtsilä. (2013), *Wärtsilä’s 2-Stroke Dual-Fuel Engine Introduced*, available at: https://www.wartsila.com/media/news/20-11-2013-wartsila’s-2-stroke-dual-fuel-engine-introduced.

Wärtsilä. (2015), *Wärtsilä Environmental Product Guide*, Finland.

Wärtsilä. (2017), *Wärtsilä Project Guides*, available at: https://www.wartsila.com/products/marine-oil-gas/engines-generating-sets/dual-fuel-engines.

WCED (UN World Commission on Environment and Development). (1987), "Report of the World Commission on Environment and Development: Our Common Future: Report of the World Commission on Environment and Development", pp. 1–300.

Wee, J.H. (2011), "Molten carbonate fuel cell and gas turbine hybrid systems as distributed energy resources", *Applied Energy*, Elsevier Ltd, Vol. 88 No. 12, pp. 4252–4263.

Weisser, G., Ag, W.S., Wik, C. and Delneri, D. (2011), "IMO Tier III – Challenging Task for the Developers of Large Diesel Engines", *13. Tagung "Der Arbeitsprozess Des Verbrennungsmotors / The Working Process of the Internal Combustion Engine"*, Graz, pp. 471–482.

Welaya, Y.M.A., El Gohary, M.M. and Ammar, N.R. (2011), "A comparison between fuel cells and other alternatives for marine electric power generation", *International Journal of Naval Architecture and Ocean Engineering*, Society of Naval Architects of Korea. Production and hosting by ELSEVIER B.V., Vol. 3 No. 2, pp. 141–149.

Welman, Kruger and Mitchell, M. (2005), *Research Methodology*, erd., Oxford University Press Southern Africa.

Wen, S., Lan, H., Hong, Y.Y., Yu, D.C., Zhang, L. and Cheng, P. (2016), "Allocation of ESS by interval optimization method considering impact of ship swinging on hybrid PV/diesel ship power system", *Applied Energy*, Elsevier Ltd, Vol. 175, pp. 158–167.

Wenzhong, G., Guolong, C., Min, H. and Shuili, C. (2007), "A Discrete Particle Swarm Optimization Algorithm for the Multiobjective Permutation Flowshop Sequencing Problem", *Fuzzy Information and Engineering. Proceedings of the Second International Conference of Fuzzy Information and Engineering (ICFIE'2007)*, pp. 323–331.

Whitfield, R.I., Duffy, A.H.B., Thomson, A., Wu, Z. and Liu, S. (2007), "An architecture for organisational decision support", *System Engineering for Future Capability*, Vol. 1 No. 1, pp. 1–17.

Whitfield, R.I., Hills, W. and Coates, G. (1999), "The application of multi-objective robust design methods in ship design", available at: http://strathprints.strath.ac.uk/6397/1/strathprints006397.pdf.

Wik, C. (2010), "Reducing medium-speed engine emissions", *Journal of Marine Engineering & Technology*, Vol. 9 No. 2, pp. 37–44.

Wik, C. (2013), "Tier III technology development and its influence on ship installation and operation", *CIMAC Congress 2013*.

Wik, C. (2016), "Low emission engine technologies for future Tier 3 legislations- Options and case studies", *Journal of Shipping and Trade*, Journal of Shipping and Trade, pp. 1–34.

Williams, C.C. and Millington, A.C. (2004), "The diverse and contested meanings of sustainable development", *The Geographical Journal*, Vol. 170 No. 2, pp. 99–104.

Williams, M. (2017), *Challenges and Opportunities in the Tanker Markets*.

Wingd. (2018), *Low-Speed Engines*, available at: https://www.wingd.com/en/documents/general/brochures/wingd-low-speed-engines-2018.pdf/.

WinGD. (2005), *Selective Catalytic Reduction*, available at: https://www.dieselnet.com/tech/cat_scr.php [Acedido:23-02-2016].

Winnes, H. and Fridell, E. (2009), "Particle emissions from ships: dependence on fuel type.", *Journal of the Air & Waste Management Association (1995)*, Vol. 59 No. 12, pp. 1391–1398.

Winnes, H. and Ulfvarson, A. (2006), "Environmental Improvements in Ship Design by the Use of Scoring Functions", *Journal of Engineering for the Maritime Environment*, Vol. 220 No. 1, pp. 29–39.

WLPGA. (2018), *LPG for Marine Engines*.

Woodyards, D. (2009), *Pounder's Marine Diesel Engines and Gas Turbines*, Butterworth Heinemann.

Woud, H.K. and Stapersma, D. (2002), *Design of Propulsion and Electric Power Generation Systems*, IMarEST, Institute of Marine Engineering, Science and Technology, London.

Xie, G. (2011), "Optimal preliminary propeller design based on multi-objective optimization approach", *Procedia Engineering*, Vol. 16, pp. 278–283.

Yang, C.-D., Luo, C.-C., Liu, S.-J. and Chang, Y.-H. (2005), "Applications of Genetic-Taguchi Algorithm in Flight Control Designs", *Journal of Aerospace Engineering*, Vol. 18 No. October, pp. 232–242.

Yang, M.H. (2015), “Thermal and economic analyses of a compact waste heat recovering system for the marine diesel engine using transcritical Rankine cycle”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 106, pp. 1082–1096.

Yang, Z.L., Zhang, D., Caglayan, O., Jenkinson, I.D., Bonsall, S., Wang, J., Huang, M., et al. (2012), “Selection of techniques for reducing shipping NOx and SOx emissions”, *Transportation Research Part D: Transport and Environment*, Elsevier Ltd, Vol. 17 No. 6, pp. 478–486.

YCharts. (2018), “European Union Natural Gas Import Prices”, available at: https://ycharts.com/indicators/europe_natural_gas_price.

Yin, R.K. (2003), *Case Study Research Design and Methods*, Third., Sage Publications.

Yoo, B.Y. (2017), “Economic assessment of liquefied natural gas (LNG) as a marine fuel for CO2 carriers compared to marine gas oil (MGO)”, *Energy*, Elsevier Ltd, Vol. 121, pp. 772–780.

Yousefi, M., Kim, J.H., Hooshyar, D., Yousefi, M., Sahari, K.S.M. and Ahmad, R.B. (2017), “A practical multi-objective design approach for optimum exhaust heat recovery from hybrid stand-alone PV-diesel power systems”, *Energy Conversion and Management*, Elsevier Ltd, Vol. 142, pp. 559–573.

Zavadskas, E.K., Turskis, Z. and Kildienė, S. (2014), “State of art surveys of overviews on MCDM/MADM methods”, *Technological and Economic Development of Economy*, Vol. 20 No. 1, pp. 165–179.

Zhen, L. and Chang, D.F. (2012), “A bi-objective model for robust berth allocation scheduling”, *Computers and Industrial Engineering*, Elsevier Ltd, Vol. 63 No. 1, pp. 262–273.

Zhou, P. and Wang, H. (2014), “Carbon capture and storage - Solidification and storage of carbon dioxide captured on ships”, *Ocean Engineering*, Vol. 91, pp. 172–180.

Zhu, B. (2009), “Solid oxide fuel cell (SOFC) technical challenges and solutions from nano-aspects”, *International Journal of Energy Research*, Vol. 23 No. 2, pp. 70–79.

Zhu, J., Wang, Y.-J. and Collette, M. (2014), “A multi-objective variable-fidelity optimization method for genetic algorithms”, *Engineering Optimization*, Vol. 46 No. 4, pp. 521–542.

Zitzler, E. and Thiele, L. (1998), *An Evolutionary Algorithm for Multiobjective Optimization : The Strength Pareto Approach. Technical Report 43, Computer Engineering and Communication Networks Lab (TIK)*, Zurich, Switzerland, available at:https://doi.org/10.1.1.40.7696.

Appendix A. Semi-structured Interview questions for the model qualification

Findings from the interviews are reported in the following paragraphs. P1 did not respond to questions 2a-c and 3d because the company he/she works for does not operate vessels.

1. Current practices for selection of the ship energy systems machinery:

a. What is the current practise for the selection of the ship energy systems in the design stage?

Both participants reported that it depends on the vessel type, the client and the shipyard collaborating with the shipping company. They mentioned that each shipyard has standardised designs however, there can be limited modifications and addition of technologies after negotiations. P1 reported that with 'larger orders' or orders of 'high-value vessels' like cruise ships there is increased flexibility and the shipyard will negotiate with the designer.

b. What objectives are considered in the process, how do you conclude that a configuration is the best? Economic and technical or economic, technical and environmental (gaseous emissions) objectives?

P1 mentioned capital, maintenance and running cost as well as operating savings. In addition, suggested that technical consideration, as well as environmental objectives, become increasingly more important to the clients especially in the cruise ship sector. On the other hand, P2 stated that capital cost and the potential of the vessel being resold are the most important objectives. Regarding the environmental objectives, they just aim to comply with the current regulatory status. However, recently adopting greener technologies is a greater incentive to the bank and it is considered an asset, in order to attain a loan or a higher loan.

c. What key performance indicators do you use for the evaluation of the different configurations?

Both participants stated that the net present value of the investment, the internal rate of return as well as the payback period are important indicators. P1 added the expected operating cost and fuel consumption.

d. In the design process, do you consider the future air pollution regulations? (Sulphur and nitrogen oxides emissions)

P1 said that it is becoming more common to consider future regulations and it depends on the client, however they install technologies to comply with the current regulations and they 'future proof' by allowing flexibility to retrofit. P2 supported this by mentioning that 'they expect for the regulations to be implemented before they act on them'.

e. For the economic objectives, only the capital cost of the investment is considered or the operating expenditures are included (fuel cost, maintenance cost)?

P1 stated that both capital and operating whereas P2 said only capital and payback period.

f. During the design phase, the machinery is selected according to a design point (design speed) or a variable operating profile of the vessel?

Both participants supported that the design is according to a design speed.

g. Before designing a vessel, do you know the areas that the vessel will sail in? Do you consider the percentage of time that the ship will sail in the Emission Control Areas?

Both participants mentioned that this depends on the client and the vessel type, it is not always known. However, when it is known it has a significant role especially with the forthcoming regulations.

2. Environmental concerns

a. Do you estimate/track the emissions from the vessel during its lifetime? And if yes what gas emissions do you consider?

P2 stated that they track the performance of the engine to assure it complies with the Tier regulations according to the manufacturer's qualification.

b. What are the most important gas emissions you are interested in mitigating?

They are interested only to the SOx and NOx emissions that are regulated.

c. What are the challenges from the air emission regulations, the ECA areas, the EEDI and MRV regulations?

The challenges are regarding the infrastructures and the availability of low sulphur fuels in order to comply with the SOx emissions limits.

d. Do you believe that a trading scheme for the CO_2 *emissions from ships is going to be forced?*

Both participants reported that it is certain that in the future a trading scheme or tax is going to be implemented.

3. Technologies

a. What are the current technologies used in order to comply with the air emission regulations? (scrubber, fuel switch, WHR, SCR, EGR, carbon capture, etc.)

Both participants mentioned the scrubber, alternative fuels, SCR and EGR and P2 also mentioned WHR.

b. What are the future trends in propulsion technologies? (fuel cells, dual fuel engines, etc.)

Both participants discussed about dual fuel engines. Regarding fuel cells, P1 suggested for auxiliary power, whereas P2 said that it is a trend but there are no certified manufacturers yet.

The both supported that hybrid or electric configurations but mostly for locally trading vessels. They both mentioned alternative, renewable forms of energy.

c. *What are the future trends on fuels? (LNG, LPG, MDO, MGO, ethane, methanol, etc.)*

They both mentioned that MDO, MGO and LSHFO are currently used for SECA areas. P1 stated that HFO will become more limited and LSHFO will be the most prominent fuel due to the 2020 regulations. Regarding the future trends on fuels, they reported that LNG, LPG and methanol are more common, as well as ethanol or hydrogen. However, P2 stated that regarding the first two there are concerns for the infrastructures, whereas for the latter ones they are reluctant due to safety reasons.

d. *Would you be interested in investing in a technology that has an increased capital cost but over the vessel's life offers less operating expenditures?*

P2 stated that 'Yes but ship owners have very short-term vision, especially since the operating costs are covered by the charterers'.

e. *Would you be interested in investing in more innovative technologies like solar panels, wind turbines, etc.? And if yes, what are the most promising?*

Both participants mentioned solar panels; however, P2 said that there are safety challenges stemming from the class societies.

4. Proposed model

a. *Do you believe that a tool that could evaluate the economic and environmental performance of alternative ship energy system configurations in the design phase would be useful?*

Both participants supported that a tool that can integrally evaluate the economic and environmental performance of the ship energy systems would be useful. Especially due to the fact that more technologies can be considered according to the preferences of the user.

b. *What is your opinion in including the gas emissions of the energy systems along with their economic performance in the evaluation process? Do you believe that this would be useful?*

They suggested that incorporating the gas emissions would be very beneficial for the charterers, as well as the class societies, regulators, ship-owners and shipyards.

c. *Would you prefer to be offered with a single optimal configuration or a set of alternative optimal configurations and select among them?*

Both participants stated that a variety of solutions rather than one would be preferred, this offers more flexibility.

Appendix B. NSGA-II algorithm parameters setting

The orthogonal array for five factors with three levels $L_{27}\ 3^5$ is displayed in Table B.1.

Table B.1 Orthogonal design table ($L_{27}\ ^{35}$)

	Factors				
Cases	**A**	**B**	**C**	**D**	**E**
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	1	3
4	1	2	2	2	1
5	1	2	2	2	2
6	1	2	2	2	3
7	1	3	3	3	1
8	1	3	3	3	2
9	1	3	3	3	3
10	2	1	2	3	1
11	2	1	2	3	2
12	2	1	2	3	3
13	2	2	3	1	1
14	2	2	3	1	2
15	2	2	3	1	3
16	2	3	1	2	1
17	2	3	1	2	2
18	2	3	1	2	3
19	3	1	3	2	1
20	3	1	3	2	2
21	3	1	3	2	3
22	3	2	1	3	1
23	3	2	1	3	2
24	3	2	1	3	3
25	3	3	2	1	1
26	3	3	2	1	2
27	3	3	2	1	3

The findings for the four metrics derived from the statistical analysis performed in Minitab are presented in this section.

A) Computational time metric

It is evident from Figure B.1 that the C factor (Population size) has the greatest variations on the means, thus the greatest impact. From the p values in Table B.2 of the means ratios, it is justified that the C factor is the only statistically significant since p-value is below 0.05 which is considered important in the literature (Stewardson and Whitfield, 2004). In this case, the aim is to minimise the computational time thus, from the response Table B.3, it is evident that the Level 3, 1, 1, 2 and 1 for each factor A, B, C, D, E respectively, minimises the time.

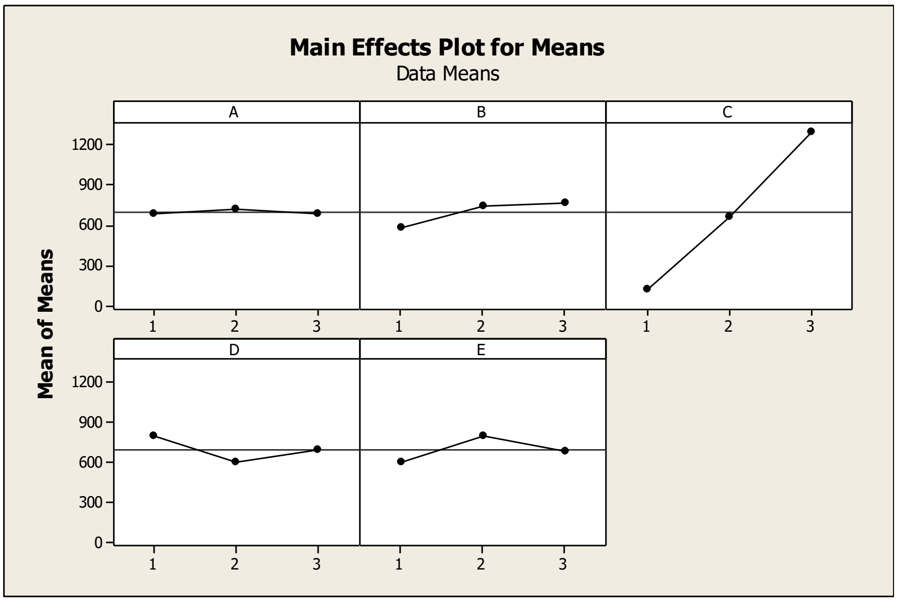

Figure B.1 Impact of factors on computational time

Table B.2 Statistical significance of factors on computational time

Factor	p (analysis on variance of means)
A	0.954
B	0.335
C	**0.000**
D	0.348
E	0.352

Table B.3 Response table of means for computational time

Level	A	B	C	D	E
1	683.4	**578.2**	**119.3**	791.1	**599.1**
2	715.5	739.2	661.5	**595.6**	793.1
3	**678.6**	760.2	1296.7	690.8	685.3

B) Dominance metric

It is evident from Figure B.2 the E factor is experiencing the greatest variation. According to the p values on the means ratios, Table B.4, it is observed that the E factor has statistical significance. In this case, the aim is to maximise the dominance metric thus, from Table B.5, it is evident that the Level 1, 2, 3, 3 and 2 for each factor A, B, C, D and E respectively, is the best-performing.

Figure B.2 Impact of factors on dominance metric

Table B.4 Statistical significance of factors on dominance metric

Factor	p (analysis on variance of means)
A	0.152
B	0.829
C	0.071
D	0.326
E	**0.000**

Table B.5 Response table of means for dominance metric

Level	A	B	C	D	E
1	**0.318**	0.221	0.150	0.214	0.071
2	0.203	**0.261**	0.267	0.210	**0.459**
3	0.202	0.240	**0.306**	**0.299**	0.194

C) Hypervolume metric

It is evident from Figure B.3 that the E factor has the greatest variations on the means, thus the greatest impact. From Table B.6 it is also observed that E factor has statistical significance below 0.05. In this case, the aim is to maximise the hypervolume and from the response table of means (Table B.7), it is evident that the Level 3, 2, 3, 3 and 2 for each factor A, B, C, D and E respectively, manages to maximise the hypervolume.

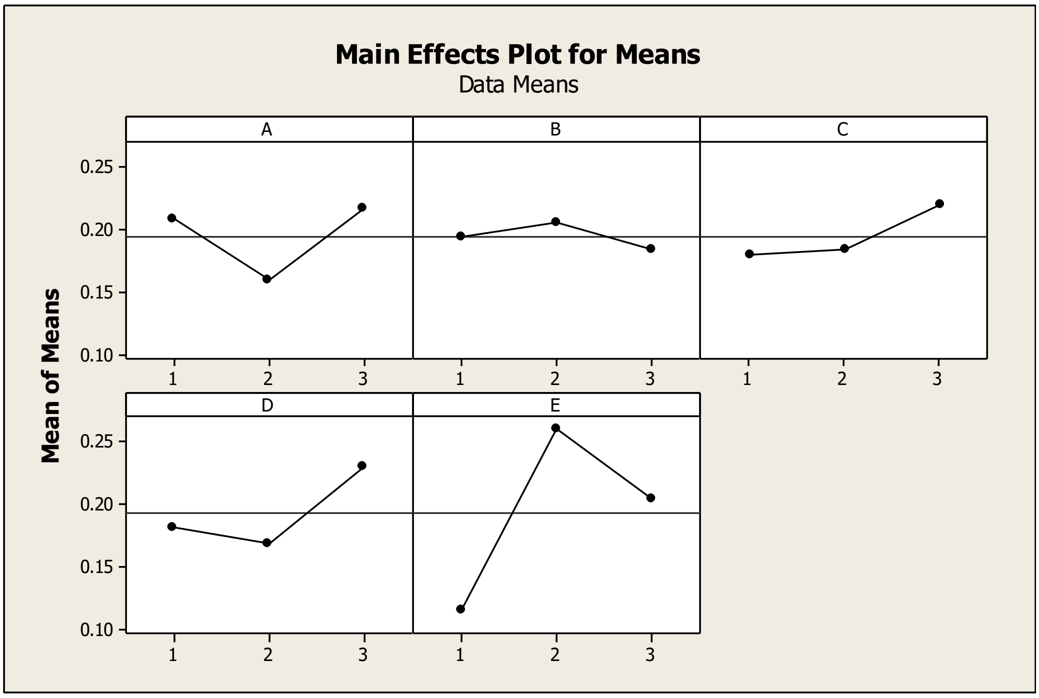

Figure B.3 Impact of factors on hypervolume metric

Table B.6 Statistical significance of factors on hypervolume metric

Factor	**p (analysis on variance of means)**
A	0.300
B	0.843
C	0.517
D	0.261
E	**0.006**

Table B.7 Response table of means for hypervolume metric

Level	**A**	**B**	**C**	**D**	**E**
1	0.207	0.194	0.178	0.182	0.115
2	0.158	**0.205**	0.183	0.168	**0.261**
3	**0.216**	0.182	**0.220**	**0.231**	0.205

D) Spread metric

The A and C factors have the greatest variations on the means (Figure B.4) and are the most statistically significant (Table B.8). In this case, the aim is to maximise the spread metric and from the response Table B.9, the Level 1, 1, 1, 1 and 2 for each factor A, B, C, D and E respectively, exhibits the best value for the spread metric.

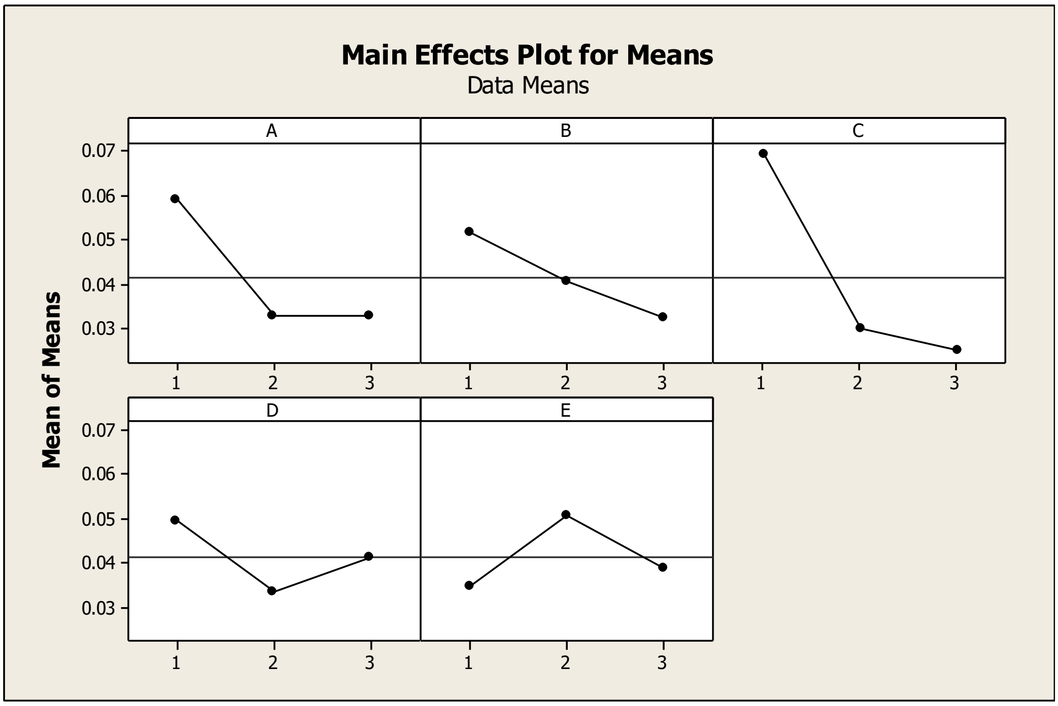

Figure B.4 Impact of factors on spread metric

Table B.8 Statistical significance of factors on spread metric

Factor	p (analysis on variance of means)
A	**0.024**
B	0.186
C	**0.001**
D	0.284
E	0.282

Table B.9 Response table of means for spread metric

Level	A	B	C	D	E
1	**0.0590**	**0.0514**	**0.0692**	**0.0497**	0.0349
2	0.0327	0.0406	0.0300	0.0333	**0.0506**
3	0.0326	0.0323	0.0251	0.0413	0.0388

Appendix C. Energy Efficiency Design Index calculation

The Energy Efficiency Design Index (EEDI) estimates the grams of CO_2 emissions per transport work (g CO_2/ tonne-mille).

The reference value for the EEDI is estimated according to the IMO (IMO, 2014), following Equation C.1.

$$EEDI_{ref} = a\ b^{-c} \qquad \text{C.1}$$

The parameters of the equation are derived from Table C.1 for the tanker and cruise ship.

Table C.1 Parameters for EEDI reference value equation

Ship type	a	b	c
Tanker	1218.8	DWT of the ship	0.488
Cruise ship with non-conventional propulsion	170.84	GT of the ship	0.214

The required value for the EEDI depends on the year the ship is build and is estimated as follows:

$$EEDI_{req} = \frac{1-x}{100}\ EEDI_{ref} \qquad \text{C.2}$$

The reduction value in this thesis, presented in Table C.2 is considered according to the IMO regulations.

Table C.2 EEDI reduction factor X

Ship type	Phase 0 (1/1/13-31/12/14)	Phase 1 (1/1/15-31/12/19)	Phase 2 (1/1/20-31/12/24)	Phase 3 (1/1/25 onwards)
Tanker (≥20,000 DWT)	0	10	20	30
Cruise ship with non-conventional propulsion (≥85,000 GT)	no required EEDI	5*	20	30

* or ships on 1/9/15

The ship needs to attain EEDI value that satisfies Equation C.3 in order to comply with the regulations.

$$EEDI_{attained} \leq EEDI_{req} \qquad \text{C.3}$$

The EEDI attained value for a no ice class ship, like the ship types considered in this thesis, is calculated according to the IMO regulations (Equation C.4). The equation was adapted in order to include the carbon capture operation; therefore, an energy penalty was considered, as well as an efficiency factor for the carbon emissions reduction.

$$EEDI_{attained} = \frac{(P_{ME}\, C_{ME} SFOC_{ME} + P_{AE}\, C_{AE} SFOC_{AE} - f_{eff}\, P_{AEeff} C_{AE} SFOC_{AE})(1-f_{cc})}{Capacity\, V_{ref}} \qquad \text{C.4}$$

Where:

P_{AEeff}	the auxiliary power reduction due to the waste heat recovery
P_{ME}	$P_{ME} = 0.75\ (MCR_{me} - P_{PTO})$, 75% of the nominal power of the engine and in case there is a shaft generator the 75% of the rated electric power of the generator is deducted
P_{AE}	$P_{AE} = 0.025\ MCR_{me} + 250 + P_{cc}$ is the auxiliary power in kW required for the ship in maximum sea load. The P_{AE} is calculated considering an average 0.95 efficiency for the generators.
P_{PTO}	is 75% of the rated electric power of the generator
P_{CC}	Energy penalty due to the carbon capture system operation
V_{ref}	ship nominal speed in knots
f_{eff}	for a waste energy recovery system equals 1
f_{cc}	the carbon capture system CO_2 reduction potential (which is restricted by the constraint on the ship available capacity for the CO_2 chemicals and carbon by-products)
C	carbon coefficient (in case there is a dual fuel engine both coefficient factors for the pilot fuel and the natural gas are considered)
Capacity	DWT for tanker and GT for the cruise ship
SFOC	specific fuel consumption at the design point (in case there is a dual fuel engine both sfoc for the pilot fuel and the natural gas)

In the case of the cruise ship that has a non-conventional propulsion, the P_{me} is zero because the ship has only electric propulsion, therefore Equation C.4 is adapted according to IMO (CLIA, 2013) as follows (Equation C.5):

$$EEDI_{attained} = \frac{((P_{AE} + \sum P_{PTI})\, C_{AE} SFOC_{AE} - f_{eff}\, P_{AEeff} C_{AE} SFOC_{AE})(1-f_{cc})}{Capacity\, V_{ref}} \qquad \text{C.5}$$

P_{PTI}	is the 75% of the rated power consumption of the shaft motors divided by the generators efficiency (0.95) and the propulsion chain efficiency (0.92).