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Optimisation of a Diesel-Electric Ship Propulsion and Power Generation System Using a Genetic Algorithm

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Abstract: In recent decades, the design of ship propulsion systems has been focusing on energy efficiency and low pollutant emissions. In this framework, diesel–electric propulsion has become a standard for many ship types and has proven its worth for flexible propulsion design and management. This paper presents an approach to the optimal design of diesel–electric propulsion systems, minimising the fuel consumption while meeting the power and speed requirements. A genetic algorithm performs the optimisation, used to determine the number and type of engines installed on-board and the engines' design speed and power, selecting within a dataset of four-stroke diesel engines. The same algorithm is then adapted and applied to determine the optimal load sharing strategy in off-design conditions, taking advantage of the high flexibility of the diesel–electric propulsion plants. In order to apply the algorithm, the propulsion layout design is formulated as an optimisation problem, translating the system requirements into a cost function and a set of linear and non-linear constraints. Eventually, the method is applied to a case study vessel: first, the optimal diesel–electric propulsion plants are determined, then the optimal off-design load sharing and working conditions are computed. AC and DC network solutions are compared and critically discussed in both design and off-design conditions.

Keywords: ship propulsion; ship design; genetic algorithm; optimisation; electric propulsion; energy efficiency

1. Introduction

Traditional ship propulsion systems mainly rely on thermal engines, such as diesel engines [1,2] or gas turbines [3], mechanically connected to either fixed or controllable pitch propellers, most of the time through a reduction gear. This propulsion plant layout has several clear advantages, such as being based on simple and well-consolidated technologies [4], ensuring reliability and safety. Moreover, it relies on a small number of efficient energy transformations, ensuring a relatively high overall propulsion efficiency when operating in design conditions [5,6]. The latter makes traditional propulsion the most proficient choice for those marine units characterised by relatively narrow operating profiles, i.e., those ships that steam most of the time at their design speed. Combined propulsion plants [7–10] coupled with controllable pitch propellers can match the operating requirements of ships that require more flexible profiles, for instance, ferries that steam at a different speed in winter or summer season or for navy vessels.

In recent decades, diesel–electric propulsion [11,12] has grown as a good competitor for ship propulsion, bringing some additional benefits to operating flexibility and reduced footprint emission [13]. This type of propulsion system has some drawbacks due to additional energy transformations that affect the overall efficiency at maximum speed [14].

On the other hand, the benefits in terms of layout flexibility are straightforward. No shaft-line neither gearbox needs to be installed, allowing the machines to be allocated

more efficiently in the available spaces, reducing the vessel's acoustic signature and noise irradiation. Moreover, there is no mechanical link between the power generation and the propeller shaft, allowing more flexible control of both engines' and propellers' revolution speeds. Eventually, the power demand can be shared between the diesel generators (D/G) with more degrees of freedom, ship safety and availability benefit, and machinery redundancy. These aspects pushed ship designers to consider diesel–electric propulsion for passenger ships, navy ships, and various special units.

The possibility to maintain the D/G in optimal operating conditions makes diesel–electric propulsion an effective solution to meet the strict pollution regulations enforced nowadays by the International Maritime Organisation (IMO) [15,16]. In other words, a diesel–electric propulsion architecture is one of the state-of-the-art responses to the design of energy-efficient and environmentally friendly ships [17].

Diesel–electric propulsion is also installed more and more on yachts and pleasure crafts as well, with a constant increase in new diesel–electric designs [18,19]. This is also due to the r improved environmental awareness [20], the greater comfort that a flexible diesel–electric propulsion system allows in terms of noise and vibrations during navigation [21], and the potential of saving fuel [22].

A significant improvement to the efficiency of diesel–electric propulsion systems is due to the recent introduction of variable revolution speed generators [23], allowing the diesel engines to work in their optimal efficiency conditions. This type of engine control logic is coupled with direct current (DC) distribution in order not to constrain the alternators to produced energy at a fixed distribution frequency, as opposed to alternate current (AC) distribution [24–26].

The operating and layout flexibility of diesel–electric propulsion systems allows many degrees of freedom in the design phase compared to traditional propulsion. However, it is not straightforward to take advantage of those degrees of freedom in the design phase; traditional approaches usually reduce the number of design choices to consider, compare and evaluate to a manageable number. The application of more advanced computational approaches can consider and compare unconventional system layouts during the design phase and select the most promising solutions and compare them in a refinement phase.

This paper aims to present a method for the optimal design of diesel–electric ship propulsion systems, based on parametric modelling of the system layout and performance, which is optimised using a genetic algorithm [27,28]. Compared to other local minimisation algorithms [29], a genetic algorithm has interesting features that suit the presented application: it allows one to efficiently deal with categorical or integer variables and non-differentiable cost functions, as it does not require to compute derivatives, and it is a global optimisation algorithm, so it is unlikely to get trapped in local minima of the cost function. For this reason, genetic algorithms find various applications in many industrial areas when it is required to deal with the selection of multiple variables affecting one complex system. Examples are the selection of a diesel engine's optimal working parameters [30], the parameter selection of a combined cycle [31], or the optimal allocation of photovoltaic systems to maximise the performance of an electric microgrid [32]. The optimisation of a geothermic plant design shown in [33] is particularly relevant to the present work, as it performs a two-stage optimisation, separating the design phase from the computation of the optimal operating parameters. Moreover, relevant applications to many aspects of ship design can be found in [34–36].

In the presented application, the algorithm is used to select the optimal type, number and design working conditions for the diesel generators to minimise the fuel consumption of the propulsion system at design speed. Moreover, the same approach is used to select the optimal plant operating mode and load sharing between the generators in off-design conditions.

The design method is applied to a case study pleasure craft, selecting the optimal propulsion layout using data of different marine diesel engines: some assumptions of the system layout are first made, then the cost function and constraints are formalised based

on ship propulsion theory [37]. The proposed method is used to select optimal layouts in two configurations, characterised by variable speed and constant speed controlled diesel generators, coupled with DC and AC distribution networks, respectively, at the same design speed. Next, the optimal propulsion load sharing in off-design conditions, i.e., at lower speeds, is computed. Results are compared and critically discussed both in design and off-design conditions to show the potential of the proposed approach.

2. Diesel–Electric Propulsion System Schemes

In the proposed approach, a diesel–electric system is considered for power generation and propulsion. The three main aspects to take into account when considering a diesel–electric system as a candidate for ship propulsion are:

- Propulsion power demand and the electric load required for auxiliary services are comparable, the efficiency gap to mechanical propulsion might not be an issue;
- The operating flexibility might be an advantage for those ship types that have very different operating profiles, characterised by, for example, very different ship speeds;
- The layout flexibility might come in handy when considering a ship with limited spaces on-board or when the low noise level is a design criterion.

Ships that match the above-described requirements, and are thus usually powered by diesel–electric systems, are, for instance, passenger or cruise ships and some navy ships or pleasure crafts.

Figure 1 presents two alternative diesel–electric plant layouts considered in this study. Figure 1a represents a typical diesel–electric propulsion system with an AC power distribution network: the diesel engines produce the alternate current through alternators and are connected to an AC network at constant voltage and frequency. As a consequence, diesel engines need to work at a constant revolution speed to maintain the network frequency. Figure 1b shows an alternative layout using a DC distribution network (DC-link): this approach requires several DC/AC and AC/DC converters with their associated energy losses, yet it has some advantages. As the frequency is not an issue, the D/G control is only focused on the voltage, and the diesel generators can operate in optimal working conditions at partial loads. In addition, DC distribution is not affected by most of the main typical alternate current issues, such as reactive current losses or harmonic distortions [24].

The standard layout for diesel–electric generation and propulsion of ships features some diesel engines of the same size, mainly for construction and maintenance convenience, as the same engines share the same spare parts. In the present study, the aim is to remove this constraint, allowing the plant to include engines of different sizes to maximise the plant's efficiency in design conditions.

(a)   (b)
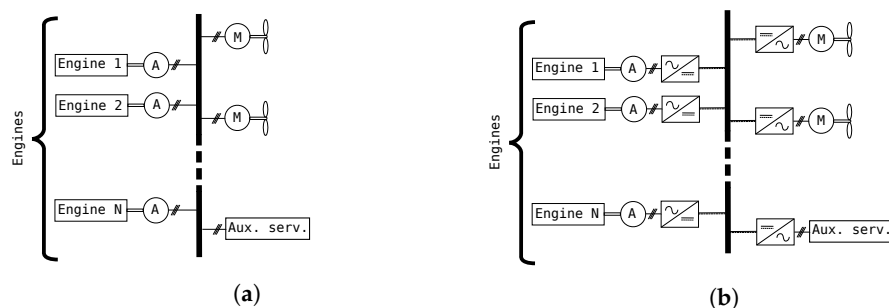
Figure 1. Generation and propulsion system layout types: AC distribution network, constant revolution speed D/G (**a**) and DC distribution network, variable revolution speed D/G (**b**).

3. Plant Optimisation

The purpose of this study is to perform the propulsion system design using an optimisation approach. The design problem is formulated as an optimisation problem, and a genetic algorithm is used to find the solution, i.e., to find the minimum fuel consumption layout at design conditions. As a second step, the same optimisation approach, with slight

modifications, is applied to determine the optimal working configuration (load sharing and engine working points) of the obtained layouts in off-design conditions, i.e., partial loads. Two alternative plant types are considered, designed and compared: AC and DC distribution. In the first plant type, represented in Figure 1a, the revolution speed of the diesel engines is constrained by the network frequency, while in the second (Figure 1b), diesel engines can be controlled at variable speeds.

In the design phase, the algorithm can select the number and type of diesel engines that are part of the propulsion plant, choosing between a number (four in this study, but the database could be reasonably enlarged) of diesel engines of different sizes and performance features. Moreover, the algorithm selects the optimal power of each engine for AC architecture and optimal power and revolution speed in DC configurations. In the two cases, the ship's design speed is guaranteed while minimising the fuel consumption.

In the off-design phase, the propulsion system is already selected: the algorithm can select the number of operating engines and their working points (power and, if possible, i.e., in DC configuration, revolution speed) in order to minimise the fuel consumption while providing sufficient power to sustain both the required off-design speed and hotel-load.

In summary:

- The algorithm is expected to select the number and type of diesel engines to install on-board;
- Moreover, the algorithm is expected to select the power output of each engine if the network distribution is AC, the power output and revolution speed if the distribution is DC;
- The selected solution layout should minimise the total fuel mass flow rate;
- The selected solution should ensure the ship reaches the expected speed;
- To sightly simplify the problem, engines of the same type are assumed to operate in the same conditions (power and revolution speed).

Thus, two alternative problems can be formulated, the first describing the AC power generation plant with constant revolution speed controlled generators, the second describing the DC plant with variable speed controlled generators. The following subsections describe all the aspects of the problem formulation, from the genetic encoding, i.e., the parametrisation of the problem, to the set up of the cost function and constraints, based on the steady-state modelling of the ship's propulsion system.

3.1. Genetic Encoding

The crucial point when using a genetic approach to solve optimisation problems is the definition of the so-called genetic encoding. Let NDG be the number of diesel generator models available in the dataset, each one in number N_i, with power P_i and revolution speed n_i, and $i = \{1, 2, ..., NDG\}$ identifying the engine model. The encoding in the case of variable speed controlled engines takes the following form:

$$\mathbf{X} = \{N_i, n_i, P_i\} \tag{1}$$

In a similar way, the genetic encoding of a solution in case the engines are controlled at constant revolution speed with AC distribution is the following:

$$\mathbf{X} = \{N_i, P_i\}, \ n_i = n_i^{des} \tag{2}$$

where n_i^{des} indicates the nominal revolution speed of the ith engine model.

The total electric power provided if a solution $\mathbf{X}$ is selected is expressed by the following relationships, respectively, in case of DC and AC distribution:

$$P_{el}(\mathbf{X}) = \sum_{i=1}^{NDG} N_i P_i \eta_{gen,i} \eta_{ACDC,i} \tag{3}$$

$$P_{el}(\mathbf{X}) = \sum_{i=1}^{NDG} N_i P_i \eta_{gen,i} \qquad (4)$$

where $\eta_{gen,i}$ is the efficiency of the ith alternate current generator, and $\eta_{ACDC,i}$ is the efficiency of the ith AC/DC converter, installed only with DC distribution.

3.2. Cost Function

The solution ranking after each generation in a genetic algorithm is performed using a cost function. In the presented application, the optimisation aims to minimise the total fuel mass flow rate of the power generation plant; thus, the following function is to be minimised:

$$f(\mathbf{X} = N_i, n_i, P_i) = \sum_{i=1}^{NDG} N_i P_i SFOC_i(n_i, P_i) \qquad (5)$$

where $SFOC_i(n, P)$ represents the engine load diagram, providing the specific fuel consumption at a given revolution speed and power, implemented in the form of a function, such as using a response surface, and the measurement units in proper accordance.

3.3. Constraints

The definition of the constraints is a crucial passage in the presented approach in order to obtain a reasonable result. First, the bounds of the solutions need to be defined:

$$\{0, n_{i,min}, P_{i,min}\} \leq \{N_i, n_i, P_i\} \leq \{N_{i,max}, n_{i,max}, P_{i,max}\} \qquad (6)$$

The number of engines for each type is required to be non-negative and less than a maximum value. The power and revolution speed boundaries are related to each of the engine models. Note that this framework can be applied both to design and off-design optimisations, setting proper boundaries of the maximum number of running engines, while, in the design phase, the number of engines on-board is to be defined, between zero and a reasonable maximum value, the off-design optimisation aims to determine the number of running engines in a given off-design condition, between zero and the number of engines on-board.

The next step is the formalisation of the required speed in the form of a non-linear constraint. In particular, the generated power P_{el} needs to be sufficient to ensure the ship's speed $V(\mathbf{X})$. If there are n_p propellers, the thrust T required to each propeller is given by the following equation:

$$T = \frac{R_t}{n_p(1-t)} \qquad (7)$$

where R_t is the ship's resistance and t is the thrust deduction factor.

The power required by the electric propulsion motors is described by the following equations, referring to DC and AC distribution, respectively:

$$P_{EPM} = \frac{(1-w)VT}{\eta_o \eta_r \eta_s \eta_{EPM} \eta_{DCAC}} \qquad (8)$$

$$P_{EPM} = \frac{(1-w)VT}{\eta_o \eta_r \eta_s \eta_{EPM}} \qquad (9)$$

where w is the wake fraction, eta_r and η_s are the relative rotational efficiency and the mechanical transmission efficiency, respectively, η_o is the propeller open water efficiency, η_{EPM} and η_{DCAC} are the efficiencies of the electric propulsion motor and the DC/AC converter, respectively. Note that t, w, eta_r depend on the ship's speed, and η_o depends on the propeller's working conditions [21].

Note that:

- The selected propulsion layout is such that the propeller's revolution speed is mechanically independent of the engines', as there is no gearbox;

- The propeller is modelled using the open-water diagrams and is assumed to have a fixed pitch.

    The speed constraint is described by the following inequality:

$$P_{el}(\mathbf{X}) \geq n_p P_{EPM} + P_{aux} \tag{10}$$

where P_{aux} the power required to satisfy the auxiliary services. Note that this should be an equality constraint: the power provided by the generation system in its working conditions should instantly match the power load. However, inequality is needed because some of the variables are integer numbers, and the solver cannot deal with integer variables and equality constraints at the same time. Moreover, only the lower bound of the power can be constrained because higher power leads to higher fuel consumption, and the optimisation will naturally lead to the lowest possible installed power that allows satisfying the speed constraint.

3.4. Optimisation Problem

The following optimisation problem, combining Equations (5), (6) and (10), needs to be solved to determine the optimal propulsion plant configuration:

$$\begin{cases} \min_{\{N_i, n_i, P_i\}} \sum_{i=1}^{NDG} N_i P_i SFOC_i(n_i, P_i) \\ s.t. : \\ n_{i,min} \leq n_i \leq n_{i,max} \\ P_{i,min} \leq P_i \leq P_{i,max}(n_i) \\ P_{el} \geq n_p P_{EPM} + P_{aux} \end{cases} \tag{11}$$

4. Case Study Ship

In order to test the proposed methodology, pleasure craft, whose main data are presented in Table 1, is considered as a case study. The ship is initially equipped by a conventional propulsion plant, composed of two four-stroke diesel engines that drive two fixed pitch propellers via independent shaft lines and gearboxes, while the electric load is provided by diesel generators. This type of propulsion system is particularly efficient for merchant ships, where no particular flexibility is required. In this study, the original propulsion plant is replaced by two alternative diesel–electric propulsion systems presented in Figure 1 and discussed earlier in this paper. The reason to consider a diesel–electric system for such an application is that the operating profile of a pleasure craft might include multiple speeds and low speeds for a relevant amount of time. Thus, it is reasonable to suppose that, in the future, electric or hybrid propulsion will be widely adopted in the pleasure craft field, similarly to other ship types that share similar operating requirements. Moreover, electric propulsion allows the implementation of zero-emission systems (for example, including batteries), which might reduce the craft's environmental impact. The two-shaft propulsion system is required to match the brake power per shaft curve presented in Figure 2.

Table 1. Main data of the case study vessel.

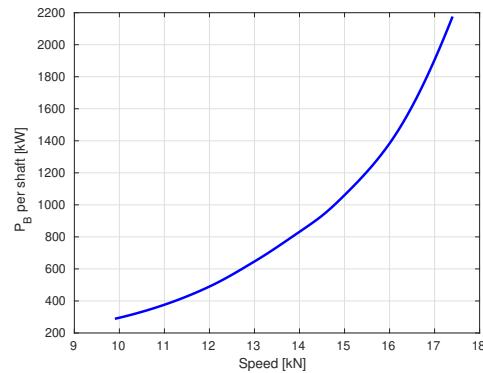|	
Length between perpendiculars, Lpp	55.400 m
Moulded breadth, B	12.500 m
Moulded Depth at weather deck, D	6.000 m
Mean Scantling Draft, T	3.400 m
Original propulsion engines:	2 × diesel engines 2525 kW @ 1900 RPM
Original gen-set	2 × 200 ekW + 1 × 148 ekW
Hotel electrical load	194 kW

Figure 2. Vessel's estimated brake power per shaft.

4.1. Engine Models

As pointed out in the previous sections, the first step of the proposed study is to determine the optimal propulsion plant layout for the above-described case study ship. In other words, a complete refitting of the propulsion system is proposed, relying on an optimisation algorithm, able to select the type and number of engines to be installed, choosing between a dataset of four engine models, whose main data are presented in Table 2. The engines' load diagrams are presented in Figure 3.

Table 2. Main features of the engine models considered in this study.

	Engine 1	Engine 2	Engine 3	Engine 4
Brake power [kW]	2240	1500	746	400
Speed [rpm]	1800	1800	1600	1800
Num. of Cyl.	16	12	8	8
Bore/stroke [mm]	170/210	170/210	170/210	130/150
Displacement [l]	76.3	52.7	38.2	15.9
BMEP [bar]	19.6	19.0	14.6	16.8
Dry weight [kg]	8590	7240	5460	1790

The bounds between which the optimisation variables can range (see Equation (6)) are shown in Table 3. Note that the maximum number of engines is set to four, as it can be considered a reasonable number in real-world applications. All the other bounds are set based on the performance data of the respective engines. The proposed problem structure is flexible enough to fit a higher number of engine types or manage the engines on-board one at a time, considering an uneven load sharing, by manipulating the number of variables of the genetic encoding and how they are related. In general, an increase in the optimisation variables does not significantly affect the computation time.

Table 3. Boundary values of the optimisation variables.

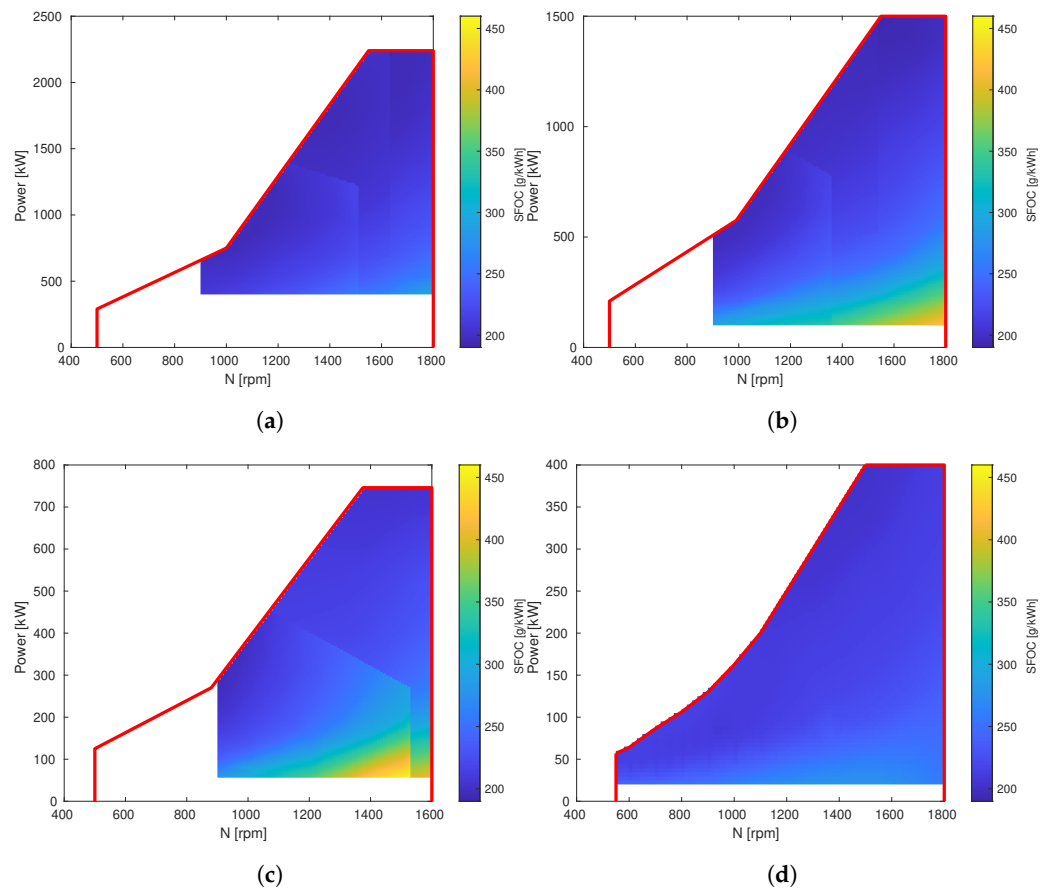| Parameter	Min	Max	Const. N
N_1	0	4	-
N_2	0	4	-
N_3	0	4	-
N_4	0	4	-
n_1	900	1800	1800
n_2	900	1800	1800
n_3	900	1600	1200
n_4	550	1800	1800
P_1	450	2240	-
P_2	300	1500	-
P_3	150	746	-
P_4	80	400	-

Figure 3. Load diagrams of the engines considered in the study: (**a**) Engine 1; (**b**) Engine 2; (**c**) Engine 3; (**d**) Engine 4.

4.2. Electrical Components

In order to perform a realistic performance prediction, i.e., to properly evaluate each solution's cost function, the electric efficiencies need to be assumed. Reasonable efficiency value ranges are listed in Table 4, the higher the component's size (i.e., power), the higher the efficiency.

Table 4. Typical efficiencies of the electric machines and conversion devices.

Component	Efficiency
Electric motors and alternators	0.95–0.97
DC/AC and AC/DC converters	0.99
DC/DC and AC/AC converters	0.96–0.98

5. Results

5.1. Design Condition

The propulsion systems have been optimised for a design speed of 17 Kn using the GA implemented in the Matlab Optimisation Toolbox. The optimal solutions are listed in Table 5 and represented in Figure 4. It can be seen that in both cases, the optimisation algorithm picks all engines of the same size; in particular, the biggest and most efficient engines are selected. The variable revolution speed plant exploits all the load diagrams of the selected engines that can run in the most efficient conditions. As a side note, it is worth mentioning that the above-defined design problem would consist of a fair amount of computation if tackled manually. Within the considered case, 256 engine combinations should be initially considered. For each of the considered combinations, the optimal set of working points matching the constraints should be then evaluated. Especially in the

variable D/G speed case, this would result in a significant amount of computation that might be handled by, for instance, discretising each engine's load diagram and using a brute force approach to evaluate all the possible working point combinations.

Table 5. Optimal solutions at design condition of 17 Kn.

	Const. N	Var. N
N_1	2	0
N_2	0	3
N_3	0	0
N_4	0	0
n_1	1800	-
n_2	-	1540
n_3	-	-
n_4	-	-
P_1	2099	-
P_2	-	1428
P_3	-	-
P_4	-	-
f.c.	840 $\frac{kg}{h}$	835 $\frac{kg}{h}$

5.2. Off-Design Conditions

The design optimisation procedure assessed the engine type, number and optimal working point in design conditions, set to 17 Kn in the presented case study. As a further step, optimal off-design configurations working points can be determined with the same algorithm at lower speeds; in particular, the range between 10 Kn and the design speed of 17 Kn has been investigated. For each propulsion system, the off-design optimal configuration is computed using the same optimisation approach, selecting the number of diesel generators running and their working point. For each propulsion plant, two alternative off-design power management strategies are considered and compared. The first option is the most widely adopted and is based on an even load sharing between the generators, while, in the second case, the generators are allowed to run with unevenly shared loads. It is worth mentioning that, while the constant speed and even load sharing optimality problems might be handled manually, the complexity increase due to the variable speed and the further addition of uneven load sharing justify the adoption of the proposed approach.
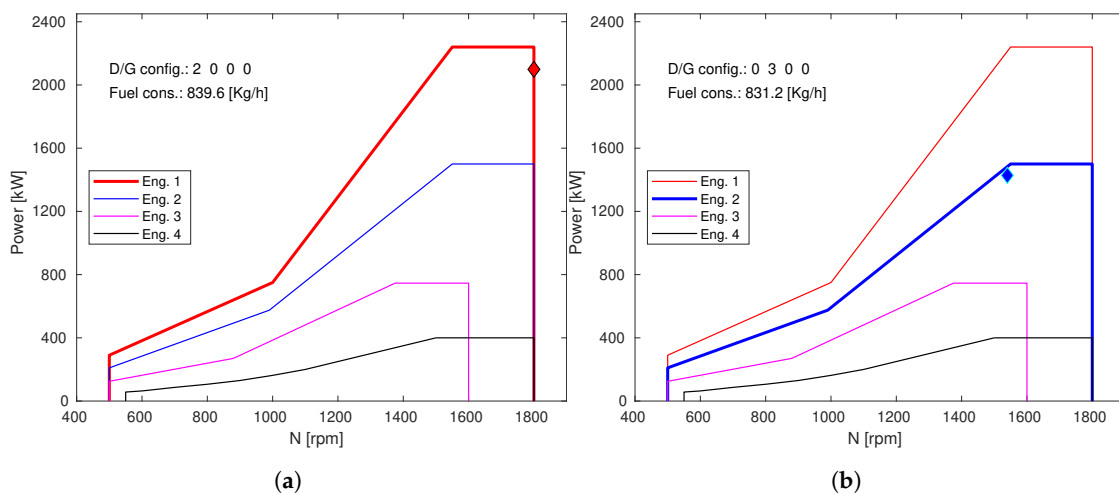

Figure 4. Solutions: constant speed D/G (**a**) and variable speed D/G (**b**).
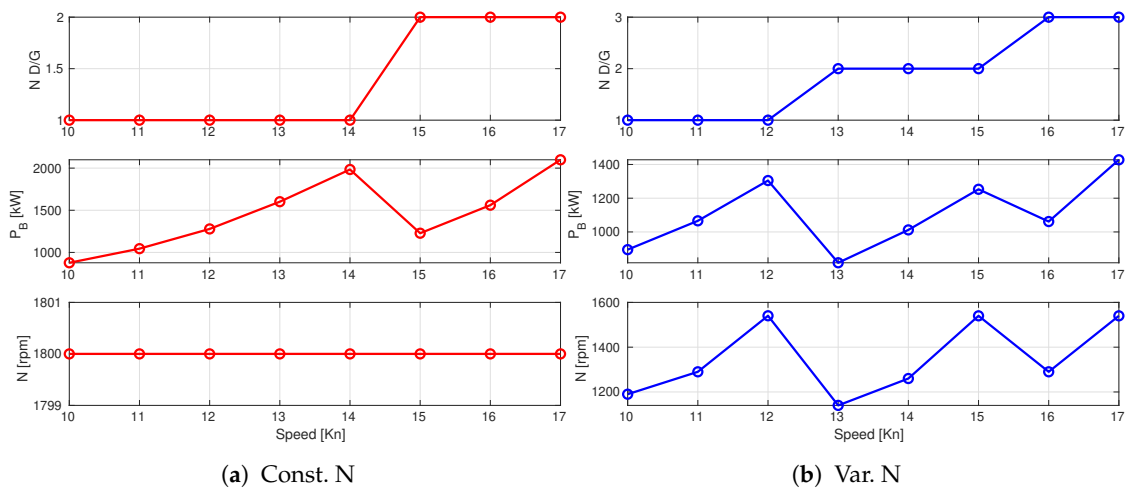
Figure 5. Off-design optimal propulsion configurations, number of D/G, revolution speed and power: constant (**a**) and variable D/G revolution speed propulsion plant (**b**).
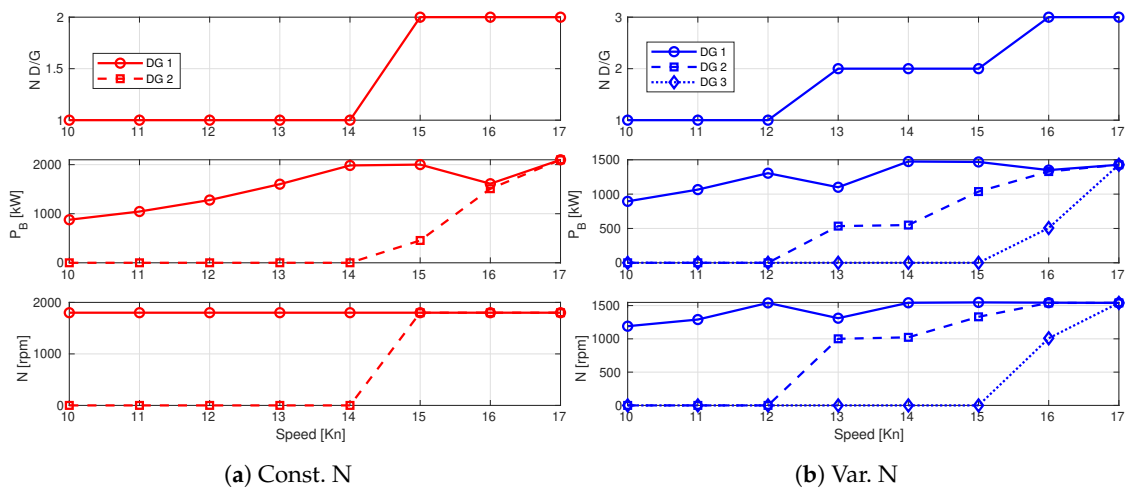

Figure 6. Off-design optimal propulsion configurations, constant (**a**) and variable revolution propulsion plant (**b**) with uneven optimal load sharing.

Figure 5 shows the optimal off-design configurations of the constant revolution speed and variable revolution speed plant with an evenly shared load. In particular, the number of engines, revolution and power set-points depending on the ship's speed, are represented; note that, in both cases, the number of engines running always increases as the revolution speed increases. This behaviour is beneficial to reduce D/Gs' frequent switch on–switch off during the vessel's operation. When the D/G revolution speed is not allowed to change, the most efficient spots on the load diagram cannot be appropriately exploited. On the contrary, variable revolution speed propulsion plant can fully exploit the engines' efficiency potential.

Figure 6 presents the same results in the case where the load is not evenly shared between generators; note that the number of generators running increases with speed as well. Moreover, note that the load of the "first" D/G has a more stable behaviour and generates most of the necessary power, while the second and eventually third D/Gs are gradually loaded while the speed increases.

Figure 7 compares the fuel consumption of the selected propulsion systems in function of the vessel's speed, considering even and uneven load sharing; note that the DC system is almost always more fuel saving, especially at lower speeds. Figure 8 represents the specific fuel oil consumption (SFOC) in the function of the vessel's speed; note that the variable speed control logic allowed by the DC system allows more stable and lower SFOC values

at lower speeds. The uneven load sharing allows even lower fuel consumption values and SFOC. Note that the considered SFOC is not related to a particular engine in this last case, yet is the power-averaged SFOC of the generation system. In both figures, the available data of the original mechanical propulsion are reported for comparison purposes; note that, as expected, diesel–electric propulsion is particularly efficient in off-design conditions. Table 6 presents a summary of the obtained results and allows a quantitative comparison.

The sudden rise in the SFOC from 14 to 15 Kn in the constant speed power plant can be explained by referring to Figure 6a,b. At 14 Kn, one D/G provides the required power under its best efficiency conditions. When increasing the ship's speed from 14 to 15 Kn, the overall power requirement rises and one D/G is not able to provide sufficient power. The load is thus shared between two D/Gs, each one working at relatively light power and, because the revolution speed is constrained, at high SFOC (low efficiency). Note that the SFOC is a specific quantity, i.e., it is power averaged, while the fuel consumption (Figure 7) increases monotonically with the ship's speed and provides a quantitative measure of the expended energy, with the SFOC indicating how efficiently the engines are generating the power. This fact should be taken into account when comparing the SFOC at different power outputs.

Moreover, note that the presented approach is strictly related to design conditions. The influence of the weather has major effects on the propulsion system: a resistance increase due to the action of wind and/or waves causes a change in the propulsion working point, depending on the ship's control logic. If the vessel is operated at a constant speed (using cruise control), an increase in power demand and propeller revolution speed is experienced, while if, more commonly, the control system keeps the propeller's revolution speed constant, the rough weather causes an involuntary speed reduction, in addition to an increase in the power output. During the vessel's operation, real-time D/G optimisation might be highly beneficial in real conditions.
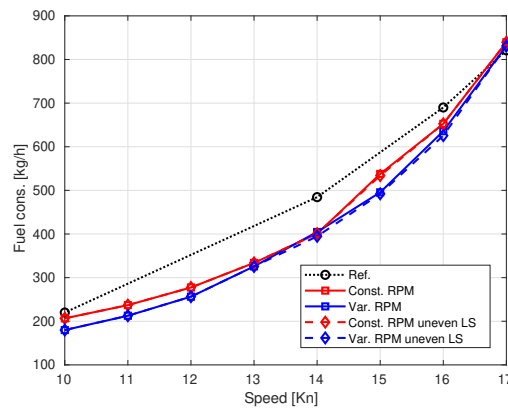

Figure 7. Constant vs. variable revolution speed performance comparison: fuel consumption with even and uneven load sharing.
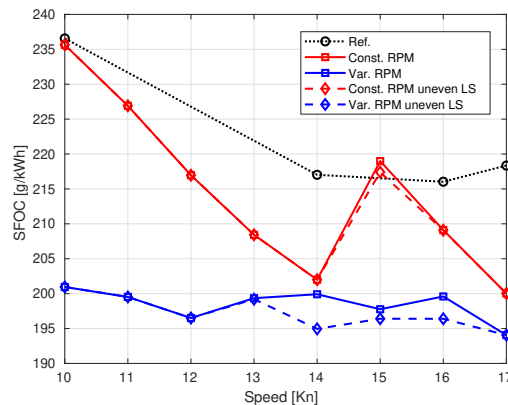

Figure 8. Constant vs. variable revolution speed performance comparison: SFOC with even and uneven load sharing.

Table 6. Quantitative performance comparison.

Speed [Kn]	10	11	12	13	14	15	16	17
D/G running								
Const. spd.	1	1	1	1	1	2	2	2
Var. spd.	1	1	1	2	2	2	3	3
Fuel cons. [kg/h]								
Ref. plant	220	-	-	-	484	-	690	821
Const. spd. even	206.7	237.0	277.4	333.8	400.7	537.8	652.6	839.6
Const. spd. uneven	206.7	237.0	277.4	333.8	400.7	533.9	652.5	839.6
Var. spd. even	179.9	212.7	256.4	325.8	404.7	495.6	635.6	831.2
Var. spd. uneven	179.9	212.7	256.4	325.6	394.6	492.1	625.7	831.2
SFOC [g/kWh]								
Ref. plant	236	-	-	-	217	-	216	218
Const. spd. even	236	227	217	208	202	219	209	200
Const. spd. uneven	236	227	217	208	202	217	209	200
Var. spd. even	201	200	197	199	200	198	200	194
Var. spd. uneven	201	200	197	199	195	196	196	194

6. Conclusions

In this paper, an optimisation procedure has been presented, oriented to the optimal design of a diesel–electric ship propulsion system. In particular, a genetic algorithm has been used to design the optimal layout of a diesel–electric propulsion plant, including diesel generators of various sizes either with an AC or DC power distribution network. The same approach with slight variations is then applied to find the optimal load sharing strategy in several off-design conditions. The proposed method is applied to a case study vessel; specifically, a pleasure craft is considered. The comparison has been discussed in detail, including the original propulsion plant data as a reference.

DC distribution coupled with variable speed generator control is highly beneficial for vessels that have operating requirements that are very demanding in terms of flexibility. The variable revolution speed control of the diesel engines allows the DC systems to keep more stable SFOC values depending on the vessel's speed, as the engines' working point can be optimised further if compared to the constant revolution speed control approach. In particular, diesel–electric propulsion systems allow great flexibility, and optimal design and off-design configurations can be achieved by numeric optimisation, allowing maximisation of propulsive efficiency in the whole vessel's speed operating range.

Numeric optimisation is an effective way to manage highly under-determined problems such as propulsion system layout design or optimal load sharing determination, and the results obtained are auspicious. The proposed approach comes in handy for propulsion plant designers, allowing them to manage high numbers of alternative options and combinations in a reasonable amount of time. When increasing the complexity of the problem, an exhaustive brute force analysis employing standard methods is not feasible.

It should be noted that the proposed approach is based on two sequential steps: first, the optimal layout to reach the design speed with all the engines running is determined, then the optimal load sharing in off-design conditions is computed, considering the propulsion system obtained in the design phase. In the future development of the proposed approach, these two steps are supposed to be nested to compute the optimal propulsion system design to match a given operating profile with two or more different design speeds.

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