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A comparison of linear and nonlinear programming for the optimization of ship machinery systems

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Abstract

The selection of a proper machinery system is one of the primary decisions to be taken during the ship design phase. Several machinery system configurations are possible, including the use of mechanical and diesel electric propulsion. Nonetheless, little data is available at the early stages of the design phase, making it challenging to define the optimal configuration to be installed on board. Moreover, the screening of different alternatives is a lengthy process, which is mostly carried out manually by the ship designers.
As a way to support decision making at the earliest stages of the ship design process, an optimization framework was developed. The framework is suitable to perform the screening and the selection of optimal machinery configurations for a predefined ship operational profile, and it includes both linear and nonlinear optimization routines. The linear approach has faster, and more reliable solvers, but requires a relatively high simplification of the behaviour of the machinery system. The nonlinear approach, while more accurately representing the system performance, requires longer computational times. In addition, the latter can be expanded to multi-objective optimizations, where the solver not only tries to reach the minimum fuel consumption for a ship, but also takes into account the required space on board.
The aim of this paper is to compare the results of the linear and the nonlinear approaches, and to provide indications on what conditions are the most suitable for the application of one, or the other approach. Both approaches are tested for two case studies, a bulk carrier and a small cruise ship.
The results show that both the optimization approaches led to the same layout of the machinery system, with the linear optimizer converging in a much shorter time. However, the attained solutions feature slightly different unit scheduling. This suggests that, while the linear approach might be the most suitable for design purposes, it is not appropriate for operational optimization.

Keywords: Optimization, ship energy systems, low carbon shipping, linear programming, genetic algorithm.

1 INTRODUCTION

1.1 Background

As humanity faces the global threat of climate change, society needs to drastically reduce the emissions of greenhouse gas (GHG). Maritime transport currently contributes to around 2.7 % of the global anthropogenic carbon dioxide (CO_2) emissions [1], but this share might increase as a consequence of the de-carbonization of other sectors and in correspondence with an absence of actions in the shipping business.

As of today, ships are still almost entirely powered by fossil fuels. Most recently, the International Maritime Organization (IMO) officially adopted an initial strategy aiming at reducing GHG emissions from shipping by 50 % by 2050, compared to the levels of 2008 [2]. A sharp change in the way ships are designed and operated is necessary so to reach this goal.

The ship machinery system is both the largest source of GHG emissions on board a vessel, and the most influencing factor in terms of fuel consumptions. Therefore, the selection of a proper machinery system is one of the most critical decisions to be made during the ship design phase. A machinery system investigation is conducted in every ship design project, with the aim of identifying the most suitable set of propulsion and auxiliary engines according to the ship's route and layout. There are several ways to conduct a machinery study, but usually the process consists of the following steps, not necessarily conducted in the mentioned order:

- Recognizing the potential engine alternatives to be compared;
- Estimating the fuel consumption with the chosen alternatives;
- Estimating the costs of the alternatives;
- Evaluating the impact of the alternatives on the ship layout;

The optimal configuration is not necessarily the cheapest one, because all the mentioned aspects influence the choice. The ship-owner might also have demands based on its current fleet, such as request for a specific engine manufacturer or engine type, due to reasons such as previous positive (or negative) experiences, crew expertise; or considerations related to maintenance and availability of spare parts.

In addition, other practical aspects should be taken into account, such as the fact that choosing the same engine type for all engines on a given ship enables the minimization of the number of spare parts required on board. Depending on the extent of the project, the machinery study can be a relatively fast process (made by a specialist within a few days), or extend over longer periods. However, even in the most extensive studies, the comparison between various alternatives is usually limited, because it requires significant amount of manual work.

Oftentimes, the process is made more challenging by the fact that the first machinery study, where the main concept is decided, is carried out under strict deadlines. After the conceptual design phase, a preliminary contract material of the ship is drafted, and so major changes in the ship design are unluckily to be introduced.

The time pressure that characterizes the ship conceptual design phase makes it challenging for the ship designers to find the time to manually compare a wide set of machinery alternatives. Consequently, the introduction tools to support the designers with automated analyses and optimization routines could substantially increase the quality of the decisions taken during these earliest phases of the ship design process.

These tools could either enlarge the range of options to be considered during the machinery selection process, or introduce efficient calculation methods as a way to make the selection process less time consuming.

1.2 Previous research

Several authors proposed the use of mathematical optimization techniques in the early ship design phases. Ölçer [3] presented the problem of identifying the optimal main design parameters in the early phases of the design process as a multi-objective, combinatorial optimization problem, and suggested different methods for handling the trade-offs between different objectives. Boulougouris et al. [4] proposed a tool for optimizing ship main parameters, i.e. energy efficiency, based on a combination of heuristics and statistical analyses of past ship designs and known modelling approaches for ship propulsion. Similarly to the work proposed by Ölçer, this paper focuses on the concept of providing support in the decision making phase, rather than generating one optimal solution, hence allowing for the contribution of human expertise in the design process.

Given the high uncertainty that characterizes the early ship design phases, several authors focused on the optimal choice of ship main features, such as length, breadth, draft, design speed, under uncertainty. Diez and Peri [5] developed a robust design optimization framework to derive optimal vessel design configurations, which preserve good performance under a large number of uncertain parameters characterized by wide uncertainty ranges. The work underlined the importance of taking into account the uncertainty of the input data to the optimization procedure, and was carried out using a particle swarm optimizer. Hannapel and Vlahopoulos [6] applied reliability-based design and robust optimization to a bulk carrier conceptual design case, proving that these methods could be effectively implemented to address ship design problems. Their results stressed once more the need to consider the impact of uncertainty during the multidisciplinary ship design process.

Focusing on the optimization of the ship machinery system, two alternative approaches are possible: mixed-integer linear programming (MILP) and mixed integer nonlinear programming (MINLP).

MILP refers to problems where: 1) the objective function is linear; 2) all constraints (both equality and inequality) are linear; and 3) some of the variables can only take integer values An MILP problem is generally solved based on the application of a branch-and bound method, where each branching and bounding iteration involves the resolution of a linear programming (LP) problem, where the integrality condition is relaxed. This makes MILP particularly powerful tools for exploring very wide search spaces, while ensuring the identification of the global optimum.

Several authors employed an MILP approach for the optimization of ship machinery systems. Solem et al. [7] developed a model for selecting engine configurations for a diesel electric machinery system for conceptual design purposes. The results of their study suggested that the use of optimization techniques could give a valuable support during the machinery selection process. Baldi et al. proposed the use of MILP-based optimization approaches for the optimization of the design of cruise ships, showing the potential for including a larger number of elements, such as the use of fuel cells [8], the limitation of dynamic loads on specific components [8] and the optimal integration of heating and cooling demands using process integration [9].

The main downside with the MILP approach is that most real problems cannot be treated as linear, or doing so involves strong approximations. While some solutions are available for dealing with non-linearity while keeping an MILP approach (e.g. piece-wise linearization, as in the work of Solem et al. [7]), these tend to result an increase in the number of integer variables and, consequently, of the computational time required to identify a solution. In addition, some nonlinear aspects of ship machinery systems cannot be easily linearized.

For this reason, many authors proposed the use of nonlinear approaches, such as the implementation of mixed-integer nonlinear programming (MINLP). Ancona et al. [10] utilized a genetic algorithm to optimize the load allocation of the various energy utilities on board a cruise ship. The study considered a fixed machinery layout, where the load of the different engines could be optimized. Moreover, the possibility to include in the system either a thermal storage or an absorption chiller was evaluated. Baldi et al. [11] presented a generic method for the optimal load sharing of the machinery system of a ship for fulfilling all mechanical, electric and thermal power requirements. The method included the use of simplified non-linear correlations of the efficiency of the various components, and the nonlinear problem was solved with a combination of SQP (sequential quadratic programming) and branch and bound methods. Trivyza et al. [12] proposed a tool for decision support in the early stages of ship design based on nonlinear optimization, using a genetic algorithm (GA). The tool proposed by Trivyza et al. included not only the engine systems, but also different types of components for emission abatement, thereby including the environmental dimension to the problem and making it multi-objective. Zahedi et al. [13] proposed the use of nonlinear optimization to the simultaneous design and operational optimization of electric propulsion systems, including a combination of batteries and Diesel engines for power supply.

The review of the above mentioned literature shows that researchers in the field have applied successfully both the MILP and the MINLP approaches for similar purposes. However, to the best of our knowledge, there is no study that critically analyses this duality.

1.3 Aim

The main purpose of this study was to compare the optimization of ship machinery systems design from an energy efficiency perspective using a MILP and a MINLP approach.

Thus, in this study, a machinery selection tool was developed as a way to assist decision makers during the early stages of a ship design process. The tool includes the possibility to implement both mechanical and diesel-electric propulsion systems on board a vessel and aims at defining which set of machinery (main engines and auxiliary generators) is the most suitable to provide the required power on board, while minimizing the fuel consumption/space requirement.

The problem was solved both by linearizing the optimization domain, and by conserving its inherent nonlinearity. The use of both linear and nonlinear programming enabled the comparison of the two approaches and the definition of the best use-case for each of them. The overall framework was tested in two case studies and the attained results are discussed in detail.

2 METHODOLOGY

2.1 Problem description

In this paper, the use of MILP and MINLP to optimize the design of a ship machinery system are compared. The problem can be stated as the choice of the propulsion system type and the number and type of engines installed.

As a general case, the ship machinery system is expected to fulfil the ship energy demand in terms of propulsion and hotel power, the latter representing the share of electricity required for onboard use. Two alternative configurations of the machinery system are possible: mechanical propulsion (MP), and Diesel-electric propulsion (DEP). In the case of MP, the main propulsion engine(s) (MPE) is/are coupled to a shaft line that is connected to the propeller. The direct coupling of the engine(s) to the shaft line allows to minimize transmission losses due to the lower number of components. Based on the required rotational speed of the propeller, the layout is marginally different based on the type of engine installed. Two-stroke engines operate at low speed and can be directly coupled to the propeller, while four-stroke engines operate at higher speeds and require the use of a gearbox, thereby including a small transmission efficiency penalty. The use of a gearbox allows for several main engines to be connected to a single propeller.

In the case of mechanical propulsion, the hotel power is produced by using auxiliary generators. The production of the hotel power is connected to several losses, including losses in the alternating current (AC) generators and in the switchboard. In this paper, for the sake of simplicity, all losses related to hotel power production were lumped in the “generation losses” term.

Auxiliary generators are not, however, the only way to generate auxiliary electric power in a MP system. MPE can also be employed for the production of hotel power by using a “power take-off” (PTO) system from the shaft. In this case, if the main engine or engines are operated at variable speed, and the electricity is produced to an AC grid, a variable frequency drive (VFD) is required, in addition to the PTO. This adds to the losses related to the PTO, but ensures higher efficiency to the main engines. The opposite principle is also possible: the auxiliary generators can be used for boosting the propulsion power production, via a “power take-in” (PTI) system. In this case, there are losses included both in the energy conversion from mechanical energy to electricity and in the PTI for transmitting the electricity back to mechanical power. Nevertheless, PTI is a useful way to ensure that there is the necessary thrust available for the ship in all conditions, enabling dimensioning the main engines according to their most commonly utilized profile, and also on their best efficiency operation point. Both the PTO and the PTI concepts allow for a general downsizing of the total installed power, and thereby for a reduction of the engine-related investment costs.

DEP refers to a machinery concept, where diesel engines are connected to generators. The generated electricity is distributed via AC or direct current (DC) buses to various consumers on board, serving both propulsion, via electrical propulsion motors, and hotel consumers. Compared to a MP arrangement, DEP includes inevitably more conversion losses due to the larger number of components. DEP is often utilized for ships that have significant variations in their load profiles, and when the share of the hotel load is considerable. For cargo ships, where the majority of the fuel energy is required for ship propulsion, the DEP concept might be inherently non-profitable, due to the additional losses in the power transmission from prime movers to the ship propeller. Figure 1 illustrates the power production alternatives with the related losses included that is utilized as basis for the study. In this case, a clear differentiation between engine types is displayed, however one single engine type could potentially be utilized either as MPE, diesel-electric (DE) engine, or auxiliary generator. In the case studies, both diesel mechanical and diesel electric propulsion concepts are studied, with the aim of finding the most efficient combination of the engines, possibly taking advantage of the PTO/PTI options.

2.2 Optimization approaches

2.2.1 General approach

An optimization problem can be generally defined as the minimization of a given objective function, subject to a set of constraints. In this case, the objective was expressed as the minimization of the total fuel consumption (C_{tot}), defined as the sum of the consumption of the MPEs (C_{MPE}), the auxiliary generators (C_{aux}) and the DE engines (C_{DE}):

$$minimize \qquad C_{tot} = C_{MPE} + C_{aux} + C_{DE} \tag{1}$$

The calculation of the three aforementioned factors depended on the chosen optimization approach, and is presented in sections 2.2.2 and 2.2.3.

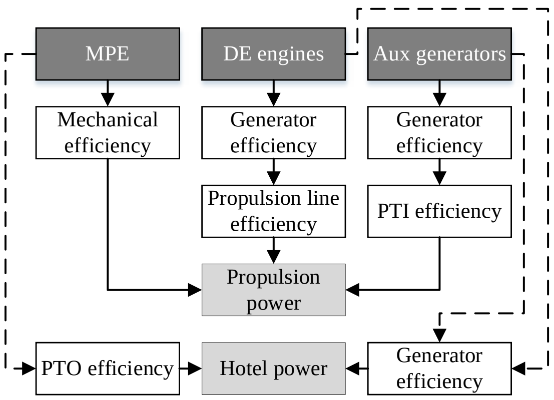

Figure 1: System layout

The problem of optimizing ship machinery system is also subject to a number of constraints. Equality constraints allow including in the problem physical principles, such as the conservation of energy (i.e. energy demand and energy generation must be equal at any time step). Inequality constraints allow including in the optimization problem the system's operational limits, such as minimum and maximum engine loads.

Propulsion power can be produced in three ways: by MPEs, with auxiliary generators through PTI, or with DE engines. Thus, the overall propulsion power in each sailing mode (P^l_{prop}), was be calculated according to Equation (2):

$$P^l_{prop} = \sum_{e \in E} \left(P^{l,e}_{MPE,prop} + P^{l,e}_{aux,PTI} + P^{l,e}_{DE,prop} \right) \tag{2}$$

The set E consist of all the possible engines types that can be installed on the vessel, while e represent a specific engine type, which is selected for installation on board. Similarly, the propulsion system has to produce enough power for on board electric use. This hotel power can be produced either by MPEs through PTO, by auxiliary generators, or by DE engines. The hotel power production in each sailing mode (P^l_{hotel}) was defined as show in Equation (3):

$$P^l_{hotel} = \sum_{e \in E} \left(P^{l,e}_{MPE,PTO} + P^{l,e}_{aux,hotel} + P^{l,e}_{DE,hotel} \right) \tag{3}$$

Both propulsion and hotel power production were computed for all installed engines (e), throughout all the defined ship sailing modes (l). The maximum number of engines that can be installed on a ship is limited. The maximum number of installed engines ($N_{\max}$) on the ship type and the power plant size, and is generally set by the expert, based on the specific demands of the case under study. Table 1 shows the maximum number of installed engines for each type in the two considered case studies.

Table 1. Maximum number of installed engines

Engine type	*Cargo ship*	*Cruise ship*
$N_{max,MPE}$	1	4
$N_{max,aux}$	2	4
$N_{max,DE}$	3	5

The optimization routine was setup so select the propulsion mode through equation (4):

$$m + d = 1 \qquad m, d \in \{0,1\} \tag{4}$$

where m is a binary variable for choosing the mechanical propulsion and d is a binary variable for choosing the diesel-electric propulsion configuration. The number of engines of type e to be installed in the ship (in^e) was constrained as follows:

$$\textstyle\sum_{e \in E} in^e_{MPE} \le N_{max,MPE} * m \tag{5}$$
$$\textstyle\sum_{e \in E} in^e_{aux} \le N_{max,aux} * m \tag{6}$$
$$\textstyle\sum_{e \in E} in^e_{DE} \le N_{max,DE} * d \tag{7}$$

Where:

$$in^e_{MPE} \in \{0,1 \ldots N_{max,MPE}\} \quad e \in E \tag{4}$$
$$in^e_{aux} \in \{0,1 \ldots N_{max,aux}\} \quad e \in E \tag{5}$$
$$in^e_{DE} \in \{0,1 \ldots N_{max,DE}\} \quad e \in E \tag{6}$$

Similarly, for every sailing mode, the active engines were selected. The integer variables related to the engines installation (in^e) and those related to the active engines in each sailing mode ($a^{l,e}$) were connected by the following relations:

$$a^{l,e}_{MPE} \le in^e_{MPE} \quad l \in L, e \in E \tag{7}$$
$$a^{l,e}_{aux} \le in^e_{aux} \quad l \in L, e \in E \tag{8}$$
$$a^{l,e}_{DE} \le in^e_{DE} \quad l \in L, e \in E \tag{9}$$

Where L is the set of all the ship sailing modes. The active engines were allowed to produce power within the limits of feasible operational loads. For this, minimum and maximum loading of the engines were defined:

$$\left(\frac{P^{l,e}_{MPE,prop} + P^{l,e}_{MPE,PTO}}{P^e{}_{MPE,DES}} \right) \ge a^{l,e}_{MPE} * f_{min} \tag{10}$$

$$\left(\frac{P^{l,e}_{aux,hotel} + P^{l,e}_{aux,PTI}}{P^e_{aux,DES}} \right) \ge a^{l,e}_{aux} * f_{min} \tag{11}$$

$$\left(\frac{P^{l,e}_{DE,prop} + P^{l,e}_{DE,aux}}{P^e_{DE,DES}} \right) \ge a^{l,e}_{DE} * f_{min} \tag{12}$$

$$\left(\frac{P^{l,e}_{MPE,prop} + P^{l,e}_{MPE,PTO}}{P_{MPE,DES}} \right) \le a^{l,e}_{MPE} * f_{max} \tag{13}$$

$$\left(\frac{P^{l,e}_{aux,hotel}+P^{l,e}_{aux,PTI}}{P^{e}_{aux,DES}}\right) \leq a^{l,e}_{aux} * f_{max} \quad (14)$$

$$\left(\frac{P^{l,e}_{DE,prop}+P^{l,e}_{DE,aux}}{P^{e}_{DE,DES}}\right) \leq a^{l,e}_{DE} * f_{max} \quad (15)$$

Where f_{min} and f_{max} represent the minimum and maximum load limit for running engines, and were set to 0.15 and 0.90, respectively. These limits were set according to the internal expertise at Deltamarin [14]. P^{e}_{DES} denotes the maximum power output of the engine *e*.

2.2.2 Linear optimization

In order to carry out a mixed linear-integer optimization, the optimization domain needed to be linearized. To do so, the engines fuel consumption was approximated to be linearly correlated with the engine load as shown in Figure 2.

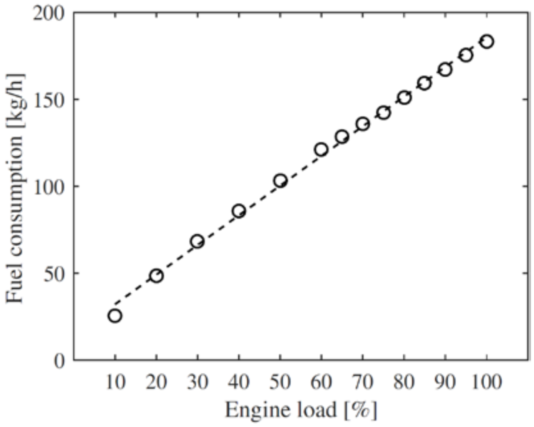

Figure 2: Linearized engine fuel consumption as a function of the engine load. Example for the engine Wärtsilä 6L20DF

The linear approximation lead to an average relative deviation by 2.55 % compared to data. The maximum deviation was of 25.74 %, and was found in correspondence to the lowest engine loads.

The efficiency of the various components that constitute the machinery system was assumed to be constant with the load. Table 2 shows the values assigned to the various efficiency factors [14].

Table 2. Efficiency factors

Efficiency	*Value [-]*
Generator	0.97
PTO	0.95
PTI	0.91
Propulsion line	0.92
Mechanical	0.97

In the MILP approach, C_{MPE} was defined as the sum of the consumption of the various engines in each sailing mode, where the fuel consumption of each engine was a linear function of its power output, as shown in Equation (20):

$$C_{MPE} = \sum_{l \in L}\left(t^{l} \sum_{e \in E} a^{l,e}_{MPE} EF^{e} + EV^{e}\left(\frac{P^{l,e}{}_{MPE,prop}+P^{l,e}_{MPE,PTO}}{P^{e}_{MPE,DES}}\right)\right) \quad (16)$$

t^{l} refers to the time spent in each sailing mode, while EF^{e} is and EV^{e} are two constants defined for each engine type. Similarly, the consumption of the auxiliary generators was computed as:

$$C_{aux} = \sum_{l \in L}\left(t_{l} \sum_{e \in E} a^{l,e}_{aux} EF^{e} + EV^{e}\left(\frac{P^{l,e}_{aux,hotel}+P^{l,e}_{aux,PTI}}{P^{e}_{aux,DES}}\right)\right) \quad (17)$$

Finally, the fuel consumption of the DE propulsion system was computed according to equation (22):

$$C_{DE} = \sum_{l \in L}\left(t_{l} \sum_{e \in E} a^{l,e}_{DE} EF^{e} + EV^{e}\left(\frac{P^{l,e}_{DE,prop}+P^{l,e}_{DE,aux}}{P^{e}_{DE,DES}}\right)\right) \quad (18)$$

The MILP problem was implemented and solved by utilizing the GLPK linear solver [15]. The relative mip gap tolerance was set to 0. The selected decision variables were the propulsion mode (mechanical or diesel-electric), and the installed engines, while the optimization space is defined by the set of the possible engines to be installed (*E*). The ship energy requirement is determined by the energy need in the various sailing modes, described in the set *L*.

2.2.3 Nonlinear optimization

Secondly, a non-linear model was developed in Matlab. The problem was solved using a two-step optimizer based on the genetic algorithm and fmincon (with multistart). The same rules and equations were utilized as in the linear model, while the specific fuel consumption (SFOC) data for the engines was interpolated with the following nonlinear form:

$$SFOC = A \cdot x^{3} + B \cdot x^{2} + C \cdot x + D \quad (19)$$

Where the engine load is *x* and *A*, *B*, *C* and *D* are the regression coefficients calculated for each engine. In this case, the engine consumption was computed as specific fuel consumption (g/kWh), so to capture the nonlinearity of the engine efficiency (see Figure 3).

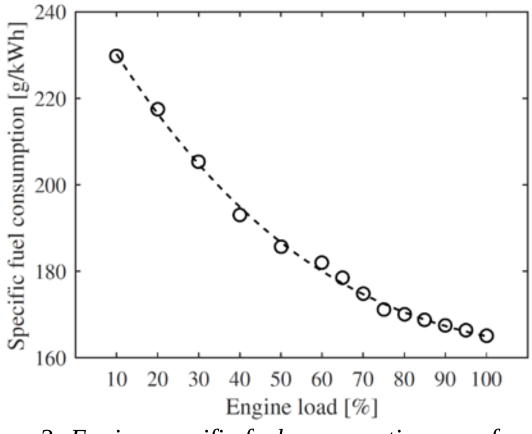

Figure 3: Engine specific fuel consumption as a function of the load. Example for the engine Wärtsilä 6L20DF

The average and maximum relative deviations from the data were of 0.31 % and 1.11 %, respectively.

Efficiency curves for the electrical propulsion line and generator efficiency were provided by Deltamarin [14] and included in the model, as illustrated in Figure 4.

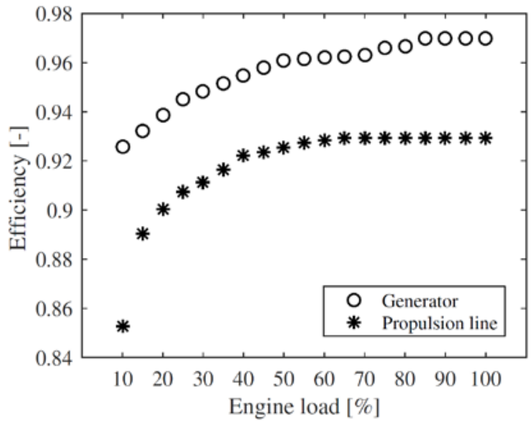

Figure 4: Generator and propulsion line efficiencies as a function of the engine load

All the other performance parameters were kept constant as in the linear model.

The overall optimization procedure was carried out according to the sketch shown in Figure 5. The genetic algorithm was selected as it is suitable to handle problems that are highly non-linear and contain integer optimization variables. The optimization routines were carried out multiple times so to ensure the validity of the attained maximums. The selected population size, maximum number of generations and function tolerance were of 500, 30 and 10^{-6}, respectively.

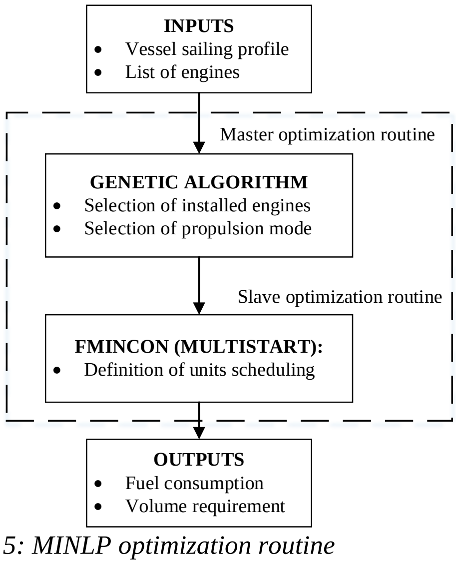

Figure 5: MINLP optimization routine

2.2.4 Multi-objective optimization

Lastly, a multi-objective optimization was setup. The optimization routine was the same as in the MINLP program, with the addition of the overall volume of the installed engines as a second objective. This parameter was added as a way to identify a range of optimal solution to be screened according to the space requirements on board. The volume of the various engines was retrieved from the manufacturer's product guides.

2.3 Case studies

The study was carried out on two case studies, a cargo ship and a small cruise ship. The data for the cargo ship was provided by Deltamarin [14], while the operational profile and power requirements for the cruise ship were retrieved from the work of Baldi et al. [16]. The typical day 3 was selected for this study, because it was the one characterized by the highest variations in the cruise operational modes. Tables 3 and 4 detail the sailing profiles and the required propulsion/hotel power requirements for the cargo and the cruise ship, respectively.

Table 3. Cargo ship: estimated propulsion and hotel power requirements in the various sailing modes

Sailing mode	Annual operation [h]	Propulsion power [kW]	Hotel power [kW]
1	2,847	0	250
2	1,533	0	600
3	197	1,204	1,500
4	2,267	2,147	450
5	1,478	1,761	450
6	438	5,100	450

In both cases, the heat requirements on board were not considered, and the engine selection was limited to the following Wärtsilä dual fuel engines [17]: 6L20DF, 8L20DF, 9L20DF, 6L34DF, 8L34DF, 9L34DF, 8V31DF and 10V31DF. The performance data for the various engines was attained through the manufacturer's product guides and Deltamarin's internal library [14], while the optimization was conducted by assuming LNG as fuel for the ship.

Table 4. Cruise ship: estimated propulsion and hotel power requirements in the various sailing modes

Sailing mode	Annual operation [h]	Propulsion power [kW]	Hotel power [kW]
1	1,649	16,793	1,824
2	1,557	16,361	1,944
3	779	14,380	2,148
4	779	542	2,127
5	1,557	0	1,994
6	1,557	2,211	2,116
7	779	3,194	1,973
8	103	3,268	1,903

3 RESULTS

3.1 Optimized machinery system and fuel consumption

Tables 5 and 6 show the results of the MILP and MINLP optimizations for the cargo ship and the cruise ship, respectively. The results suggest that in both cases a mechanical propulsion system is the most efficient configuration.

The comparison between the results of the MILP and MINLP approaches suggests that the two approaches led to comparable results. In both case studies, MILP and MINLP selected the same engines and the estimated annual fuel consumption differed by less than 1.4 %.

The discrepancy in the estimated annual fuel consumption can be explained by the different approximations of the efficiencies of the machinery system, as detailed in section 2.

Table 5. Cargo ship: optimization results

	MILP	*MINLP*
Propulsion mode	Mechanical	Mechanical
Annual fuel consumption [ton]	2,230	2,261
MP engine	8V31DF	8V31DF
Aux engines	6L20DF	6L20DF
	6L34DF	6L34DF

Table 6. Cruise ship: optimization results

	MILP	*MINLP*
Propulsion mode	Mechanical	Mechanical
Annual fuel consumption [ton]	13,512	13,448
MP engine	4x10V31DF	4x10V31DF
Aux engines	8V31DF	8V31DF
	6L34DF	6L34DF

3.2 Unit scheduling

The optimization routine provided as result also the unit scheduling, i.e. the power produced by each engine in every sailing model. The power produced by MPE engines is used either for propulsion (prop) or to cover the required hotel power through the use of PTO. Similarly, auxiliary engines are used both to cover the hotel power requirements and to supply propulsion power through PTI. Tables 7 and 8 depict the optimized unit scheduling for the cargo ship attained through the MILP and the MINLP approach, respectively. The results show that the two approaches led to almost the same unit scheduling, except for the sailing mode 2, where the hotel power is produced by the auxiliary engine 1 (6L20DF) in the MILP case, and by the auxiliary engine 2 (6L34DF) in the MINLP. The change in the selected auxiliary engine is due to a more accurate estimation of the engine consumption at low loads, but does not affect the overall fuel consumption in a significant way (see Table 5).

Table 7. Cargo ship: MILP unit scheduling

Sailing mode	*MPE prop*	*MPE PTO*	*Aux_1 hotel*	*Aux_2 hotel*	*Aux_1 PTI*	*Aux_2 PTI*
1	0	0	258	0	0	0
2	0	0	0	619	0	0
3	1,241	1,579	0	0	0	0
4	2,213	474	0	0	0	0
5	1,815	474	0	0	0	0
6	3,960	0	0	464	0	1,383

Table 8. Cargo ship: MINLP unit scheduling

Sailing mode	*MPE prop*	*MPE PTO*	*Aux_1 hotel*	*Aux_2 hotel*	*Aux_1 PTI*	*Aux_2 PTI*
1	0	0	265	0	0	0
2	0	0	624	0	0	0
3	1,241	1,579	0	0	0	0
4	2,213	474	0	0	0	0
5	1,816	474	0	0	0	0
6	3,960	0	0	468	0	1,383

Tables 9 and 10 depict the optimized unit scheduling for the cruise ship attained through the MILP and the MINLP approach, respectively. In this case, four identical MP engines are installed. The MILP, due to its linear nature, is not suitable to identify the optimal load allocation between the four MPE engines. The common assumption is that the power requirement is allocated evenly among the active engines. Looking at the results of the MILNP problem, it is possible to conclude that, in this case, this assumption is correct, as the nonlinear approach shows that an even engine loading is the one leading to the lowest fuel consumption. Similarly, the MILP optimizer was also successful in identifying the number of active MPE engines in the various sailing modes.

Table 9. Cruise ship: MILP unit scheduling

Sailing mode	*MPE_1 prop*	*MPE_2 prop*	*MPE_3 prop*	*MPE_4 prop*	*MPE_1 PTO*	*MPE_2 PTO*	*MPE_3 PTO*	*MPE_4 PTO*	*Aux_1 hotel*	*Aux_2 hotel*	*Aux_1 PTI*	*Aux_2 PTI*
1	4,328	4,328	4,328	4,328	480	480	480	480	0	0	0	0
2	4,217	4,217	4,217	4,217	512	512	512	512	0	0	0	0
3	4,942	4,942	4,942	0	8	8	8	0	0	2,190	0	0
4	0	0	0	0	0	0	0	0	2,193	0	596	0
5	0	0	0	0	0	0	0	0	0	2,056	0	0
6	2,279	0	0	0	2,227	0	0	0	0	0	0	0
7	3,293	0	0	0	1,617	0	0	0	0	450	0	0
8	3,369	0	0	0	1,544	0	0	0	0	450	0	0

Table 10. Cruise ship: MINLP unit scheduling

Sailing mode	*MPE_1 prop*	*MPE_2 prop*	*MPE_3 prop*	*MPE_4 prop*	*MPE_1 PTO*	*MPE_2 PTO*	*MPE_3 PTO*	*MPE_4 PTO*	*Aux_1 hotel*	*Aux_2 hotel*	*Aux_1 PTI*	*Aux_2 PTI*
1	4,328	4,328	4,328	4,328	480	480	480	480	0	0	0	0
2	4,217	4,217	4,217	4,217	512	512	512	512	0	0	0	0
3	4,942	4,942	4,942	0	8	8	8	0	0	2,201	0	0
4	0	0	0	0	0	0	0	0	2,210	0	596	0
5	0	0	0	0	0	0	0	0	0	2,071	0	0
6	2,279	0	0	0	2,227	0	0	0	0	0	0	0
7	3,293	0	0	0	997	0	0	0	0	1,078	0	0
8	2,947	0	0	0	2,003	0	0	0	0	0	0	450

Some slight differences appeared in the power production from the auxiliary generators, this is because the MINLP approach used a non-linear representation of their efficiency, while this was kept constant in the MILP case. Lastly, with respect to the selection of the active engines, some differences appeared in the sailing modes 7 and 8, where the MINLP solution converged toward a different scheduling of the elements of the machinery system.

3.3 Multi-objective optimization

The results of the multi-objective optimization are depicted in Figure 6.

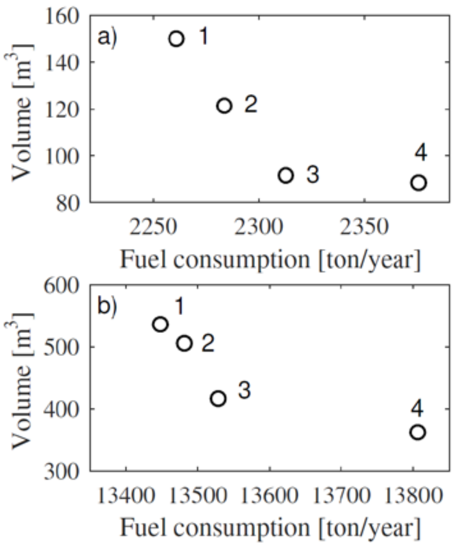

Figure 6: Results of the multi-objective optimization: a) cargo ship 1; b) cruise ship 2. The installed machinery for each configuration, indicated by numbers, is provided in Table 11.

Table 11 shows the selected machinery system in the various cases, for the containership and the cruise ship, respectively.

Table 11. Multi-objective optimization: installed units

Cargo ship	*MP engines*	*Aux engines*
1	8V31DF	6L20DF 6L34DF
2	6L34DF	8L20DF 8L34DF
3	8L34DF	2x8L20DF
4	9L20DF	6L20DF 8L34DF
Cruise ship		
1	4x10V31DF	8V31DF 6L34DF
2	4x10V31DF	8V31DF 8L20DF
3	4x10V31DF	9L20DF
4	6L20DF 8L20DF 8L34DF 9L34DF	2x8V31DF 6L34DF

The results of the multi-objective optimization show that the machinery system configuration leading to the lowest annual fuel consumption has a volume of 150.2 m^3 and 536.1 m^3, respectively for the cargo and the cruise ship. However, other solutions are possible. For example, configuration 2 for the cargo ship would result in a reduction of the volume requirement by 39 %, and in an increase of the annual fuel consumption by 2.3 %. Similarly, the volume requirements for the machinery system of the cruise ship could be reduced by 22 % by utilizing the set of engines selected in configuration 3. In this case, the increase in annual fuel consumption would be of around 0.6 %.

4 DISCUSSION

The results of the investigation suggested that MILP and MINLP approaches led to the same optimized machinery systems. Similarly, the estimated annual fuel consumptions were comparable and differed by less than 1.4 %. This indicates that the MILP is a suitable tool to address the considered problem, enabling to attain fast and quality solutions. In fact, the MILP optimizations were solved in seconds/few minutes, while the MINLP required up to 5 - 6 hours to be completed.

Looking at the unit scheduling that were attained by the two approaches, it emerged that the optimal solutions were characterized by an even loading of the propulsion engines (for the cruise ship case study), confirming the soundness of the common assumption to equally allocate the power requirement among the active propulsion engines. The general applicability of this assumption should however be further investigated. In addition, the results indicate that the MILP was capable of correctly identifying the right engines to be operated in the various sailing modes. The discrepancies that emerged with the MINLP solution were due to a non-accurate treatment of the variation of the engines' efficiency as a function of the load. A possible way to increase the accuracy of the MILP simulations is the use of piece-wise linearization of the engines performance. This would enable the inclusion of the nonlinear engine performance in the linear framework.

The MINLP approach is characterized by large possibilities for extension and refinement. In this study, the engine specific fuel consumption, the generator and the propulsion line efficiencies were the only non linear parameters accounted for. In practice, the selection of machinery system selection is a more complex task, which is not merely aiming at identifying the configuration leading to the lowest fuel consumption. The inclusion of other parameters, like the cost of the equipment, and constraints on the ship's emission levels, would increase the significance of the results attained through the MINLP approach and enlighten the limitations of the MILP optimization. On the other hand, the use of piece-wise linearization, that would allow improving the accuracy of the modelling when using an MILP approach, was not investigated in this paper and is expected to have an influence on the results.

The choice of the solvers is also an element of discussion. In this paper, we chose either open-source tools (such as GLPK for linear optimization) or very widespread ones (such as Matlab built-in nonlinear optimization tools) in order to compare solutions that are commonly used in research papers dealing with the optimization of ship energy systems, and that are sensitive for use in professional contexts. It should also be pointed out the fact that, given the relatively low complexity of the problem addressed in this paper, we do not expect the solver to have a high impact on the solution. It is true, however, that a more theoretical comparison should include state-of-the-art solvers that can show the true potential of both approaches, especially when applied to more computationally intensive problems.

In this regard, the results of the multi-objective optimizations gave a clear indication of how designing the machinery system looking only at the overall fuel consumption does not yield the best solution. As discussed in section 3.3 suboptimal solution resulted in a substantial reduction of the space required for the machinery system, with minor increases in the overall fuel consumption. These trade-off considerations are essential to be made during the ship design phases, and should also include economic aspects.

All the simulation indicated that the lowest fuel consumption could be attained by implementing a mechanical propulsion system. The diesel-electric propulsion layout, despite the lower overall efficiency, has however other advantages, such as more compact layout and better maneuvering performance. In addition, as all engines can be used both for propulsion and for auxiliary power generation, the use of a diesel-electric approach generally leads to a lower total installed engine capacity, which emerges as an advantage when minimizing the cost, but not the fuel consumption. These aspects are very case specific and could not be captured as part of this study.

In general, this study overlooked several aspects to be considered during an actual machinery study. For instance, only a small selection of four-stroke, dual fuel engines with fixed speed was included in the study. Including more engine alternatives, different fuel options and other types of power source would be required for a holistic machinery study. Additionally, further details for the machinery should be added, such as possible exhaust gas cleaning methods and ship heat requirements on board, coupled with an estimation of the prospects for waste heat recovery. This would enable designing the overall ship energy system, including recovery boilers and, potentially, waste-to-power recovery systems (i.e. organic Rankine cycle power systems).

Further studies are therefore needed so to explore the most efficient ways of utilizing the optimization methods for a proper selection of a ship machinery system. Nevertheless, the conducted study revealed valuable aspects of both MILP and MINLP optimization approaches, as well as the potential of using multi-objective optimization routines.

5 CONCLUSION

This study compared the use of linear and nonlinear programming for the optimization of ship machinery systems. An optimization framework was developed and tested on two case studies. The input parameters to the optimization framework were the information of a specific ship (power requirements for propulsion and onboard use as a function of sailing mode) and a range of engine candidates to be used in the ship machinery system. As an output, the solvers provided the set of engines to be installed so to minimize the annual fuel consumption. In addition, the nonlinear programming approach was extended so to estimate the volume occupied by the machinery system, so to carry out multi-objective optimizations.

The results attained by utilizing the developed optimization framework suggest that both approaches are suitable to identify the set of engines to be installed on a ship so to minimize its fuel consumption. The two approaches led to the same results with respect to the selected engines, and to comparable estimations for the unit scheduling and the annual fuel consumption. Nonetheless, the linear programming approach should be preferred, because of its substantially shorter computational time.

The multi-objective optimization showed that the trade-off between fuel consumption and volume required by the engines should be considered when selecting the machinery system for a ship. In particular, it emerged that the volume requirement could be decreased by 20 % to 30 % by accepting an increase of the annual fuel consumption in the range between 0.6 % and 1.4 %.

The optimization framework should be further extended to enable a holistic machinery study.

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NOMENCLATURE

Acronyms

a	variable for indicating active engines
AC	alternating current
C	fuel consumption, ton/year
CO_2	carbon dioxide
d	binary variable for diesel electric configuration
DC	direct current
DE	diesel-electric
DEP	diesel-electric propulsion
E	available engine set indexed by e
EF, EV	constants in the linear fuel consumption of the engines
f_{max}, f_{min}	load limit for the engines
GA	genetic algorithm
GHG	greenhouse gases
IMO	International Maritime Organization
in	variable indicating the number of engines installed

L	time step indexed by l
LP	linear programming
m	binary variable for mechanic propulsion
MP	mechanical propulsion
MPE	main propulsion engine
MILP	mixed integer linear programming
MINLP	mixed integer non-linear programming
prop	propulsion
PTI	power take-in
PTO	power take-off
SFOC	specific fuel oil consumption, g/kWh
SQP	sequential quadratic programming
VFD	variable frequency drive
t	temperature, °C

Subscripts and superscripts

aux	auxiliary
de	diesel-electric
DES	maximum engine power output
prop	index for propulsion related processes
tot	total

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