applied sciences

Article

Optimal Selection of the Diesel Generators Supplying a Ship Electric Power System

Panayiotis Michalopoulos [1], George J. Tsekouras [2], Fotios D. Kanellos [3,*] and John M. Prousalidis [1]

[1] School of Naval Architecture and Marine Engineering, National Technical University of Athens, Heroon Polytechniou 9, 15780 Athens, Greece
[2] Department of Electrical and Electronics Engineering, University of West Attica, 250 Thivon Str., 12241 Athens, Greece
[3] School of Electrical and Computer Engineering, Technical University of Crete, University Campus, Akrotiri, 73100 Chania, Crete, Greece
* Correspondence: fkanellos@tuc.gr; Tel.: +30-2821037339

Featured Application: Evaluation of electric generation system during the ship design or selection process.

Abstract: It is very common for ships to have electric power systems comprised of generators of the same type. This uniformity allows for easier and lower-cost maintenance. The classic way to select these generators is primarily by power and secondarily by dimensions and acquisition cost. In this paper, a more comprehensive way to select them, using improved cost indicators, is proposed. These take into account many factors that have a significant impact in the life-cycle cost of the equipment. A realistic and detailed profile of the ship's electric load spanning a full year of her operation is also developed to allow for a solution that is tailor-made to a specific case. The method used is highly iterative. All combinations of genset quantities and capacities are individually considered to populate a power plant, taking into account the existing redundancy requirements. For each of these and for every time interval in the load profile, the engine consumption is Lagrange-optimized to determine the most efficient combination to run the generators and the resulting cost. The operating cost throughout the year is thus derived. In this way, the method can lead to optimal results as large data sets regarding ship operation and her power system's technical characteristics can be utilized. This intense calculation process is greatly accelerated using memorization techniques. The reliability cost of the current power plant is also considered along with other cost factors, such as flat annual cost, maintenance, and personnel. The acquisition and installation cost are also included, after being distributed in annuities for various durations and interest rates. The results provide valuable insight into the total cost from every aspect and present the optimum generator selection for minimal expenditure and maximum return of investment. This methodology may be used to enhance the current power-plant design processes and provide investors with more feasible alternatives, as it takes into consideration a multitude of technical and operational characteristics of the examined ship power system.

Keywords: power-plant design; generator selection; consumption; Lagrange optimization; load profile; reliability cost; return on investment

check for updates

Citation: Michalopoulos, P.; Tsekouras, G.J.; Kanellos, F.D.; Prousalidis, J.M. Optimal Selection of the Diesel Generators Supplying a Ship Electric Power System. *Appl. Sci.* **2022**, *12*, 10463. https://doi.org/10.3390/app122010463

Academic Editors: Federico Barrero and Mario Bermúdez

Received: 20 September 2022
Accepted: 13 October 2022
Published: 17 October 2022

1. Introduction

The shipping industry is ever growing and today numbers more than 63,000 commercial ships worldwide. Each year, more than 2000 new ships are built in the world [1], while the global shipbuilding industry market is expected to exceed $195 billion by 2030 [2]. In this context, the cost related to building, acquiring and operating a ship is a major concern to investors, but also has a significant impact in the world economy.

One aspect of ship design is its electric power system. This is usually overshadowed by the propulsion plant and thus overlooked in the decision-making process. However, if properly examined, it can turn out to be a substantial financial concern, especially when the requirements for electric power are increased, such as in large container ships, or even more, as technology moves towards electric propulsion.

With this goal in mind, researchers have proposed many innovative hybrid multi-energy plants [3] that include such renewable sources as photovoltaics [4,5], wind turbines [6], fuel cells [7], and batteries or supercapacitors for energy accumulation [8,9].

For classic power plants with diesel generator sets, the common and easiest way to operate them is by sharing the load proportionally among them and adding or removing generators to the grid when the load reaches certain thresholds. This simplistic management scheme allows for little efficiency improvement.

On the other hand, several techniques have been presented to achieve performance optimization and efficiency increase in a ship energy efficiency management plant (SEEMP) [10,11]. These involve sophisticated load management and distribution [12,13], smart grids and microgrids [10,14], multiagent systems [15,16], distributed power management [17] and other methodologies, even exotic ones using quantum computing [18]. According to a complicated but also efficient approach, the load distribution on the gensets is optimized according to their fuel consumption curves [19], leading to notable fuel savings.

However, little has been discussed on the selection process of the gensets. A classic ship power plant is typically designed using the following steps. First, the number of generators is determined, usually based on reservation or redundancy requirements. Afterwards, the nominal power of the generators is calculated so that the maximum total load and the maximum critical load can be adequately supplied according to the reservation and redundancy requirements. Finally, the manufacturer and the exact type of the generators is determined, based on financial criteria, usually purchase price and average fuel consumption. At this point, if the cost seems too high, the design process is restarted in a spiral fashion and all the parameters are redetermined until an acceptable outcome is eventually reached, as in Figure 1. This may be satisfactory, but optimality is not guaranteed. Furthermore, the whole process is mostly empirical and thus not efficient.

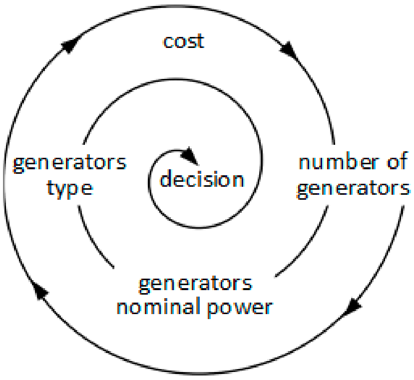


Figure 1. Typical genset selection process.

The goal of this paper is to present a new method that will definitely produce the optimum result in very little computation time and with little effort. It is noted that there is no best solution fitting all cases. On the contrary, each problem has unique requirements and constraints necessitating particular handling. To this end, the proposed method uses as inputs a detailed load profile of a real passenger ship based on real data, and all upcoming calculations are performed in this realistic context.

Additionally, the cost of gensets is much more than just their acquisition price and their average fuel consumption. Therefore, several parameters are also contemplated, among them the cost of installation, maintenance and payroll of the crew members assigned to it and detailed and optimized fuel and lubricating oil consumption. The reliability of the installation is also considered and the cost it entails. This way, the true life-cycle cost of the installation is estimated.

Furthermore, insight is provided allowing financiers to preview various interest rates and number of annuities combinations in order to select the most suitable return on investment (ROI) scheme.

In Section 2, the methodology followed is described in detail. In Section 3, the applied computational speed improvement technique is described. In Section 4, a representative case study and the results obtained are provided, while discussion on the presented work and results are given in Section 5.

2. Methodology

2.1. Overview

An auxiliary graphical overview of the calculation process is shown in Figure 2 and described in detail in the following:

Load profile creation:

Preliminarily, a detailed load profile of the ship is drafted to become the frame in which all calculations will be based upon. More details are provided in Section 2.2.

Genset pool:

A pool of diesel engine generators and their specifications is formed to combine and populate the ship's power plant. More details are provided in Section 2.3.

Algorithm main loop:

A loop begins by selecting from the pool one genset type after the other.

Genset installed capacity:

Their installed capacity is determined so that they are sufficient to supply the maximum load of the ship, taking into account any redundancy requirements. More details are provided in Section 2.4. Note that all generators in the power plant are assumed to be of the same type. If their quantity is excessive (i.e., >18), the current generator type is rejected and the loop continues with the next iteration and type selection.

Operating cost estimation:

For every time interval throughout the load profile, the Lagrange optimization method is used to establish the genset combination that will supply this particular load with the smallest fuel and lubricating oil consumption. This produces the lowest operating cost and System Marginal Cost (SMC) for each time period. More details are provided in Section 2.5. All operating costs are summed to produce the total operating cost throughout the year for the particular genset type.

Reliability cost estimation:

The Capacity Outage Probability Table (COPT) of the selected power plant is estimated. For every time interval throughout the load profile, this is used to evaluate the expected loss of load energy (LOLE) separately for each type of load and load conditions of each time interval in the profile. Afterwards, these are summed up to produce the total LOLE for each load type throughout the year. More details are provided in Section 2.6.

For every time interval in the load profile, the above SMC and LOLE values are used to calculate the total cost of power loss, for the whole year, for the selected generator type.

Initial cost estimation:

The initial cost includes acquisition and installation of the genset and it is broken down to annuities for a range of years and for a range of interest rates. More details are provided in Section 2.7.

Total cost estimation:

The flat cost related for maintenance and payroll is estimated. Then, this is added to the aforementioned operating cost and initial cost to form the total annual cost. The reliability cost is also added separately, providing the total annual cost with reliability considerations. These are both calculated for the range of annuities and interest rates mentioned above and for the current generator type. More details are provided in Section 2.9. Afterwards, the loop continues with the next genset type selection.

Optimal genset selection:

After the loop completes and all genset types are evaluated, the least expensive is selected and the total annual cost of the plant with and without reliability considerations is displayed, for the given range of annuities and interest rates.

The whole process is illustrated below. Subsequently, each individual aspect is more thoroughly discussed.

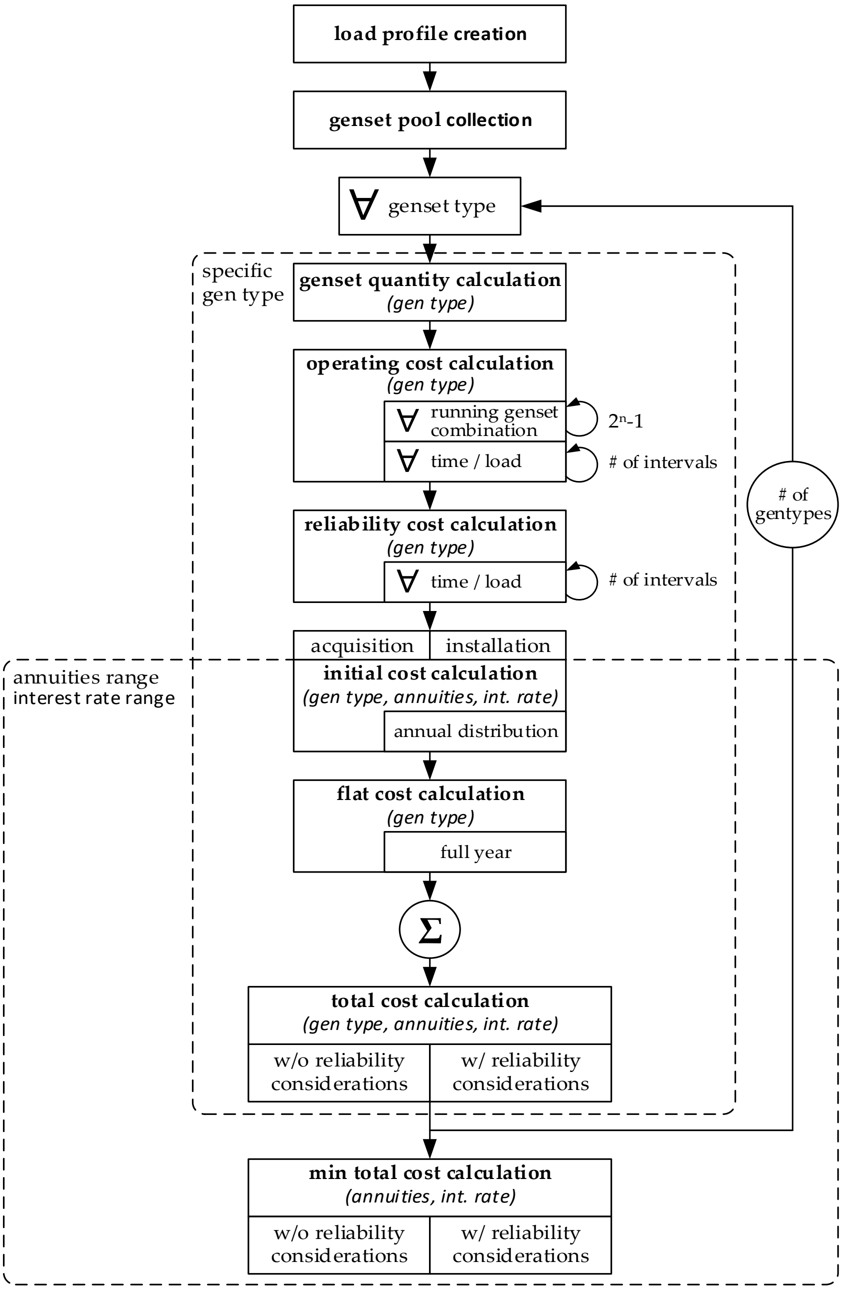


Figure 2. Calculation process overview.

2.2. Load Profile

The electric load of a ship varies greatly versus time and is very specific to her condition and performed operations. For example, the load of a ferry is much greater when she is underway filled with passengers than when she is at port with only a skeleton crew. Moreover, as the ship's schedule is usually predetermined, a load profile can be drafted with sufficient accuracy.

On the other hand, the load requirements of each ship are very distinctive and vary greatly, not only among different types and sizes but also among similar ships with different operating schedules. For example, a ship will have a different load signature when she is mostly underway and has only brief port time than when she is on a daily short-cruise routine. Therefore, it makes sense for a generator selection process to be shaped around the specific load requirements of the ship. For the purposes of this study, as well as for further research, a complete profile of the electric load of a passenger ship has been created. It is based on actual data from a real ship and it spans the range of a full operational period with relatively high resolution.

A ship is a complex structure like a small autonomous mobile city, containing a large variety of equipment. These extend from propulsion and energy production to air-conditioning, galleys and other hotel facilities. As such, the electric load associated with each of them may be characterized as more or less significant. In general, the total load $P_{load}(t_j)$ for every time t_j can be divided into K parts $P_{load-k}(t_j)$, first being the least and K-th being the most significant. In this paper, it is divided into inessential (P_{load-1}), essential (P_{load-2}), and critical parts (P_{load-3}).

$$P_{load}(t_j) = \sum_{k=1}^{K} P_{load-k}(t_j) \tag{1}$$

Inessential load refers to equipment that may become unavailable for a long time without any significant effect on the ship's operation, the performance of her crew or the living conditions of her passengers. This can be air-conditioning, hot water and lighting in living quarters, etc.

Essential load refers to equipment that when unavailable has a significant impact on the ship's operation, the performance of her crew and the living conditions of her passengers. This can be ventilation and lighting in compartments with running machinery, transfer pumps, air compressors, etc.

Finally, critical load refers to equipment that when unavailable seriously affects the safety of the ship and all those onboard. This can be auxiliaries necessary for running the gensets, propulsion and navigation (when the ship is underway), firefighting, damage control, etc.

2.3. Generator Specifications

In order to provide applicable results for this process, more than 30 actual generator sets, from several manufacturers, were studied and used to determine the optimal one (Table 1). The specifications in Table 1 were collected or derived from their datasheets.

The most characteristic information of a generator is its nominal power P_{nom}. This is provided along with its minimum and maximum power P_{min} and P_{max}, respectively. These are the limits of the equipment outside which operation is not permitted.

$$P_{min} < P_{nom} < P_{max} \tag{2}$$

For the reliability calculations, the probability of a genset not being available, also known as the forced outage rate (FOR) [20], was used.

The fuel type, fuel consumption and lubricating oil consumption were used to estimate the operating cost of the engine, while its physical characteristics and its acquisition price were used to estimate the installation cost.

It is noted that engines have additional restrictions and costs in their operation e.g., minimum running time and a minimum time between shutting down and starting up. There is also a maximum power increase/decrease rate and a starting cost. This information can be considered in future work.

Table 1. Generator data collected.

Specification
Electrical
Nominal power Minimum power percentage Maximum power percentage P_{max} Forced outage rate (FOR)
Mechanical
Fuel type Fuel consumption curve Lubricating oil consumption Weight Length Width Height
Cost
Acquisition cost Maintenance cost

2.4. Power Requirements

This paper assumes that all generators used in a single power plant are of the same type. Therefore, the maximum load can be supplied by n^* gensets of nominal power P_{nom} each, as shown in (3).

$$n* = \left\lceil \frac{\max\limits_{\forall t_j} P_{load}(t_j)}{P_{nom}} \right\rceil \quad (3)$$

This number is adequate for the ship's needs, if no redundancy is required, or if there is an extra emergency generator to take up all critical loads. However, if no extra emergency generator exists and the power plant is to withstand the failure of a single genset, then $n^* + 1$ generators will be required. Similarly, if the whole compartment may fail, then $2 \cdot n^*$ gensets are required in a different location. This is summarized in Table 2.

Table 2. Number of generators required.

Redundancy	Generator Quantity n
none or emergency generator	n^*
1 generator	$n^* + 1$
full: 1 power compartment	$2 \cdot n^*$

2.5. Operating Cost

The amount of fuel consumed by an engine is a function of its power output or load. As the power increases, so does the consumption versus time (see the fuel consumption curve in Figure 3). However, the consumption versus power and time (i.e., energy), also called specific consumption, reveals the existence of a point of optimal operation (see the corresponding specific fuel consumption curve in Figure 3).

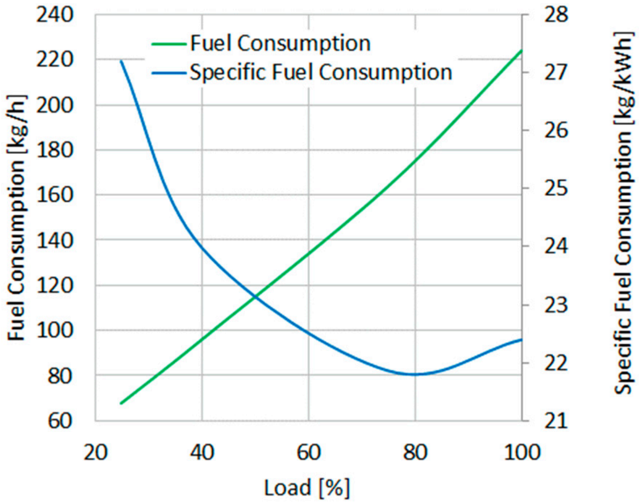


Figure 3. Fuel consumption curves.

The fuel consumption cost F_{fuel} may accurately be approximated by a second- or third-degree polynomial function (4) of the electric power P_m produced, with coefficients derived from its fuel consumption curve, or specific fuel consumption curve, provided by the manufacturer or actually measured.

$$F_{fuel}(P_m) = a + b \cdot P_m + c \cdot {P_m}^2 + d \cdot {P_m}^3 \quad (4)$$

In this paper, the approximation was calculated using a second-degree polynomial; therefore, F_{fuel} became:

$$F_{fuel}(P_m) = a + b \cdot P_m + c \cdot {P_m}^2 \quad (5)$$

On the other hand, it is specified that the lubricating oil consumption may accurately be approximated as proportional to the electric power P_m produced.

$$F_{lub}(P_m) = e \cdot P_m \quad (6)$$

Therefore, the total operational cost became:

$$F_{operation}(P_m) = a + (b + e) \cdot P_m + c \cdot {P_m}^2 \quad (7)$$

It is common practice to share the load equally among the running generators. This is efficient when all generators are of the same type and have the exact same consumption curve. However, this is never reality, since even generators of the same type will have significant differences in their consumption curves, due to their running hours, maintenance history, mechanical ware, etc. These curves can be obtained by taking periodic measurements. It has been proven that taking into account these differences and distributing the load using optimization methods, allows for extra fuel savings [19].

The quantity n of the generators required has been established above. Assuming, for the sake of generality that each one is different, there are $2^n - 1$ possible combinations $B_{combination}$ of them running. For every one $A_{operation-v}$ of them and for a particular time period t_j, the load requirements $P_{load}(t_j)$ were distributed in each running generator m producing power $P_m(t_j)$ with operating cost $F_{operation-m}(P_m(t_j))$. This distribution was optimized using the Lagrange method [19,21], because of its suitability to solve optimization problems that are constrained with equalities and/or inequalities. As such, that the total operating cost $F_{operation-A_{operation\text{-}v}}$ for this case became minimal (8) under the constraints (9) and (10).

$$F_{operation-A_{operation-v}}(t_j) = \min \sum_{m \in A_{operation-v}} F_{operation-m}(P_m(t_j)) \quad (8)$$

$$P_{load}(t_j) = \sum_{m \in A_{operation-v}} P_m(t_j) \quad (9)$$

$$m \in A_{operation-v} : P_{\min-m} \leq P_m(t_j) \leq P_{\max-m} \quad (10)$$

The system marginal cost $SMC_{operation-v}(t_j)$ was also calculated:

$$SMC_{operation-v}(t_j) = \frac{\partial F_{operation-m}(P_m(t_j))}{\partial P_m}, \forall m \in A_{operation-v} \quad (11)$$

Out of all combinations $B_{combination}$, the most efficient was selected, as in (12), and the total cost due to fuel and lubricating oil consumption throughout the year (i.e., N_T time intervals) was calculated, as in (13).

$$F_{operation}(t_j) = \min_{\forall v \in B_{combination}} F_{operation-A_{operation-v}}(t_j) \quad (12)$$

$$Cost_{operation} = \sum_{j=1}^{N_T} F_{operation}(t_j) \cdot \Delta t_j \quad (13)$$

The whole process is illustrated in Figure 4.

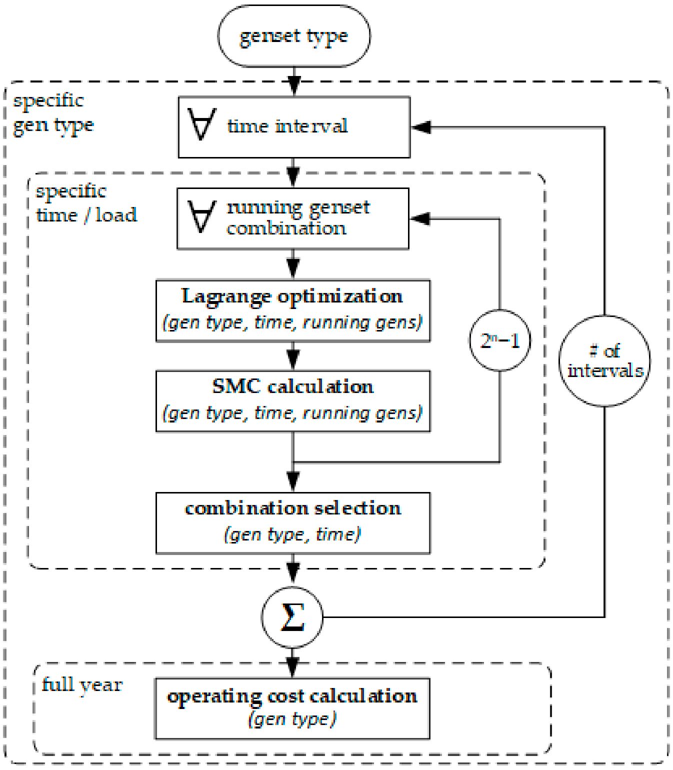


Figure 4. Operating cost calculation process.

If all the engines populating the power plant have identical behavior, the optimization process may be simplified using equal distribution. However, the algorithm uses optimization to address different duty cycles of the gensets and any future expansion of this work.

2.6. Reliability Cost

The reliability of a system is a factor of paramount importance. However, most of the time, industrial systems use rather simplistic and crude redundancy techniques to achieve the required reliability levels.

A more innovative and detailed way is using the COPT of the power plant. This is formulated, for N_P amount of generator combinations each with power-outage probability p_i, during an amount of N_T time intervals each with duration Δt_i. From this, the expected Loss Of Load Power (LOLP) is derived. This is the amount of time the available power $P_{available\_power\_i}$ is not sufficient to supply the ship's load $P_{load}(t_j)$, thus leading to a power outage, expressed here using the step function $u()$.

$$LOLP = \sum_{j=1}^{N_T} \sum_{i=1}^{N_P} p_i \cdot \Delta t_j \cdot u\left(P_{load}(t_j) - P_{available\_power-i}\right) \tag{14}$$

Similarly, the expected LOLE is derived, showing the amount of active energy not supplied to the load for the same time period and is expressed here using the ramp function $r()$.

$$LOLE = \sum_{j=1}^{N_T} \sum_{i=1}^{N_P} p_i \cdot \Delta t_j \cdot r\left(P_{load}(t_j) - P_{available\_power-i}\right) \tag{15}$$

This is also equal to:

$$LOLE = \sum_{j=1}^{N_T} \sum_{i=1}^{N_P} p_i \cdot \Delta t_j \cdot \left(P_{load}(t_j) - P_{available\_power-i}\right) \cdot u\left(P_{load}(t_j) - P_{available\_power-i}\right) \tag{16}$$

Furthermore, the LOLE can be individually expressed for each load category as:

$$LOLE_k = \sum_{j=1}^{N_T} \sum_{i=1}^{N_P} p_i \cdot \Delta t_j \cdot r\left(\sum_{b=n}^{k} P_{load-b}(t_j) - P_{available\_power-i}\right) \tag{17}$$

One way to calculate the cost of LOLE is by assuming a constant cost per load category $Cost_{loss\_energy-k}$, as seen in:

$$Cost_{LOLE} = \sum_{k=1}^{K} LOLE_k \cdot Cost_{loss\_energy-k} \tag{18}$$

A more innovative way is by assuming a cost proportional to the SMC calculated earlier:

$$Cost_{LOLE} = \sum_{j=1}^{N_T} \sum_{k=1}^{K} LOLE_k(t_j) \cdot SMC(t_j) \cdot Factor\_Cost_{loss\_energy-k} \tag{19}$$

2.7. Initial Cost

The first type of cost that comes to mind is the initial cost $F_{initial-total}$ of the generators. This is usually limited to their purchase price A_m, provided by the vendors.

However, when building a ship, there is an additional cost resulting from the space allocated for the generators and its impact on the ship's size. This is estimated as a fraction of the total ship cost C, which in turn is approximated using semiempirical relations like the following, where a and b are constants and DWT is the DeadWeight Tonnage [22].

$$C = \alpha \cdot \mathrm{DWT}^{\mathrm{b}} \tag{20}$$

A more detailed way to approach this is by considering the area E_m and the volume V_m occupied by the generator and also its mass M_m, along with their associated unit costs $Cost_{Area}$, $Cost_{Volume}$ and $Cost_{Mass}$, respectively, as shown below:

$$F_{installation-area} = \sum_{m=1}^{n} \left(E_m \cdot Cost_{Area}\right) \tag{21}$$

$$F_{installation-volume} = \sum_{m=1}^{n} \left(V_m \cdot Cost_{Volume}\right) \tag{22}$$

$$F_{installation-mass} = \sum_{m=1}^{n} \left(M_m \cdot Cost_{Mass}\right) \tag{23}$$

Therefore, the total installation and initial costs become:

$$F_{installation-total} = \sum_{m=1}^{n} \left(E_m \cdot Cost_{Area} + V_m \cdot Cost_{Volume} + M_m \cdot Cost_{Mass}\right) \tag{24}$$

$$F_{initial-total} = \sum_{m=1}^{n} \left(A_m + E_m \cdot Cost_{Area} + V_m \cdot Cost_{Volume} + M_m \cdot Cost_{Mass}\right) \tag{25}$$

As the operating period of the ship is set to one year, all costs need to refer to this. In order for the initial cost to be projected to the total annual cost, the investment scheme must be examined. For an interest rate i_{cap} and a number of T_{per} annuities, the Capital Recovery Factor (CRF) [23] becomes:

$$CRF\left(i_{cap}, T_{per}\right) = \frac{i_{cap} \cdot \left(1 + i_{cap}\right)^{T_{per}}}{\left(1 + i_{cap}\right)^{T_{per}} - 1} \tag{26}$$

Therefore, the annual cost for the total recovery of the investment, or equivalent initial cost $F_{initial-eq}$, becomes:

$$F_{initial-eq}\left(i_{cap}, T_{per}\right) = F_{initial-total} \cdot CRF\left(i_{cap}, T_{per}\right) \tag{27}$$

2.8. Flat Cost

No machinery may be left running unattended and without adequate maintenance. There is additional cost associated with this: the spare parts and the consumables used. This kind of work also requires specialized crew members, devoting a major portion of their time. As a consequence, their payroll was also included. This flat cost F_{flat}, has been statistically approximated as cost per calendar hour $Cost_{flat-m}$ for the m-th generator and for a whole year became:

$$F_{flat} = 8760 \cdot \sum_{m=1}^{n} Cost_{flat-m} \tag{28}$$

2.9. Total Cost

Taking into account all the above, the equivalent annual cost of the electric power generating equipment is the following:

$$F_{total}\left(i_{cap}, T_{per}\right) = F_{initial-eq}\left(i_{cap}, T_{per}\right) + F_{flat} + Cost_{operation} \tag{29}$$

If reliability considerations are also taken into account, the equivalent annual cost becomes:

$$F_{total\_LOLE}\left(i_{cap}, T_{per}\right) = F_{initial-eq}\left(i_{cap}, T_{per}\right) + F_{flat} + Cost_{operation} + Cost_{LOLE} \tag{30}$$

3. Computational Speed Improvement

Performing the above calculations proved to be a very computationally intensive task, even for modern computers, requiring several hours to complete. The major cause of delay was the Lagrange optimization and its repetition for every combination of running gensets, as well as for every time interval in the load profile, as previously seen in Figure 4.

The classic method of proportional load distribution is trivial and thus much faster. However, it has none of the efficiency benefits provided by the otherwise-rigorous Lagrange optimization. Achieving improved generator efficiency and fuel savings outweighed the convenience and speed of the classic method. Moreover, it is a well-established and documented method [24], especially for load distribution among thermal engines [25,26].

Dynamic programming could also be used, but it seemed more complex and less efficient, as it is a multilayer method that would be better suited to solve time-dependent problems [27].

To alleviate the speed concern, the memorization technique, shown in Figure 5 and described next, was also applied.

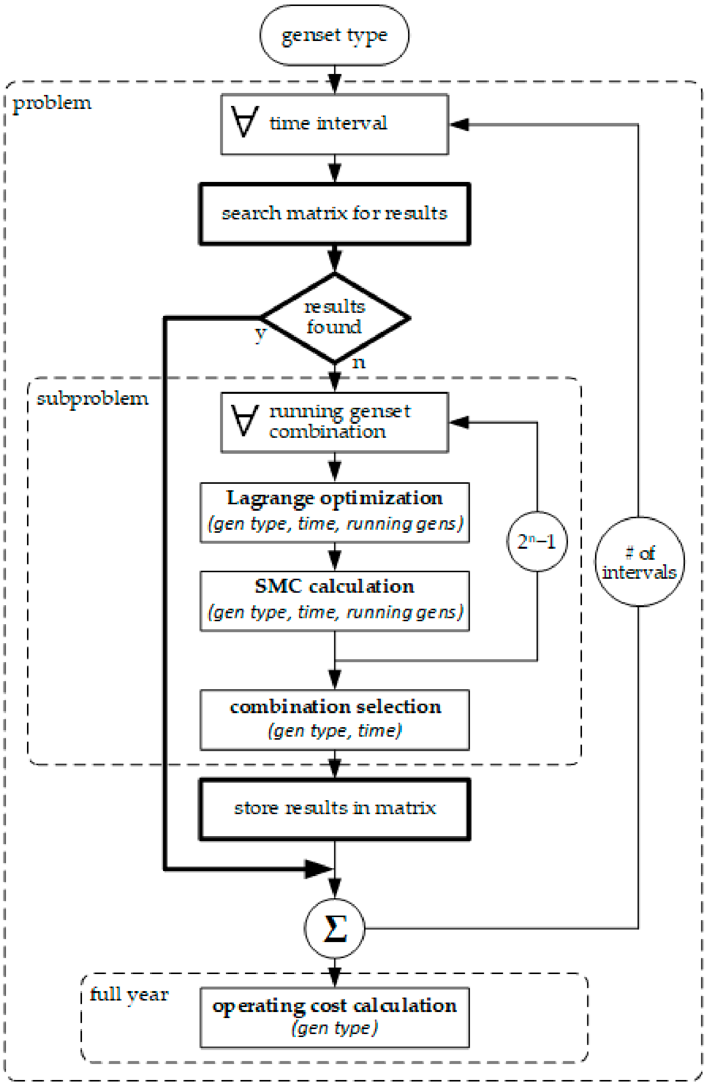


Figure 5. Speed improvement modification.

If the load profile has a duration of m months and a resolution of s samples per hour, then it will contain q intervals, where:

$$q = m \cdot 30 \times 24 \cdot s \tag{31}$$

Consequently, a profile of one year with a resolution of 30 min contains 365·24·2 = 17,520 intervals. On the other hand, the quantity n of generators populating the power plant, as determined in Section 2.4, can be quite high. Depending on the nominal power of a genset type and the redundancy and load requirements of a certain interval, the combinations of running generators can be as much as $2^n - 1$.

Therefore, for an average n and for g different genset types, the Lagrange optimization code is executed on average l times, where:

$$\bar{l} = q \cdot (2^{\overline{n}} - 1) \cdot g \tag{32}$$

This amount can easily be in the order of several million, hence the large total execution time.

Then again, it is apparent that for the same generator type and the same total load, the optimization outcome is the same. If the calculation of the operating cost is the problem, then the Lagrange optimization section, with all its repetitions, is the subproblem. Due to the uniformity of the load profile, many load conditions are the same; therefore, an overlapping of subproblems exists. This is a strong indication that running time can be reduced [28].

According to the memorization technique, an empty matrix is created for storing all optimization (i.e., subproblem) results. Any time such a calculation is required, the code quickly checks the matrix for an existing solution. If one is found, meaning that this particular optimization was performed before, the results are retrieved and the detailed calculation is bypassed.

This approach achieved a computational time reduction of more than 300 times and the running time of the code was reduced from several hours to less than a minute.

4. Case Study

As a case study, the above method was applied to a real passenger ship. To populate her power plant and to come up with tangible results, an extended data base comprising the functional parameters from several real diesel generators was used. Of course, many different scenarios can also be tested and numerical data better, may easily be applied.

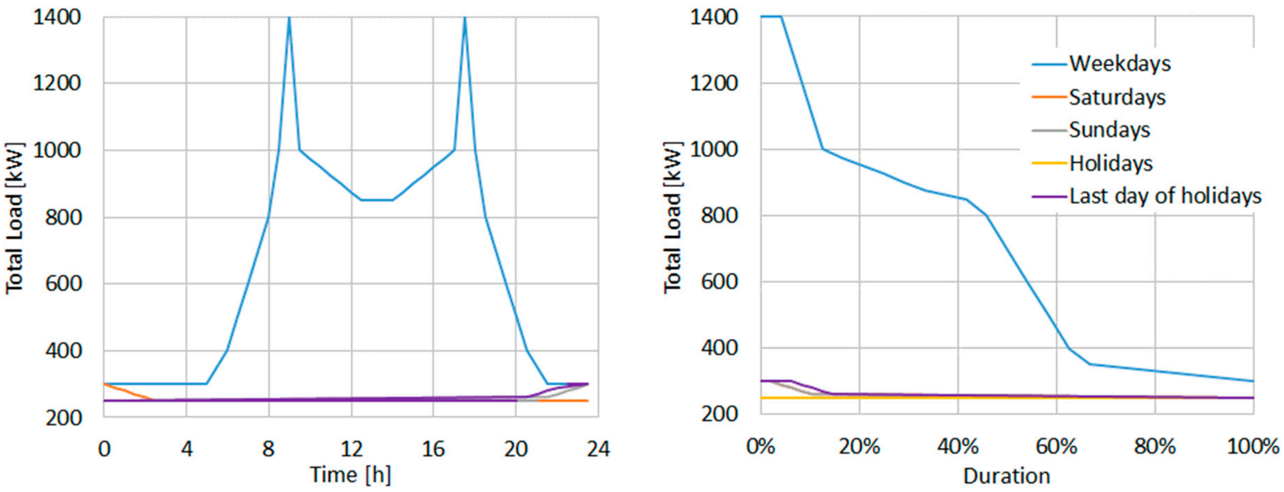
4.1. Load Profile

The ship performs the same routine every year. Its load profile was formed to span this time period with a resolution of 30 min. In detail, she completes an 8-hour cruise every weekday, as shown in Table 3.

Table 3. Ship's weekday routine.

Status	**Duration**
at port	8.5 h
preparation for departure	1 h
underway	8 h
preparation for arrival	1 h
at port	5.5 h
Total:	24 h

Weekends are holidays and only maintenance takes place. The crew also has 4 weeks of holidays every year. The total electrical load is therefore drafted as in Figure 6.



(**a**) (**b**)

Figure 6. Load profile of ship: (**a**) versus time; (**b**) load duration curve.

As mentioned above, the total load is distinguished in critical, essential and inessential load. The critical load was measured and approximated as follows in Table 4.

Table 4. Critical load approximation.

Status	Critical Load
at port	20 kW
preparation for departure	100 kW
underway	100 kW
preparation for arrival	100 kW

Noncritical load was divided into essential and inessential, as follows in Table 5.

Table 5. Essential and inessential load division.

Status	Essential Load	Inessential Load	
at port	70%	30%	of noncritical
preparation for departure	60%	40%	of noncritical
underway	60%	40%	of noncritical
preparation for arrival	60%	40%	of noncritical

For reliability purposes, the cost of losing essential load was estimated at 100 times more that of losing inessential load. Similarly, the cost of losing critical load was estimated to be 100 times even higher, as shown below in Table 6.

Table 6. Relative reliability cost.

Load Type	Relative Cost
inessential	1
essential	100
critical	10,000

4.2. Generator Data: Electrical

The generators examined [29–37] covered an area of nominal power from 30 to 2250 kW. The whole range, along with their respective allowable limits of minimum and maximum power, may be seen in Figure 7. A common FOR equal to 0.0113 was used.

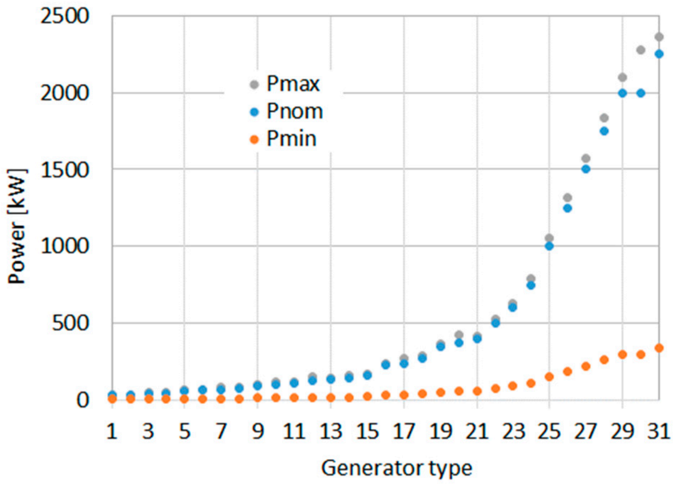


Figure 7. Power nominal, min, max.

4.3. Generator Data: Mechanical

The equipment runs on light fuel (i.e., marine diesel) with a cost of 0.40 €/kg. Its fuel consumption was approximated by a second-degree polynomial (with coefficients *a*, *b* and *c*) versus its power output, as seen in Figure 8.

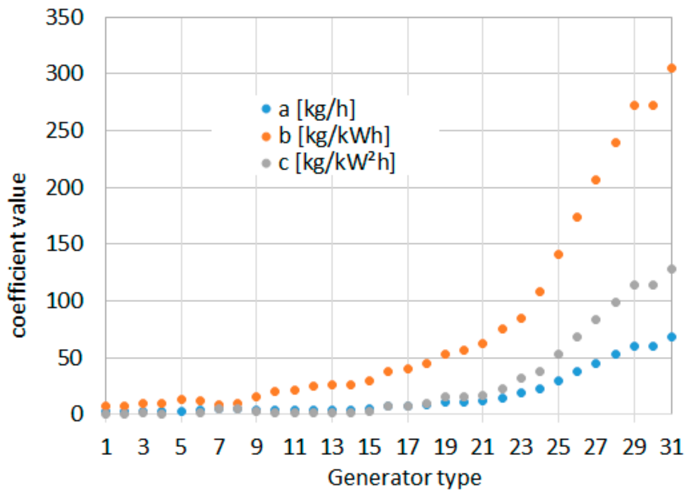


Figure 8. Fuel consumption coefficients.

The lubricating oil consumption cost was found to be proportional to the output power and was approximated in all cases as 0.006 €/kWh. The dimensions and the weight of the engines are shown in Figure 9.

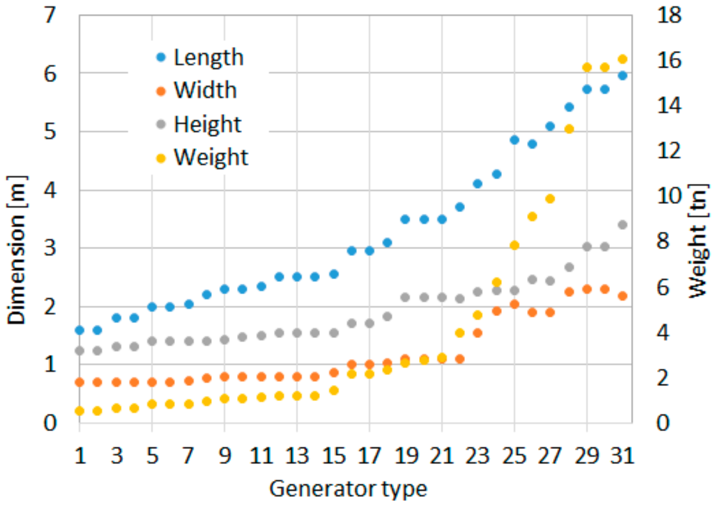


Figure 9. Dimensions and weight.

4.4. Generator Data: Cost

The acquisition and the maintenance cost of each genset are shown in Figure 10.

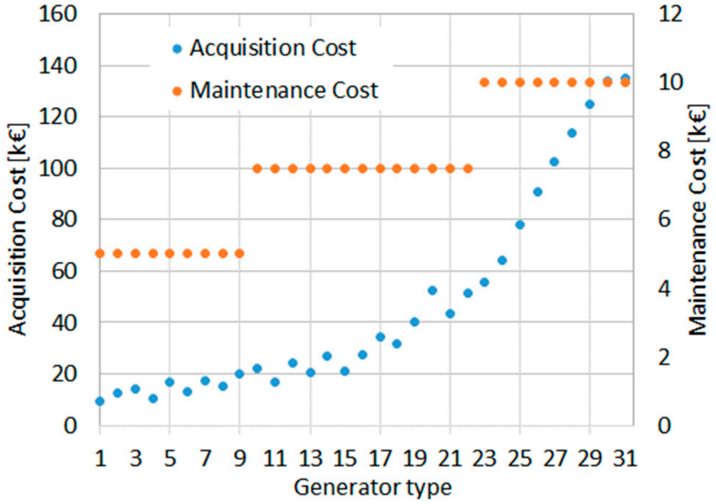


Figure 10. Acquisition cost and maintenance cost.

The unit costs of installation due to area, volume and weight used were the following, as seen in Table 7.

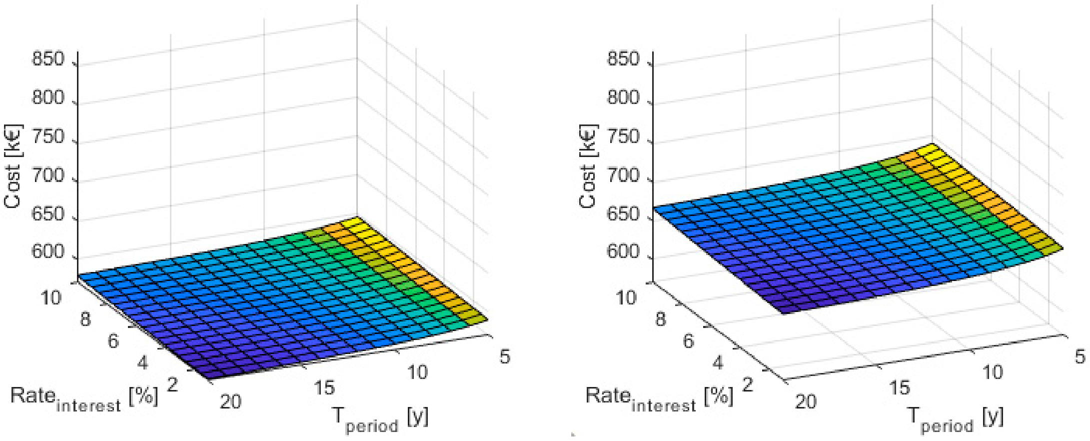
Table 7. Installation unit costs.

Installation Cost Type	Unit Cost
due to area	0 €/m^2
due to volume	463 €/m^3
due to weight	0 €/kg

The complete set of data can be found in Table A1 in the Appendix A.

4.5. Results

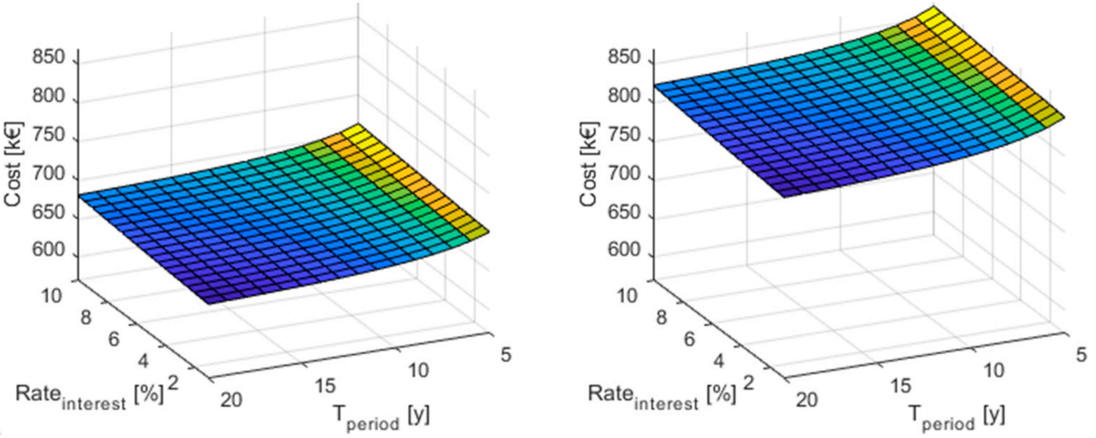
Assuming that no redundancy ($n = n^*$) is required, the most efficient combination turned out to be one engine of 1500 kW nominal power when reliability was not considered. On the other hand, the most efficient combination turned out to be three engines of 500 kW nominal power each when reliability was considered, as seen in Figure 11.



(**a**) (**b**)

Figure 11. Minimum annual total cost for the best solution for power plant without redundancy: (**a**) without reliability considerations; (**b**) minimum annual total cost for the best solution with reliability considerations.

Assuming that redundancy of a whole power compartment ($n = 2 \cdot n^*$) is required, the most efficient combination turned out to be two engines of 1500 kW nominal power each when reliability of the ship power system was not considered. On the other hand, the most efficient combination turned out to be four engines of 750 kW nominal power each when reliability of the ship power system was considered, as seen in Figure 12.



(**a**) (**b**)

Figure 12. Minimum annual total cost for the best solution for power plant with full redundancy: (**a**) without reliability considerations; (**b**) minimum annual total cost for the best solution with reliability considerations.

The results can be summarized as follows in Table 8.

Table 8. Results summary.

	No Redundancy		**Full Redundancy**	
	w/o Reliability	**w/ Reliability**	**w/o Reliability**	**w/Reliability**
Selected power plant	1 × 1500 kW	3 × 500 kW	2 × 1500 kW	4 × 750 kW
duty cycle 1 engine	100%	64%	100%	70%
duty cycle 2 engines	-	33%	0%	30%
duty cycle 3 engines	-	3%	-	0%
duty cycle 4 engines	-	-	-	0%
min optimal annual cost *(20 annuities with 1% interest rate)*	€572,000	€656,000	€666,000	€804,000
max optimal annual cost *(5 annuities with 10% interest rate)*	€596,000	€691,000	€713,000	€865,000

5. Discussion

As observed in the examined designs, a ship with 1400 kW maximum load requirement can be sufficiently supplied by a single 1500 kW generator, assuming that no redundancy and reliability considerations exist.

When reliability begins to matter, one might expect a solution of two 750 kW engines. However, the proposed combination was three 500 kW engines. Although the total power supply capability remained the same, the larger number of engines is obviously more reliable.

Despite the fact that in the first case, the large engine ran most of the time at a load less than 30% of its nominal value, it was still more economical than the combination of the second case, which probably ran more efficiently per engine.

Next, when full redundancy became a requirement, as was expected, the scheme of the first case (without reliability) doubled, even though again only one generator was running at any certain time.

The same did not occur when both full redundancy and reliability were required, and the scheme of the second case was not doubled like before. Instead, four engines with 750 kW nominal power were selected as more efficient. This configuration is seen in many types of ships. Again, although the total power in both plants with full redundancy was the same, the cost of the reliable one was higher.

6. Conclusions

In this paper, a novel method was introduced to facilitate the selection process of the generators in a ship power plant. It uses many parameters related to all aspects of the life-cycle cost of the engines and to the actual operating routine of the ship; however, computational time is significantly low. This way, the designers can have a complete idea of the cost involved in their selection and its return on investment.

This method may be used for different operation scenarios simply by changing the numerical data. It can also be used for applications other than shipping, since industrial installations have similar needs. Even more exotic applications may also benefit from this, by calibrating the indicators used here, or simply adding new ones.

An idea for future work could be performing a sensitivity analysis to determine how much each the examined factors affect the outcome.

Another probably useful addition might be the consideration of the minimum running time, the minimum time between shutting down and starting up, the power-increase rate, and the starting cost.

Finally, it might prove advantageous to expand this method by testing combinations of different gensets and possible exploitation of renewable energy onboard. This way, ships with shaft generators and electric propulsion, but also terrestrial power factories, may be examined.

Author Contributions: Conceptualization, P.M., G.J.T., F.D.K. and J.M.P.; methodology, P.M. and G.J.T.; software, P.M. and G.J.T.; validation, P.M., G.J.T. and F.D.K.; formal analysis, P.M. and G.J.T.; investigation, P.M. and G.J.T.; resources, P.M., G.J.T., F.D.K. and J.M.P.; data curation, P.M. and G.J.T.; writing—original draft preparation, P.M.; writing—review and editing, P.M., G.J.T. and F.D.K.; supervision, J.M.P.; project administration, J.M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The diesel generator data used are shown in detail below.

Table A1. Genset data.

#	P_{nom}	Fuel Consumption Coefficients			Weight	Dimensions			Price	Flat Cost
		a	b	c		L	W	H		
	[kW]	[kg/h]	[kg/kW h]	[kg/kW^2 h]	[tn]	[m]	[m]	[m]	[k€]	[€/h]
1	30.0	2.3621	6.8028	0.0000	0.55	1.60	0.70	1.25	9.5	5.0
2	42.0	2.7085	9.1712	1.0078	0.55	1.60	0.70	1.25	12.5	5.0
3	62.0	2.6823	13.1900	−0.2520	0.64	1.80	0.70	1.30	14.4	5.0
4	72.0	4.6770	8.9067	4.7872	0.66	1.80	0.70	1.30	10.6	5.0
5	92.0	3.9904	15.1600	2.8723	0.80	2.00	0.70	1.40	16.7	5.0
6	105.0	3.4487	19.7160	1.2598	0.81	2.00	0.70	1.40	13.2	5.0
7	131.0	3.7951	24.9560	1.2598	0.84	2.04	0.71	1.40	17.5	5.0
8	141.0	4.0156	26.4930	1.7637	0.96	2.20	0.77	1.40	15.4	5.0
9	238.0	6.8343	39.6330	7.5587	1.05	2.30	0.80	1.43	20.3	5.0
10	370.0	11.0550	56.7160	15.6210	1.10	2.30	0.80	1.48	22.2	7.5
11	2000.0	60.4700	272.2400	113.3800	1.11	2.34	0.80	1.49	16.7	7.5
12	30.0	2.3621	6.8028	0.0000	1.16	2.50	0.80	1.55	24.1	7.5
13	45.0	2.6377	9.9838	0.6299	1.18	2.50	0.80	1.55	20.6	7.5
14	65.0	3.2807	11.9050	1.2598	1.18	2.50	0.80	1.55	26.7	7.5
15	80.0	4.8974	9.8389	5.2911	1.43	2.57	0.87	1.55	21.1	7.5
16	110.0	3.5117	20.7230	1.2598	2.14	2.96	1.00	1.72	27.3	7.5
17	140.0	3.9893	26.3720	1.6797	2.18	2.96	1.00	1.72	34.3	7.5
18	160.0	4.4722	29.1260	3.0235	2.36	3.10	1.03	1.83	31.8	7.5
19	230.0	6.7713	37.9200	7.5587	2.67	3.50	1.10	2.16	40.2	7.5
20	275.0	7.9130	44.8170	9.4484	2.75	3.50	1.10	2.16	52.6	7.5
21	350.0	10.7080	53.1630	15.1170	2.86	3.50	1.10	2.16	43.7	7.5
22	400.0	11.5740	62.0440	16.3770	3.96	3.70	1.10	2.14	51.7	7.5
23	500.0	14.6450	74.9570	22.6760	4.79	4.11	1.54	2.25	55.4	10.0
24	600.0	18.6610	84.4690	31.4950	6.19	4.28	1.91	2.28	64.4	10.0
25	750.0	22.2040	107.9600	37.7940	7.85	4.86	2.05	2.28	78.2	10.0
26	1000.0	29.9200	140.7200	52.9110	9.08	4.79	1.90	2.45	90.8	10.0
27	1250.0	37.4790	173.7200	68.0280	9.91	5.10	1.90	2.44	102.7	10.0
28	1500.0	45.1950	206.4800	83.1460	12.95	5.42	2.24	2.68	113.9	10.0
29	1750.0	52.7530	239.4900	98.2630	15.70	5.73	2.30	3.02	124.6	10.0
30	2000.0	60.4700	272.2400	113.3800	15.70	5.73	2.30	3.02	133.8	10.0
31	2250.0	68.0280	305.2500	128.5000	16.07	5.97	2.18	3.40	134.9	10.0

P_{min} = 15% P_{nom}, P_{max} = 105% P_{nom}, FOR = 0.0113, fuel type = light fuel, lubricating oil consumption cost = 0.006 €/kWh.

References

1. Shipping Fleet Statistics: 2021—GOV.UK. Available online: https://www.gov.uk/government/statistics/shipping-fleet-statistics-2021/shipping-fleet-statistics-2021--2 (accessed on 14 September 2022).
2. Shipbuilding Market Size, Share, Report, Analysis, Growth—2030. Available online: https://www.alliedmarketresearch.com/shipbuilding-market-A08511 (accessed on 14 September 2022).
3. Tsekouras, G.J.; Kanellos, F.D.; Prousalidis, J. Simplified Method for the Assessment of Ship Electric Power Systems Operation Cost Reduction from Energy Storage and Renewable Energy Sources Integration. *IET Electr. Syst. Transp.* **2015**, *5*, 61–69. [CrossRef]
4. Tsekouras, G.J.; Kanellos, F.D. Optimal Operation of Ship Electrical Power System with Energy Storage System and Photovoltaics: Analysis and Application. *WSEAS Trans. Power Syst.* **2013**, *8*, 145–155.
5. Sun, Y.; Yan, X.; Yuan, C.; Tang, X.; Malekian, R.; Guo, C.; Li, Z. The Application of Hybrid Photovoltaic System on the Ocean-Going Ship: Engineering Practice and Experimental Research. *J. Mar. Eng. Technol.* **2019**, *18*, 56–66. [CrossRef]
6. Huang, X.; Sun, S. Application of Wind Power Generation Technology in Ships. In Proceedings of the 2022 IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers, IPEC 2022, Dalian, China, 14–16 April 2022; pp. 1591–1593.
7. Chen, X.; Guo, Y. Research on Energy Management Strategy of Fuel Cell-Battery Hybrid Power Ship. In Proceedings of the SPIE—The International Society for Optical Engineering, Guangzhou, China, 10–12 December 2021; Volume 12164.
8. Chen, H.; Zhang, Z.; Guan, C.; Gao, H. Optimization of Sizing and Frequency Control in Battery/Supercapacitor Hybrid Energy Storage System for Fuel Cell Ship. *Energy* **2020**, *197*, 117285. [CrossRef]
9. Jeong, B.; Jeon, H.; Kim, S.; Kim, J.; Zhou, P. Evaluation of the Lifecycle Environmental Benefits of Full Battery Powered Ships: Comparative Analysis of Marine Diesel and Electricity. *J. Mar. Sci. Eng.* **2020**, *8*, 580. [CrossRef]
10. Kanellos, F.D.; Tsekouras, G.J.; Prousalidis, J. Onboard DC Grid Employing Smart Grid Technology: Challenges, State of the Art and Future Prospects. *IET Electr. Syst. Transp.* **2015**, *5*, 1–11. [CrossRef]
11. Ballou, P.J. Ship Energy Efficiency Management Requires a Total Solution Approach. *Mar. Technol. Soc. J.* **2013**, *47*, 83–95. [CrossRef]
12. Sudhoff, S.D. Currents of Change. *IEEE Power Energy Mag.* **2011**, *9*, 30–37. [CrossRef]
13. Feng, X.; Zourntos, T.; Butler-Purry, K.L.; Mashayekh, S. Dynamic Load Management for NG IPS Ships. In Proceedings of the IEEE PES General Meeting, PES 2010, Minneapoli, MI, USA, 25–29 July 2010.
14. Fang, S.; Xu, Y.; Wen, S.; Zhao, T.; Wang, H.; Liu, L. Data-Driven Robust Coordination of Generation and Demand-Side in Photovoltaic Integrated All-Electric Ship Microgrids. *IEEE Trans. Power Syst.* **2020**, *35*, 1783–1795. [CrossRef]
15. Feng, X.; Butler-Purry, K.L.; Zourntos, T. Real-Time Electric Load Management for DC Zonal All-Electric Ship Power Systems. *Electr. Power Syst. Res.* **2018**, *154*, 503–514. [CrossRef]
16. Zeng, Y.; Zhang, Q.; Liu, Y.; Zhuang, X.; Lv, X.; Wang, H. An Improved Distributed Secondary Control Strategy for Battery Storage System in DC Shipboard Microgrid. *IEEE Trans. Ind. Appl.* **2022**, *58*, 4062–4075. [CrossRef]
17. Tang, D.; Wang, H. Energy Management Strategies for Hybrid Power Systems Considering Dynamic Characteristics of Power Sources. *IEEE Access* **2021**, *9*, 158796–158807. [CrossRef]
18. Si, Y.; Wang, R.; Zhang, S.; Zhou, W.; Lin, A.; Zeng, G. Configuration Optimization and Energy Management of Hybrid Energy System for Marine Using Quantum Computing. *Energy* **2022**, *253*, 124131. [CrossRef]
19. Michalopoulos, P.; Kanellos, F.D.; Tsekouras, G.J.; Prousalidis, J.M. A Method for Optimal Operation of Complex Ship Power Systems Employing Shaft Electric Machines. *IEEE Trans. Transp. Electrif.* **2016**, *2*, 547–557. [CrossRef]
20. Nasioulas, E.C.; Tsekouras, G.J.; Kanellos, F.D. Bottom-up Reliability Analysis of a Base Load Diesel Engine Driven Electric Power Unit. *WSEAS Trans. Power Syst.* **2014**, *9*, 327–340.
21. Bertsekas, D.P. *Constrained Optimization and Lagrange Multiplier Methods*, 1st ed.; Athena Scientific: Nashua, NH, USA, 1996; ISBN 978-1-886529-04-5.
22. Bureau of Transport Economics. *An Estimate of Operating Costs for Bulk, Ro-Ro and Container Ships*; Australian Government Publishing Service: Canberra, Australia, 1982; ISBN 978-0-642-01774-1.
23. Jäger, L. *Handbook of Capital Recovery (CR) Factors*; Books on Demand GmbH: Norderstedt, Germany, 2021; ISBN 978-3-7534-5672-0.
24. Momoh, J.A. *Electric Power System Applications of Optimization*; Marcel Dekker Inc.: New York, NY, USA, 2001; ISBN 0-8247-9105-3.
25. Saccomanno, F. *Electric Power Systems: Analysis and Control*, 1st ed.; Wiley-IEEE Press: Piscataway, NJ, USA; Hoboken, NJ, USA, 2003; ISBN 978-0-471-23439-5.
26. Tsekouras, G.J.; Kanellos, F.D.; Tsirekis, C.D.; Mastorakis, N.E. Optimal operation of thermal electric power production system without transmission losses: An alternative solution using Artificial Neural Networks based on external penalty functions. In Proceedings of the 12th WSEAS International Conference on Artificial Intelligence, Knowledge Engineering and Databases (AIKED 2013), Cambridge, UK, 22–24 February 2013.
27. Chow, G.C. *Dynamic Economics: Optimization by the Lagrange Method*; Oxford University Press: Oxford, UK, 2011; p. 248, ISBN 978-0-19-985503-2.
28. Karumanchi, N. *Algorithm Design Techniques: Recursion, Backtracking, Greedy, Divide and Conquer, and Dynamic Programming*; CareerMonk Publications: Madinaguda, India, 2018; ISBN 978-81-932452-5-5.
29. Approximate Diesel Generator Fuel Consumption Chart. Available online: https://www.generatorsource.com/Diesel_Fuel_Consumption.aspx (accessed on 14 September 2022).

30. Argyriou SA Generator Sets—Industrial. Available online: https://www.argyriousa.com.gr/ell/product/ILEKTROPARAGOGA-ZEYGI-Viomixanika (accessed on 14 September 2022).
31. Wartsila. LNG Shipping Solutions. Wartsila, 2017. Available online: https://cdn.wartsila.com/docs/default-source/oil-gas-documents/brochure-lng-shipping-solutions.pdf?sfvrsn=12 (accessed on 12 October 2022).
32. Dual Fuel Engines. Available online: https://www.wartsila.com/marine/products/engines-and-generating-sets/dual-fuel-engines (accessed on 12 October 2022).
33. Wartsila. Wärtsilä 50DF Product Guide. Wartsila, 2018. Available online: https://cdn.wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w50df.pdf?sfvrsn=9 (accessed on 12 October 2022).
34. MAN Diesel & Turbo, MAN L51/60DF; MAN Diesel & Turbo. Available online: https://mandieselturbo.com/docs/default-source/shopwaredocuments/man-51-60df0a0c6de48eda40e380a07ede431aa5bd.pdf?sfvrsn=1 (accessed on 12 October 2022).
35. CIMAC. *Guidelines for the Lubrication of Medium Speed Diesel Engines*; CIMAC: Solihull, UK, 2008.
36. GenSets Closed Type 1500 rpm. Available online: https://www.genitries.gr/product-category/gennitries-ilektroparagoga-zeygi/iz-kleistoy-typoy/ (accessed on 14 September 2022).
37. Marine Generators. Available online: https://www.zenoro.com/marine-generators/ (accessed on 14 September 2022).