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An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems

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ABSTRACT

By adopting the concept of modularity, this paper introduced an optimal framework which facilitates life cycle assessment and life cycle cost assessment, thereby supporting rapid and reliable decision-making in the marine industry. The benefits of the proposed framework were discussed through two case studies where the optimal configurations of marine propulsion systems were determined from the economic and environmental perspectives. First, the performance of a short-route ferry using the hybrid system was compared with those of equivalent ships using diesel-electric and diesel-mechanical propulsion systems respectively. Research findings revealed the excellence of the hybrid system in both economic and environmental aspects. Second, the same method was applied to an offshore tug vessel to determine an optimal engine configuration. Results of analysis emphasised that the selection of multiple small-sized engines is more effective than two medium-sized engines. Both studies have proven that the proposed framework would be useful and practical for accelerating the life cycle analysis which allows ship designers and owners to obtain the long-term view of economic and environmental impacts for particular products or systems without demanding process. The paper also opened up the possibility of extending the application of the proposed framework to the areas where proper decision-making is essential but under-used.

1. Introduction

1.1. Background

As the world population continues to grow, globalisation has led to a remarkable growth in the sea-borne trade, which accounts for more than 80% of global freight transport. The heavy-reliance on maritime transport has significantly contributed to exacerbating the marine pollution. In response to this fact, the ICCT (2011) predicted that greenhouse gas emissions from shipping activities will triple by 2050.

Such adverse environmental prospects have played as the driving force behind the introduction of a series of stringent maritime regulations aiming to curb the marine pollution from the world fleet (MARPOL, 2011). Those environmental regulations urge shipbuilders and marine engineers to strive to develop cleaner technologies, suggesting that the green shipping is one of the most urgent issues in the marine industry.

For instance, IMO has provided a series of guidelines as means to calculate, monitor and reduce greenhouse gas emission (IACS, 2013). Although the IMO's guidance is a simple and handy tool in estimating CO_2 emissions during the ship operations, there are still demands for estimating the holistic environmental impact of marine vessels in accordance with the lifecycle of those ships.

In addition to environmental issues, ship designers and owners have paid equal efforts to build/operate ships in cost-effective manners to survive in fierce market competition. Since numerous new systems and technologies are flooding the industry, proper decision-making among various options may be an essential process.

On the other hand, the current practice of analysing economic impacts of the marine vessels are somewhat biased by the short-term perspectives of stakeholders (Fuller, 2010). For example, ship-builders strive to reduce the costs of ship construction by selecting cheaper products or systems while disregarding the long-term cost-saving potentially achieved by relatively expensive ones.

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Symbol list

$EC_{main,i}$	energy consumption of scrapping/recycling material, I (kWh)
EI_t	environmental impact for any of GWP, AP, EP or POCP for each pollutant (kg)
FS_i	specific fuel oil consumption as a function of engine load, I (g/kWh)
LS	specific lubricant oil consumption (g/kWh)
$Mtr_{main,i}$	composition of material, i
N_e	normalization factor for any of GWP, AP, EP or POCP for each pollutant
P_i	engine load (%)
$RPr_{mat,i}$	recycling price of material, i (€)
T_i	time spent in each operating mode (years)
TEC_{main}	total energy consumption of main engine scrapping/recycling (kWh)
TRB_{main}	total recycling benefit of main engine (€)
$WC_{main,i}$	weight of material, I (kg)
ϵ_e	amount of pollutant for the given time frame (kg)
ϵ_{fc}	fuel price (€)
ϵ_{lc}	lubricant price (€)

Abbreviations

AP	acidification potential
BWTS	ballast water treatment systems
CFD	computational fluid dynamics
CM	construction of main engine
DE	diesel-electric
DM	diesel-mechanical
DNV-GL	Det Norske Veritas (Norway) and Germanischer Lloyd (Germany)
DP	dynamic positioning
EP	eutrophication potential
Eurostat	European Community Statistical Office
GHG	greenhouse gas
GWP	global warming potential
HFO	heavy fuel oil
ICCT	The International Council on Clean Transportation
IMO	International Maritime Organization
ISO	International Organization for Standardization
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LCA	life cycle assessment
LCCA	life cycle cost assessment
LCIA	life cycle impact assessment
LO	lubricant oil
MM	maintenance of main engine
MARPOL	marine pollution
MDO	marine diesel oil
OM	operation of main engine
POCP	photochemical ozone creation potential
RoPax	roll-on-roll-off-passenger-ship/ferry
SFOC	specific fuel oil consumption
SLOC	specific lubricant consumption
SM	scrapping of main engine
SMEs	small and medium-sized entrepreneurs

1.2. Introduction to life cycle and cost assessment

From cradle to grave, a ship is engaged in various activities leading to spending money, consuming energy and producing emissions. In order to estimate the overall cost and the environmental impact of the vessel in question, the flows of cash, energy and emissions pertinent to every single ship activity in various life stages need to be tracked and analysed.

While the reliability of current practices on estimating economic and environmental impacts in the marine industry is perceived to be low, there have been demands for an enhanced approach which helps shifting our focus from a short-term view to a long-term one, thereby achieving proper decision making with higher reliability at the early design stage (Fuller, 2010).

In this context, LCA and LCCA have been proven useful to estimate the holistic economic and environmental impacts of particular products and/or systems (ISO, 2008). To support such analyses, several commercial software such as GaBi (2017), KCL-ECO, LCAiT, PEMS, SimaPro (2016) and TEAM have been introduced (Dašić et al., 2007). These software provide users modelling tools and solvers with the comprehensive database to estimate the environmental impact of particular items (Sharma and Weitz, 1995). Not surprisingly, a number of LCA and LCCA research in various industries have been implemented with the commercial software. Some examples are described here:

An LCA study associated with alkaline hydrogen fuel cell was carried out by Benjamin et al. (2013) aiming to find the impact of using gas atomised sponge nickel instead of cast and crush sponge nickel and platinum. A new LCA methodology for the construction phase is reported in Raugei et al. (2014). Duan et al. (2015) carried out a study in the field of urban transportation to determine the energy demand in their life cycle. A study carried out by Havukainen et al. (2017) dealt with assessing the environmental impact of municipal solid waste management incorporating a mechanical waste treatment with incineration for the specific site of Hangzhou, China. Esteve-Turrillas and Guardia (2017) conducted a life cycle assessment to compare the recovered cotton from recycled garments with cotton from traditional and organic crops. Pereira et al. (2017) applied LCA method to evaluate the carbon footprint during local visitors' travelling in Brazil using a route from Rio de Janeiro to Sao Paulo in their case study.

Noticeably, the automobile industry was one of the most proactive field in terms of LCA studies. There are some remarkable examples can be summarized as below:

In order to reduce the environmental impact during the life of a car Dhingra and Das (2014) applied LCA in the manufacturing industry. Delogu et al. (2016) carried out an environmental and economic life cycle assessment of a lightweight solution for an automotive component. They compared talc-filled and hollow glass microspheres-reinforced polymer composites. Their results stated that overall the end-of-life phase is not affected significantly due to weight reduction. Similarly, Raugei et al. (2015) carried out a coherent life cycle assessment of range of light weighting strategies for compact vehicles using advanced lightweight materials (Al, Mg and carbon fibre composites).

LCA and LCCA methods have also been applied to the shipbuilding industry in order to investigate the holistic cost and environmental impacts across ship design options.

Blanco-Davis and Zhou (2014) examined the economic-environmental effects of two different hull coating methods and three different types of BWTS. Ling-Chin et al. (2016) applied LCA method to a case study on evaluating the economic-environmental benefits of a hybrid power system on a Ro-Ro vessel. They concluded that the LCA was an effective process for proper decision