Sustainability assessment of ship energy systems at the design phase: Integrating environmental and economic aspects

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Abstract
Sustainable development of the shipping sector is becoming increasingly important for policy, decisions makers, as well as, academia. A gap in assessing the sustainability of ship systems exists, even though the ship energy systems have the major environmental and economic impacts over the vessel's operational lifetime. The purpose of this paper is to present the status of sustainability assessment in the shipping sector and introduce a method that can facilitate the integrated assessment of environmental and economic sustainability of ship systems lifetime at the design phase, by taking into consideration the operational and regulatory requirements of the vessel.

Keywords: operational profile, ship energy systems, sustainability

Introduction
Motivation

Shipping consists a vital part of the international trades; according to the International Chamber of Shipping ninety percent of the world imports and exports are performed by ships. Since 'international trade is the indisputable foundation for economic growth and prosperity' (Hart et al., 2012), maritime operations are an essential component of the world's economy (Mansouri et al., 2015) and a major contribution on the global supply chain (Cheng et al., 2013).

Shipping operations have a significant contribution as well on the overall emissions from the transportation sector (Eyring et al., 2010). According to studies it is estimated that the NOx, SOx and CO_2 emissions from seagoing ships consist respectively the 10-15%, 4-5% and 2-3% (Gaspar et al., 2014) of the overall global emissions and they tend to increase.

The reduction of anthropogenic and greenhouse gas emissions is a major challenge society is facing. Thus, the improvement of ship sustainability performance, due to the size of shipping operation, consists a starting point for the improvement of the overall transportations sustainability; and helps in approaching the environmental targets set on the transportation sector.

Accordingly, regulations have been imposed from the International Maritime Organization (IMO) in order to set limits for the NOx, SOx and particulate matter PM emissions from ships (IMO, 2011). Two areas are acknowledged according to the regulations: the global areas and the Emission Control Areas (ECA). In the latter, more stringent limits are imposed to SOx and NOx emissions from ships (IMO, 2011). In addition, regulations like the Energy Efficiency Design Index, the Ship Energy Efficiency Management Plan and the Monitoring, Reporting and Verification system have been introduced to improve the ship energy efficiency and reduce the CO_2 emissions. Furthermore, the EU is discussing whether the emissions trading scheme should include shipping operations (Eyring et al., 2010).

Moreover, shipping companies adopt green performance in order to improve their reputation and cover society's demand for green practices, since there is a positive effect of green performance on competitiveness (Cheng et al., 2013). This environmental friendly attitude is preferred from customers (Armstrong and Banks, 2015) and rewarded with financial and non-financial benefits like the Green Award.

Thus, the sustainable development of the shipping sector is becoming increasingly important for policy and decisions makers and has been introduced in the agenda of the main shipping stakeholders (Basurko and Mesbahi, 2014). However, the incorporation of sustainable performance is delayed due to the lack of guidelines (Basurko and Mesbahi, 2014) and the challenges the main shipping stakeholders' face in order to achieve environmental performance with the minimum compromise of the economic performance (Cheng et al., 2013)

Literature Review

Sustainability in shipping is a relatively new area of interest and has attracted recently great attention from the academia. However, neither a way to define it exactly nor a guidance for defining it has been established (Cabezas-Basurko et al., 2008). In the literature, there have been some attempts to define and assess sustainability or some aspects of sustainability.

Life Cycle Assessment (LCA) is a common tool applied to assess the environmental impact of transportation and some studies specifically adopted LCA in the shipping sector. Fet (2002) performed an environmental reporting of marine transportation, Chatzinikolaou and Ventikos (2015a, 2015b) and Daskalakis et al. (2015) presented studies on the life cycle air emissions from ships, Ling-Chin and Roskilly (2016) investigated alternative retrofit power plants with respect of their life cycle environmental performance. Finally, Kameyama et al. (2007) and Tincelin et al. (2010) developed LCA software to estimate the environmental impact.

The focus of the previous studies is on the environmental aspect of sustainability only, whereas some of the authors that assess also the other aspects of sustainability are presented in Table 1. Basurko and Mesbahi (2014) presented a method to assess 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 aggregating the results by using ecopoints for normalization. However, ecopoints is not a quite appropriate technique for shipping operations, due to the assumptions made based on specific location. Hasegawa and Iqbal (2000) and Popa et al. (2014) do not manage to capture the economic life cycle performance of the vessel and Ellingsen et al. (2002) present a ship type specific model.

Table 1 – Papers addressing sustainability on shipping sector

Authors	Sustainability Indicators			Subject
	Environmental	Economic	Social	
Basurko and Mesbahi (2014)	LCA	LCC	BAMES	marine technologies
Landamore et al. (2007)	LCA	LCC	-	maritime systems
Ellingsen et al. (2002)	LCA	LCC	-	fishing ships
Hasegawa and Iqbal (2000)	LCA	Required Freight Rate	-	inland transportation alternatives
Popa et al. (2014)	LCA	Material financial impact	-	ship

From Table 1 it can be inferred that in order to assess the environmental dimension of sustainability the tool used is LCA, however this method is not quite compatible with ships or has to be critically used (Fet, 2002). Currently there are no available databases for LCA in shipping (Chatzinikolaou and Ventikos, 2014), so the databases of the land based power plants have to be used, leading to inaccurate results. Another issue is that in maritime sector there is no model available for assigning the emissions found in the inventory to the midpoint impacts (Chatzinikolaou and Ventikos, 2015b) or predicting the social and economic performance (Basurko and Mesbahi, 2014). Thus, assumptions of the land based models are used, which compromises the accuracy of the results since most of the operations the ship performs are at sea. 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 a complex system like ship. As an example, the real operational profile of the ship cannot be modelled within LCA.

The last comment consists a major drawback of the LCA technique. The operational profile is highly dependent from the vessel's type, the strategy of the ship-owner and operator, the fluctuations of the market and the fuel prices (Solem et al., 2015), thus in order to accurately estimate the life cycle environmental and economic performance the operational profile needs to be incorporated in the process. In addition, the operational profile expresses the trends in the supply chain and supply chain management. As it defines the speed the ship sails and therefore the lead-time, the voyage the vessel will follow so it dictates the time spend on environmental zones, the fuel choice and as a result the ports the ship needs to stop in order to refuel and the time spend there.

From the studies reviewed in Table 1 it is also evident that Life Cycle Cost (LCC) tool is mostly used, since the LCC is a tool appropriate for assessing the economic dimension of sustainability utilized in systems engineering (Basurko and Mesbahi, 2014).

For the assessment of the social aspect of sustainability only one case was found in the literature, due to the fact that there are no specific guidelines to assess social sustainability on the marine environment (Cabezas-Basurko et al., 2008). In addition, most of the existing tools are highly dependent on the socioeconomic situation and on the specific location (Basurko and Mesbahi, 2014), so the tools are not compatible with shipping operations. Interpreting the results of the social assessment tools is also challenging, since the majority of the tools are built on subjective assumptions (Basurko and Mesbahi, 2014).

From the literature, it is concluded that some attempts to assess ship sustainability have been made. However, there is a gap on a specific method that can incorporate the real operational profile of the vessel, include the regulatory requirements and the interconnections of the ship systems and accurately assess the ship systems environmental and economic sustainability, by overcoming the controversies between the aspects of sustainability and managing the trade-offs between them.

Therefore, the purpose of this paper is to introduce a method that can facilitate the integrated assessment of sustainability of ship systems lifetime, by taking into consideration the operational and regulatory requirements of the vessel. This enables to include the supply chain trends in respect of technological trends, volatility on fuel prices and markets demand on voyage and sailing speed selection. The proposed method is applied on the design phase, since it is the most important phase in order to efficiently address sustainability (Fet, Aspen, et al., 2013) and manage trade-offs among the aspects of sustainability (Winnes and Ulfvarson, 2006). In this paper, the focus is on environmental and economic dimensions of sustainability of ship systems only and the social dimension is not included, due to the subjectivity issues discussed previously. The economic and environmental performance of alternative systems is assessed in the design phase, with respect of the regulatory and operational requirements that are imposed in the shipping operations; a case study is performed to exemplify the method.

Methodology

Introduction to the method

Due to the limitations of the existent methodologies for the environmental and economic sustainability assessment of ship energy systems the following method was developed. The proposed method focuses on the ship energy systems, which, according to the literature, have the major environmental and economic impact over the vessel's lifetime (Chatzinikolaou and Ventikos, 2014; Ling-Chin and Roskilly, 2016). In addition, the attention is on the design phase when alternative technical options are considered and the decisions made for environmental efficiency lead also to cost efficiency (Andersson et al., 2016). The approach incorporates appropriate environmental and economic indicators that are estimated according to the vessel's operating profile and can be either presented separately or integrally assessed in order to evaluate trade-offs.

Methodological Steps

The methodology is described in six steps that are outlined and explained in detail in the following paragraphs.

1. Definition of Sustainability:

In this paper, sustainability is defined as the environmental and economic sustainability of ship energy systems over the vessel's lifetime. The social aspect is out of the scope of this research, due to the limitations of existing tools for marine technologies and the potential subjectivity introduced by using the existent tools. In this paper, the environmental impact is expressed as the air emissions from the exhaust gas of the ship systems, which are regulated and can be accurately estimated from the components' manufacturer data. The chosen approach has been already used in the literature to express the environmental impact of vessel's power plant (Fet, Margrethe Aspen, et al., 2013; Gaspar et al., 2014).

2. Selection of Indicators:

The selection of indicators has a significant role in the method and it is directed by the definition of sustainability. Indicators underline the measuring parameters that can be used in order to compare alternative synthesis of the systems. The determination of the energy system to be used in the design phase is affected by various factors that are going to be represented from the indicators selected for the assessment. The indicators selected for the assessment of the ship systems are shown in Table 2:

Table 2- Sustainability Indicators

Environmental	**Economic**
NOx emissions	Capital Cost
SOx emissions	Operational Cost
CO_2 emissions	
PM (Particulate Matter)	
VOC (Volatile Organic Compounds)	

The emission indicators selected are among the key compounds emitted from ships (Lloyd's Register, 1995), and have a major effect on the atmosphere and human health. In addition, these emissions are according to the literature the most significant in shipping and some of them are strictly regulated, like NOx and SOx, or it is forecasted that are going to be regulated in the future (CO_2).

3. Technical Analysis of Systems:

In this step the description and modelling of the systems is performed. Technologies available now and those that will be available in the future are identified and analysed. The approximation of systems performance expresses the most important factors needed to estimate the sustainability indicators. The values needed from the models are found from the performance curves provided by manufacturers' data or from literature and technical reports.

At this step, the interactions among the systems are modelled, in order to integrally evaluate the systems environmental and economic performance. The integrated consideration of the systems has a great impact in the optimum synthesis of the systems, due to the highly interactive relationships among the systems (Gaspar et al., 2014). Another important step in the analysis of the systems is to include the component's limitation and compliance with other components, by introducing constraints. Thus, the results represent solutions that are feasible.

4. Simulation of Systems Performance for life cycle operation:

For the evaluation of the lifetime environmental and economic performance of the systems, the systems are simulated for the life cycle operation of the vessel with real operational requirements as depicted in Figure 1.

5. Indicators Calculation:

As it is observed from Figure 1, the outputs from the simulation of the systems performance are the amount of emissions and the amount of fuel consumed. Thus, these parameters can be used in order to estimate the environmental indicators, as well as the economic indicators projected on the vessel's lifetime.

6. Multi-criteria Decision Making:

In order to include both the environmental and economic aspect of sustainability in shipping, conflicting objectives are considered (Mansouri et al., 2015). Thus, in order to display the trade-offs among the objectives the solutions are displayed in a Pareto set of solutions. The solutions of the Pareto optimal frontier are such that a solution cannot be more cost efficient without at the same time producing more emissions and vice versa, cannot be more environmental efficient without being more costly. With the Pareto set of solutions trade-offs can be visually displayed, contrary to adopting weighting techniques (Quariguasi Frota Neto et al., 2009), and informed decisions can be made based on the values of economic and environmental performance.

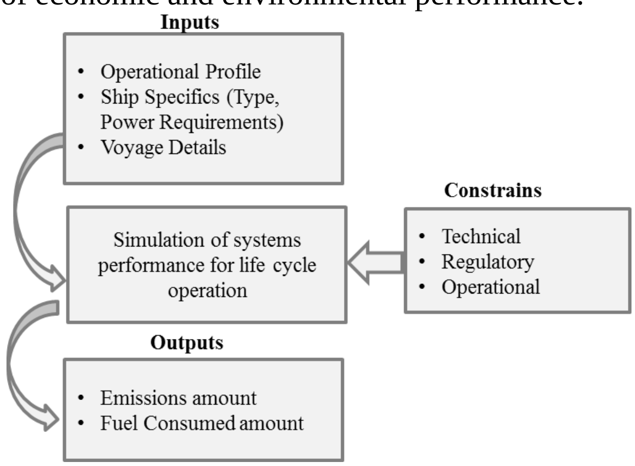

Figure 1– Simulation Flowchart

7. Sensitivity Analysis:

After the solutions are found, a sensitivity analysis is performed on some critical parameters that may vary in the future according to supply chain trends, like fuel prices, emissions' limits and operational profile. The sensitivity analysis is carried out in order to track the most sensitive and uncertain parameters and the results of the analysis can be used in the decision process.

Case Example and Results

Case Specifics

In the following section, the method previously outlined will be applied in a specific case example. The method is applied only into the main engine and emission reduction technologies and not in the integrated energy systems of the vessel. Steps 6 and 7 are also not included in this paper. The latter steps are going to be addressed in future research.

The environmental and economic performance of alternative systems of an Aframax crude oil tanker (115000DWT) is investigated in the paper. The operational requirements of the specific case ship is to transport crude oil from the Persian Gulf to Port of Atlantic City in North America. The distance of the one-way voyage is 9129nm. The area of the Port of Atlantic is regulated as an ECA, thus a percentage of time at ECA waters is considered. The operational profile is according to a real speed distribution of an Aframax tanker for the year 2011 for laden conditions (Banks et al., 2013). The lifetime of the vessel is assumed 20 years and a percentage of time where the ship is not operating due to maintenance issues is included. The fuel and urea prices, as well as the equipment cost and maintenance cost are taken from the literature or technical reports.

In order to achieve emissions reduction on the ECA waters there are two alternatives in the current practice: fuel switching or emission reduction technologies. A conventional machinery arrangement is identified as the base case scenario, in order to meet the power requirements and the environmental regulations. The method is performed comparing the base case with alternative case scenarios in order to evaluate the environmental and economic performance. The alternative machinery configurations are depicted in Table 3.

For the reduction of SOx emissions a dry scrubber or Marine Diesel Oil (MDO) is used, in comparison with the baseline marine fuel Heavy Fuel Oil (HFO) and for the reduction of NOx emissions a Selective Catalyst Reduction (SCR) is utilised.

Table 3– Alternative Options

Alternatives	**Fuel**	**NOx emissions**	**SOx emissions**
Base Case- HFO	HFO	SCR on ECA	scrubber on ECA
Alternative 1 – HFO & MDO	HFO	SCR on ECA	MDO on ECA
Alternative 2- MDO	MDO	SCR on ECA	

Results

The method was applied in the specific case scenario and sustainability indicators were calculated. A selection of the sustainability indicators are presented in Table 4, where the relative differences of the two alternatives with the base case are shown. The other indicators from Step 2 of the methodology were excluded, since in the specific case their values do not differ significantly.

Table 4– Relative Difference of indicators with Base Case

Alternatives	**SOx**	**NOx**	**CO2**	**Capital Costs**	**Operational Costs**	**Total Costs**
Base Case	-	-	-	-	-	-
Alternative 1	-0.25%	0.00%	-0.05%	-28.57%	+4.11%	-1.74%
Alternative 2	-96.32%	-8.12%	+1.76%	-28.57%	+51.78%	+37.40%

Comparing to the base case scenario there is a reduction of the capital cost of the equipment for both cases, due to the switch of the fuel for the reduction of the SOx emissions and not the installation of another component. Even though an increase of the operational cost is evident, due to the higher price of the MDO the total life cycle cost of the Alternative 1 is decreased comparing to the base case and current practice. In addition, it is evident that the SOx, which depend on the fuel are decreased on both cases of MDO, a major decrease is obvious on Alternative 2 where MDO is the only fuel used and a slight decrease when MDO is partially used on Alternative 1. The NOx emissions are also affected from the fuel, not as significantly as in the previous case, thus a reduction of NOx emissions is evident only on Alternative 2. For CO_2 emissions results, MDO has adverse effects, as there is a slight increase on Alternative 2.

Following the methodological steps, the solutions are presented as a Pareto set of solutions, where an overview of the best solution according to the objectives is determined. The Pareto solutions are developed on the following graphs for two objectives each time.

The current Pareto charts are a preliminary research output aiming to explore the value of this method. It is expected that the value of this method will be more apparent in future applications with more complex configurations and alternatives.

In Figure 2, the two objectives are the total cost and the amount of the CO_2 emissions. From Figure 2 it is obvious that the dominant solution regarding the two objectives is Alternative 1 with HFO and fuel switch for ECA waters.

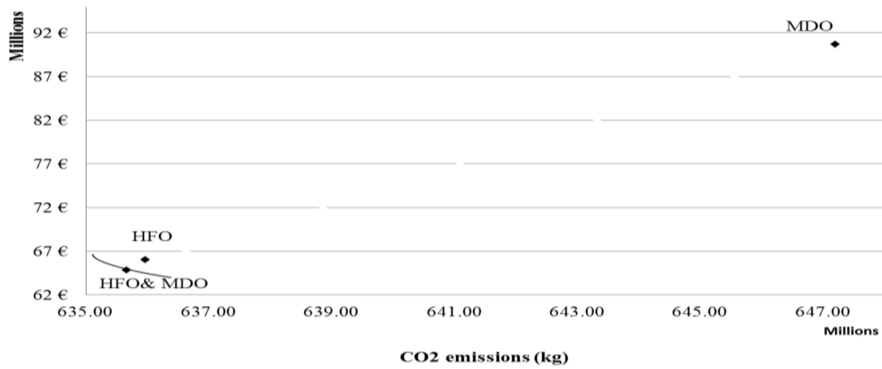

Figure 2– Pareto Solutions CO_2-Life cycle Cost

On the other hand, on Figure 3 where the two objectives are the NOx emissions and the total cost, it is evident from the Pareto frontier that two are the optimum solutions and there is a trade-off between the objectives. Along the same lines, for the SOx- life cycle cost, there is a trade-off between the major decrease of the SOx emissions in Alternative 2 and the significant increase of cost, comparing to Alternative 1.

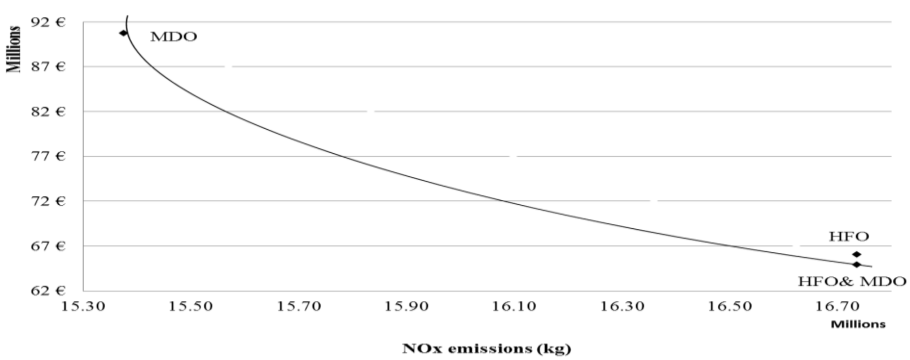

Figure 3– Pareto Solutions NOx-Life cycle Cost

From the analysis it is concluded that the base line design which is currently followed is not the optimum solution regarding, both environmental and economic indicators. Among the alternatives analysed in this scenario the optimum solution is the Alternative 1 where HFO is the basic fuel and the vessel complies with the SOx regulations by fuel switching and to the NOx limits by using a SCR. In this solution, comparing to the base case, the total cost decreased by 1.74%, the SOx by 0.25%, the CO_2 by 0.05% and the NOx remained the same.

Furthermore, it is inferred from the Pareto graphs that in some cases there is a single optimum solution and in other cases there is Pareto frontier of dominant solutions and the selection depends on the user’s preferences. However, the visualization helps the decision process and makes the trade-offs among the solutions palpable. In addition, it is concluded that by implementing different objectives the results differ, thus for future research a method needs to be developed in order to aggregate the environmental indicators and in the end offer a single Pareto graph, with an economic axis and an aggregated environmental axis.

Discussion and Concluding remarks

The method presented in this paper can be utilized in order to assess the environmental and economic sustainability of various alternative ship energy systems in the design phase, where irreversible and significant decisions are made. A limited case example of the method was performed in order to explore the value of this method. A more extended scenario including more technologies and complex configurations is going to be addressed in the future.

Results show that some alternatives perform better into one objective and worse into a different objective, making the decision difficult. With this method and the visual representation of the results the trade-offs between the aspects of sustainability can be explored and more informed decisions can be made. Thus, this method can be of great value for ship owners and designers and help in the decision process of the design phase, by evaluating different alternative systems.

In addition, new constrains can be added on the emission limits to simulate the future regulations or the user’s preferences. Sensitivity analysis can be performed on fuel prices, emission taxes prices and operational profiles to analyse how the overall result is affected from these variables. Alternative novel technologies, not widely applied, can be introduced and evaluated, in order to demonstrate the future designs when the environmental regulations become stricter. The tool is adjustable to the user’s preferences, so specific goals can be set for the indicators and preferences on technologies can be introduced.

The life cycle performance simulation of the systems can be performed for different operational profiles, a slow steaming or a higher speed profile. In that respect, it can be appraised how the environmental and economic performance of the ship energy systems affects the overall lead-time of the supply chain.

In conclusion the method developed in this paper aims to guide designers into considering the environmental and economic sustainability of the ship systems over the vessel’s lifespan at the design phase, in order to improve the ship systems sustainability. In consequence, since shipping transportations consist a vital part of the global supply chains, the improvement of ship systems sustainability will positively affect the overall global supply chain sustainability.

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