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Stochastic Approach for Power Generation Optimal Design and Scheduling on Ships

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***Abstract*—Recently an increase in electrical power installed on board ships has been revealed, especially for large Cruise ships and All Electric Ships (AES). In this context, the traditional approaches to Electrical Power Load Analysis (EPLA) and generation system size have become inadequate and inaccurate. Aim of this work is to propose an alternative method to perform an EPLA based on a stochastic modelling of loads, which are then combined together with a variant of the Monte Carlo Simulation (MCS) in order to calculate the total power demanded. The optimal selection of the generation system size is modelled as a Mixed-Integer Non Linear Problem (MINLP) and solved applying Genetic Algorithms (GA). The results here proposed shown that there is the real opportunity to apply stochastic approach in order to reduce the mission and installation costs of shipboard power systems with significant savings.**

***Index Terms*—Electric vehicle, Uncertainty management, electric power load analysis, optimal scheduling, power system optimal planning.**

I. INTRODUCTION

The always increasing interest in environmental issue has encouraged both the marine rulers (i.e. International Maritime Organization IMO) and stakeholders (i.e. shipyards and owners) to introduce new technologies focused on the energy efficiency improvement on board ships (e.g. high efficiency motors, variable frequency drives [1], energy storage systems, waste heat recovery systems and DC grid for future ships). Considering these new technologies and their behaviour in time, in most cases the power required by each device seems to be variable (i.e. the power required by these machineries is balanced by their electrical motors with variable frequency). This introduces new uncertainties performing an EPLA, which have to be considered also in design phase in order to efficiently design the on board power system. In this perspective, the traditional methods to perform the EPLA might need some revision in terms of approach, methods and applications. In fact, the traditional methods adopted in order to calculate the power required by each user by performing the EPLA in ship design assume deterministic factors (e.g. load factors, demand factors and utilization factors). These factors have been evaluated in the past with analysis based on dated ships [2]-[4]. Then, total power required by the ship is calculated as the arithmetic sum of the power absorbed by each user installed on board (i.e. of each load). Once the total power required by the ship (e.g. considering all the main ship operative scenarios) has been calculated, it is possible to select the generation, the energy storage and the distribution system characteristics. In this context, it is possible to note that the EPLA is one of the most critical phases of the power system design. In order to cope with the increasing uncertainties and to improve the EPLA performances, new methodologies based on stochastic characterization of loads and their combination with a Monte Carlo Simulations (MCS), have been already proposed and explained in literature [2]-[4]. These methodologies allow the designer, also in early stage of ship design, to predict the load probability density function (PDF) in each ship operative scenario as well as considering the whole ship life cycle. The principal contribution of this work is to propose a probabilistic approach to perform an EPLA in ship design phase (i.e. with a formulation similar to those described in [2] and [3]) when no field data are available (e.g. that is a standard condition in marine applications) and combine these results with a power generation system optimization problem. This problem is formulated considering as objective function both the management (i.e. the costs related to the fuel consumption) and the installation costs of specific sets of generators in order to allow the designer to select the cheapest and most efficient solution.

Due to the main characteristics of the problem, such as the non-linearity formulation of the objective and constraints functions and the use of integer or binary variables in order to model the possible sizes and generators scheduling, respectively, the problem has been defined as a Mixed Integer Non-Linear Programming (MINLP) [5]. In this perspective, the problem is modelled and solved in MATLAB's environment by applying Genetic Algorithms (GA) as solver. In fact, this solver allows adopting the previous formulation of the problem, instead of a linearization or decomposition of the problem in order to evaluate the solution. On the other hand, despite the truthful formulation, it is possible that the solution proposed by the solver is not the global minimum (i.e. the problem is not convex). Results of this combination between a stochastic approach to EPLA and optimization of the power generation system are the reduction of both the environmental footprint and of the design and management costs of the ships.

The paper is organized as follow: section II reports a description of the models proposed in order to perform an EPLA, section III presents the problem statement for the power system generation optimization. Finally, section IV reports the case study with the main results obtained applying the proposed methods and section V draws some conclusions.

II. APPROACHES TO THE ELECTRICAL POWER LOAD ANALYSIS

The main task of the EPLA is to calculate the total power required by the users on-board the ship in each main operative condition. The essential information in order to perform the EPLA using one of the methods here proposed (i.e. load factor, stochastic or simulative approach) are reported in Fig. 1, where the main results of this analysis are also shown (i.e. the possibility to select the power generation size, the energy storage characteristics, the machinery and cable sizes and, finally, to perform calculation on daily and yearly power required and the corresponding fuel consumption).

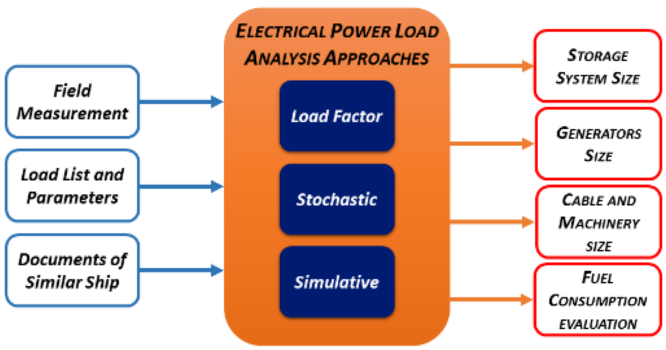

Figure 1. Inputs and results of EPLA

It is possible to state that the EPLA is one of the most critical phases in marine power system design due to its central position in the whole process. Due to the aim of this work, the simulative method to perform the EPLA is not presented. However, it is possible to confirm that this method is not suitable to be applied in preliminary ship design because of the high number of detailed information required in order to correctly model the shipboard power system [2].

A. Deterministic approach

The main information to perform an EPLA based on load factor analysis are (e.g. as already reported in Fig. 1) field measurements if are available, documents from similar ships and a load list as detailed as possible, which is necessary in order to consider and account the main characteristics of each electrical device installed on board. These are also useful information in order to identify the load factor corresponding to each device [2], [6]. The Load Factor (LF) is one of the most used factor in marine field in order to perform a load analysis. LFs are conventionally defined as in *(1)* and applied to each user in each ship operative condition.

$$LF_{ij}=\frac{1}{T_j \cdot P_{MAX_{ij}}}\int_0^T p_{ij}(\tau)d\tau \qquad (1)$$

where, LF_{ij} is the load factor for the i^{th} load considering the j^{th} ship operative condition, T_j is the reference time horizon for the j^{th} ship operative condition, $P_{MAX_{ij}}$ is the maximum power required by i^{th} load considering the j^{th} ship operative condition and $p_{ij}(\tau)$ is the instantaneous value of power required by the i^{th} user in the j^{th} ship operative scenario.

Multiplying the rated power of the i^{th} user with the load factors LF_{ij} corresponding to the j^{th} scenario it is possible to calculate its power absorbed in this condition. Further, in order to calculate the power required in each ship operative condition P_{abs_j}, it is necessary to add the power absorbed by each user (i.e. for all the N users installed on board) in each scenario, as reported in equation *(2)*. As a direct result, the total power required to generation is traditionally calculated as the maximum value of P_{ABS_j} (i.e. for $j=1, 2, \ldots, S$, where S is the total number of ship operative conditions considered).

$$P_{abs_j}=\sum_{i=1}^{N} LF_{ij}\cdot P_{nom_{ij}} \qquad (2)$$

This approach can be direct and straightforward to be applied, even in the early stage of ship design. Nevertheless, this is based on factors often assessed with information and data concerning dated ships. Additionally, these factors have been evaluated by applying the Central Limit Theorem [4]. Because of these reasons, this method is often conservative in demand power predicting.

B. Stochastic approach

This method is based on the assumption that it is possible to define a Probability Density Function (PDF) and a Cumulative Distribution Function (CDF) for each load installed on-board. In this perspective, the first step is to stochastically characterize each load (i.e. identify the stochastic variables that affect the behaviour of the electric users). In this work, three different categories for each user have been selected and implemented [2], [3]. The first category identifies loads that are always switched on or off in a specific ship operative condition. These, can be described through one single random variable (e.g. this describe the amount of electrical power absorbed by the load when it is switched on). The second category describes loads that cycle on and off, independently from other loads or configurations. This category of loads can be described through two random variables and it may present conditional probabilities. The first variable describes the amount of time the load is switched on. The second, on the other hand, account for the electrical power demanded by the user under exam in the operative condition considered when it is switched on. The latter category, describes loads that cycle on and off depending on the configuration or on the behaviour of other users. This category presents conditional probabilities.

Once each load has been characterized and the random variables are selected, in order to perform a statistical analysis, a PDF has to be chosen for each random variables. A Monte Carlo Simulation is then performed in order to calculate the PDF of the total power absorbed in each ship operative scenario. Furthermore, it is possible to consider the whole ship life as a time horizon of the analysis and so calculating the corresponding total power required by applying the total probability theorem to the previous PDFs.

In contrast with the deterministic method to perform an EPLA, the stochastic approach allows the designer to consider, from the early phase of design, some important aspects such as the maximum power absorbed by the users in each scenario, the probability distribution of power demand, modal value, mean value and allows to perform risk analysis and long term load predicting. On the other hand, the result of the traditional approach is merely a number identifying the value of total power absorbed by the loads.

In Fig. 2, the main steps of the stochastic EPLA are reported [2]. First, the input data are introduced and each load is statistically characterized. Then, the Monte Carlo Simulation method is performed in order to obtain the desired outputs (i.e. PDFs and CDFs for the total power absorbed by the loads in each ship operative scenarios) [7], [8]. After that, the results are compared with the selected reference values and, in case of excessive difference, the number of simulations is updated and the Monte Carlo process repeated until this condition is satisfied, as it is shown in Fig. 2.

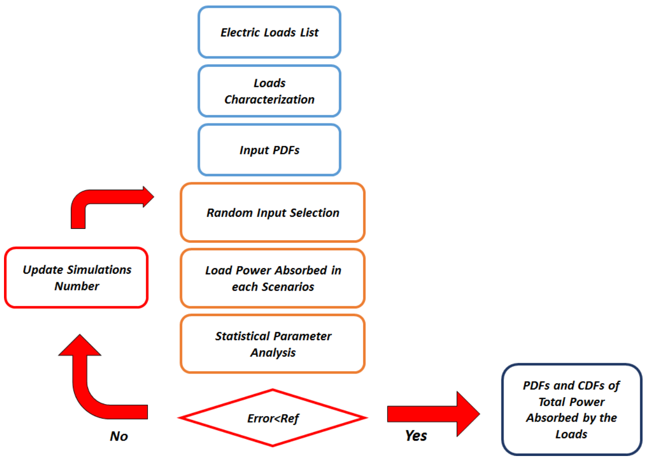

Figure 2. Stochastic EPLA with Monte Carlo Simulation

These kinds of resulting distributions are conditioned to the probability of occurrence of each ship operative conditions. Therefore, considering the events as independents and mutually exclusives, it is possible to "un-conditioning" them by applying the total probability theorem in order to calculate the power required along the reference time horizon as reported in equation *(3)*.

$$P_{X_{TL}}(x)=\sum_{j=1}^{N} P_{X_{Sj}}\left(x\middle|S_j\right)\cdot P_S\left(S_j\right) \qquad (3)$$

An example of the results available applying this methodology is here reported in Fig. 3, where the un-conditioned total load PDF and CDF are proposed for the ship chosen as case study in this work.

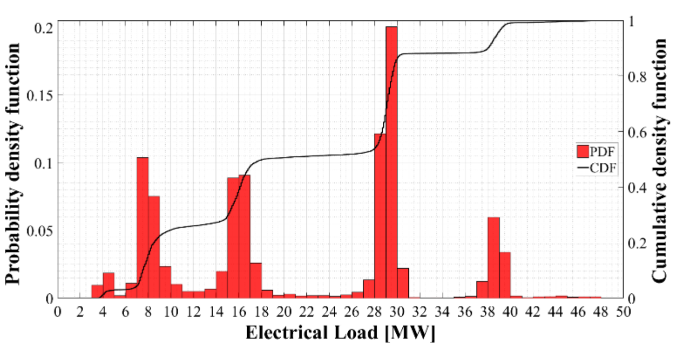

Figure 3. Typical PDF and CDF for the Total Load

It is possible to highlight that there are five points with significant probability (i.e. around 3, 8, 16, 29, 39 MW). These are strictly related with the load modal values in each ship operative scenario (e.g. shore, manoeuvring, cruising 10 kn, cruising 15 kn and crusing 20 kn) considered. In this context, the modal and mean values are useful inputs in order to select how many generators should be in service (i.e. scheduling problem) and how they are loaded in each scenario. The maximum value (e.g. close to 48 MW) and the percentile 95 value (e.g. close to 38 MW) are significant information in order to calculate the total power required to the whole generation system. In the sections III and IV, where the optimization problem is stated and applied to the case study, the information about the load distribution will be used as input data (e.g. reported in TABLE V).

III. Power Generator Optimal sizing and Scheduling, Problem Statement

In literature, several optimal problems have been presented in order to correctly size generators and energy storage systems [9]-[13]. The formulation proposed in this work is focused on the optimal generators sizing and management considering the operational and investment costs. An innovative aspect proposed in this work is the possibility to perform a stochastic EPLA and combine its results with the power generation system optimization. Furthermore, despite the fact that some works presented in literature, i.e. [6] and [9], are focused on the optimal generator sizing, in this work it is possible to select generators with heterogeneous or homogeneous sizes. Moreover, a formulation to calculate the installation costs is also proposed.

It is to be noted that this kind of approaches presents remarkable differences to the traditional methods used in marine power system design and management, despite in land application they could seem to be consolidated techniques. This is mainly due to the limited availability of data and measurements on board and to the nature of the ship design (i.e. almost every ship can be considered as a prototype). Furthermore, in ship design there are many sources of uncertainties such as the power required by each user (e.g. which depends on the nature of the user, on the passengers behavior, the weather conditions faced and so on), the power required by the propulsive motors (e.g. depending again on the weather conditions and on the scheduled time-table of the ship). In this context a stochastic approach to load prediction can be more effective than a deterministic approach (e.g. where the generation system is often oversized).

A. Objective function and problem's constraints

As already stated, the objective function of the constrained minimization problem accounts for both installation and management costs *(4)*, subject to generator operating limits constrains *(5)*, spinning reserve constrains in order to avoid black out risk *(6)*, power equilibrium constrain between the required and generated power *(7)*. Furthermore, in order to correctly manage each generator and select the best number of them to install, it is required that each one should be in function at least in a ship operative scenario *(8)*. Furthermore, it is good practice to guarantee the power required in each condition also considering the fault of one generator *(9)*.

$$\min_{P_R,u} \sum_{i=1}^{G} \left\{ \sum_{j=1}^{S} P_{ij} \cdot SFOC_{ij} \cdot T_j \cdot \frac{1}{\eta_{ij}} \cdot FC + (P_{R_i} \cdot C_{INST_i}) \right\} \quad (4)$$

Subject to

$$P_{ij}^{MIN} \leq P_{ij} \leq P_{ij}^{MAX} \quad (5)$$

$$\frac{\sum_{i=1}^{G} P_{R_i} \cdot u_{ij} - P_{LOAD_i}}{P_{LOAD_i}} \leq SR \quad (6)$$

$$\sum_{i=1}^{G} P_{ij} = P_{LOAD_j} \quad (7)$$

$$\sum_{j=1}^{S} u_{ij} \geq 1 \quad (8)$$

$$\sum_{i=1}^{G} u_{ij} \leq G - 1 \quad (9)$$

where, P_{ij} is the power supplied by the i^{th} diesel generator in the j^{th} operative condition, as defined in equation *(10)*, $SFOC_{ij}$ is the i^{th} diesel generator specific fuel oil consumption considering the j^{th} operative condition, T_j represents the reference time horizon for the j^{th} ship operative condition, η_{ij} accounts for the i^{th} diesel generator efficiency and FC is the unit fuel cost. Finally, C_{INST_i} identifies the i^{th} diesel generator monthly installation cost *(11)* weighted over a ship life period (i.e. 25 years).

$$P_{ij} = P_{R_i} \cdot u_{ij} \cdot GLF_{ij} \quad (10)$$

$$C_{INST_i} = C_M + \frac{C_m - C_M}{P_{GEN_{Max}} - P_{GEN_{Min}}} \cdot (P_{R_i} - P_{GEN_{Min}}) \quad (11)$$

where, P_{R_i} is an integer variable belonging to a discrete domain based on real commercial sizes for diesel generators. This set of possible sizes of diesel generators is defined between a minimum value $P_{GEN_{Min}}$ and a maximum $P_{GEN_{Max}}$. In addition, C_M and C_m are their related specific installation costs, respectively set equal to 500 \$/kW and 350 \$/kW. The binary variable u_{ij} represents the generator operating states (i.e. $u_{ij} = 0$ when the i^{th} generator is off in the j^{th} scenario and $u_{ij} = 1$ otherwise). Further, GLF_{ij} is the i^{th} diesel generator working point in the j^{th} operative condition *(12)*.

$$GLF_{ij} = \frac{\sum_{i=1}^{G} P_{R_i} \cdot u_{ij}}{P_{LOAD_j}} \quad (12)$$

B. Problem's parameters

In order to define the $SFOC_{ij}$, a fifth order polynomial approximation has been applied and it is shown in Fig. 4. On the other hand, considering the generator efficiency η_{ij}, in this case, an exponential approximation has been adopted. Furthermore, the unit fuel cost *FC* has been selected equal to 660 $/t [6], [9] and in Table I, the main parameters used in this work for the Genetic Algorithms (GA) are reported.

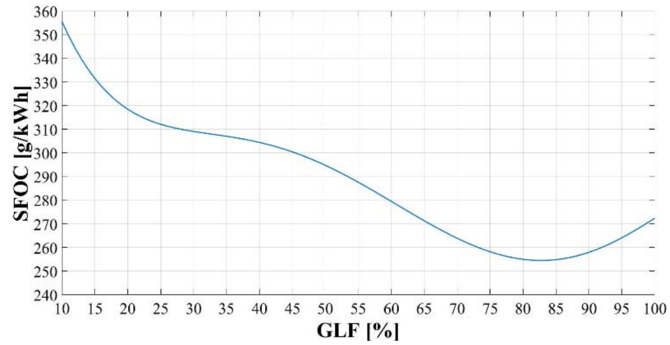

Figure 4. Specific Fuel Oil Consumption Curve [6],[1]

TABLE I. MAIN PARAMETERS USED TO SET THE GA

Crossover rate CR	Elite Count EC	Population number PN
0.55	0.00625 x PN	800

In section IV, results from the deterministic and stochastic approaches will be used as information for the optimization problem in order to compare the cost of each approach and design configuration.

IV. CASE STUDY

In this work, a large cruise vessel with electric propulsion system has been selected as case study. For this ship, the two proposed approaches in order to perform the EPLA are applied and the optimization problem to identify the optimum scheduling of the diesel generators is solved.

A. Input parameters and design conditions

The case study ship main characteristics, such as the number of diesel generators installed, their rated power and the resulting Installation Costs (IC) calculated as in *(11)* are reported in Table II. It is to be noted that the IC are the monthly cost related to the selection of these diesel generators and not their global cost (i.e. which can be easily calculated multiplying the IC for the reference ship's life of 25 years). In Table III, the main results obtained applying the deterministic approach to EPLA are proposed, i.e. the power required (Pabs) in each scenario.

TABLE II. CASE STUDY DESIGN CHARACTERISTICS

Diesel Generators Installed (DG)	6
DG Rated Power [kW]	12600
Installation Costs (IC) [$]	99600

TABLE III. RESULTS OF THE DETERMINISTIC EPLA

Scenarios	Shore	Maneuvring	Cruising 10kn	Cruising 20kn	Cruising Max
Pabs[kW]	17920	33208	31228	43158	62898

Considering the design scheduling reported in Table IV, over a defined mission of a month (e.g. 720 h) together with the cost of the fuel set to 660 $/t, he Mission Costs (MC) results equal to 4793200 $. This cost is to be considered in addition to the IC for the six diesel generators, resulting in a Total Cost (TC) of 4892800 $.

TABLE IV. DESIGN SCHEDULING

Scenarios	Shore	Maneu vring	Cruising 10kn	Cruising 20kn	Cruising Max
Time Horizons [h]	155	5.2	52	168	339.8
Scheduling	G1-G2	G1-G2-G3	G3-G4-G5	G3-G4-G5-G6	All gen.
GLF	71.1 %	87.9 %	82.6 %	85.6 %	83.2 %
SFOC [g/kWh]	278.5	255.5	256.5	258.7	255.5

These conditions are considered as a baseline condition (i.e. to allow a comparison between the proposed approaches) in the following analysis. It is to be highlighted that, the time horizons for each ship operative scenario have been keep constant in each optimization. The optimization problem is solved considering six diesel generators of the same (i.e. Homogeneous) or with two possible different sizes (i.e. Heterogeneous). In order to compare results from the deterministic and stochastic approaches to EPLA, the optimum problem is here solved for both the methods. In this perspective, in Table V, the modal values obtained applying the stochastic approach to EPLA to the case study are proposed for each ship operative scenario under exam.

TABLE V. STOCHASTIC EPLA MAIN RESULTS

Shore	Maneuvring	Cruising 10kn	Cruising 20kn	Cruising Max
9156 kW	10600 kW	14360 kW	17750 kW	31630 kW

Once each input data has been set, it is possible to perform the optimization. The optimal size and scheduling of the diesel generators, considering the ship's main operative condition are proposed and commented together with the resulting costs (e.g. installation and management costs).

B. Simulation conditions, results and comments

In Table VI a scheme of the four simulation conditions is proposed. As already stated, the design conditions proposed in Tables II-IV are considered as a base line condition to allow a comparison with the results from the optimization. In order to verify the goodness of the optimization algorithm, this is applied to the case study ship adopting as inputs the information obtained from the deterministic approach to EPLA (i.e. the same conditions used by the designers to select the generators' size and scheduling). This optimization is performed for both homogeneous and heterogeneous sizes of the diesel generators.

TABLE VI. SIMULATION SUMMARY AND CONDITIONS

SIMULATION	EPLA APPROACH	SIZING APPROACH
A	Deterministic	Homogeneuous
B	Deterministic	Heterogeneous
C	Stochastic	Homogeneuous
D	Stochastic	Heterogeneous

To allow a comparison between the deterministic and stochastic approaches, the optimization problem is solved also for the latter with both homogeneous and heterogeneous sizes of the diesel generators.

1) Simulation A

As specified in Table VI, the simulation A considers as inputs the information obtained by the deterministic approach to EPLA (e.g. reported in Table III). The results of this optimization are reported in Table VII, where six generators of 10.8 MW are considered instead of six generators of 12.6 MW (e.g. the base line condition). In table VII the solution to the scheduling problem is also proposed, reporting which generator (G) must be switched on in each operative condition. Furthermore, generator load factor (GLF) in percentage of their rated power (i.e. dispatch problem) and their specific fuel oil consumption (SFOC) are reported in Table VII for completeness.

TABLE VII - OPTIMIZATION RESULTS FOR THE DETERMINISTIC APPROACH TO EPLA - HOMOGENEOUS SIZES

	Shore	*Maneuvring*	*Cruising 10kn*	*Cruising 20kn*	*Cruising Max*
Sched.	G3-G5	G1-G3-G4-G5	G2-G3-G4-G5	G1-G3-G4-G5	G1-G2-G3-G4-G6
GLF [%]	83.0%	76.9%	72.3%	86.1%	79.9%
SFOC [g/kWh]	256.0	259.2	263.8	255.5	257.2

The MC obtained are equal to 4756000 \$, the IC to 89600 \$ with a TC of 4845600 \$ per month. The total saving is pointed out by this solution are 1% on the costs and 14% on the installed power.

2) Simulation B

In simulation B the same information used in simulation A are considered but, on the other hand, heterogeneous sizes of the diesel generators are allowed. The optimal solution considers three generators of 9.37 MW and other three generators of 10.8 MW. The MC are equal to 4748600 \$, the IC to 90800 \$ and the TC are equal to 4839400 \$. A possible saving close to 2% compared to the total design costs and 20% of the installed power are highlighted. In Table VIII, the solutions to the scheduling and dispatch problems are proposed.

TABLE VIII - OPTIMIZATION RESULTS FOR THE DETERMINISTIC APPROACH TO EPLA - HETEROGENEOUS SIZES

	Shore	Maneuvring	Cruising 10kn	Cruising 20kn	Cruising Max
Sched.	G2-G4	G1-G2-G3-G4-G6	G1-G2-G3-G4-G6	G3-G4-G5-G6	G1-G2-G3-G4-G5
GLF [%]	88.8%	66.8%	62.8%	89.0%	86.8%
SFOC [g/kWh]	255.5	271.3	277.5	255.6	255.5

3) Simulation C

Simulation C considers as inputs the results obtained applying the stochastic approach to EPLA (i.e. reported in Table V). The solution to this problem proposes six generators of the same size (i.e. 9.37 MW), with MC, IC and TC equal to 3058200 $, 80600 $ and 3138800$, respectively. The possible monthly saving is close to 36.5% on the costs and 25.6 % on installed power. The scheduling and dispatch problem solution are proposed in Table IX.

TABLE IX - OPTIMIZATION RESULTS FOR THE STOCHASTIC APPROACH TO EPLA - HOMOGENEOUS SIZES

	Shore	***Maneuvring***	***Cruising 10kn***	***Cruising 20kn***	***Cruising Max***
Sched.	G3-G4	G1-G5	G2-G5	G1-G2-G5	G1-G2-G4-G6
GLF [%]	48.9%	56.5%	76.6%	63.1%	84.4%
SFOC [g/kWh]	298.7	287.7	259.4	277.1	255.6

4) Simulation D

Simulation D adopts as input the same of simulation C but allows heterogeneous sizes of the generators. The solution to this problem considers three generators of 9.37 MW and three of 9.6 MW. The MC, IC and TC are equal to 3059100, 81300 and 3140400 $, respectively. The possible monthly saving is close to 36.5% on the costs and 24.7 % on installed power . The solutions to the scheduling and dispatch problems are proposed in Table X.

TABLE X - OPTIMIZATION RESULTS FOR THE STOCHASTIC APPROACH TO EPLA WITH NON-HOMOGENEOUS SIZES

	Shore	***Maneuvring***	***Cruising 10kn***	***Cruising 20kn***	***Cruising Max***
Sched.	G2-G3	G4-G6	G1-G2	G1-G2-G3	G1-G2-G3-G5
GLF [%]	48.9%	55.2%	76.6%	63.1%	83.9%
SFOC [g/kWh]	298.7	289.9	259.4	257.0	255.7

The reductions in the power installed revealed in each simulation have some important benefits in terms of weight, complexity of the system, installation costs and Green House Gas (GHG) emissions reduction. As result of these analyses, the best possible solution (i.e. in cost perspective) is the one with the stochastic approach to EPLA and homogeneous size of the generators.

V. CONCLUSIONS

Due to the large development of full electric solutions for power generation and delivery on board ships, the need of an innovative and more effective approach to load prediction in design phase and during the operational life of the ships has been put in evidence. A stochastic approach for power demand prediction has been proposed and described. It was also compared with the traditional deterministic methodology applying both to a problem of optimization for the selection of power generators size. The solutions have been compared in terms of costs, which can be reduced by 36.5%, while the installed power can be reducing of 25.6%. The figure of the costs are to be considered representatives in a comparative perspective, the great advantages of the stochastic approach can be strongly perceived. In spite of these results, a further validation based on field measurements is required and, in this perspective, future improvements and studies will be focused on this validation.

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