DECISION SUPPORT SYSTEM FOR POWER GENERATION MANAGEMENT FOR AN 110000+ GRT CRUISE SHIP

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SUMMARY

The aim of this work is to provide a methodology for the power generation optimization on large cruise ships in order to improve their operating efficiency, fuel saving and, consequently, to reduce exhaust gas emissions. The electrical load analysis is compared to the machinery reports of actual data in order to investigate if the estimated required power is appropriately close to the real power demand. Relevance is given to the average load of the diesel-generators, which expresses an indication of how the generators work. The model of the ship electric distribution system represents one of the main objectives of this work along with the power system simulations. These were developed through the definition of load profiles, both by the onboard recordings and by machinery reports data. Therefore, the same cruise profile is analyzed under different scenarios, the real and the optimized one, in order to highlight the critical state of the system and any possible margin for improvement.

1. INTRODUCTION

There are around 70000 ships involved in the international trade, and this constitutes the 90% of the whole world trade [1]. Therefore, sea transport has a considerable attention for conducting its operations in a way that leads to a remarkably low impact on the global environment. In this context, the International Maritime Organization (IMO) has introduced two rules in order to further limit the gas emissions also through an improvement of the overall ships energy efficiency of the. Recently, among the IMO technical and operational measures, the Energy Efficiency Design Index (EEDI) has become mandatory for new ships [2]; the Ship Energy Efficiency Management Plan (SEEMP) has been introduced for all ships, both new and existing ones. Particularly, SEEMP is an operational measure, which establishes a mechanism to improve the energy efficiency of shipping operation, providing also an approach for shipping companies to manage ship and fleet efficiency performance on a long term, following a defined policy. The guidance on the development of the SEEMP includes also best practices for fuel-efficient operations of ships, in which some useful advices on energy management can be found, e.g. “a review of electrical services on board can reveal the potential for unexpected efficiency gains”. In addition, thanks to the development of on purpose computer software the optimization of operations, the establishment of improvement goals and the tracking of possible progress may all be considered as sound policies in in modern ship management.

Finally, it has to be stressed that renewable energy sources, such as: wind and solar (or photovoltaic) technology, have improved enormously in the recent years and they should be considered for onboard applications, even if these are not object of study in the present work. The fuel consumption reduction has always been one of the main drivers in ships management, since it is one of the main source of cost.

Cruise ships are characterized by reduced power requirement for a substantial portion of their operating time, being in “port” condition where no propulsion power is required. The energy management control used today in the marine vessel is fairly simple, mainly because of the relatively low number of units usually installed onboard and low variety of prime mover types and fuels used. The extensive knowledge in “inland” power generation and distribution has found limited use in the marine application, until now. While the methods of unit commitment [3], economic dispatch and contingency analysis [4] have been extensively used for decades in terrestrial power systems, their applicability to traditional shipboard systems has been limited.

Nevertheless, at least in principle, these methods may provide potentially a significant operational cost reduction, along with improvements in planning and intelligent handling of the power plant.

The ship under investigation in this work is a large cruise vessel, described by the following main characteristics:

- Gross Tonnage= 110000 GRT,
- Displacement = 57000 t,
- Length over all = 290 m,
- Draft = 8.3 m,
- Cruise Speed= 21.5 kn,
- Propulsion Power Installed = 42 MW.

2. ELECTRICAL POWER LOAD ANALYSIS

A cruise ship is characterized by the need to fulfill very high and uninterrupted requirements of electric energy for the hotel services (i.e. the lighting of restaurants and of all the entertainment spaces and, more important, the supply of the air conditioning of the cabins and of the spaces for passengers and crew). These requirements may reach the 40% of the total power supplied by the plant.

Beside a varied power request profile, an important characteristic of this ship typology is the need of a rigorous respect of the timetables, even in adverse sea conditions or in case of possible failure of one of the prime movers. In such conditions, thanks to electric propulsion system, it is possible to continue the navigation with possibly reasonable ship speed decrease.

2.1 ELECTRICAL LOAD BALANCE

As the literature shows [5], "the electrical load balance specifies the electric power requirements of the ship in the different operative conditions and it sets how to satisfy them, that is how to balance demand and generation". The electric system design begins with a list of the electric power users to be installed onboard [6], and this establishes the basis of the electric balance.

In these lists, users are divided depending on the service supplied. For a merchant vessel, and thus for cruise ships, these are usually divided as follows:

- Hull: deck + safety:
    - Deck: rudders, capstans, winches, and so forth.
    - Safety: auxiliary of navigation, radar, gyrocompass, log, depth recorder, anti-fire pumps, stabilizers, radio-communications.
- Cargo: winches, cranes, elevators, auxiliary boilers and refrigerators for cargo, cargo pumps for tanks.
- Engine room: electric auxiliaries of engine system and generator sets, auxiliaries for unloading-loading of engine room liquids.
- Hotel: conditioning + galley + room:
    - Conditioning: chillers and heaters, fans and extractors for conditioning and ventilation of spaces.
    - Galley: galley auxiliaries, pantry, bar, ice chambers, elevators.
    - Room: personal hygiene, washing, drinking water pumps, laundries, lifts, cinemas and entertainment plants.
- Light: normal and emergency light, inside and outside of engine room spaces.

The electric load analysis of this Cruise ship [6] has been done characterizing the users into the eight groups as mentioned above and eight main operational conditions as follows. In this contest, for each group of users, some considerations are to be done:

- Hull and deck service; in this case the power demand is significant only in maneuvering condition.
- Safety service; the power requirement can be assumed almost constant around 200 kW and it is quite negligible compared with the power demands of other groups of users.
- Propulsion service; this is the most onerous demand of power and varies principally according to the speed.
- Engine service; the power requirement of this service is quite constant; in this group, there are all the auxiliaries for the propulsion and also for the other systems onboard except for air conditioning service.
- Air conditioning service; primary importance for Cruise ships, this power requirement can be considered fairly constant.
- Galley service, the demand of power is quite constant.
- Accommodation service; it can be considered constant compared to the whole power demand in each condition.
- Lighting service; as the previous one, it can be considered constant for the same reasons.

No considerations are made about Emergency condition because it is a very important and specific topic, out of the aim of this work.

Ship operational conditions have to be identified in order to calculate the average electrical power demand of each service. Typically, for a merchant vessel it is possible to define the following main conditions:

- Continuing operative conditions during navigation:
    - At Tropics.
    - At the Equator or during the summer.
    - With cold temperatures or in the winter.
    - In narrow water.
- Continuing operative conditions during stops o in port, normal:
    - In port, unloading or loading.
    - In port, at works.
    - In the road.
- Occasional operative conditions
    - Engine plant starting.
    - Maneuvering.
    - Fire emergency.
    - Flooding emergency.

Generators are sized considering the worst combination of the former conditions (i.e. worst ship operating scenario) as reported in *(1)*.

$$P_{gen} = MAX(P_{cruising\ summer}, P_{cruising\ winter}, \ldots\ldots, P_{port}) \tag{1}$$

In the case of cruise ships, due to their typical activities, significant required power fluctuations at different hours, with peak situations, might happen.

2.2 CRITICAL ANALYSIS OF MACHINERY REPORTS DATA

The aim of this analysis is to compare the available data derived from the machinery reports with the theoretical electric balance, in order to investigate the possible difference between them. In this context, it will be possible to asses if the estimation of the required power, performed at the design stage, results close enough to the real demand or it is significantly different, by defect in the worst case (i.e. in a safety point of view).

Before analyzing the machinery reports data, some considerations are necessary about the electrical loads analysis, for a consistent comparison. Firstly, in the theoretical electrical load analysis just two "port" conditions are evaluated (i.e. Summer and Winter), whereas the introduction of another "port" condition can be helpful to better compare the results (i.e. in Spring and Fall). This has been done assuming that the required power value in the "spring/autumn port" condition is simply the arithmetic mean between the power required by the "summer port" and "winter port" conditions. The definition is based on the assumption that external temperatures in middle seasons are an average between summer and winter ones and that HVAC (i.e. Heating, Ventilation and Air Conditioning) system is of primary impact on the electrical load balance. Then an assumption on the "navigation" conditions is made. In this work only the "navigation at 20 kn condition" is considered; being 20 kn the ship speed modal value, derived from onboard data record systems.In order to comply with such hypothesis, firstly, the examined conditions information have been divided into two main parts:

- "Propulsion", which provides only for the thrust on the propellers because these are the most onerous users in term of power onboard.
- "Hotel", as the difference between the total electric power supplied and the "Propulsion" power. Therefore the term "Hotel" does not refer here only to the traditional hotel services (i.e. air conditioning, galley, accommodation services), but also to the other group of users, such as hull and deck, safety, lighting and engine services.

Concerning the machinery reports data [7], firstly reports of the twenty cruises in nearly two years (from July to May of the second year) were analyzed, with focus on:

- Routes of the cruises.
- Dates/Seasons of each cruise.
- Hours per route.
- Ship average speed.
- Load on the propulsion motors.
- Total electrical energy demand.

Before showing the results of this analysis, an essential consideration about the comparison of the data in "navigation" condition has to be done. Because the ship speed varies between 13 kn and 21 kn, while in the theoretical electric balance there is only the "navigation at 20 kn" condition, in order to compare homogeneous data a correction has been done. An analysis on the power required for propulsion is carried out [8] on the same ship, considering different weather scenarios. As an example of this analysis, actual data and the corresponding polynomial curve are shown in the following Figure 1.

With an acceptable approximation, as evidenced in Figure 1, the propulsion power (*P*) has been modeled as a polynomial cubic curve in terms of speed (S). As a result, it is possible to evaluate the value of the power at desired speed:

$$P = AS^3 + BS^2 + CS + D \qquad (2)$$

The coefficients *A, B, C* and *D* were calculated trough the previous analysis [8] in different weather conditions (e.g. Beaufort number between 1 and 12). Then they were applied to obtain the power required for the propulsion of the ship at different speed values between 13 and 21 kn. Finally, this propulsion load was added to the "hotel" load, assumed independent from the ship speed, in order to obtain the total electrical load.

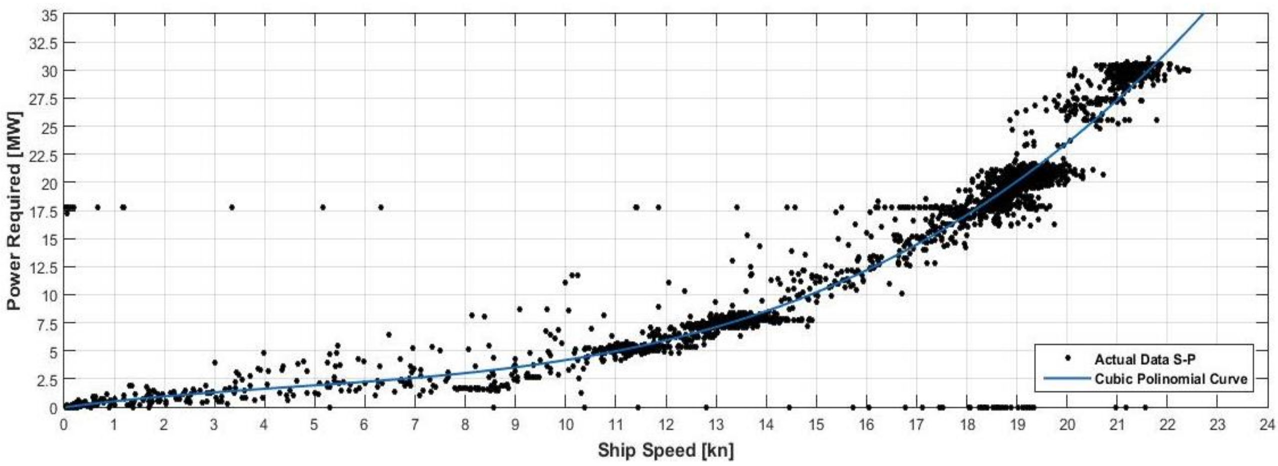


Figure 1: Actual data for the power required by propulsion (P) depending on the ship speed (S) in "calm weather" condition and corresponding polynomial cubic curve [8]

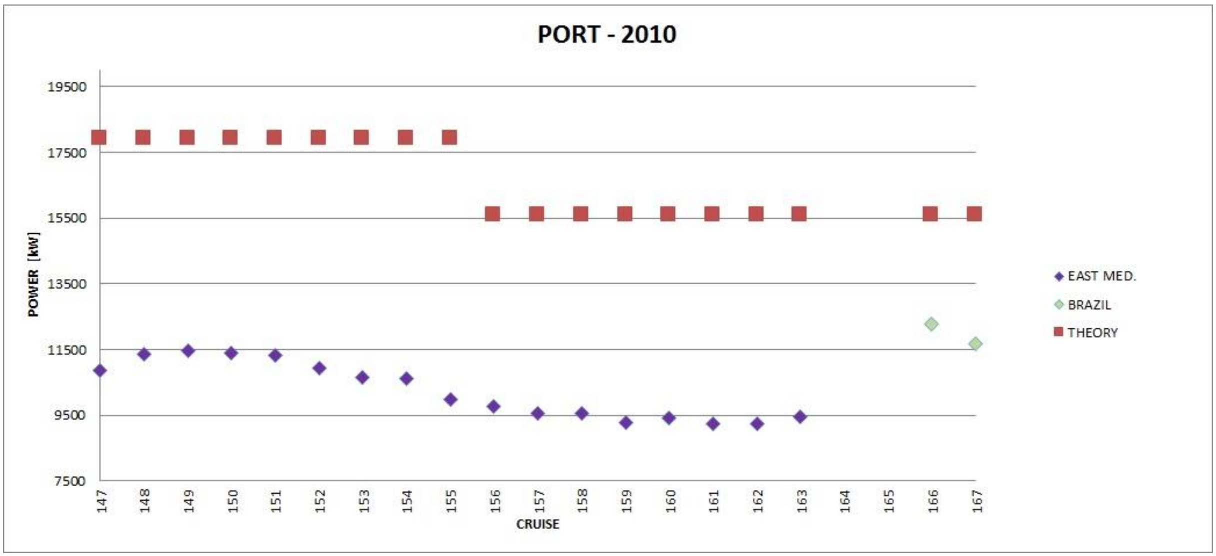


Figure 2: Comparison between the machinery reports data and the electrical load analysis (theory) for different cruises during the first analyzed year

Figure 2 shows, for each cruise, the comparison between the data obtained from the machinery reports and the data from the theoretical electrical load analysis, in "port" condition (this is the most truthful condition being the only one where no propulsion load is present, so no correction is necessary).

The "step" in the values of the theoretical data is due to the season's change, In the report data there is no this abrupt step but a smoother influence of seasons can be evidenced (the cruises started in July and finished in December).

It can be noted that, both in winter and in autumn/spring, the theoretically estimated power demanded is rather precautionary: indeed, there is a difference of about the 50% over the real power demand. The same results are found for the 'maneuvering in and out' conditions, but this is a very difficult situation to be predicted in advance and in such case a large amount of margin is also due to safety perspective.

The following Figure 3 shows the comparison between the machinery reports data and the electrical load analysis in 'navigation' condition. It is evident the distinction between the average ship speed and the reference value of 20 kn for each cruise. The red circles represent the hypothetical power if the ship sails at 20 kn, to be compared with the black squares, that represent the theoretical power derived from the electrical load analysis. In such condition the required power estimated at the design stage, is quite close to the real demand. Moreover, the years under investigation present some technological improvements carried out by the ship-owner.

It was noted that the power required by the users in the last year of the range under analysis has been strongly reduced by about 3 MW. This is in agreement with the improvements [9] in:

- Introduction of Led technology.
- Installation of inverters on ventilation and exhaust fans, on conditioning stations and machinery auxiliary pumps.
- HVAC whole systems.

This has led to a significant reduction in the power demand and consumption, especially in 'port' conditions.

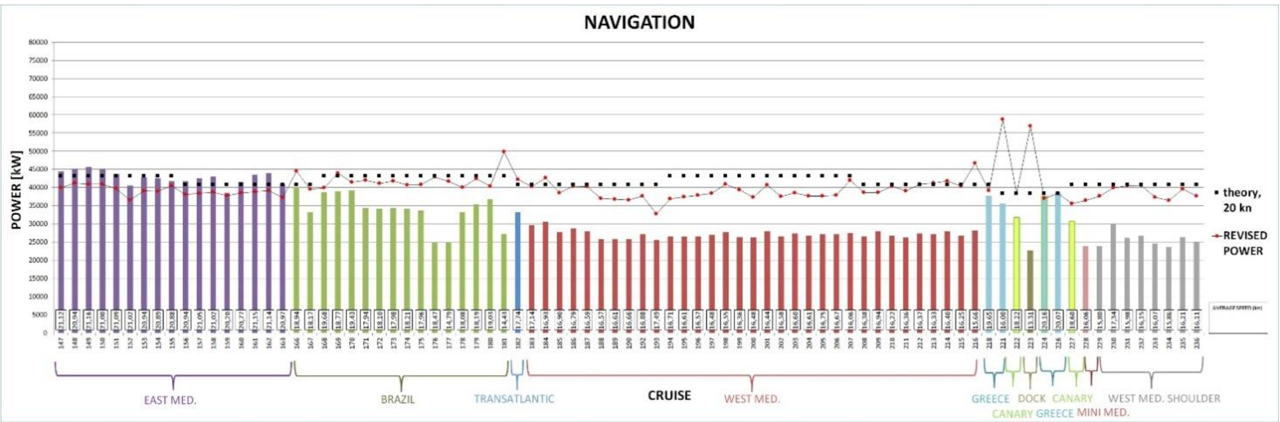


Figure 3: Comparison between the machinery reports data and the electrical load analysis in navigation condition, along the different investigated years

Such improvements have implied a significant impact also on the overestimation of required power evidenced in the 'port' condition.

A great incentive in the direction of energy efficiency and fuel savings was the increment of fuel cost of some years ago. Moreover, with the introduction of new environmental rules regarding the 'port' condition, the MGO (Marine Gas Oil) instead of IFO 380 (Intermediate Fuel Oil) is to be used for diesel generators, being the former less polluting than the second one, even if more expensive. Concerning the 'maneuvering' conditions (i.e. maneuvering in and maneuvering out), the estimated required power seems to be again over-sized, but due to safety implications, no considerations are made on this aspect. In 'navigation' condition, the real power required by the users is quite close to the theoretical one, hence evidencing a good approximation in demand power estimation (this is due to the electrical load analysis method described in 2.1, in which the generators are sized in relation to the worst condition, in this case the 'navigation' one).

3. POWER GENERATION OPTIMIZATION

The machinery reports provide some interesting information regarding the average percentage of load-ability of the six main diesel generators in equation (3) and, in addition, the average percentages of load for each of them [5] weighted on the operation hours of the examined unit (4).

For sake of clarity of the following formulations, it is to be mentioned that a "cruise" gathers the sequence of several routes, which in turn are the single route from one touristic location to the following one. Then, each routes is also divided in the ship operative conditions reported above.

$$\%LOAD_{D/G_i} = \frac{\sum_j \left[h_{i,j} \cdot \%LOAD_j\right]}{\sum_j h_{i,j}} \qquad (3)$$

Where:

- $\%LOAD_{D/G_i}$ is the average percentage of load-ability referred to the i-th diesel generator.
- hi,j is the operating hours of the i-th diesel generator during the j-th scenario of the route.
- $\%LOADj$ is the average percentage of load referred to the j-th scenario of the route.

The average percentage of load referred to the j-th cruise is then calculated as:

$$\%LOAD_j = \frac{kWh_{end,j} - kWh_{start,j}}{\sum_i (h_{i,j} \cdot P_{nom,i})} \qquad (4)$$

Where:

- $kWh_{start,j}$ is the energy (kWh) supplied by the system, measured at the end of the j-th cruise.
- $kW_{end,j}$ is the energy (kWh) supplied by the system, measured at the beginning of the j-th cruise.
- $P_{nom,i}$ is the nominal power of the i-th diesel generator, expressed in kW.
- hi,j is again the operating hours of the i-th diesel generator during the j-th scenario of the route.

Hence, this average percentage of load (3), in reference to the j-th cruise, considers the ratio between the total energy (kWh) supplied by the system and the available one. This considering the generators running at their nominal power. It is to be noted that the average load-ability in (3) is calculated for each generator. On the other hand, the average percentage of load (4) regarding the j-th cruise is constant for every diesel generator.

Figure 4 shows the average percentages of load-ability for one diesel generator (i.e. D/G1 since this can be considered representative of the behavior of the others diesel generators), weighted on the time of the cruise, for every cruise from January to May of the same year. The same is done also for the other years.

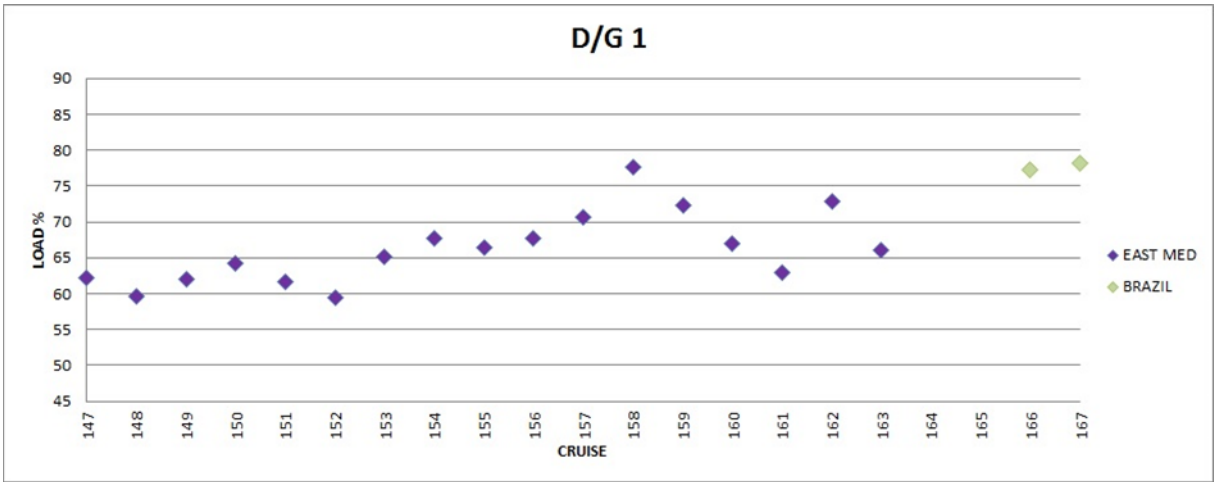


Figure 4: Average percentages of load for generator 6 in 2012

3.1 SHIP NETWORK MODEL

A simplified model of the ship network has been developed in order to properly analyze the electrical behavior of the system in terms of power flows and voltage profiles. The model is able to account for electrical losses in both transformation and distribution. The main starting documents for the analysis are:

- "One line schematic wiring diagram" [10].
- "Propulsion system-one line diagram" [11].
- "Electrical load analysis" [12].

Analyzing these documents, two levels of distribution are identified: the Medium Voltage (i.e. 11 kV), and the Low Voltages (i.e. 440 V, 230 V and 115 V at 60 Hz) [13]. Concerning the medium voltage distribution, at 11 kV, the following components have been implemented in the model:

- Six Diesel-generators, 12600 kW each, equally divided between two main switchboards: hence, there are three generators at the port main switchboard and three generators at the starboard main switchboard as shown in Figure 5.
- Two propulsion electric motors, with nominal power of 21 MW each, with their exciting systems, transformers and synchro-converters, one for each switchboard.
- Six thrusters, 1720 kW each, three of them are bow thrusters while the remaining are stern thrusters. They are equally divided between the switchboards.
- Four compressors of air conditioning, 1575 kW each, equally divided between the switchboards.

In addition, from these main switchboards, the connections to the low voltage distribution branch off through transformers. Concerning the low voltage distribution, the following substations are found:

- Engine room substation, port section.
- Port ventilation-auxiliary service section.
- Galley substation.
- Laundry substation.
- Entertainment substation.
- Accommodation substations 1 to 7.

Considering the huge amount of users present onboard, the complexity about the connection among them (e.g. the "Accommodation substation 1", which is referred only at the main vertical zone number 1, includes more users than those strictly stated in the section "Accommodation service" in the electrical load analysis) a simplified distribution diagram has been chosen and implemented. The aim of this simplification is to remain faithful as much as possible to the original diagram, while following the simplest method of grouping of users, especially for the low voltage ones.

Concerning the users at medium voltage, some assumptions have been made:

- The two motors for electric propulsion identify the group named "Propulsion service". This is a good approximation since in this group the propulsion electric motors are the main users in terms of required power. [14]
- The four air conditioning units identify the group "Air conditioning service", which includes both the air conditioning compressors and all the 'AHU' (i.e. air handling units).

Concerning the users at low voltages, the following aggregated users have been considered [15]:

- Engine service (at 440 V). In the simplified diagram, this group is divided into two parts, i.e. engine room substation port and engine room substation starboard. It includes the original engine room substation (port and starboard sections), engine room substation spare section, engine room substation (port and starboard) ventilation-auxiliary service sections.
- Galley (at 440 V).
- Accommodation (at 440 V): this group includes the original laundry, entertainment and accommodation substations (from 1 to 7).
- Lighting.

In Figure 5 the network diagram is shown. A ship operating in its standard conditions is considered in this model [16]. Therefore, the double connections of the two propulsion electric motors to the main switchboards have been considered (e.g. the port propulsion electric motor is normally connected both to the port main switchboard and to the starboard main switchboard and vice versa). This is because each switchboard supplies half of the two motors. Hence, for instance, in case of failure of the port switchboard, the starboard generators can supply half of the starboard motor and half of the port motor.

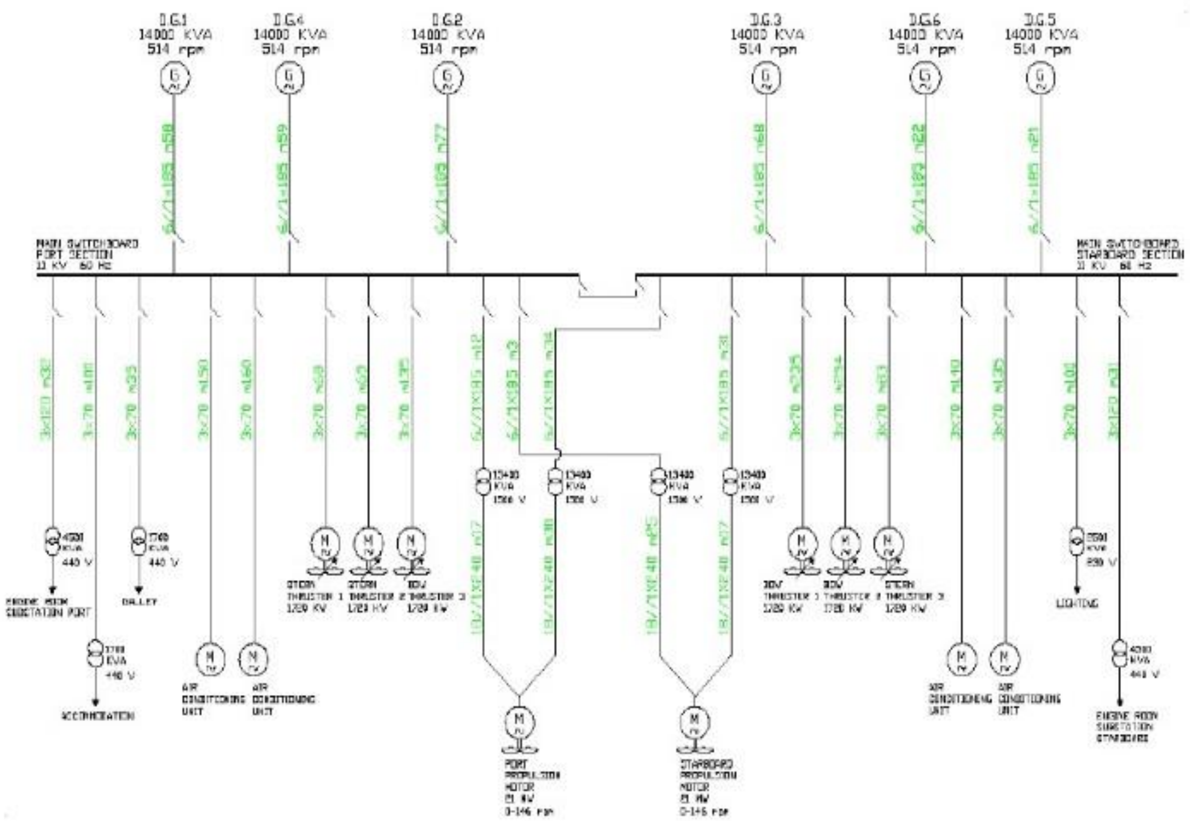


Figure 5: Model scheme of the network

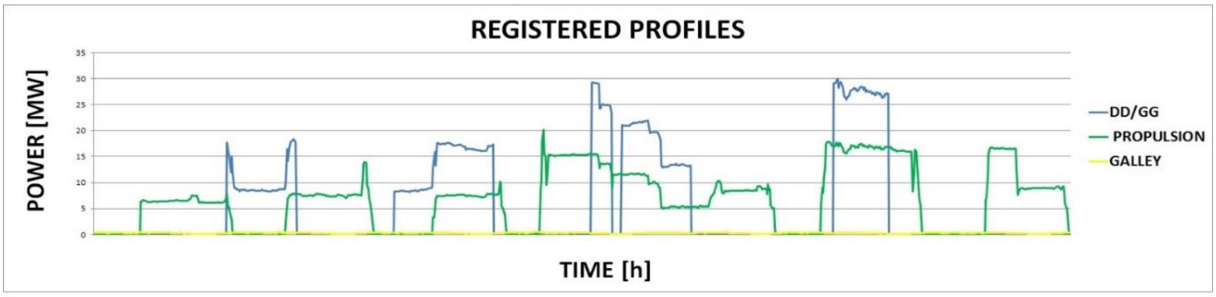


Figure 6: Propulsion load profiles recorded

With this configuration, it is possible to ensure that the failure of any component allows the propulsion to be, at least, at the 50 % of the power required in normal condition, as requested by the rules [17].

3.2 LOAD MODEL AND PROFILES ACQUIRED FROM SCADA

The power generation management is analyzed through the load profiles of a particular cruise, which are gathered from two different sources:

- Machinery report data [18] and theoretical load analysis, these will lead to "theoretical" profiles.
- Records made on board [19], these will lead to "real" profiles.

The registrations made on board, with a frequency of ten minutes, regarded:

- The power generation of the six diesel-generators [MW].
- The voltage, both for the six diesel-generators and the port propulsion electric motor [kV].
- The current of the two propulsion electric motors and the "galley" user [A].

For what concerns the power supplied to the system each diesel-generator has its registration. Therefore the total power generation supplied to the system at time t' can be found as the sum of power generations of each diesel-generator. In order to deduce the whole generation profile, firstly the behavior shown in Figure 6 has been considered, which shows the generation power throughout the intervals of time where the "propulsion" load profile and the "galley" load profile are globally defined. Secondly, it can be noted that the "hotel" power profile can be easily expressed as in equation (5):

$$P_{HOTEL} = P_{GEN} - P_{PROP} - P_{GALLEY}\ [MW] \quad (5)$$

Where:

- P_{HOTEL} is the "hotel" power value [MW].
- P_{GEN} is the power generated by the diesel-generators [MW].
- P_{PROP} is the "Propulsion" power [MW].
- P_{GALLEY} is the "Galley" power [MW], two average values of "hotel" power can be found:
- $P_{HOTEL\ PORT}$ is the average "hotel" power, during the "port" operative condition [MW].
- $P_{HOTEL\ NAV}$ is the average "hotel" power, during the "navigation" operative condition [MW].

In addition, it is put in evidence in equation (6) that:

$$P_{HOTEL,NAV} > P_{HOTEL,PORT} \quad (6)$$

This is because, in "hotel" profile, it is included for practical reasons also the engine service, as already explained. Hence, this group will require an increase of power demand simultaneously with the increase of the propulsion power. Adding these average values of "hotel" power to the intervals where only the "propulsion" and "galley" load profiles are known makes it is possible to find the whole 'generation' profile. Hence, where the power generation was unknown, it has been approximated by adding an average value for the 'hotel' amount to the known values of 'propulsion' and 'galley'.

Figures 7 shows the 'hotel' load profile, derived as explained above (i.e. the whole load profile subdivided in 'propulsion', 'galley' and 'hotel' load profile; and the 'generation' profile).

Then, the average values of the 'generation' profile have been calculated for each operative condition during the cruise, in order to compare them with the values of the machinery report. In this context, the percentage error has been calculated as in equation (7).

$$\varepsilon = \left| \frac{P_{MRD} - P}{P_{MRD}} \right| 100 \quad (7)$$

Where:
- P_{MRD} is the power from machinery report [MW].
- P is the power from the registrations [MW].

A low error was observed for the 'port' and "navigation" operative conditions. As consequence, in the time intervals where the power generation was unknown the approximation can be considered efficient. On the other hand, the error can be significant in the 'maneuvering' conditions. Indeed to find an average value of 'hotel' during the 'maneuvering' conditions (which include the use of the thrusters) is very difficult for many reasons, the main being:

- Port layout.
- Weather conditions, especially in terms of wind.
- Master's training and expertise.

Figures 7: 'Hotel' profile, Generation profile divided in 'hotel', 'propulsion' and 'galley', compared to the average values of machinery report and Generation profile

In addition, for ineluctable safety reasons, the maneuvering is usually made with one or two diesel-generators more than the necessary. Moreover, this is a very transitory condition compared to the others and it might be not advantageous to focus on its optimization. Therefore, the percentage error is at least tolerable.

Finally, as already done for the "theoretical" load profiles, an internal subdivision can be done among the hotel" services users, thanks to the theoretical electrical load analysis. Then, the average percentages of load for each diesel-generator have been evaluated considering their operative hours (3), in order to compare them with the same values reported in the machinery reports. Even in this case a percentage error δ has been calculated with the equation (8).

$$\delta = \frac{Load\%_{MRD}\text{-}Load\%}{Load\%_{MRD}} \qquad (8)$$

Where:

- $Load\%_{MDR}$ is the load percentage from machinery report.
- *Load%* is the load percentage from the registrations.

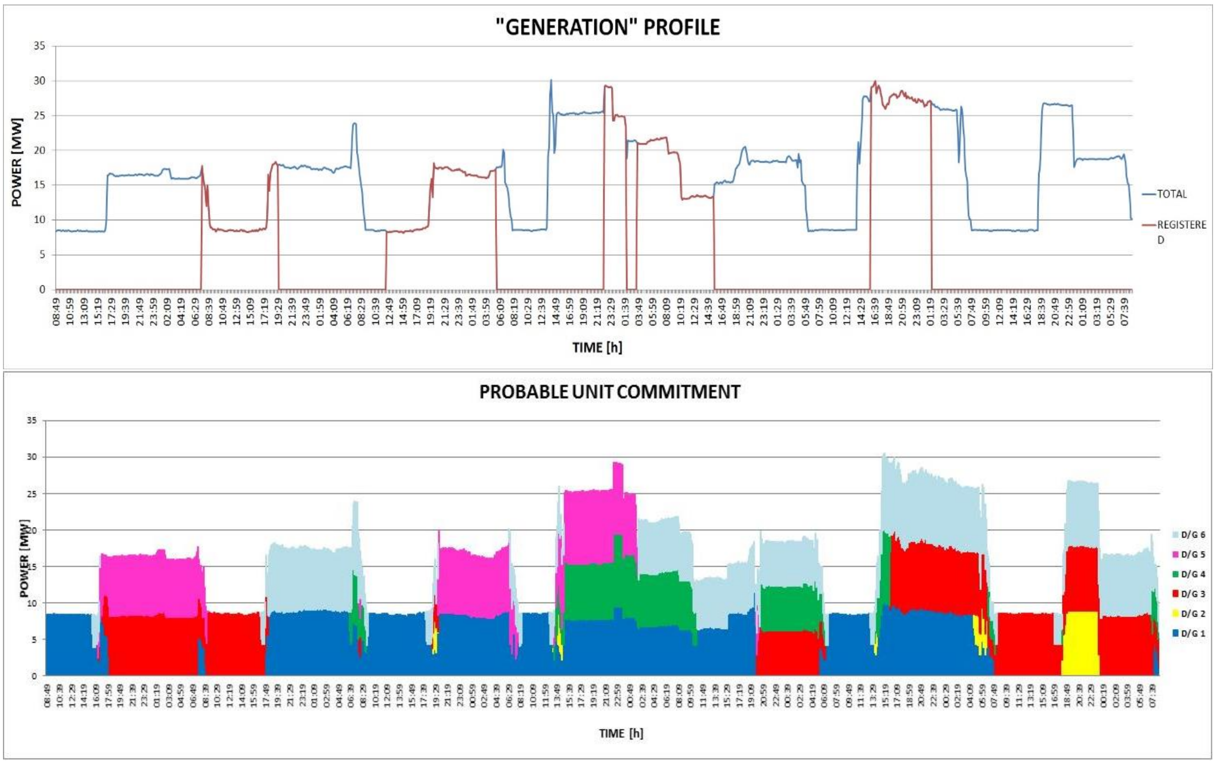
This percentage error is quite limited. Considering the complexity of the problem and the aim of this work, it can be assumed as a good model. The following Figures 8 shows the 'generation' profile with the original recorded one in evidence and the relevant unit commitment.

3.3 COST CURVE FOR OPTIMIZATION

From the technical guide of the diesel engines [20], a typical specific fuel oil consumption curve (sfoc) at constant speed can be assigned. The following Figure 9 shows the actual values compared with the theoretical curve derived from the engine project guide. Hence, in order to take into account the real trend, a tuning of the curve with available data is carried out as follows:

- The difference between the sfoc real value and the theoretical one at the same load has been evaluated.
- A double rigid translation of the theoretical curve over the real values in 'port' and 'navigation' conditions is made.

The following simulations involve as input the 'cost curve' concerning the generators data. This cost-curve is obtainable by the specific fuel oil consumption curve and from hypothesis on the cost per fuel ton of fuel, it is possible to obtain the cost curve.



Figures 8: 'Generation' profiles with focus on the original recorded profile, Probable unit commitment

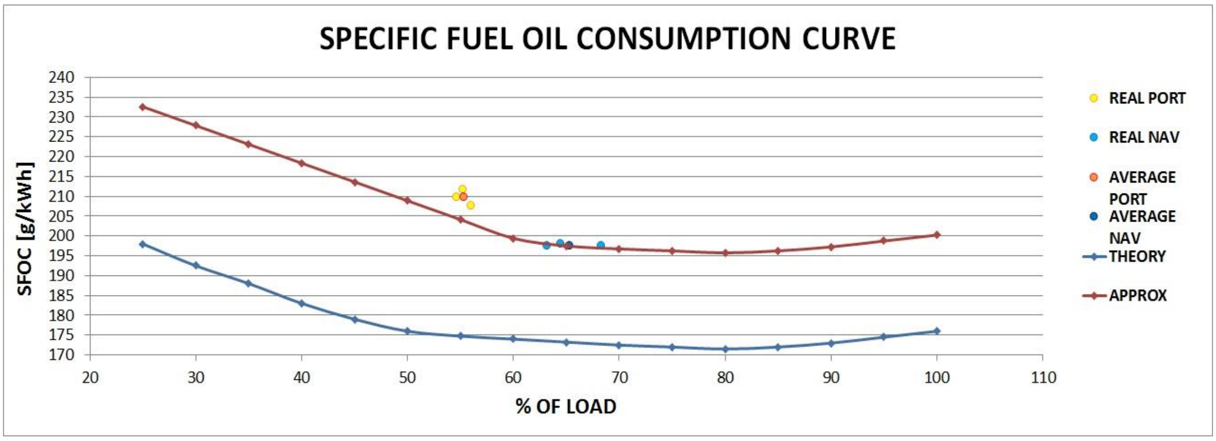


Figure 9: Difference between the real data and the theoretical curve; rigid translation of the theoretical curve through the two average points of sfoc; calibrated and theoretical sfoc curves

Two different prices per fuel ton have been assumed, in order to evaluate the different cost between the intermediate fuel oil (IFO 380) and marine gasoil oil (MGO). This is due to the fact that in port the diesel engines must be fed with MGO, which is less pollutant but more expensive than IFO 380. Hence, two average costs are defined, based on the following average prices of the bunkers:

- 600 USD/t for IFO 380.
- 1000 USD/t for MGO.

Actually, both prices can be subjected to significant fluctuation along the years and especially in this recent period values are significantly lower. This does not compromise the validity of the methodology but it has an effect on the quantitative conclusions about calculations.

The cost curve is derived calculating:

$$\frac{\$}{h} = \frac{\$}{t}\bigg|fuel \cdot \frac{1}{10^6} \cdot sfoc \cdot P \qquad (9)$$

Where:

- *Sfoc* is the specific fuel oil consumption, expressed in g/kWh.
- *P* is the power, expressed in kW.

The whole network has been modeled with MATPOWER [21], which is an open-source package of MATLAB used to solve power flow and optimal power flow (OPF) problems. MATPOWER uses all the standard steady-state models normally employed for power flow analysis. Internally, the magnitudes of all values are expressed in "per unit" and angles of complex quantities are expressed in radians. In addition, all off-line generators and branches are removed before solving the power flow or OPF problem. All buses are numbered consecutively, and generators are reordered using the bus number.

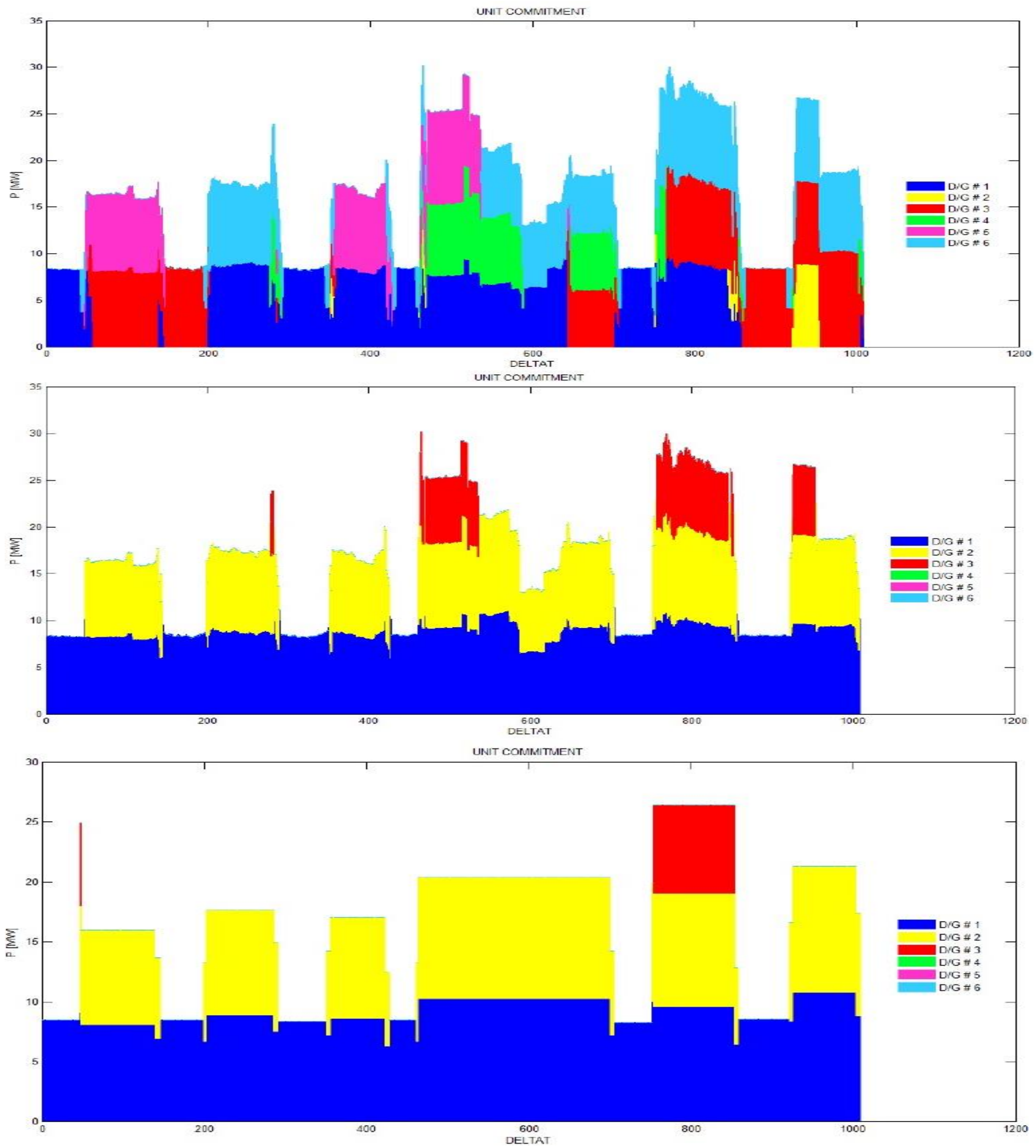
4. RESULTS

The simulations are based on two algorithms:

- The power flow algorithm, concerning the simulation of the "recorded cruise".
- The optimal power flow algorithm, concerning the simulation of the "optimized cruise", which has been run with both the "theoretical" load profiles and the "recorded" one.

The results are shown in Figure 10 where unit commitment of the 'recorded' and 'optimized' curve; together with the unit commitment of the 'optimized' cruise with 'theoretical' load profiles are presented one below the other.

The first clear difference between the unit commitment of the 'recorded' and 'optimized' cruises is the sequence of starting/turning off the diesel-generators. Indeed, in the actual cruise profile, all the six generators have been used, whereas in both the optimized cruises three generators have been employed. In a maintenance perspective the cost resulting from the continuous starting and turning off should not be neglected. From the simulations of the optimized cruises, a better management of the load distribution is shown to be possible. This is because the generators work at a running point closer to the minimum consumption one. Between the two optimized cruises, the one which has the "theoretical" load profiles as inputs produces a better result, since it does not consider the improvements about energy efficiency recently implemented onboard.



Figures 10: Unit commitment of the 'recorded' and ‘optimized‘ curve; Unit commitment of the 'optimized' cruise, with 'theoretical' load profiles

As previously reported, when dealing with the “recorded cruise” the hourly cost is evaluated with an auxiliary function. However, it is an output of the optimal power flow in the simulation of the “optimized” cruise. At the same time, in order to have the cost at time t*, which is an average value over 10 minutes, the sum of the hourly cost for all the generators has to be divided by six. Then it is possible to calculate the total cost of fuel for the diesel-generators as the sum of all the partial costs. Figures 11 show the cost trends over time and the total cost of fuel for each simulation.

As shown, the best power generation management has also an influence in economic terms, indeed the total cost of fuel in the simulations is:

- Total cost of the “recorded” cruise = 411000 USD.
- Total cost of the “optimized” cruise, with “recorded” load profiles = 390000 USD.

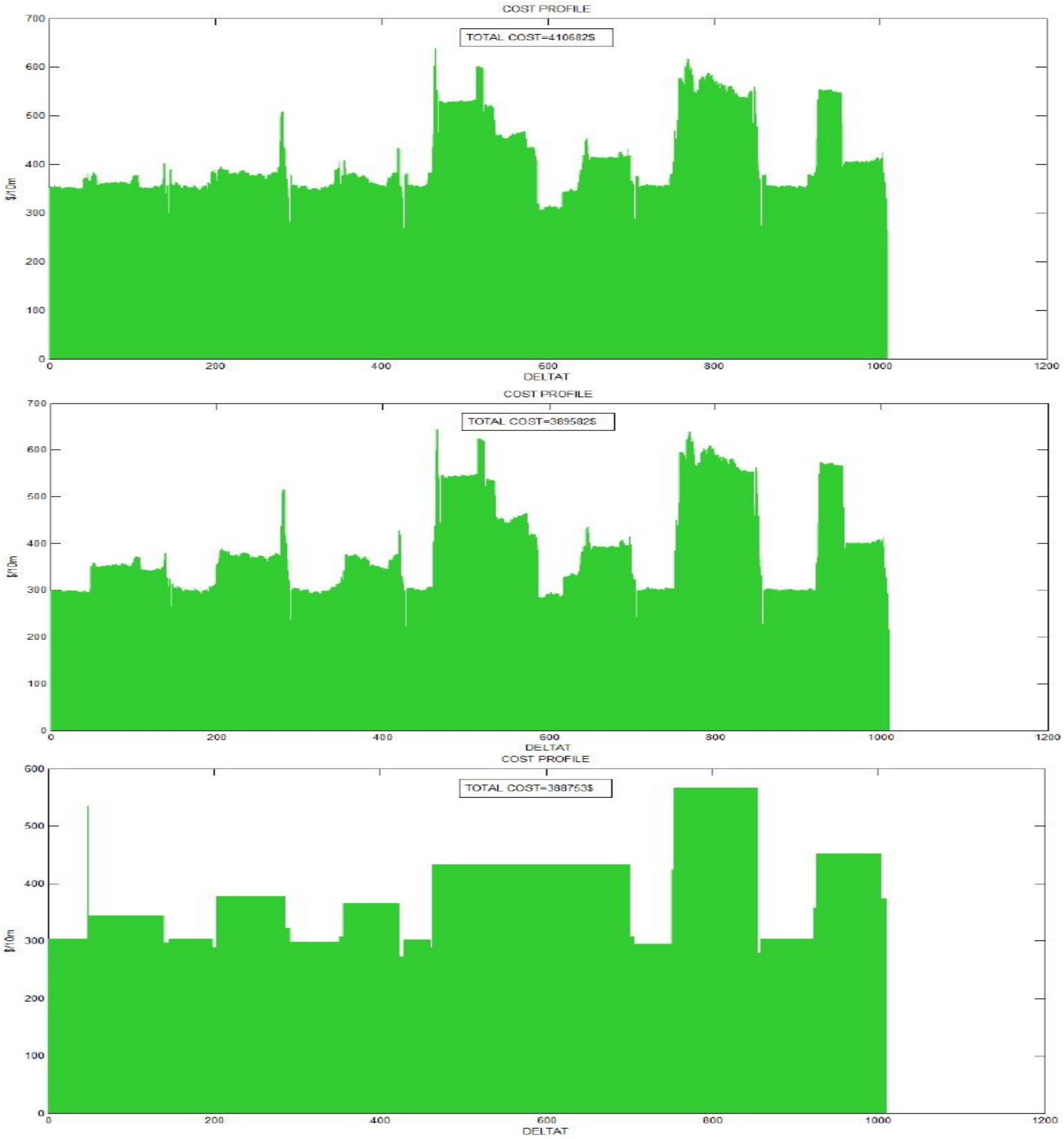
- Total cost of the “optimized” cruise, with “theoretical” load profiles = 390000 USD.

Therefore, the difference between the optimized and the recorded cruise leads to (in economic terms):

- A saving of 21100 USD, which correspond to a 5.1 % of percentage difference, concerning the “optimized” cruise with “recorded” load profiles.
- A saving of 22000 USD, which correspond to a 5.3 % of percentage difference, concerning the “optimized” cruise with “recorded” load profiles.

This particular output makes this simulation tool interesting for the possible determination of budgets. It is to be pointed out again that specific figures are in relation with the assumed bunker prices at the time of the application.

The optimal power flow provides also the optimal voltage profiles, while for the ”recorded” cruise the voltage profiles have been used both to derive the propulsion load profiles and as input of the generator’s characteristics, since they are modeled as PV buses.



Figures 11: Cost profile of the 'recorded' and ‘optimized’ cruise; Cost profile of the 'optimized' cruise, with 'optimized' load profiles

5. CONCLUSIONS

The work has presented a possible optimization methodology that can be applied for the ship power generation management. The simulation has highlighted that the optimization can lead to the following results:

- Optimization of the unit commitment, in terms of diesel generators starting/turning off sequence and in terms of load distribution among the committed generators, with the consequent achievement of an average working point closer to the minimum consumption.
- Reduction of the total cost of fuel for the diesel-generators close to the 5 %.
- Reduction of the network losses due to the Joule effect, thanks to the optimization of the voltage profiles, which considers an increase of the voltage level of all the system around the 5 %.

Indeed, keeping the supplied power constant, an increase of the voltage causes a reduction of the current and therefore of the losses, being these proportional to the square of the current.

Further analyses are necessary in order to fully validate the approach and extend it further on a whole fleet.

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7. REFERENCES

1. IMO, "Guidance for the development of a ship energy efficiency management plan (SEEMP)," 2009.
2. IMO, "Guidance on treatment of Innovative Energy Efficiency Technologies for Calculation and Verification of the Attained EEDI," in (*MEPC.1/Circ.796*), 2013.
3. WOOD, A. J. WOLLENBERG B. F. and SHEBLE, G. B. Power generation, operation and control 3rd Edition, Wiley, 2014.
4. RADAN, D. SORENSEN A. J. and JOHANSEN, A. K. "Probability based generator commitment optimization in ship power system design," Proceeding of the 10th WSEAS International Conference on Computers, ser. INCOOP'06. Stevens Point, Wisconsin USA: World Scientific and Engineering Academy and Society (WSEAS), pp. 905-910, 2006.
5. PATEL, M. R. Shipboard Electrical Power Systems, New York: CRC Press, 2012.
6. FINCANTIERI, "Elecric balance of Costa Serena," 2009, pp. 1-6.
7. COSTA CROCIERE, "Machinery reports of Costa Serena," 2010, pp. 1-6.
8. BOVERI A. P. and CASSOLA, M. "Effect of Heavy Weather Conditions on Passenger Ship Energy Performances," in Master Thesis, Genoa, University of Genoa, 2014, pp. 50-62.
9. COSTA CROCIERE S.p.A., "Bilancio socio-ambientale 2011," *Technical material property of Costa Crociere,* 2012.
10. COSTA CROCIERE S.p.A., "One line schematic wiring diagram".
11. COSTA CROCIERE, "Propulsion system-one line diagram," in *Technical material property of Costa Crociere*.
12. COSTA CROCIERE S.p.A., "Electric Load analysis," in *Technical material property of Costa Crociere*.
13. ABB S.p.A., "Generalità sui sistemi navali e sulle installazioni di bordo," *Quaderno di applicazione tecnica n°12*.
14. PIATTELLI, M. Impianti elettrici Navali, Genova: Tilgher, 2012.
15. PATEL, M. R. Shipboard Propulsion, Power Electronics, and Ocean Energy, New York: CRC Press, 2012.
16. COSTA CROCIERE S.p.A., "Medium Voltage and Low Voltage Network Operation Description," in T*echnical Material property of Costa Crociere*.
17. PIATTELLI, M. Propulsione elettrica navale, Genova: Tilgher, 2008.
18. COSTA CROCIERE S.p.A., "Machinery report of Costa Pacifica," in T*echnical material property of Costa Crociere*.
19. COSTA CROCIERE S.p.A., "Registrations made onboard of Costa Pacifica," in *Technical material property of Costa Crociere*.
20. WARTSILA, "Projact guide - Wartsila 46".
21. MURILLO-SANCHEZ C. E. and THOMAS, R. J. "MATPOWER: Steady-state Operations, Planning and Analysis Tools for Power System Research and Education," *IEEE Transaction*, vol. 26, no. 1, pp. 12-19, Feb. 2011.
22. LAHIRI, S. MIU, K. KWATNY, H. BEYTIN G. and PATEL, J. "Fuel optimization under quality of service constrains for shipboard hybrid electric drive," in *Resilient Control System (ISRCS),* no. 4th International Symposium on, 2011, pp. 137-141, 2011.