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Optimal load allocation of complex ship power plants

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ABSTRACT

In a world with increased pressure on reducing fuel consumption and carbon dioxide emissions, the cruise industry is growing in size and impact. In this context, further effort is required for improving the energy efficiency of cruise ship energy systems.

In this paper, we propose a generic method for modelling the power plant of an isolated system with mechanical, electric and thermal power demands and for the optimal load allocation of the different components that are able to fulfil the demand.

The optimisation problem is presented in the form of a mixed integer linear programming (MINLP) problem, where the number of engines and/or boilers running is represented by the integer variables, while their respective load is represented by the non-integer variables. The individual components are modelled using a combination of first-principle models and polynomial regressions, thus making the system nonlinear.

The proposed method is applied to the load-allocation problem of a cruise ship sailing in the Baltic Sea, and used to compare the existing power plant with a hybrid propulsion plant. The results show the benefits brought by using the proposing method, which allow estimating the performance of the hybrid system (for which the load allocation is a non-trivial problem) while also including the contribution of the heat demand. This allows showing that, based on a reference round voyage, up to 3% savings could be achieved by installing the proposed system, compared to the existing one, and that a NPV of 11 kUSD could be achieved already 5 years after the installation of the system.

1. Introduction

The shipping industry, despite its low contribution to global anthropogenic CO_2 emissions today (2.7% of the total as of 2012 [1]), will have to face increasingly stronger challenges in the future in relation to its contribution to global warming [1]. Most predictions suggest that shipping volumes (and, therefore, emissions) are expected to increase in the foreseeable future [1]. On the other hand, it has been shown that for achieving the 2 °C climate goal shipping should reduce its CO_2 emissions by more than 80% by 2050 compared to 2010 levels [2].

International regulations, such as the revised version of the International Convention for the Prevention of Pollution from Ships (MARPOL) [3], have started to put limits on ship emissions. Even further efforts are expected to be required if local regulations will be implemented. The European Union, for instance, is planning actions for achieving a 40–50% reduction in CO_2 emissions from ships visiting European harbours by 2050 [4], and in Sweden the fairway dues soon might be calculated against the clean shipping index which includes CO_2 emissions.

1.1. Energy efficiency in shipping

Many new practices and technologies are being introduced for improving energy efficiency in the shipping sector. These measures are normally subdivided between operational and design.

Operational measures include efforts that do not require the installation of new equipment on board. Optimal voyage planning allows maximising the cargo transported while reducing the length of ballast legs [5], while adapting routes for avoiding conditions of bad weather can reduce the negative impact of high waves and strong winds on ship fuel consumption [6,7]; improving trim and draft setting, together with optimising the schedules and practices for hull and propeller polishing, lead to reduced ship resistance for a given speed [8–10]; slow steaming can also dramatically reduce

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Nomenclature

Abbreviations

AB	auxiliary boiler
AE	auxiliary engine
CO_2	carbon dioxide
GB	gearbox
HRSG	heat recovery steam generator
HT	high temperature
LHV	lower heating value
LT	low temperature
MINLP	mixed integer-non linear programming
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	main engine
MCR	maximum continuous rating (kW)
NPV	net present value (USD)
OM	operational mode
SCR	selective catalytic reactor
SG	shaft generator
SM	shaft motor
USD	US dollar
WHR	waste heat recovery

Roman symbols

b	constraint vector
c_p	specific heat (J/kg K)
f	objective function
f_{corr}	correction function for off-design operations
$g(x)$	constraint function
$n_{i,on}$	number of components in the i-th group running
N_{cyl}	number of cylinders
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
P	power (kW)
$P_n(x)$	x-th degree polynome
$\dot{Q}$	heat flow (kW)
V	volume (m^3)

Greek symbols

η	efficiency
$\eta_{mech,TC}$	turbocharger mechanical efficiency
η_{vol}	engine volumetric efficiency
λ	component load
$\lambda_{xx \rightarrow yy}$	load of component *xx* related to the fulfilment of the demand *yy*

Subscripts

ca	charge air
cyl	cylinder
des	design
eg	exhaust gas
el	electric
eng	engine
eq	equality (constraint)
mech	mechanical
neq	inequality (constraint)
prop	propulsion
th	thermal

the fuel bill: as the amount of cargo transported decreases linearly with the speed, while the power demand from the engines roughly depends on the cube of the speed, the advantage is obvious [11,12].

Retrofit and design measures, on the contrary, refer to physical technical solutions. This connects to the development of the performance of individual parts of the systems, such as the engine [13–16], the propeller [17,18], and the hull [19]. Additional energy sources can be used both for propulsion (e.g., sails and rotors [20,21]) and for auxiliary power generation (e.g., fuel cells [22]). Waste energy on board can be recovered in different ways, among other for heating, power [23–25], and cooling [26,27].

1.2. Challenges of ship on board energy management

Differently from a number of land-based systems, ships can operate in many different conditions and, hence, with large variations in power demand. This is even more challenging in the case of some specific ship types, such as cruise ships, where demand of energy in different forms (mechanical, electric, thermal) and of comparable size are observed. When in port, mechanical power demand for propulsion is virtually zero, while it can be predominant in sailing conditions, depending on the speed of the vessel. Demand for thermal energy can depend on the outer temperature of air and water, as well as on the number of passengers on board. Electric power demand can similarly vary as a function of environmental and operational conditions. These conditions require the ship power plant to be able to handle many combinations of energy demands with high efficiency.

Historically, ship energy systems have been built accordingly to a rather simple setup: one main engine connected to the propeller for propulsion, two (or more) auxiliary engines for auxiliary electric power generation, and a boiler for on board thermal power generation. According to this setup the three on board power demands (mechanical power for propulsion, electric power and thermal power for auxiliaries) are fulfilled by three systems individually [28]. In the latest years, however, the increasing requirements in terms of energy efficiency have fostered the introduction of new on board power plants with a higher degree of integration.

Different types of hybrid propulsion systems (i.e. systems where the systems for the generation of propulsive and electric power are interconnected) are gaining ground in the sector, as they allow for increased flexibility in fulfilling both propulsive and electric power demand. Such systems proved to allow fuel savings of 1–2% [29]. These systems require however additional effort both in the design phase [30] and in the definition of the control strategy [31,32], as the increase in the number of connections between different parts of the system allows for the load to be fulfilled using a potentially high number of combinations of engines running at different loads.

In most ships, the waste heat available from the engines is largely sufficient for fulfilling on board demand for thermal energy [33], and further uses for waste heat are today a common research topic [34–36]. On cruise ships, however, thermal energy demand is higher than on other ship types [37].

Systems with a higher degree of integration between the generation of mechanical, electric and thermal power are more complex as a consequence of the high number of relevant interactions among the different component of the systems [38]. This situation makes it more challenging to identify how to operate the system optimally from the perspective of its fuel consumption.