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Multi-criteria decision-making for marine propulsion: Hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives

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HIGHLIGHTS

- An effective decision making process was introduced.
- The excellence of hybrid ship was demonstrated.
- Research findings give insight into the optimal approach for multi-criteria decision analysis.
- The presented MCDA methodology can be used to support future R&D in various industries.

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ABSTRACT

The paper introduces a new decision-making process which is used to compare the performance of a ship with either diesel electric hybrid propulsion or conventional propulsion systems. A case study was carried out to compare the performance of both propulsions from cost, environmental and risk perspectives. This paper also overviews the modern approaches of multi-criteria decision-making and highlights some of their shortcomings in particular the fact that these approaches often rely on different criteria such as financial, environmental or risk. This paper aims to overcome this shortcoming by enhancing the process of multi-criteria decision analysis. The key process in this research was to convert all incomparable values into monetary values, thereby enabling the impacts of each criterion to be compared and integrated in a straightforward manner. Results of the case study showed that the use of a hybrid propulsion system could reduce annual operational costs by $ 300,000 (2% total cost) compared with a diesel electric system and almost $ 1 million (7%) compared to a diesel mechanical propulsion system. In order to investigate the optimal use of the hybrid propulsion system, various operational scenarios were identified and applied to the proposed decision-making process. The results showed that operating the ship in hybrid mode during manoeuvring and berthing is more desirable as the holistic cost can reduce in almost $ 1 million. The advantages of the proposed decision making process was illustrated by comparing the results obtained from a conventional decision-making process using the analytical hierarchical method. It is believed that the research findings not only present general understanding of the possible advantages of hybrid propulsion for stakeholders, but provide them with an insight into the enhanced approach into the multi-criteria decision analysis.

1. Introduction

1.1. Overview of hybrid ships

With an increasing demand to develop more efficient and cleaner ships, hybrid technology has drawn attention from the marine industry. Thanks to the breakthrough in battery technology which can improve the flexibility of selecting power sources, the last few years showed a number of developments in hybrid ships propulsion.

MV Viking Lady, the world's first hybrid ship equipped with a 500 kWh battery system, was launched in 2013 [1]. A series of hybrid ships followed on from this; the new offshore supply vessel of *MV Edda Ferd* was constructed in 2013 which was the first large electric battery-powered car ferry, *MV Ampere*, was delivered in 2015 [2]. For UK domestic services, three hybrid ro-ro passenger ferries, namely *MV Lochinvar, MV Hallaig,* and *MV Catriona,* were built between 2011 and 2016. They are currently in operation in Scotland [3].

Various industrial reports and academic research have showed that

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Nomenclature

List of symbols

C_E	energy cost
C_{EC}	cost for economic impact
C_{EI}	cost for environmental impact
$C_{F,i}$	fixed cost at i
C_{GWP}	cost for tCO_2e
C_k	cost for emission substance, k
C_{RI}	cost of risk impact
C_{RPN}	cost of RPN value ‘1’
C_T	total cost
$C_{v,j}$	variable costs at substance, j
EI_{GWP}	total global warming potential of the system/product
EI_k	environmental impact for potential, k
EF_j	emission factor at emission substance, j
EM	electricity margin (20%)
EP	electricity price
FC_i	fuel consumption at propulsion load, i
FP	fuel price
GWP_j	global warming potential at emission substance, i
RPN_h	RPN at hazard, h
SM	sea margin (20%)
$SFOC_i$	specific oil consumption at propulsion load, i
t_i	time spent at propulsion load, i
$EIF_{j,k}$	environmental impact factor of emission, j, regarding a particular environmental impact indicator, k
i	propulsion load
j	emission substance
k	environmental impact potential
l	number of environmental impact indicator
m	number of emission substance
n	number of propulsion load

hybrid ships will contribute to greener shipping.

Lindstad and Sandaas [4] investigated the environmental advantage of hybrid offshore support vessels with dynamic positioning system, compared with a conventional diesel electrical system. Ling-Chin and Roskilly [5] introduced a new life cycle assessment (LCA) approach in order to evaluate the performance of a hybrid ro-ro cargo vessel in terms of environmental impact, whereas Dedes et al. [6] investigated the economic impact of the hybrid system for slow speed ocean-going ships in terms of fuel saving. In addition, Wang et al. [7] adopted life cycle assessment (LCA) and life cycle cost analysis (LCCA) methods for a short route hybrid ferry and pointed out that hybrid systems in collaboration with main and auxiliary engines could contribute to a significant reduction in fuel consumption.

Lan et al. [8] proposed a structured model for estimating the optimal size of hybrid propulsion systems consisting of photovoltaic (PV), diesel engine and battery systems for five voyage scenarios.

Wen et al. [9] developed an interval method to determine the optimal size of an energy storage system (ESS) combined with a photovoltaic power system. The results obtained from a wide range of engine loads were compared from economic and environmental perspectives.

Diab et al. [10] compared onshore hybrid renewable systems with the equivalent sets of on-board systems, revealing that the combination of solar and battery systems can improve the efficiency of ship performance.

Geertsma et al. [11] reviewed recent developments in propulsion, power supply systems and their control strategies while discussing opportunities and challenges for these systems and controls. Their findings illustrated that hybrid structures with advanced control strategies could reduce fuel consumption and emissions up to 10–35% with the enhancement of noise, maintainability, manoeuvrability and comfort.

Geertsma et al. [12,13] introduced an electric drive model and integrated into the mechanical propulsion model introduced, whereas Veneri et al. [14] reviewed a number of naval applications from traditional to more innovative electric propulsion and generation architectures.

Roskilly et al. [15] showed that significant reduction in both CO_2 and NO_x emissions could be achieved through the life cycle and cost analyses for hybrid propulsion systems.

To reduce propulsion power loss, Zhao et al. [16] suggested an optimal power management for ship propulsion system concerning improving efficiency while reducing emissions. Aneke and Wang [17] reviewed energy storage technologies applicable to the hybrid ships. Jeong et al. [18] illustrated the advantages of a hybrid ship by comparing its performance with equivalent ships with diesel-electric and diesel-mechanical propulsion systems. They also presented an enhanced

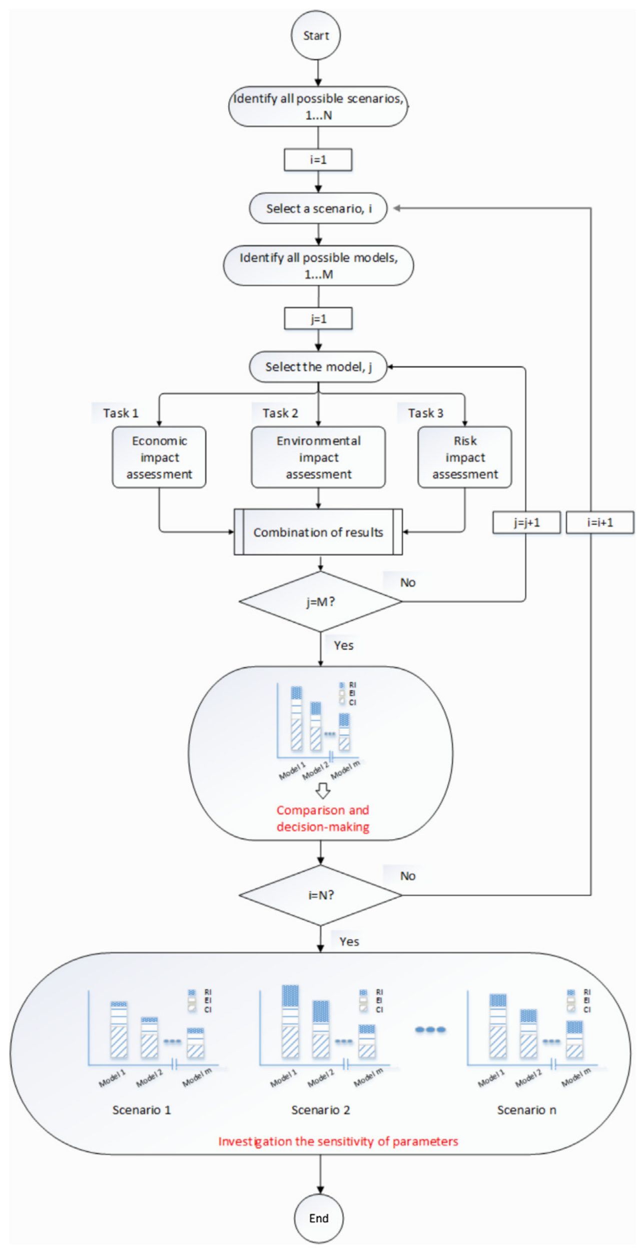

Fig. 1. Schematic of SHIPLYS LCT concept.