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Whole Ship Energy Optimization: the Case Study of a Chemical Tanker

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Abstract - Italiano

La presente dissertazione investiga la possibilità di ottimizzare l'uso di energia a bordo di una nave per trasporto di prodotti chimici e petrolchimici. Il software sviluppato per questo studio può essere adattato a qualsiasi tipo di nave. Tale foglio di calcolo fornisce la metodologia per stimare vantaggi e miglioramenti energetici, con accuratezza direttamente proporzionale ai dati disponibili sulla configurazione del sistema energetico e sui dispositivi installati a bordo. Lo studio si basa su differenti fasi che permettono la semplificazione del lavoro; nell'introduzione sono indicati i dati necessari per svolgere un'accurata analisi ed è presentata la metodologia adottata.
Inizialmente è fornita una spiegazione sul layout dell'impianto, sulle sue caratteristiche e sui principali dispositivi installati a bordo. Vengono dunque trattati separatamente i principali carichi, meccanico, elettrico e termico. In seguito si procede con una selezione delle principali fasi operative della nave: è seguito tale approccio in modo da comprendere meglio la ripartizione della richiesta di potenza a bordo della nave e il suo sfruttamento.
Successivamente è svolto un controllo sul dimensionamento del sistema elettrico: ciò aiuta a comprendere se la potenza stimata dai progettisti sia assimilabile a quella effettivamente richiesta sulla nave.
Si ottengono in seguito curve di carico meccanico, elettrico e termico in funzione del tempo per tutte le fasi operative considerate: tramite l'uso del software Visual Basic Application (VBA) vengono creati i profili di carico che possono essere gestiti nella successiva fase di ottimizzazione.
L'ottimizzazione rappresenta il cuore di questo studio; i profili di potenza ottenuti dalla precedente fase sono gestiti in modo da conseguire un sistema che sia in grado di fornire potenza alla nave nel miglior modo possibile da un punto di vista energetico. Il sistema energetico della nave è modellato e ottimizzato mantenendo lo status quo dei dispositivi di bordo, per i quali sono considerate le configurazioni di "Load following", "two shifts" e "minimal".
Una successiva investigazione riguarda l'installazione a bordo di un sistema di accumulo di energia termica, così da migliorare lo sfruttamento dell'energia disponibile.
Infine, nella conclusione, sono messi a confronto i reali consumi della nave con i risultati ottenuti con e senza l'introduzione del sistema di accumulo termico. Attraverso la configurazione "minimal" è possibile risparmiare circa l'1,49% dell'energia totale consumata durante un anno di attività; tale risparmio è completamente gratuito poiché può essere raggiunto seguendo alcune semplici regole nella gestione dell'energia a bordo. L'introduzione di un sistema di accumulo termico incrementa il risparmio totale fino al 4,67% con un serbatoio in grado di accumulare 110000 kWh di energia termica; tuttavia, in questo caso, è necessario sostenere il costo di installazione del serbatoio. Vengono quindi dibattuti aspetti economici e ambientali in modo da spiegare e rendere chiari i vantaggi che si possono ottenere con l'applicazione di questo studio, in termini di denaro e riduzione di emissioni in atmosfera.

Abstract

This dissertation investigates the possibility to optimize the energy use on a chemical tanker. The software created for this study can be adapted to all the ships. This tool provides the methodology to estimate energy advantages and improvements, with accuracy directly proportional to the availability of data on the energy system configuration and on the devices installed on board.

The study is based on different steps that allow the simplification of the work; in the introduction, necessary available data and the adopted methodology are presented.

At first, the plant is introduced through a diagram and by explanation of its main characteristics and components. After that, mechanical, electrical and thermal loads are considered separately, and different operational phases are selected among the working time of the chemical tanker; this approach is made in order to understand better the request of power and its exploitation.

Afterwards, a check on the sizing of the electrical system on board is made: this allows comprehending if the power estimated by the designers is similar to the effective one exploited on the ship.

Later on, curves of mechanical, electrical and thermal power as a function of time for all the operational phases are obtained; power profiles that can be managed during the optimization stage are achieved through the use of the software Visual Basic Application (VBA).

The optimization is the core of the study; power profiles got by the previous stage are managed in order to obtain a system that can provide power to the chemical tanker in the best way from the energy point of view. The energy system of the ship is modelled and optimized, maintaining the status quo of the devices. “Load following”, “two shifts” and “minimal” configurations are put into account in this analysis.

A further investigation is made considering the possibility to install a thermal energy storage system on board, in order to improve the energy configuration and exploitation.

Finally, conclusions are made. Real tanker’s consumption and results obtained with and without the addition of a thermal energy storage system are compared. Through the “minimal” configuration is possible to save about 1,49% of the total energy consumed during one operational year; this saving is completely “free” because it can be achieved only by following some simple rules in energy management. The addition of the energy storage increases the total saving up to 4,67% with a tank capacity of about 110000 kWh; however, in this case the tank installation cost is expected. Economical and environmental discussions are made in order to clarify and explain the advantages that can be achieved in terms of money and emissions.

Introduction

i.1 Background

i.1.1 International Shipping

Today, shipping is one of the largest drives of world's globalised economy, as it contributes to more than 80% of global world trade by volume, and 70% by value. The evolution of global trade in the last decades suggests a big increase even after the step back caused by the economic crisis in 2008, and this growing trend is very likely to continue in the future, fostered by the growth in non-OECD countries (Organisation for Economic Cooperation and Development) [17].

As a result of this trend, merchant shipping has been growing steadily over the past years, hand in hand with world trade. In the period between 1999 and 2004 merchant shipping increased its economic turnover by a striking average of 22% per year [17]. This growth, together with the rising global economy, is explained by phenomena like containerisation, increased economy of scale, and advances in marine engineering [17]. Under these conditions, the cost of freight is not a major concern anymore when deciding where to purchase goods and materials.

The low cost of transport by sea has also been historically connected to very low prices for marine fuels (normally referred as ”bunkers”). During latest years, however, the increase in bunker prices has made fuel cost the largest problem for many shipping company [17]. If as late as in the early 70s the fuel bill accounted for around 13% of total ship costs, for the period between 2006 and 2008, fuel costs were estimated to account for between 43% and 67% of total operating costs depending on vessel type [17].

This is not the first period in history when oil prices (and, consequently, bunker prices) have experienced this kind of increase. During the oil crisis of the 70s fuel costs had risen to over 50% of ship operating costs, creating the deepest recession for the maritime sector since the Great Depression. Even if there is disagreement among experts on the forecasts, reference scenarios hypothesised by the major international agencies assume increasing prices in medium to far time horizons. This is a crucial matter since fuel prices have a direct, strong impact on the uptake of new technologies for increasing energy efficiency, as well as on the implementation of existing ones [17].

Transportation by sea requires energy for propulsion, which with today's technological standard is provided by the combustion of fossil fuels. The oxidation of carbon content in the fuel, in turn, releases carbon dioxide (CO_2), which stays in the atmosphere for centuries and contributes to global warming.

Even if contribution to global CO_2 emissions is relatively low and hard to evaluate, shipping is estimated to account for 1.2% to 2.5% of the total global CO_2 emissions [17].

Shipping might become the major contributor to global greenhouse gases (GHG) emissions if present trends are not diverted [17].

Two main policy instruments have been issued by the International Maritime Organisation (IMO) in the effort of reducing shipping impact on global warming: the Energy Efficiency Design Index (EEDI), which sets minimum limits on the emissions of CO_2 per unit of transport work from newly built vessels, and the Ship Energy Efficiency Management Plan (SEEMP), which aims at improving awareness for energy efficiency on existing vessels [17].

As reported by the European Environmental Agency (EEA), shipping contribution to the national SO_x and NO_x deposition is estimated to be between 10% and 30% of the total for most of the

European countries having a significant portion of their borders facing the sea [17]. Meeting the requirements imposed by new regulations on the matter (especially in Emission Control Areas (ECAs), where limits are even more stringent) will require either the installation of costly equipment on board, or the switch to cleaner and more expensive fuels. In both cases, fuel-related costs are expected to increase in the near future because of the more stringent requirements on emissions to air.

i.1.2 The Propulsion System

In the year 1876 – thus, 130 years ago – Nikolaus Otto invented the combustion engine.

The combustion engine was, thus, discovered, but it wasn't originally good for ship propulsion because it used too much expensive petrol.

Even 50 years before the invention of the Otto motor, the Frenchman, Carnot, described a thermo-dynamic cyclic process with theoretically the highest possible degree of efficiency.

With the above in mind, Rudolf Diesel developed a combustion engine, which operated according to the Carnot-principle, and had the same patented in 1892. The 'diesel engine' reached a spectacularly high efficiency of 20, then 30, then 40 and finally 45% [18].

Around 1910, diesel motors began to be built into ships as the main source of propulsion. The entire diesel engine took up approximately as much space as three boilers and, thereby, replaced a steam propulsion system, which was comprised of 2 turbines, 15 boilers and countless auxiliary units [18]. Furthermore, diesel motor required 30% less fuel.

From 1910 to today, the diesel engine has gone through an unparalleled technical development. Similar to the propeller, the diesel engine was able to be adapted to every demand on size and output performance [18].

In addition, the 'combined heat and power' principle, which is talked about so often today, has been common practice in ships with diesel propulsion for ages. Heat is detracted from the diesel engine's exhaust gases, which, in spite of everything else, still contain about 50 % of the thermal energy that is used by connecting turbo chargers and steam boilers so that the efficiency of the entire system rises to over 70 % [18].

The diesel engine, thanks to its many advantages, has displaced every other type of propulsion in shipping and is absolutely market dominating. Today, approx. 90% of all merchant vessels is propelled by diesel engines, worldwide [18].

It displaced the steam turbine, which today only plays a secondary role in regard to ship propulsion and the nuclear powered merchant vessels, which were built in the 60's of the previous century [18].

The diesel engine also displaced ships with gas turbine propulsion. These ships had airplane jet engines, which functioned as so-called gas generators, which, in turn, powered turbines [18].

A comparison between the degrees of efficiency and specific fuel consumption of the various types of propulsion is necessary. Steam engines reach efficiencies about 10-15%, followed by gas turbines (21%), steam turbines (30%) and diesel engines (45%) [18]. Considering specific fuel consumption, steam engines reach values about 950 g/kWh, followed by gas turbines (435 g/kWh), steam turbines (300 g/kWh) and diesel engines (160 g/kWh) [18].

Most modern ships use a reciprocating diesel engine as their prime mover, due to their operating simplicity, robustness and fuel economy compared to most other prime mover mechanisms. The rotating crankshaft can be directly coupled to the propeller with slow speed engines, via a reduction gearbox for medium and high-speed engines, or via an alternator and electric motor in diesel-electric vessels [18]. Most modern larger merchant ships use either slow speed, two stroke, crosshead engines, or medium speed, four stroke, trunk engines [18]. Some smaller vessels may use high-speed diesel engines. The size of the different types of engines is an important factor in selecting what will be installed in a new ship. Slow speed two-stroke engines are much taller, but the footprint required, is smaller than that needed for equivalently rated four-stroke medium speed diesel engines [18]. As space above the waterline is at a premium in passenger ships and ferries (especially ones with a car deck), these ships tend to use multiple medium speed engines resulting in a longer, lower engine room than that needed for two-stroke diesel engines. Multiple engine installations also give redundancy in the event of mechanical failure of one or more engines, and the potential for greater efficiency over a wider range of operating conditions. As modern ships' propellers are at their most efficient at the operating speed of most slow speed diesel engines, ships with these engines do not generally need gearboxes [18]. Usually such propulsion systems consist of either one or two propeller shafts each with its own direct drive engine. Ships propelled by medium or high-speed diesel engines may have one or two (sometimes more) propellers, commonly with one or more engines driving each propeller shaft through a gearbox [18]. Where more than one engine is geared to a single shaft, each engine will most likely drive through a clutch, allowing engines not being used to be disconnected from the gearbox while others keep running. This arrangement lets maintenance be carried out while under way, even far from port. Dual fuel engines are fuelled by either marine grade diesel, heavy fuel oil, or liquefied natural gas (LNG). Having multiple fuel options will allow vessels to transit without relying on one type of fuel. Studies show that LNG is the most efficient of fuels although limited access to LNG fuelling stations limits the production of such engines [18]. Vessels providing services in the LNG industry have been retrofitted with dual-fuel engines and have been proved to be extremely effective. Benefits of dual-fuel engines include fuel and operational flexibility, high efficiency, low emissions, and operational cost advantages [18]. Liquefied natural gas engines offer the marine transportation industry with an environmentally friendly alternative to provide power to vessels, with an emission reduction compared to diesel-fuelled engines of approximately 90% [18].

i.1.3 Whole System Optimization

Regulations on the environmental impact from international shipping, namely with limitations on SO_x, NO_x and CO_2 emissions, will contribute in making fuel price a more and more crucial part of a shipping company's business, as previously discussed. Large improvements can be obtained by increasing the efficiency of those components having the highest impact on ship fuel consumption. Manufacturers are in fact working on improving performance for the respective parts: engines and propellers are more efficient now than they have ever been. However, the pure increase in performance for single components can lead to sub-optimization. As very little focus has been put in the past years over fuel consumption, ship energy systems tend to be far from an optimal design when it comes to energy efficiency. Ships are complex energy systems, with variable demands of mechanical, electrical and thermal power for a number of different purposes to be combined with the energy offered by Diesel engines and boilers, with large opportunities for heat recovery [6]. The optimization of such a system is, therefore, a very challenging process, that cannot be reached with conventional design methods. For this reason, it's important to use design software that can provide useful information for modelling and optimization of ship energy systems. The whole method is applied to the case study of a chemical tanker. The availability of data for a one-year operational time will allow optimization to be performed on real operational curves, therefore taking into account the system behaviour in off-design conditions.

i.2 Available Data

In order to conduct an accurate analysis, it's very important to have the more data as possible about the chemical tanker and its energy system. Data can be divided into two different categories:

1) Data available by the manufacturers;
2) Data measured on the field during the chemical tanker activity.

Both categories have to be available and in particular following data represent the requirements to perform this study in the best way:

- Energy system description;
- Electrical balance, that is the list of all the electrical devices installed on board together with their consumption;
- Thermal balance design calculations;
- Manual of use and maintenance of the principal engines installed on board;
- Manual of use and maintenance of the auxiliary engines installed on board;
- Manual of use and maintenance of exhaust and auxiliary boilers installed on board;
- Manual of use and maintenance of the principal generator installed on board;
- Data for a one-year operational time, in particular mechanical, electrical and thermal consumption with a certain frequency (in this case is 15 min).

These last data, measured on the field during the chemical tanker operation, are extremely important because they allow comparing real data with design data provided by the manufacturers. This analysis generates a more clear vision in the optimization of the system, and it permits to create discussions about the devices installed on board, through considerations regarding their utility and their correct size.
As it can be noted, a frequency of 15 min. is very high, especially if the considered range of time is long (one year) and loads are not very variable in this range: this fact contributes to produce a very detailed analysis but it makes the study difficult to be managed during some stages.

i.3 Methodology

There can be many different ways to conduct an optimization analysis: the compromise is to choose the most accurate and fast one, which can be managed through the available tools and data. In the light of these considerations, the study is based on different steps that allow the simplification of the work while maintaining a high grade of accuracy.
The adopted methodology is divided into different stages, as shown below:

1) At first, mechanical, electrical and thermal loads have to be considered separately, and different operational phases have to be selected among the working time of the chemical tanker [6]; this approach is made in order to understand better the request of power and its exploitation.

2) Afterwards, it's necessary verifying if electrical loads measured on the tanker are close to the ones calculated by the manufacturers; this allows comprehending if the power estimated by the designers is similar to the effective one exploited on the ship. This phase is very important because it shows immediately if devices installed on board are correctly sized.

3) A third crucial step is to obtain curves of mechanical, electrical and thermal power as a function of time for all the operational phases considered; this stage allows identifying those loads that can be considered constants and those that are variables. The goal is obtaining power profiles that can be managed during the optimization phase. At the end of this third

stage, it's important verifying that the energy provided by the achieved power profiles correspond to the real energy consumed by the tanker during the range of time under observation.

4) The core of the study is the simulation and optimization phase through software; power profiles obtained by the previous stage are managed in order to get a system that can provide power to the chemical tanker in the best way from the energy point of view. The energy system of the ship is modelled and optimized, maintaining the status quo of the devices. Further analysis is made considering the possibility to install other devices on board in order to improve the energy configuration.

5) The final stage is the application of this study on the chemical tanker. To obtain the maximum efficiency and to respect the forecasted optimization, it can be very useful to give a course to the crew based on the management of energy sources on board, in such a way to limit its wasting and in order to raise staff awareness.

i.4 Simulation Software

Simulation software is a powerful instrument that allows studying a model and then projecting the results to the real case study. Once, there were only conventional design methods that cannot be considered a good compromise to solve complicated problems as the one under study. Modern design software can model a system with optimal approximation. Over the years, simulation software have become more and more accurate thanks to computing power increasingly high, that allows taking into account a larger number of details that usually are considered negligible during a conventional study. The software flexibility is a crucial characteristic and for this reason the choice of the right software is dictated by its capacity to model and simulate in the best way the design and off-design conditions of the particular system under study.

i.5 Expected Results

From the optimization study of the energy system two main results are expected:

1) An increase of efficiency regarding the production of energy by the components already installed on board;

2) An increase of efficiency regarding the use of energy on board.

The first objective can be centred through the optimization of the regime to which the on-board devices must operate, such as main engines and auxiliary ones.
The second objective can be achieved by optimizing the use of energy on board during the operational phases of the ship.
Both the results are converted into advantages in terms of money and emissions reduction.

1. Energy System Description

The energy system that provides mechanical, electrical and thermal loads to the chemical tanker is shown below [6]:

- **Main engines rated power:** 7680 kW (2x 3840)
- **Auxiliary engines rated power:** 1364 kW (2x 682)
- **Main generator rated power:** 3200 kW
- **Exhaust boilers rated power:** 1400 kg steam / hour (700x2) at 14 bar
- **Auxiliary boilers rated power:** 28 000 kg of steam / hour (2 x 14000) at 14 bar

The main load for the ship is the one related to propulsion, ranging between 3000 and 7000 kW depending on the speed of the ship (in a first approximation is $P_{prop} \propto v^3$) [6].

The electric load varies depending on operations: under normal conditions it swings between 300 and 500 kW. The peaks in consumption occur in port, during the loading - unloading (for cargo pumps the installed power is 1310 kW). During the seagoing phase, main consumptions are related to the inert gas compressors and to the pumps of the cooling system [6].

Heat balances, using the actual temperature of the seawater, estimate the thermal load. For "standard" consumption, exhaust boilers are widely enough, and moreover they have to download the excess steam [6]. A big consumption of heat is necessary for the cleaning of storage tanks between a load and the other. The consumption associated with heating of the load occurs very rarely, because generally both petroleum and chemists products have the right viscosity at ambient temperature. Cleaning storage tanks and heating loads requires the use of one auxiliary boiler [6].

There are two different configurations for the propulsion system. The first (Figure 1) is related to the shaft generator connected to the main engines (ME_1, ME_2); the second layout (Figure 2) refers to operation with auxiliary engines running (AE_1, AE_2).

The first layout can refer to "SG" since it makes use of the so-called "Shaft Generator", instead of the second one that refers to "AE" since it makes use of auxiliary engines [6].

The layout SG is basically the one used with greater frequency, since it allows the generation of current with higher efficiency. The main engines are in fact more efficient than the auxiliary ones [6].
However, this choice is made unconsciously by the operators, because in reality much depends on the load of the engines: it would be much more convenient for example, at low speed, working only with one main engine at full load with the electrical load deflected on the auxiliary engines, rather than working with two main motors at low load. In any case, unless something goes wrong, the SG

layout is always used when the tanker is sailing. Further use of it, it's made during unloading of the load, since the power required can largely overcome the power provided by auxiliary motors [6].

The main use of AE is during the waiting in port (because the main engines are off), and whenever there is a problem with the main generator.

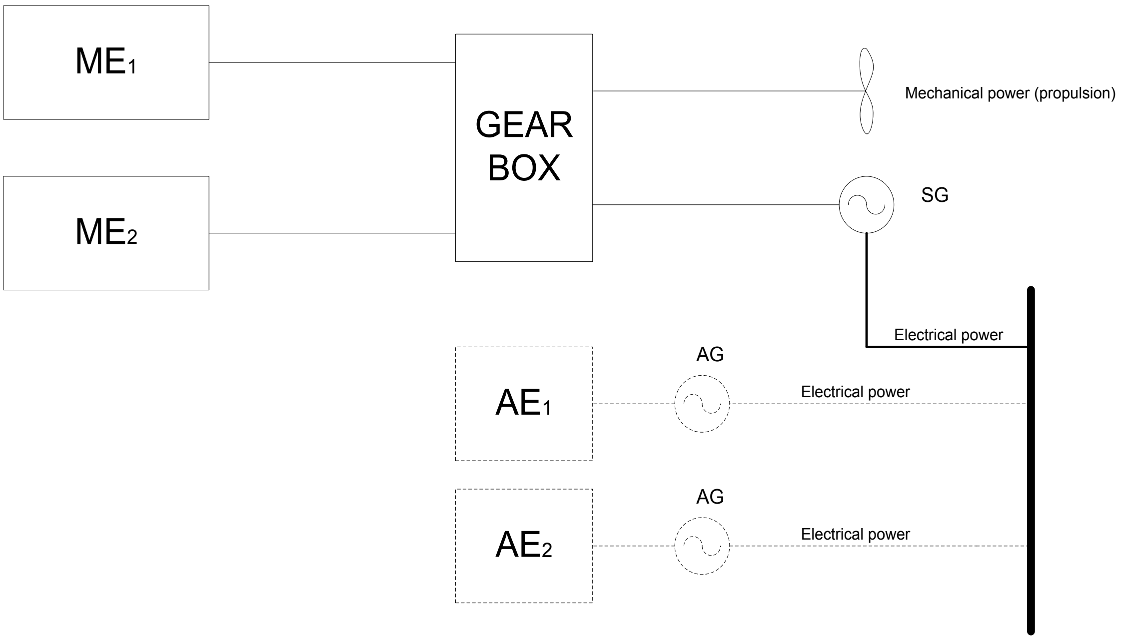

Figure 1: Layout "SG" – Shaft Generator

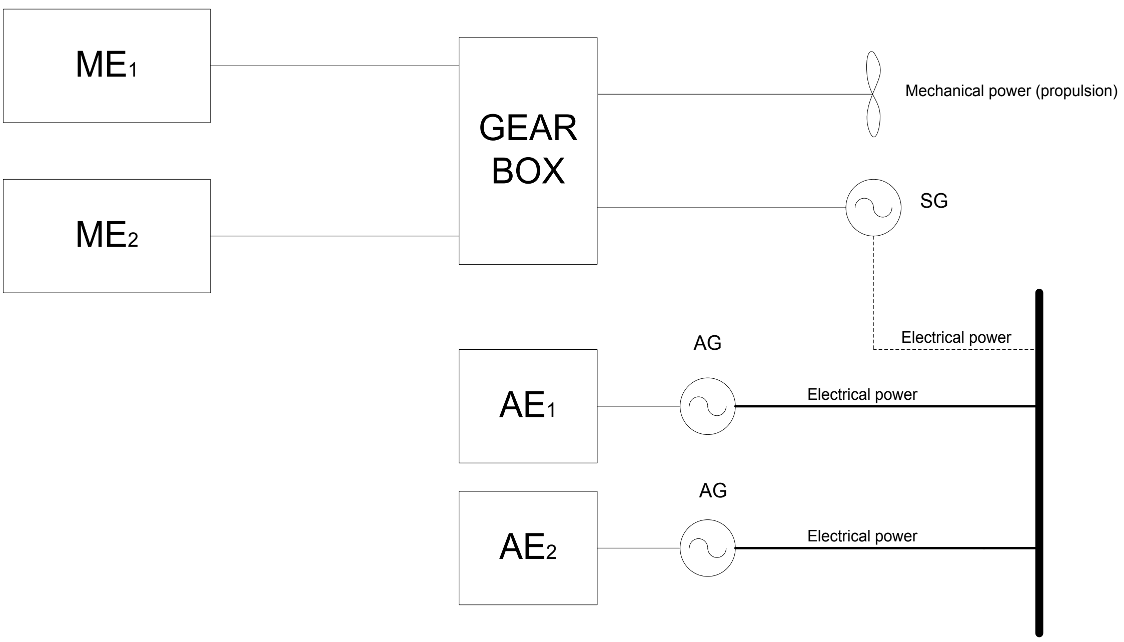

Figure 2: Layout "AE" – Auxiliary Engines

2. Selection of the Operational Phases

Understanding the origin of power request is very useful during an optimization analysis, because it can show in which points the system can be improved. Regarding the activity of a chemical tanker, the power request can swing significantly during its operative life [7], so it's very useful dividing it in different phases. The available electrical balance, that is the list of all the electrical devices installed on board together with their consumption, suggests a division into 4 distinct stages [8]:

- Normal seagoing condition;
- Normal seagoing with ballasting, heating and cleaning;
- Port cargo handling;
- Port in – port out.

During the "normal seagoing condition", the chemical tanker sails loaded of goods: on the ship there are no particular activities [6]. This phase it's very important for two reasons: it takes a large amount of time during the annual operation of the tanker and a large consumption of power is expected due to propulsion (this consumption varies as a function of speed).

The phase "normal seagoing with ballasting, heating and cleaning" is the phase in which the ship is travelling unloaded to reach the port in which it can take the new load. The wasted trip is called "ballast trip" or "ballast leg", hence the term "ballasting" [6]. During the ballast trip, it's often necessary preparing the holds for the next load, cleaning them from the residues of the previous cargo (hence "cleaning"). This requires a high production of steam on board [6]. The term "heating" refers to the heating of load in the case it has a particular high density: this requires again the use of auxiliary boilers [6]. This phase it's very important for two reasons: a large consumption of power is expected due to propulsion, furthermore there is higher consumption of electrical and thermal power than the normal seagoing condition (due to heating and cleaning on board). Although this phase indicates the whole travel during which the tanker is unloaded, hereinafter this phase will regard only cleaning and heating periods in navigation: with no heating and cleaning on board, the phase is considered of "normal seagoing condition".

The port cargo handling is the phase characterized by the peaks in electrical consumption that occur in port, during the loading – unloading of goods: this stage is crucial for the optimization study.

Finally, port in – port out is the phase of manoeuvre in port. However, this phase can be considered negligible since it takes very short time during the annual activity. Furthermore, this stage sometimes is put into account because many ships are equipped with bow propellers for manoeuvring, which have significant power consumption. This is not the case for the tanker under study, and consequently the consumption in this stage is very similar to the one of pure navigation.
Looking at the excel sheet that describe the punctual consumption of the tanker, it's possible to notice that there is another important stage to be considered: the waiting in port [7]. Although mechanical load is not requested and electrical and thermal ones are almost constant, this phase takes a large amount of time (almost half of the annual activity of the chemical tanker) [7].
In the light of these considerations, the following phases will be taken into account in the further analysis; abbreviations are going to be used for simplicity, as Table 1 shows:

Table 1: Abbreviations of the Operational Phases [6]

Operational Phase	Abbreviation
Normal seagoing condition	**‘FUL’**
Normal seagoing with ballasting, heating and cleaning	**‘BAL’**
Port cargo handling	**‘CAR’**
Waiting in port	**‘WAI’**

3. Comparison between Real and Design Electrical Loads

It's necessary verifying if electrical loads measured on the tanker are close to the ones calculated by the manufacturers; as previously said, this allows comprehending if devices installed on board are correctly estimated concerning the power they provide.
At the end of the list of all the electrical devices installed on board, the total power requested is indicated for each phase [8]. This data are simply an estimation of the designers concerning the electrical consumption on board during the four phases. However, for the waiting in port there are no data available, thus the check is made concerning the first three stages (FUL, BAL, CAR).
Table 2 shows the estimation of requested power:

Table 2: Estimation of requested Power [8]

Normal seagoing condition (kW)	Normal seagoing with ballasting, heating and cleaning (kW)	Port cargo handling (kW)
552,2	**1273,9**	**3035,1**

At first, it's necessary making the division of all the four operational phases previously discussed also in the excel sheet which describes the punctual consumption of the chemical tanker in one year of activity.
In order to avoid problems related to the automatic association, every punctual value of power over the operational year is associated to one of the four main phases manually. Automatic association is possible but hazardous because it requires high knowledge about the energy system on board. This selection is made following some guidelines that are summarized below:

- The normal seagoing condition is characterized by request of propulsion load and with no particular activities that require an increase of electrical and thermal request of power.
- The normal seagoing with ballasting, heating and cleaning has more demand of thermal power than the previous phase; it requires propulsion load as well.
- The port cargo-handling phase is characterized by no propulsion and high demand of electrical power due to cargo operations.
- The waiting in port requires neither propulsion nor particular demand of electrical and thermal power.

After these considerations, it is feasible to associate every single value of power to one of these four main phases.
Subsequently this fundamental analysis, it is possible to compare the consumption estimated by the designers with the real energy consumption on the ship. The methodology to do that is summarized below:

- For the three phases considered (waiting in port is excluded), two operations are put into account: the first one is a mean value, the second one is the operation that requires the largest amount of power over the year.
- For both the operations, the punctual consumption of energy is calculated simply multiplying the value in kW by the amount of time considered (15 min.). Afterwards, the punctual consumptions of energy are summed. Therefore the real consumption of energy is obtained (for both the operations of the three phases).
- After that, the value of power previously estimated (Table 2) is multiplied by the amount of time that the two operations of the three phases require: the design consumption of energy is obtained.
- At the end, a ratio between the design and the real consumption of energy is calculated for both the operations of the three phases, as Table 3 shows:

Table 3: Ratio between Design and Real Energy consumption

Operational phase	Mean Operation $\left(\frac{design\ kWh}{real\ kWh}\right)$	Most expensive Operation $\left(\frac{design\ kWh}{real\ kWh}\right)$
Normal seagoing condition	**1,60**	**1,49**
Normal seagoing with ballasting, heating and cleaning	**1,48**	**1,26**
Port cargo handling	**2,43**	**1,96**

Table 3 shows a certain degree of safety for all the phases under study. Also in the most expensive operation, the energy consumption estimated by the manufacturers exceeds at least 26% the real one. Furthermore, the degree of safety seems not to overcome an excessive value: these facts suggest that the size of the electrical devices on board is well estimated.

4. Load's curves for the Simulation

4.1 Calculation of Average Power values

A further crucial step is to obtain curves of mechanical, electrical and thermal power as a function of time for all the operational phases considered. The goal is to get power profiles that can be managed during the optimization stage.
With a simple filtering operation, it is possible to consider separately the four phases previously defined [7]. Information regarding thermal power demand for tank cleaning are not available, therefore this required power is going to be taken into account only from the optimization stage (chapter 5) and is going to be estimated on the basis of actual consumption of the ship.
Here, annual curves of mechanical, electrical and thermal loads related to the four phases are reported [7].

4.1.1 Normal Seagoing Condition

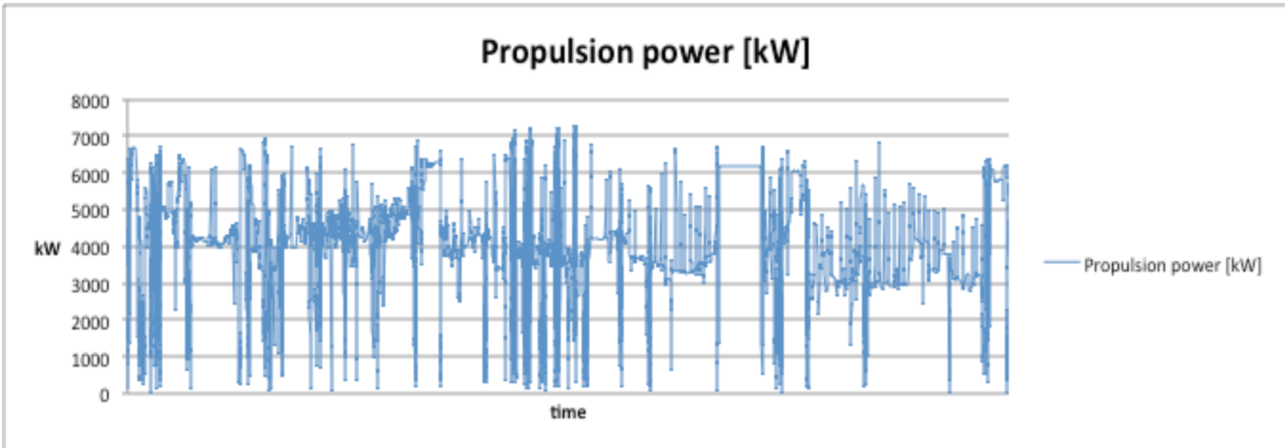

Figure 3: Annual Mechanical Power – 'FUL' phase [7]

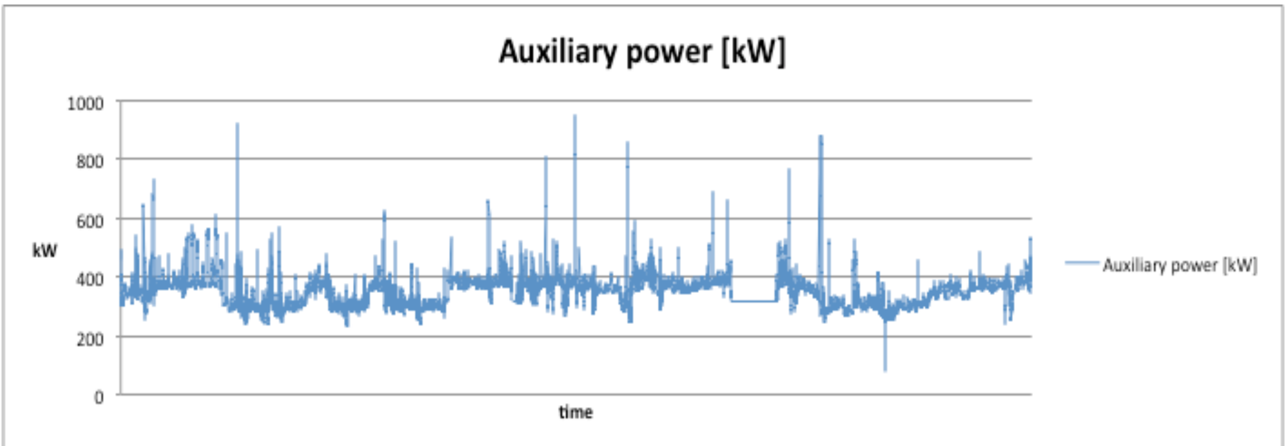

Figure 4: Annual Electrical Power – 'FUL' phase [7]

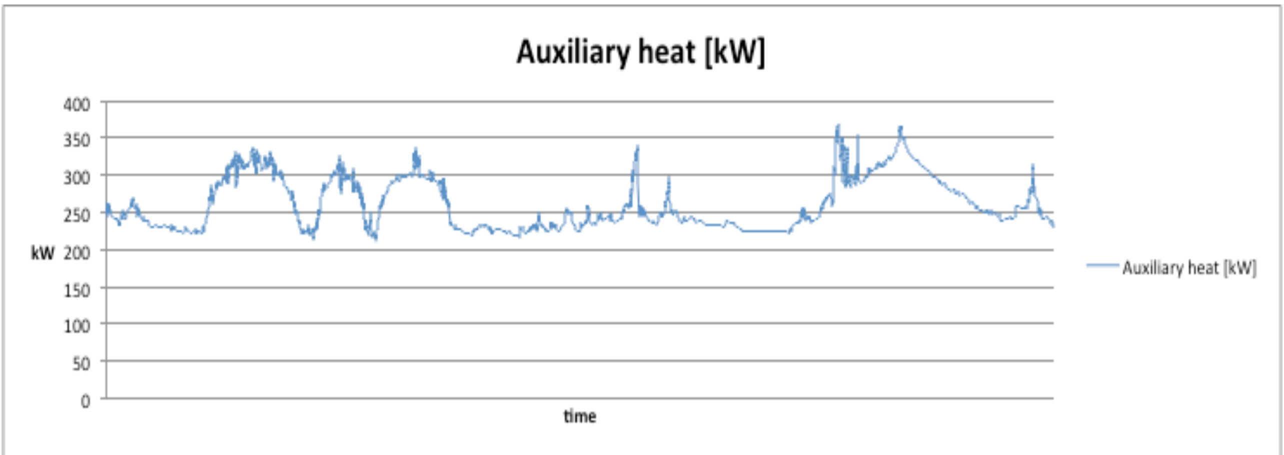

Figure 5: Annual Thermal Power – 'FUL' phase [7]

4.1.2 Normal Seagoing with Ballasting, Heating and Cleaning

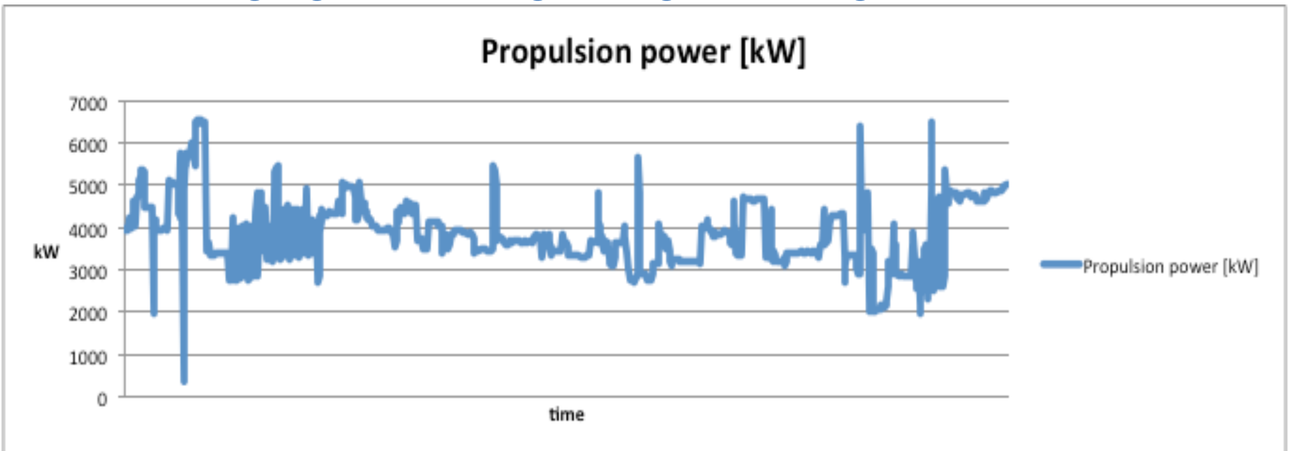

Figure 6: Annual Mechanical Power – 'BAL' phase [7]

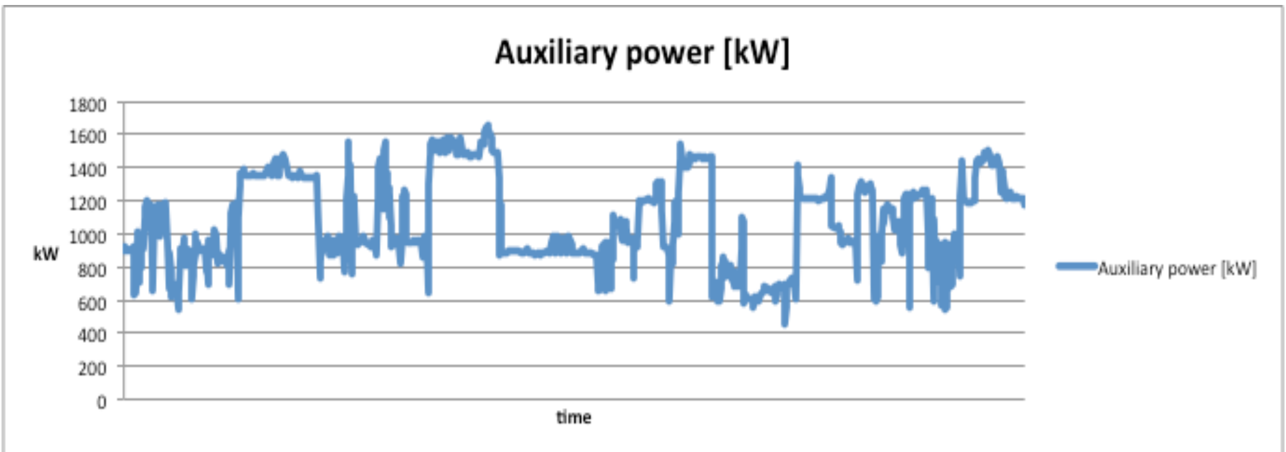

Figure 7: Annual Electrical Power – 'BAL' phase [7]

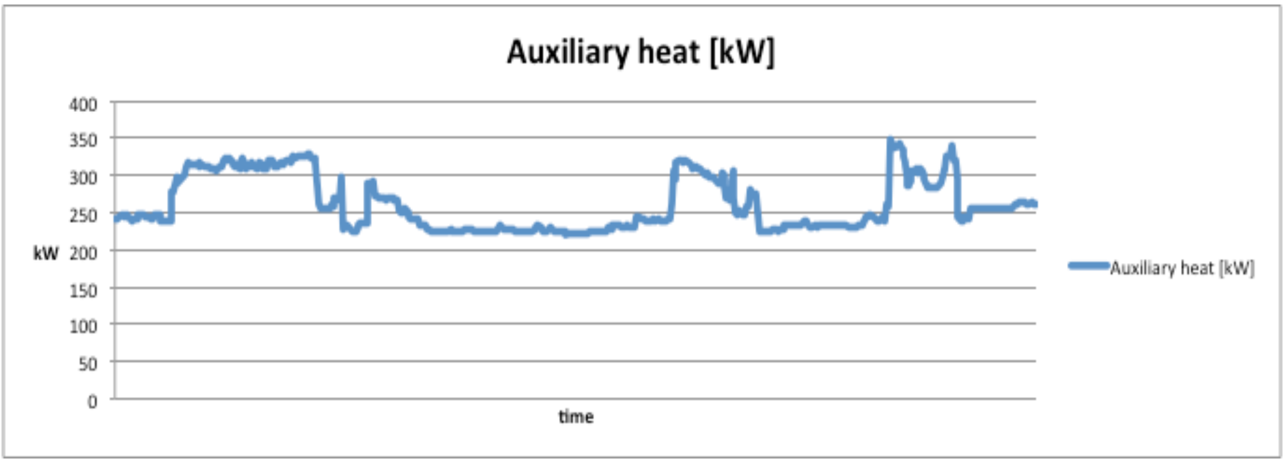

Figure 8: Annual Thermal Power – 'BAL' phase [7]

4.1.3 Port Cargo – Handling

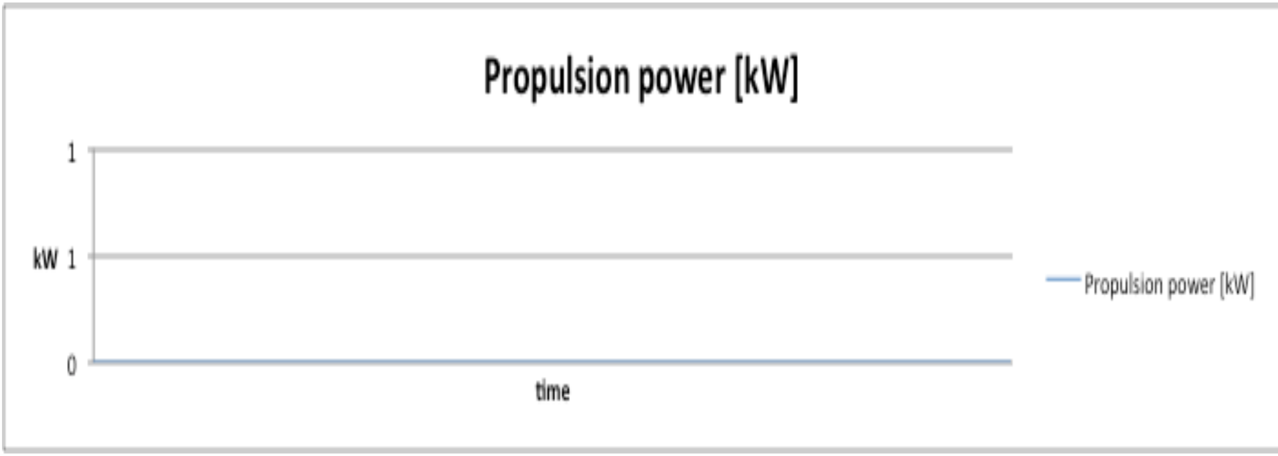

Figure 9: Annual Mechanical Power – 'CAR' phase [7]

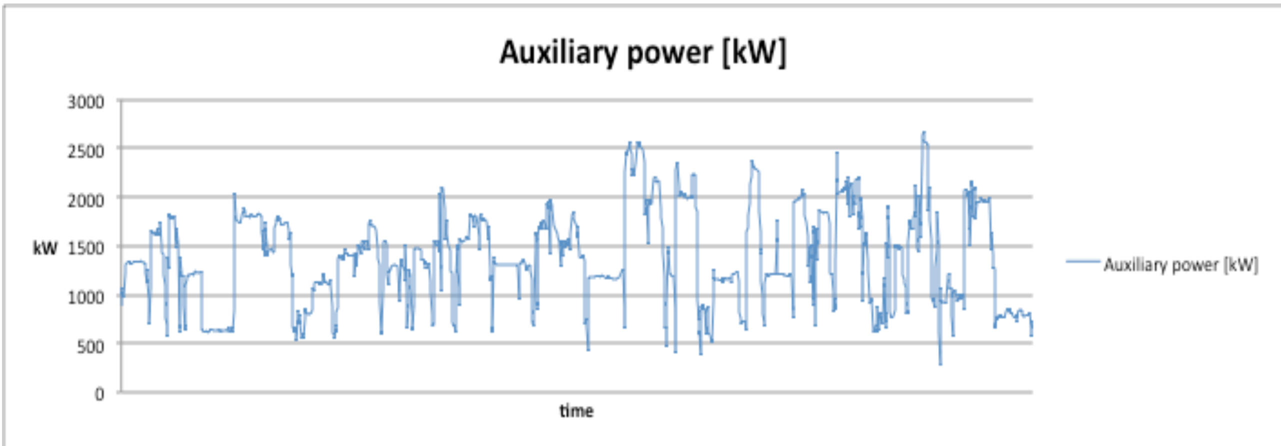

Figure 10: Annual Electrical Power – 'CAR' phase [7]

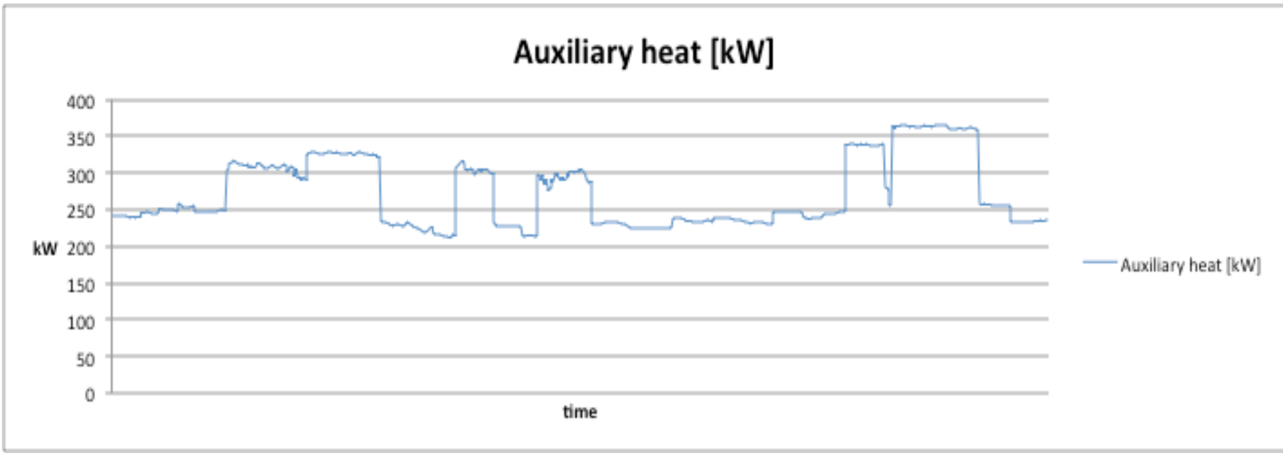

Figure 11: Annual Thermal Power – 'CAR' phase [7]

4.1.4 Waiting in Port

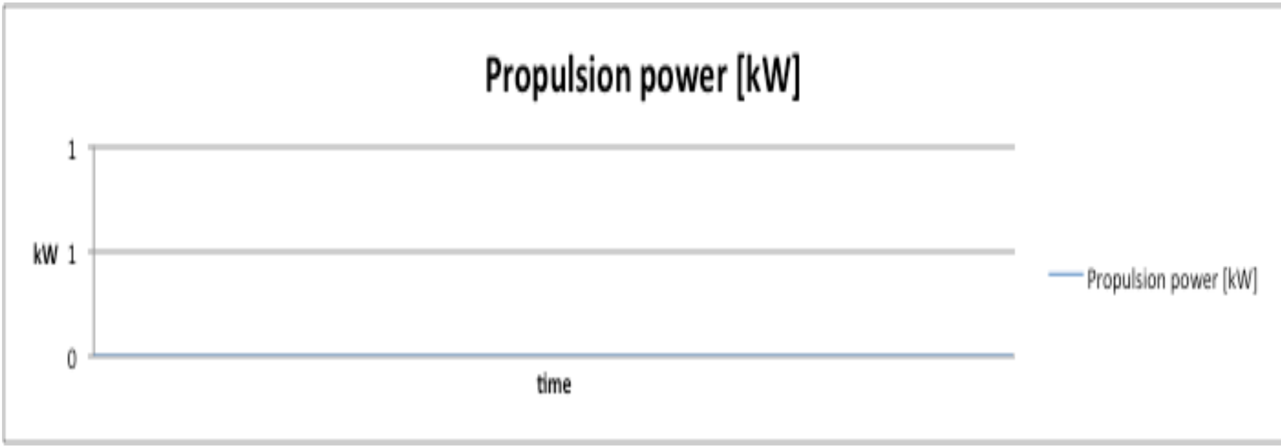

Figure 12: Annual Mechanical Power – 'WAI' phase [7]

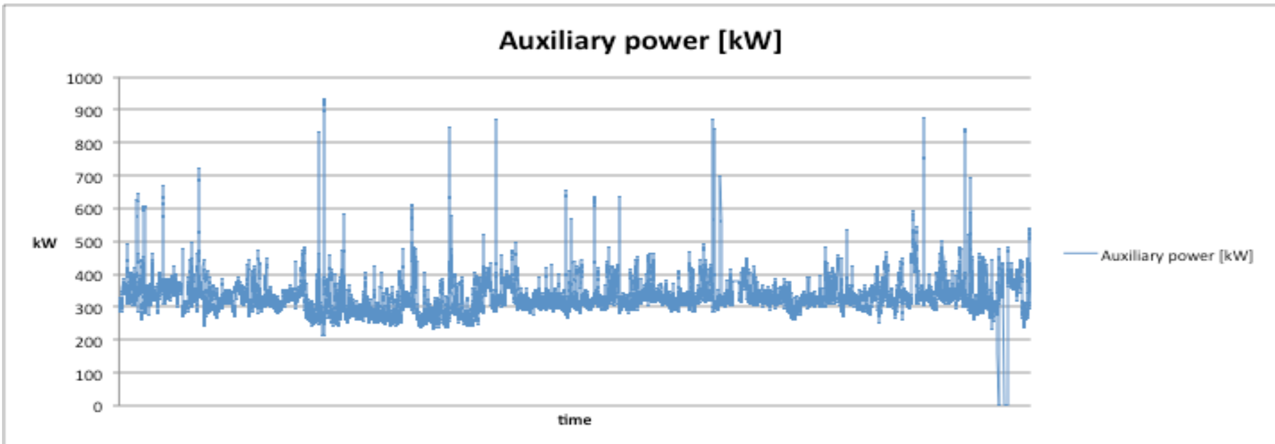

Figure 13: Annual Electrical Power – 'WAI' phase [7]

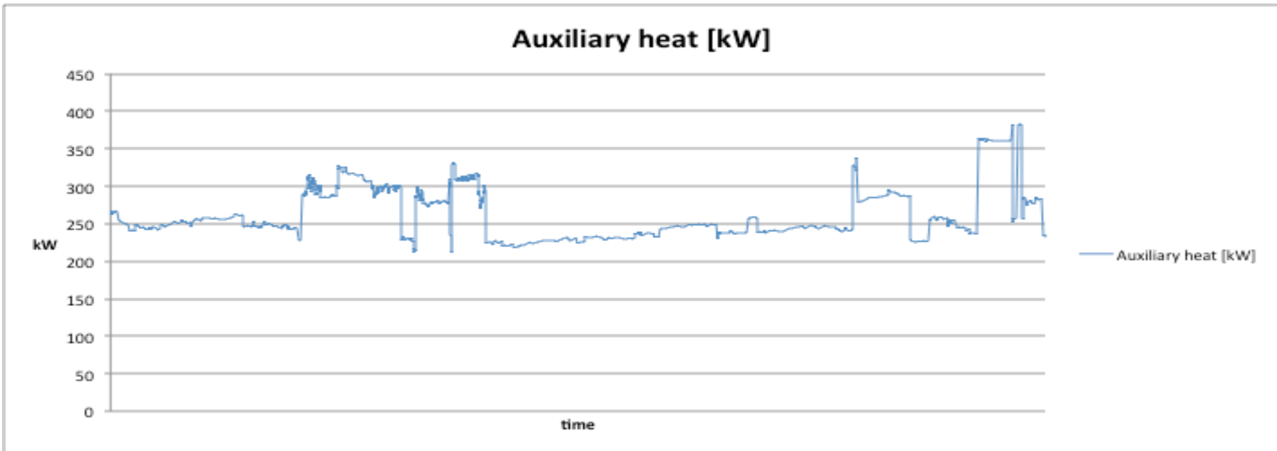

Figure 14: Annual Thermal Power – 'WAI' phase [7]

4.1.5 Results

As Figures 3-14 show, most of the loads have almost a constant profile during the operational year [7]. This is advantageous for the optimization stage through software, because it allows managing power demands with simplicity. However, some of the loads previously shown are not constant over the range of time considered. They are:

- Mechanical load in normal seagoing condition;
- Mechanical load in normal seagoing with ballasting, heating and cleaning;
- Electrical load in normal seagoing with ballasting, heating and cleaning;
- Electrical load in port cargo – handling.

Mechanical loads swing due to speed regulation; instead electrical loads vary because of the different request of power necessary to perform operations as load handling [6].
It is possible calculating the average values of power related to the main four phases. Variable loads are underlined in yellow. As Table 4 suggests, thermal demand is almost constant over the whole operational year (tank cleaning is not included, as previously said). Furthermore, during the FUL phase, power demand is slightly greater than the one in BAL phase, because in normal seagoing condition the tanker is full of goods so, in order to maintain the same cruise speed, the requested power is higher than the case in which the tanker is empty (in BAL phase).

Table 4: Average Values of Requested Power over the four Main Phases (one year) [7]

Load	'FUL'	'BAL'	'CAR'	'WAI'
Mechanical (kW)	4135	3803	0	0
Electrical (kW)	344	1081	1385	329
Thermal (kW)	260	260	272	261

After that, it's possible estimating energy consumption. The amount of hours related to all the four phases during one operational year is reported in Table 5. It is shown that FUL and WAI phases represent almost half operational time each one; BAL and CAR phases are one order of magnitude lower than the other two.

Table 5: Annual hours of the four phases [7]

	'FUL'	'BAL'	'CAR'	'WAI'
Annual hours (h)	**4334**	**384**	**512**	**3550**

Then, energy consumption over one operational year is reported in Table 6. Main consumptions are mechanical ones, due to high demand of power for propulsion.

Table 6: Average Values of Annual Requested Energy over the four Main Phases [7]

Load	'FUL'	'BAL'	'CAR'	'WAI'	Total
Mechanical (MWh)	**17922**	**1460**	**0**	**0**	**19382**
Electrical (MWh)	**1489**	**415**	**709**	**1167**	**3780**
Thermal (MWh)	**1128**	**100**	**139**	**926**	**2293**

4.2 Loads' Distribution during the four Phases

The goal is obtaining power profiles that can be managed during the optimization phase through software. Sometimes average values don't represent the real profile in a good manner, so it can be useful analysing the distribution of power request during one operational year, in order to estimate power inputs to be taken into account in the simulation. The range of power is chosen for all the four phases, depending on their fluctuation over the period considered. Once again, thermal power request for tank cleaning is not put into account, as previously explained.
Figures 15-24 below show the distribution of mechanical, electrical and thermal loads during the four phases (over one operational year); then, observations on the values of power request that must be considered in the optimization stage are proposed.

4.2.1 Mechanical load

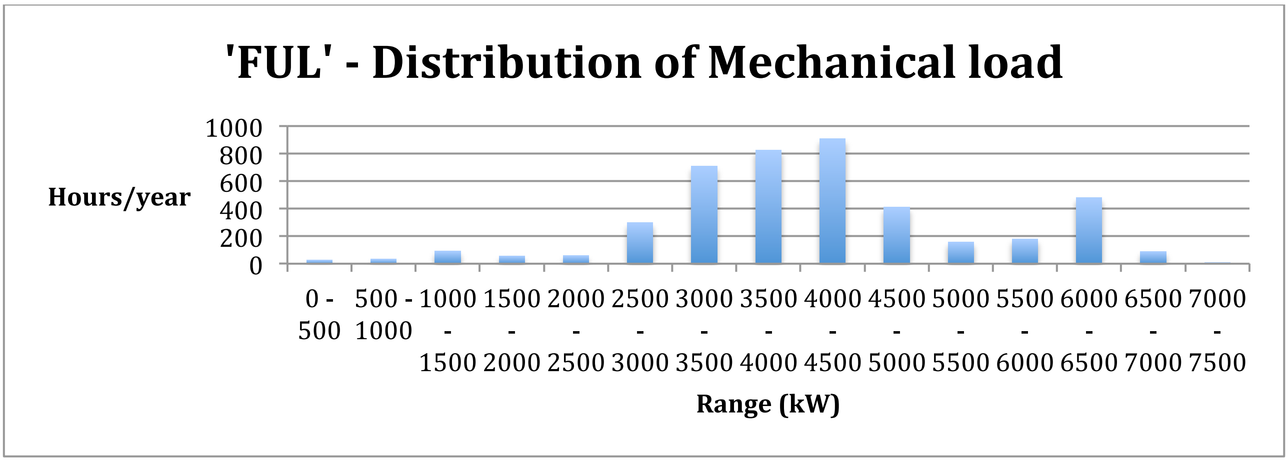

Figure 15: Distribution of Mechanical load – 'FUL' phase [7]

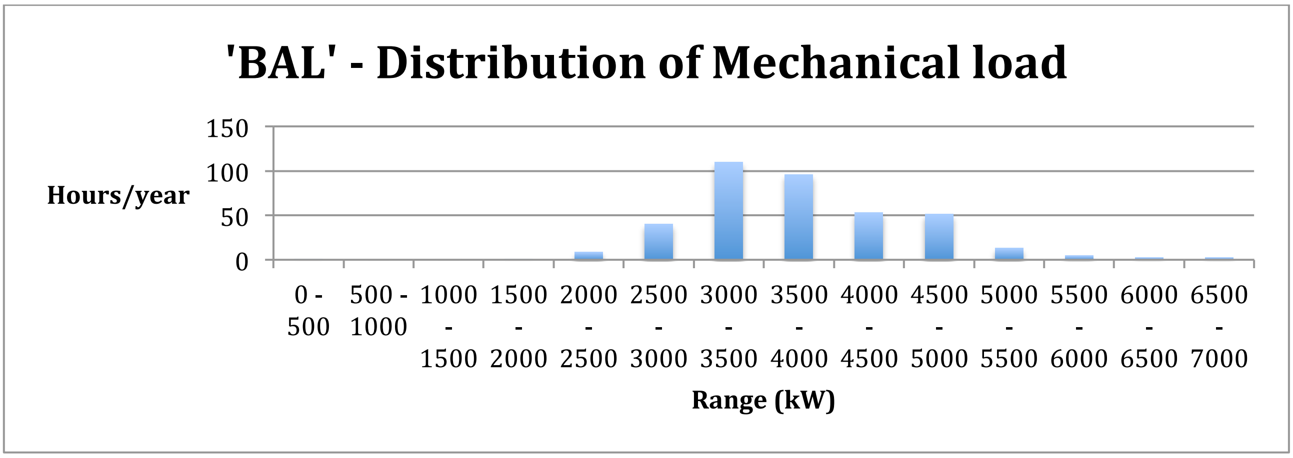

Figure 16: Distribution of Mechanical load – 'BAL' phase [7]

4.2.2 Electrical load

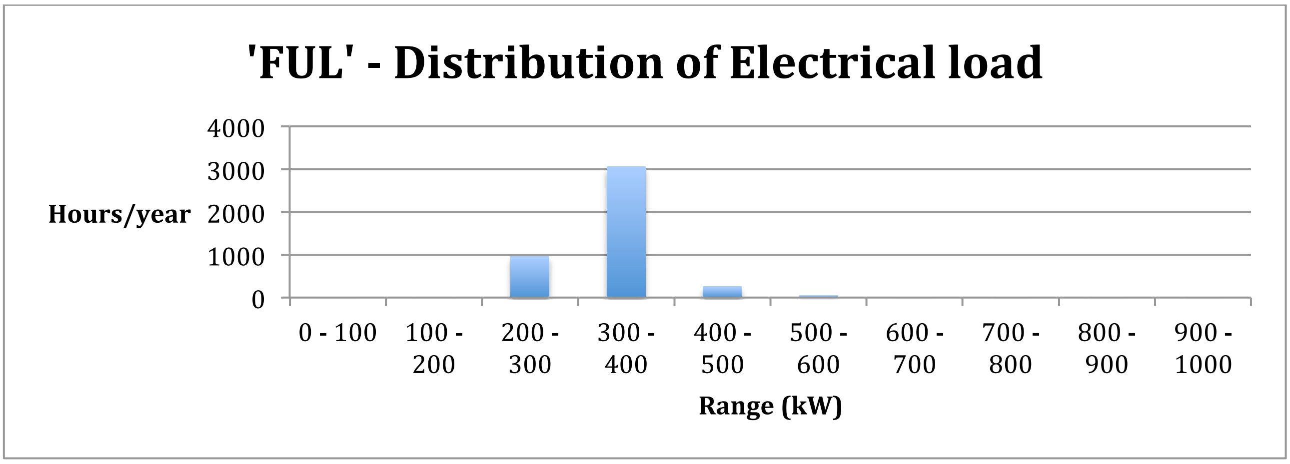

Figure 17: Distribution of Electrical load – 'FUL' phase [7]

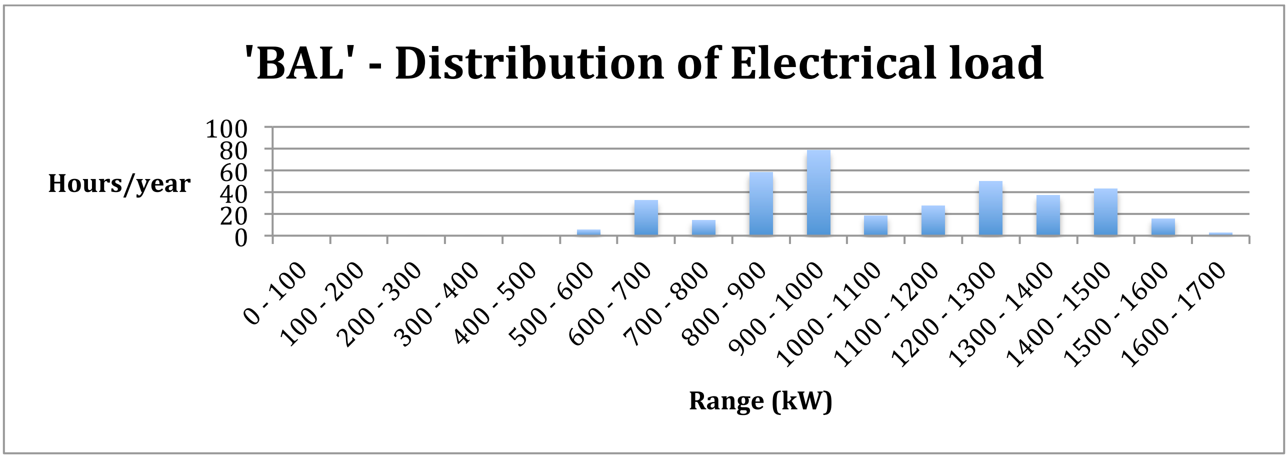

Figure 18: Distribution of Electrical load – 'BAL' phase [7]

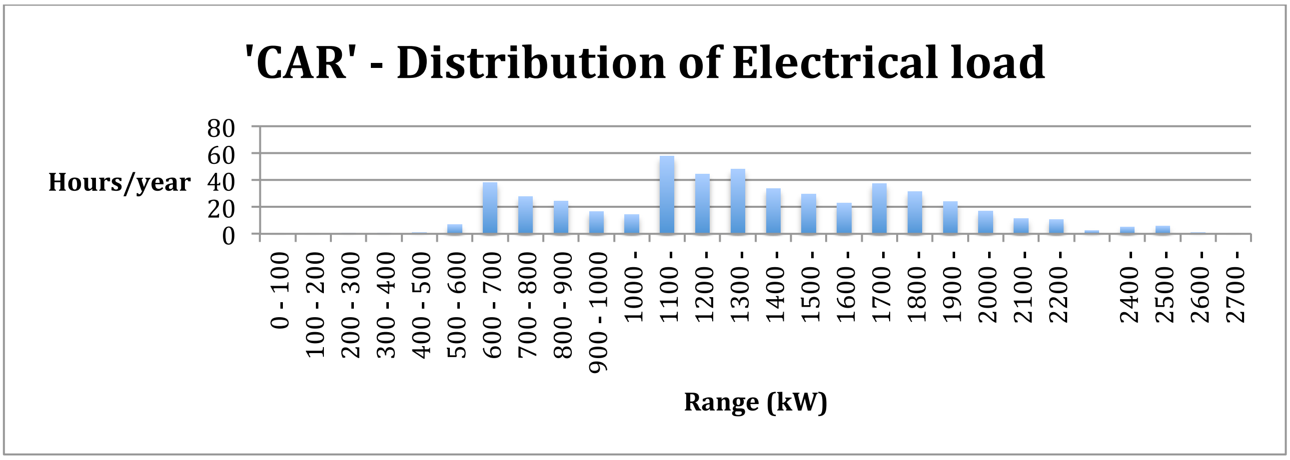

Figure 19: Distribution of Electrical load – 'CAR' phase [7]

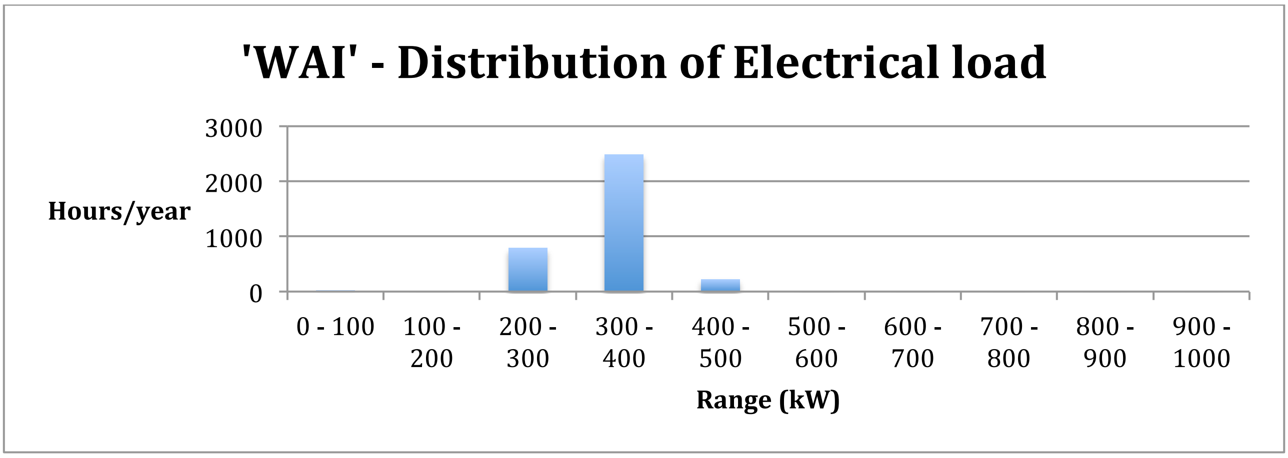

Figure 20: Distribution of Electrical load – 'WAI' phase [7]

4.2.3 Thermal load

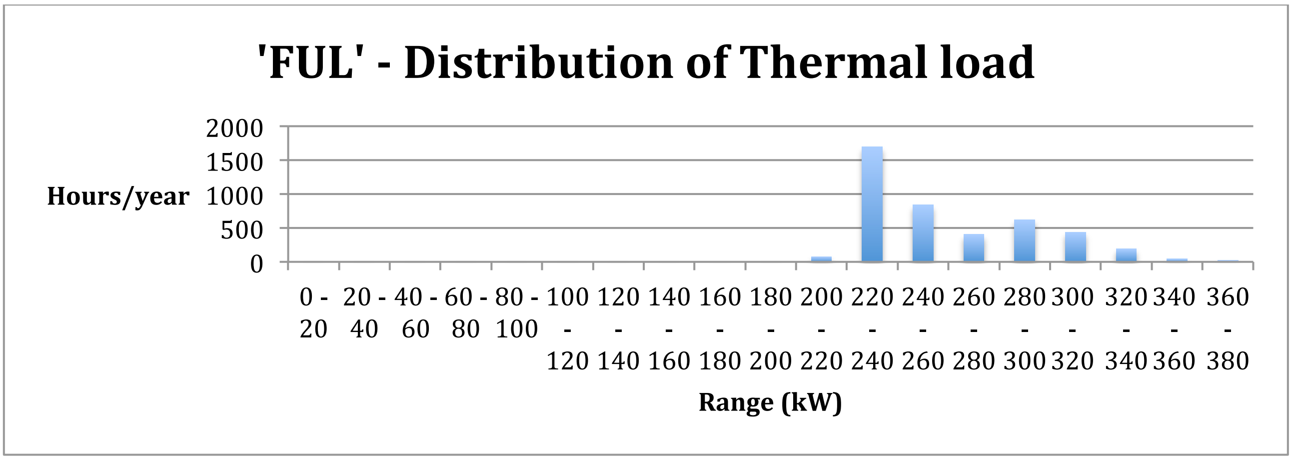

Figure 21: Distribution of Thermal load – 'FUL' phase [7]

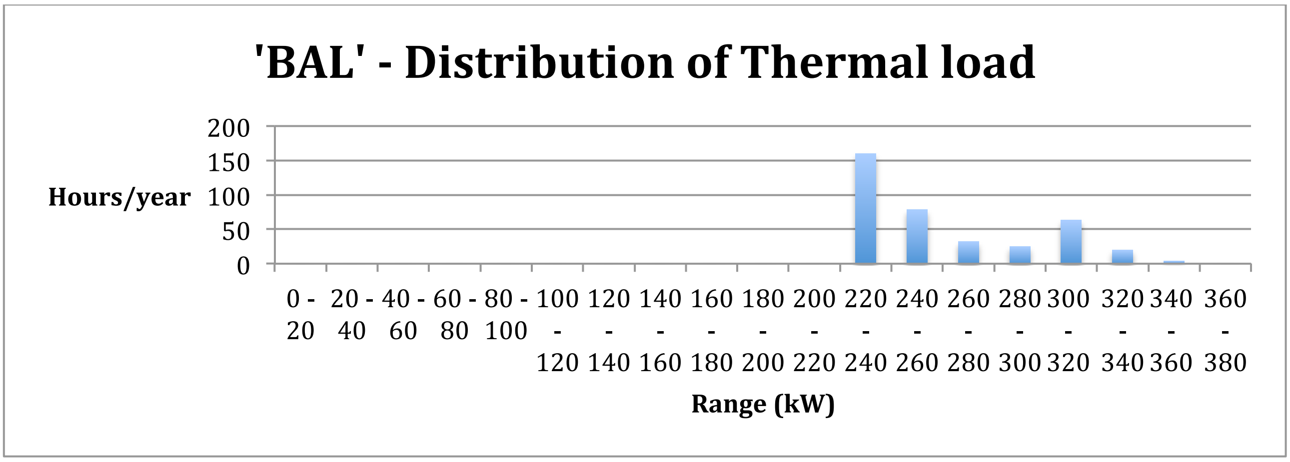

Figure 22: Distribution of Thermal load – 'BAL' phase [7]

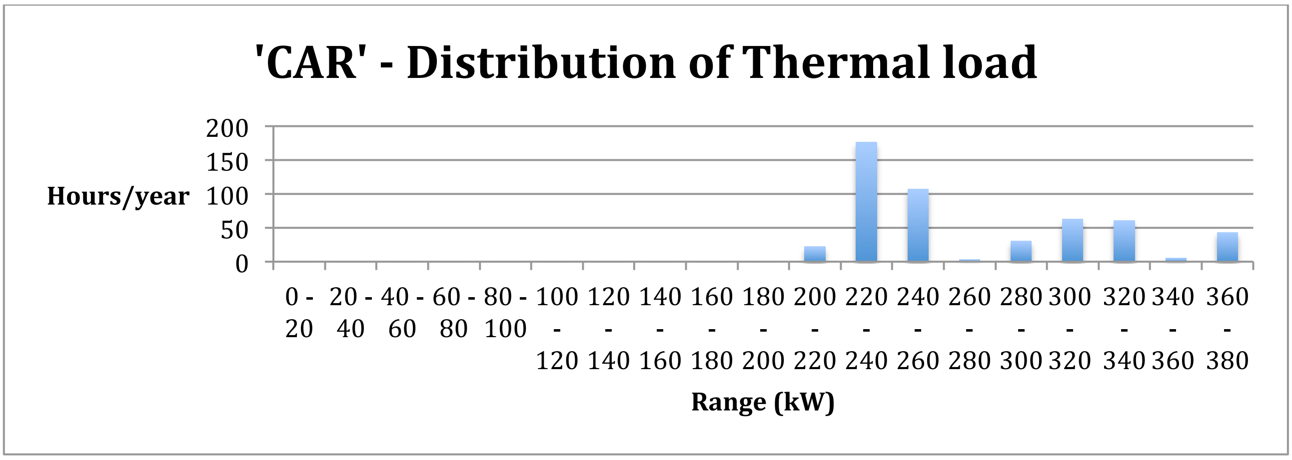

Figure 23: Distribution of Thermal load – 'CAR' phase [7]

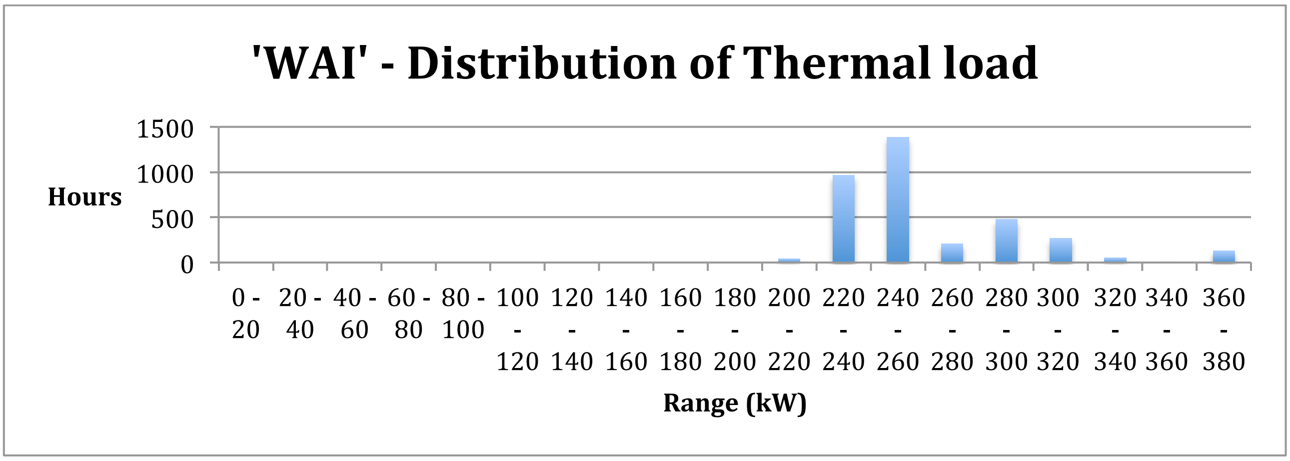

Figure 24: Distribution of Thermal load – 'WAI' phase [7]

Mechanical load is not requested during the phases of 'port-cargo handling' and 'waiting in port', since there is no propulsion demand [6], so the distribution of load is not represented.

Figures 15-24 show different behaviours and situations that are going to be explained.

At first, there are few distributions that show high similarity to the profile of power estimated by the mean values found before. For instance, the distribution of the electrical load during the FUL phase reflects the result obtained by mean values: it was found that during this phase the mean value of requested power was 344 kW. Through the distribution of power, the same result is achieved: there is only one strong peak in the range of power 300-400 kW and other two little peaks in the previous and in the next ranges (200-300 kW and 400-500 kW). For this and a few other distributions, the calculated mean value of power is in accordance with the distribution study.

However, most of the cases demonstrate that the estimated mean value doesn't reflect the real situation in a good way. In many loads the distribution is wide, so the profile of power must be represented in a different manner.

A solution that could allow manipulating and simulating the power profile is necessary; otherwise the study could become inaccurate. To solve the problem, the software Visual Basic Application (VBA) is used: it works with excel interface and it tries to find a solution to the problem. Its use is explained in the next section, together with the obtained results.

4.3 Use of Visual Basic Application (VBA)

Through Visual Basic Application, an excel sheet is created in order to solve the problem related to those loads that show a wide distribution of power during the operational year.
Here, the logic of the spread sheet is explained: it is composed by different steps and it considers one single load of one single phase, so the procedure must be repeated for all the loads of all the phases under study. The most important characteristic of this sheet is to be adapted to all the ships and tankers that need an energy optimization, being useful not only for this particular treated case.

1. At first is possible to set values of requested power and number of hours that this request occurs during the year. This stage can be completed simply using values of power and number of hours considered in the previous distribution study. Mechanical load during the FUL phase may be considered as example. From the distribution study the request of power is divided into different ranges: all of them are characterized by a number of hour that represents the request of power that occurs in these ranges. Concerning the FUL phase, the ranges are developed every 500 kW; in order to identify each range with a single value, it's possible to assume mean values as 250 kW (that identifies the range 0 – 500 kW), 750 kW (that identifies the range 500 – 1000 kW), etc. Finally it's possible associating to each value of power the related number of hour representing the request of power that occurs in the same range. The sheet provides also the total number of hours related to the request of power of the load under study for the whole phase considered, together with the peak of power performed in the same phase.
2. After that, it's possible to press the button "shake", which provides the mixing of the entered values in a random order. This tool allows avoiding the creation of a profile with an increasing request of power (if the user set the inputs following the ascending order) and it permits to generalize the situation. However, if the case under study must be characterized by a certain sequence of values, the user, after the setting of values following the desired order, can escape the button "shake", switching to the next step.
3. Subsequently, pressing the button "curve creation", the profile of power is created. Every single hour is represented by a single value of power and the succession is shown in the excel sheet.
4. Finally, it's possible setting the number of times the user wants to repeat the created profile during the year. The software modifies the profile maintaining the same amount of requested energy, regardless the number of times the profile is repeated. Increasing the number of time of the profile repetition, the calculation looses a certain amount of hour due to the inconvenience to consider the hours as decimal numbers. For instance, if a certain request of power lasts for 33 hours over the year and the user wants repeating the whole profile 10 times (during the same year), each of these profiles should be characterized by 3,3 hours of the same request of power. This is not convenient because the tool is set on kWh considering the hours as integers, hence the software takes into account the integer value (in this case 3 hours); the remaining part is spread over the whole year, together with the remaining parts of all the values of power considered.

Figure 25 shows the just described interface of the spread sheet, concerning the mechanical load of the FUL phase.

total hours	4335
max power [kW]	7.250
rows considered	15
curve repetition	10

Curve creation

SHAKE

4270

	Mean power [kW]	total hours/phase	Mean power of interest [kW]	total hours/phase	hours/repetition	hours/10		
1	1750	57	1750	57	5	0,5	1	1802
2	750	33	750	33	3	0,3	2	1802
3	6250	482	6250	482	48	4,8	3	1802
4	250	27	250	27	2	0,2	4	1802
5	3750	824	3750	824	82	8,2	5	1802
6	5250	157	5250	157	15	1,5	6	802
7	6750	90	6750	90	9	0,9	7	802
8	5750	180	5750	180	18	1,8	8	802
9	2250	59	2250	59	5	0,5	9	6302
10	2750	298	2750	298	29	2,9	10	6302
11	3250	710	3250	710	71	7,1	11	6302
12	4250	908	4250	908	90	9	12	6302
13	1250	91	1250	91	9	0,9	13	6302
14	7250	9	4750	410	41	4,1	14	6302
15	4750	410				0	15	6302
16							16	6302
17							17	6302
18							18	6302
19							19	6302
20							20	6302
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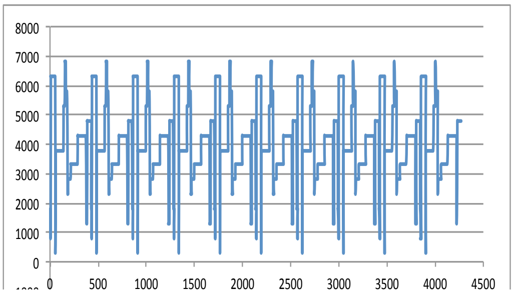

Figure 25: Interface of the spread sheet

The final goal of this stage is obtaining curves of mechanical, electrical and thermal loads over one year. Here, there are two different ways that can be crossed:

1) The phases under study (FUL, BAL, CAR, WAI) may be considered one after the other, as if the ship performs at first the whole phase of seagoing, then the whole phase of ballasting, then the whole phase of cargo and finally the whole phase of waiting in port. This approach is easy to be conducted; the energy point of view doesn't care about the order of the phases, even during the next stage of optimization. However, there could be a problem if in the subsequent optimization a system of energy storage would be taken into account.
2) The second way considers a certain sequence of phases, repeating it a certain number of times during the operational year. This fact avoids the problem of energy storage mentioned in the first way, because it simulates a more real profile of requested power (the phases alternate with each other through a logical sequence). Putting into account an energy storage system, the more the profile of power is similar to the reality the more is possible to estimate with a great accuracy the periods during which it's possible to accumulate energy and the periods during which this energy can be exploited.

The second way requires some hypothesis and it's more difficult to be conducted than the first one; however it's going to be chosen due to the possibility to consider an energy storage system in the further optimization.
The first decision is the choice of the sequence of phases that is going to be repeated over the operational year. This sequence is shown below [7]:

1) WAI
2) CAR
3) BAL
4) CAR
5) FUL

After a phase of waiting in port, there is a phase of unloading of goods, followed by a ballast trip during which the holds are cleaned for the next load. After that, a loading phase is expected and finally the loaded ship performs a phase of seagoing towards the next destination, then the cycle restarts [7]. Obviously the sequence can be changed according to the requirements of the ship under study.
The second and final decision is to determine how many times this sequence must be repeated during the year. This choice depends on the activity of the ship over the year. For this tanker, the number of repetition is set to 10 [7]. Even in this case, the number of repetition can be changed.

Figures 26-29 show mechanical, electrical and thermal loads over one year considering the sequence explained before and putting into account 10 repetitions of this sequence. These curves are going to be considered as input in the next optimization stage.

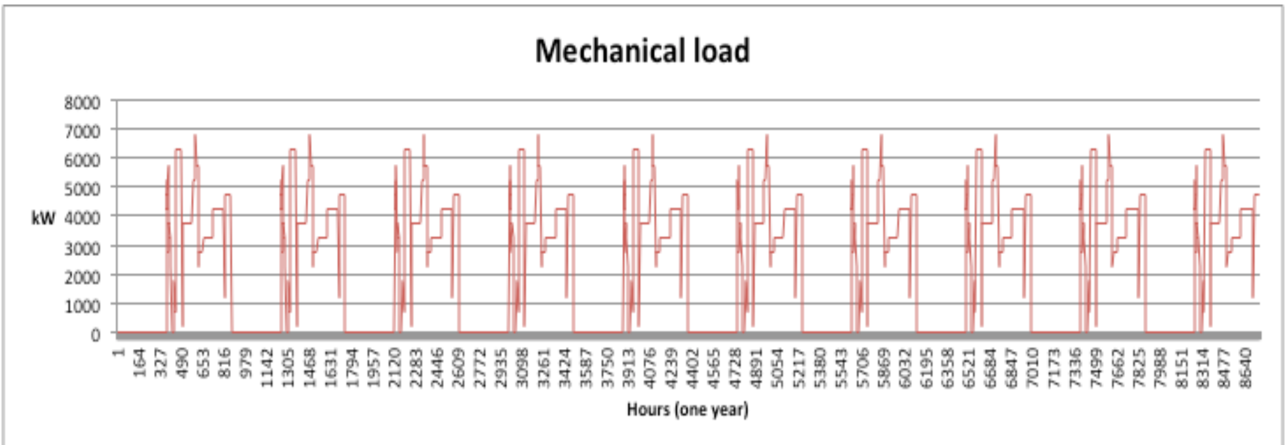

Figure 26: Mechanical load Profile over one operational year

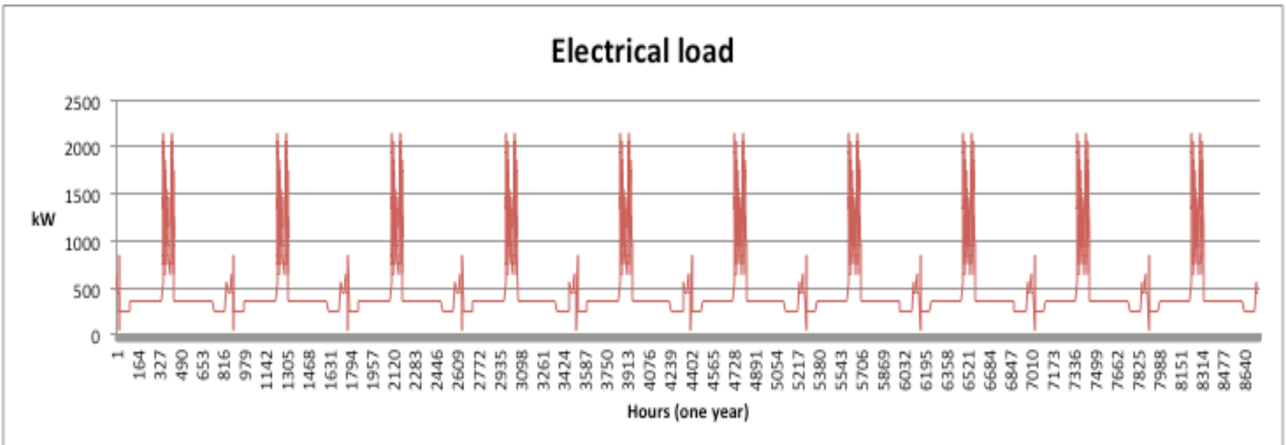

Figure 27: Electrical load Profile over one operational year

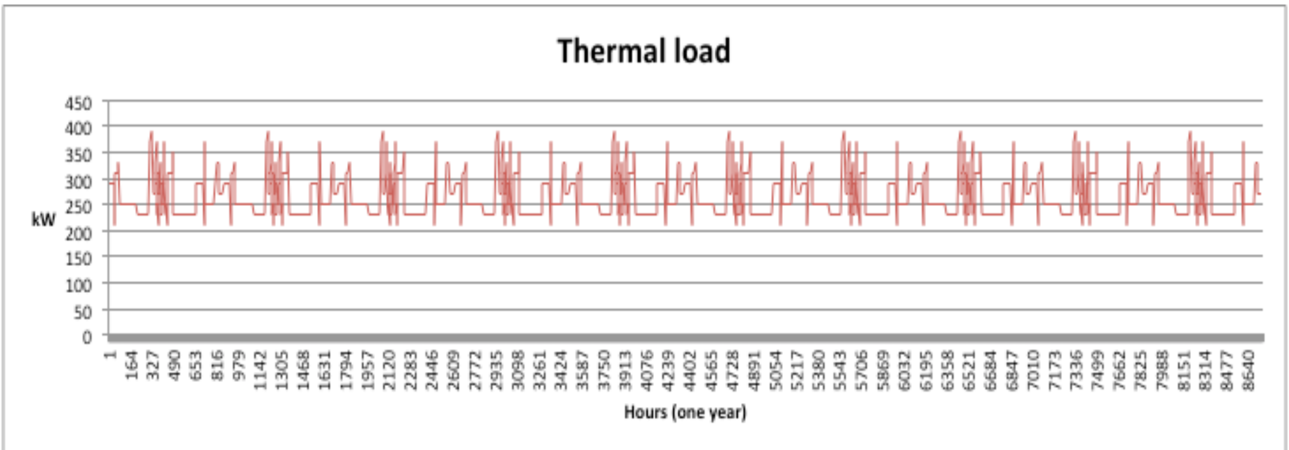

Figure 28: Thermal load Profile over one operational year

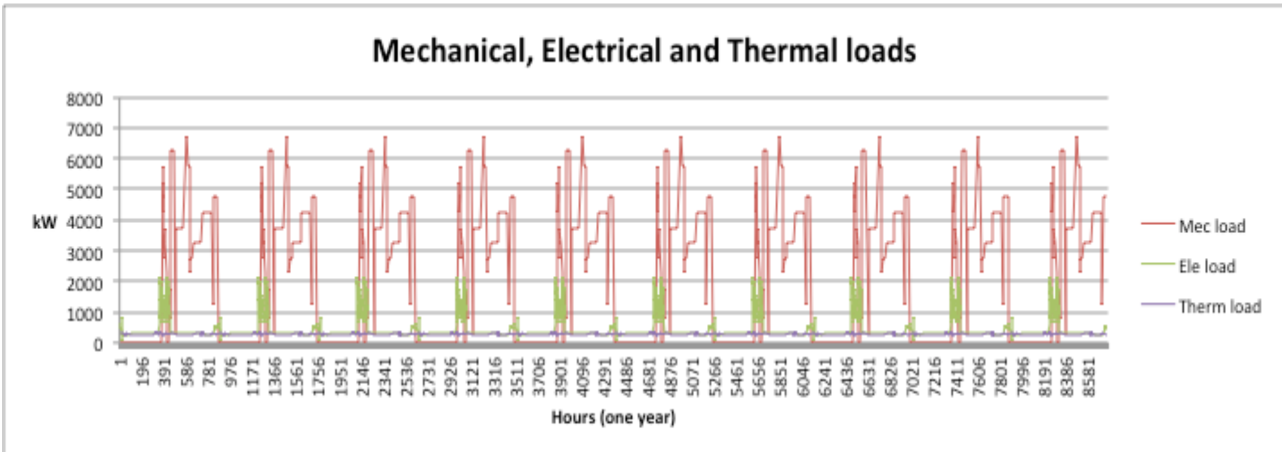

Figure 29: Mechanical, Electrical and Thermal load Profiles over one operational year

After the approximation of these curves, an accuracy check is needed. The parameter that is able to show the precision of the results is the produced energy. A comparison between the energy provided by the obtained curves and the real ones is necessary. In both the cases of thermal load, tank-cleaning contribution is missing and is going to be considered in the next chapter. Table 7 below proves that the difference is always less then 1%, so the optimization can be performed through the achieved model curves. This difference is due to the approximation made during the choice of the ranges of power and particularly considering a mean value as representative of each range of power (in other words the assumptions made in step 1 of section 4.3).

Table 7: Energy check

Energy check	Mechanical load (kWh)	Electrical load (kWh)	Thermal load (kWh)
Obtained Curves	19 447 500	3 751 000	2 288 800
Real Curves	19 380 779	3 783 027	2 295 719
Difference (%)	+0,34	-0,85	-0,30

5. Optimization of the on-board Energy System

5.1 Assumptions

At the beginning of this analysis it's fundamental identifying which devices work during the four phases (FUL, BAL, CAR, WAI). Table 8 shows the situation:

Table 8: Devices for Energy Production on-board [6]

Phase	Mechanical Energy	Electrical Energy	Thermal Energy
FUL	Main Engines	Shaft Generator	Exhaust Boilers
BAL	Main Engines	Shaft Generator	Exhaust Boilers + Auxiliary Boilers
CAR	Main Engines	Shaft Generator	Exhaust Boilers
WAI	Auxiliary Engines	Auxiliary Generator	Auxiliary Boilers

Some of these considerations are obvious; other ones are the result of a rational reasoning.
In the FUL phase, the main engines and the shaft generator produce mechanical and electrical power respectively; exhaust boilers are enough for thermal power due to its low request during the normal seagoing [6].
In the BAL phase, the main engines and the shaft generator produce mechanical and electrical power as well; here, because of the high request of thermal power due to operations as tank cleaning, exhaust boilers are not sufficient and they are helped by auxiliary boilers [6].
In the CAR phase, even if the ship is not sailing, the main engines are on and the shaft generator produce electrical power; this is a reasonable approximation because during the cargo there are some peaks of electrical request of power that cannot be provided by the auxiliary engines [6]. Also in this case, exhaust boilers are enough for thermal power due to its low request [6].
In the WAI phase, main engines are off, so the auxiliary engines and the auxiliary generator produce mechanical and electrical power respectively. Auxiliary boilers provide thermal request of power [6].

After this fundamental overview, it's necessary defining some assumptions that will characterize the optimization study. Table 9 shows the hypothesis made:

Table 9: Assumptions for the optimization study

Device	Description	Unit	Assumption
Main Engines	**Gear box efficiency**	**/**	**0,987**
	Propulsion shaft efficiency	**/**	**0,990**
	Shaft generator efficiency	**/**	**0,950**
Auxiliary Engines	**Auxiliary generator efficiency**	**/**	**0,950**
Exhaust Boilers	**C_l exhaust gas**	**kJ/kg K**	**1,070**
	T exhaust gas	**°C**	**150,00**
	Stoichiometric ratio	**/**	**14,50**
	Fuel stoichiometric mass flow	**kg/h**	**733,00**
	Exchange efficiency	**/**	**1,00**

Assumptions are estimated by following manuals of use and maintenance of the devices together with values taken from literature and values obtained by simulations.

As it's described in chapter 1, main engines are connected to a gearbox, which provides both mechanical and electrical powers. Gearbox and propulsion shaft efficiencies have to be considered for propulsion [11], while gearbox and shaft generator ones for electrical load [14].

Auxiliary engines provide only electrical power and they are not connected to a gearbox, so the only one efficiency to be considered is the auxiliary generator efficiency [6].

Finally, Table 9 shows the assumptions made for thermal exchange in the exhaust boilers. Values of c_l and stoichiometric ratio are obtained by literature [2]. The stoichiometric condition is linked to the full load (100%) of the main engines; this is an approximation because the air mass flow is unknown, therefore this data is estimated through the use of the stoichiometric ratio. The total mass flow is considered as the sum of the fuel mass flow (M_{fuel}), depending on the load of the main engines, and the fuel mass flow in stoichiometric conditions ($M_{fuel_{stoich}}$ = 733 kg/h) [13] multiplied by the stoichiometric ratio ($Stoich\ ratio$) [15]. Equation (1) shows the approximation:

$$M_{tot} = M_{fuel} + (M_{fuel_{stoich}} \times Stoich\ ratio) \qquad (1)$$

The exhaust gas temperature should never be less than 150°C: the marine fuels are rich in sulphur (3.5% by mass is the limit) which oxidizes to SO2 or SO3, and, consequently, to sulphuric acid [6]. It is assumed that exhaust boilers are designed to cool the exhaust gas till a fixed temperature (150°C); the exchange efficiency (which put into account energy dissipations) is always considered equal to 1.

Finally, as previously said, information regarding thermal power demand for tank cleaning are not available, so this demand is going to be estimated on the basis of actual consumption of the ship [7]. This evaluation shows that for tank cleaning 2100 kW of thermal power are required for every hour during the BAL phase. This value must be added to the existing request of thermal power already considered in the previous analysis.

5.2 Methodology

As Table 10 shows, the devices that consume fuel are: main engines (ME), auxiliary engines (AE) and auxiliary boilers (AB).

Table 10: Energy in – Energy out [6]

Devices	Energy in	Energy out
Main Engines	Fuel	Mechanical
Auxiliary Engines	Fuel	Mechanical
Shaft Generator	Mechanical	Electrical
Auxiliary Generator	Mechanical	Electrical
Exhaust Boilers	Thermal	Thermal
Auxiliary Boilers	Fuel	Thermal

In the light of these data, the optimization study is divided into three macro sections: the first for the main engines, the second for the auxiliary engines and the last one for the auxiliary boilers.
Each device is studied following three different configurations:

1. The "load following configuration": the load is always shared equally between the 2 devices;
2. The "two shifts configuration": the requested load is shared equally between the two devices if it's higher than the load that a single device can provide. On the other hand, if instead the requested load is lower, only one device works and the other one is switched off.
3. The "minimal consumption configuration": through the study of the curves of specific consumption of the devices, it's possible minimizing the consumption of fuel.

Table 11 proves the adopted methodology.

Table 11: Methodology: Sections and Configurations

<table>
<tr><th>Macro sections</th><th>Configurations</th></tr>
<tr><td rowspan="3">Main Engines</td><td>Load following</td></tr>
<tr><td>Two shifts</td></tr>
<tr><td>Minimal consumption</td></tr>
<tr><td rowspan="3">Auxiliary Engines</td><td>Load following</td></tr>
<tr><td>Two shifts</td></tr>
<tr><td>Minimal consumption</td></tr>
<tr><td rowspan="3">Auxiliary Boilers</td><td>Load following</td></tr>
<tr><td>Two shifts</td></tr>
<tr><td>Minimal consumption</td></tr>
</table>

Also this spread sheet can be adapted to all the ships and tankers that need an energy optimization, being useful not only for this particular treated case.

5.3 Main Engines

5.3.1 Available Data

Main engines produce mechanical power for propulsion; when they are on, the shaft generator supplies the electrical power and the exhaust gas is recuperated by exhaust boilers, which provide thermal power to the tanker [6].
As Table 8 shows, this situation is related to FUL, BAL and CAR phases: the only one exception is during the BAL phase, because thermal power provided by exhaust boilers is not enough, then they are helped by auxiliary boilers.
The relevant available data of the main engines are:

1. Specific fuel consumption as function of the main engine's load [13];
2. Fuel mass flow as function of the main engine's load [13];
3. Temperature of the exhaust gas after the turbine of the main engine, as function of load [13];

Table 12 summarizes these data:

Table 12: Available Data of the Main Engines [13]

Power (kW)	Load (%)	Specific fuel consumption (g/kWh)	Fuel mass flow (kg/h)	T after turbine (°C)
4224	110	192,9	815	335
3840	100	190,9	733	328
3264	85	189,0	617	335
1920	50	199,0	382	391

It's necessary interpolating these data in order to estimate the specific consumption, the fuel mass flow and the temperature after turbine for all the punctual values of requested power.
A curve is created, which reproduce the trend of the specific fuel consumption (Figure 30) and the fuel mass flow (Figure 31) of the main engines. For the temperature after turbine, the curve that approximates its trend is shown in Figure 32. Below Figures 30-31, the equation that interpolates the punctual values is represented.

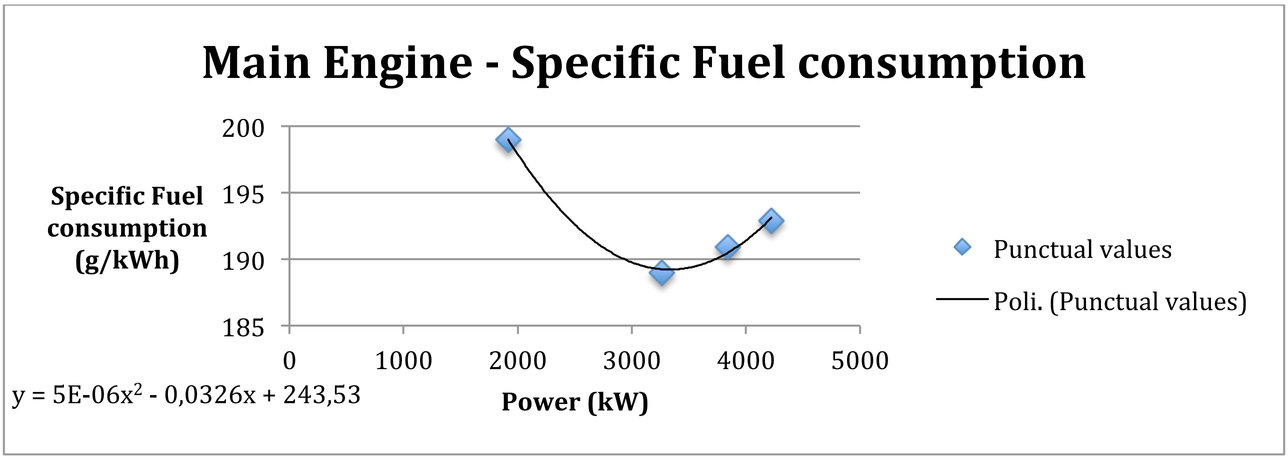

Figure 30: Specific Fuel consumption of the Main Engines [13]

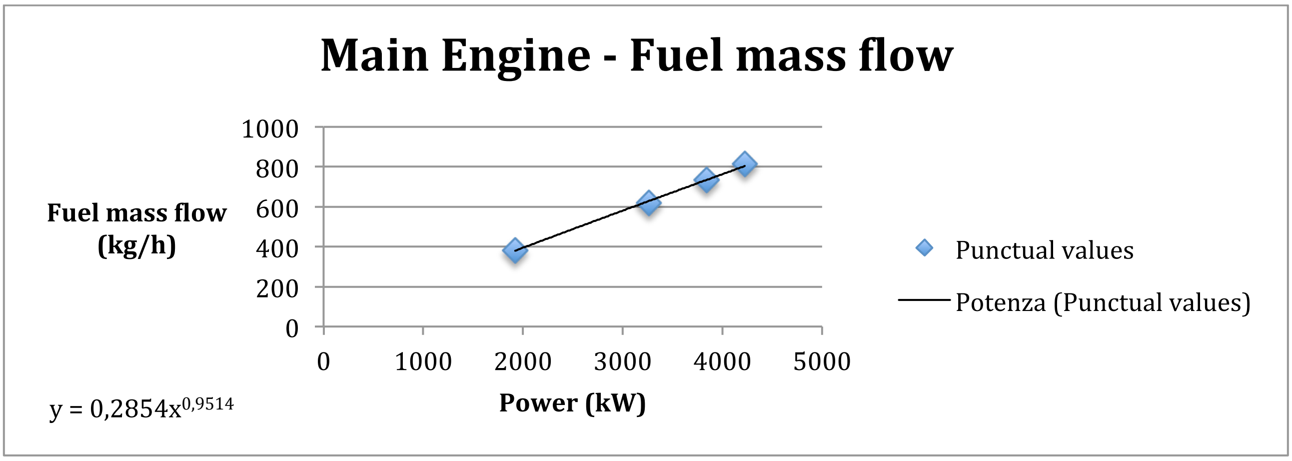

Figure 31: Fuel mass flow of the Main Engines [13]

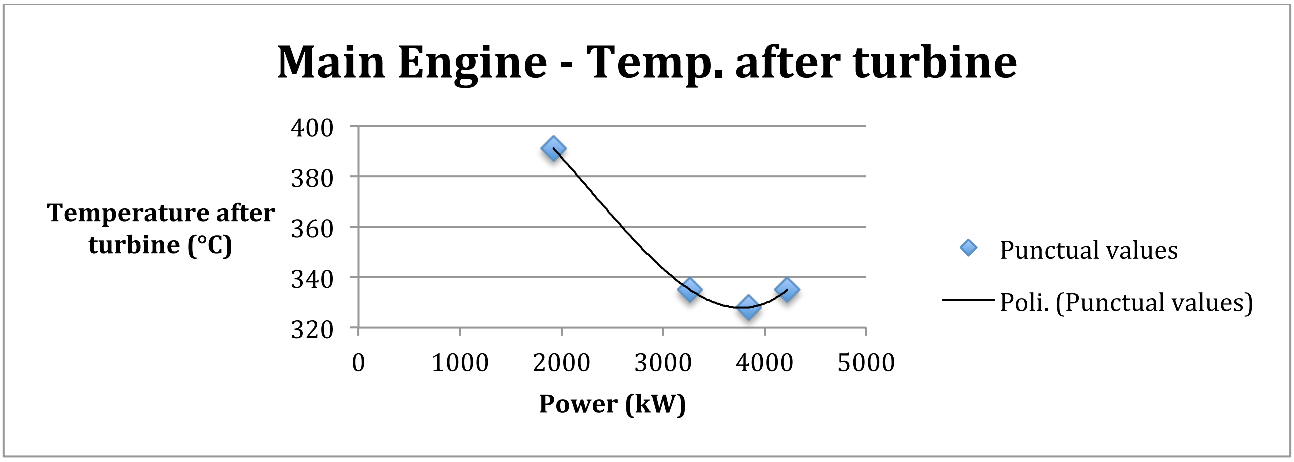

Figure 32: Temperature after turbine of the Main Engines [13]

Figure 30 shows a typical trend of a specific fuel consumption curve of a Diesel engine; minimal consumptions coincide with a load approximately equal to 85%. Furthermore, increasing the request of power, fuel mass flow increases and temperature after turbine decreases until full load.
The specific fuel consumption permits the calculation of the total consumption of fuel and allows the comparison between the consumptions obtained through different repartition of the load between the two engines.
The fuel mass flow and the temperature after turbine are fundamental for the estimation of the thermal power that exhaust boilers can provide, depending on the regime of the main engines. The thermal power provided by the exhaust boilers is represented by equation (2) [16]:

$$Q_{therm} = M_{tot} \times c_l \times (T_{aft} - T_{exh}) \times \eta_{exch} \qquad (2)$$

As Table 9 shows, c_l, T_{exh} and η_{exch} are fixed, so the only values that depend on the regime of the main engines are M_{tot} and T_{aft}: this is the reason why their trend is interpolated.

Mechanical and electrical values of power, after being incremented by considering the efficiencies mentioned above, are summed together: the main engines, in fact, have to satisfy both the request of power at the same time [6]. The corresponding thermal power produced is used to satisfy the thermal request of power: as it happens during the BAL phase, if the request is higher than the production, one auxiliary boiler is switched on.
After these considerations, the two main engines are going to be studied following the three configurations previously anticipated: load following, two shifts and minimal consumption.

5.3.2 Load Following

In the "load following" configuration both the main engines are always on: the sum of mechanical and electrical load is shared equally between them, even if this sum is lower than the load that can be provided by only one engine.
The production of thermal power is the consequence of the load to which the engines are running: in FUL and CAR phases this production is higher than the request, while during the BAL phase the situation is reversed and auxiliary boilers are switched on in order to supply the missing thermal power.
Through the interpolations of the curves previously described, it's possible evaluating the total annual consumption of fuel of the main engines (Table 13).

Table 13: Fuel annual consumption of the Main Engines – Load Following

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
3905,11	368,31	162,67	0	4436,10

The need of auxiliary boilers during the BAL phase is confirmed: the thermal power produced by the exhaust boilers, in fact, is always higher than the thermal request of power, except during the BAL phase. Moreover, during FUL and CAR phases, the excess of thermal power is wasted: this excess could be exploited through the use of thermal energy storage, which is treated in the following chapter.

5.3.3 Two Shifts

In the "two shifts" configuration, if the sum of mechanical and electrical load is equal or lower than the power that one single engine can supply, one of the two main engines is switched off. On the other hand, if this sum is higher than the power that one single engine can provide, the load is shared equally between the two engines. Results are shown in Table 14.

Table 14: Fuel annual consumption of the Main Engines – Two Shifts

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
3860,95	367,89	150,99	0	4379,83

The difference with the previous configuration is the use of one single engine instead of two when the request of power can be provided by only one of them. The ship has two Diesel engines, which curve of specific fuel consumption is represented in Figure 30. The specific consumption increases with the decrease of the engine's load: hence it's obvious that it's convenient working with one engine at high load than two engines at low load. Therefore, every time the requested power can be supplied by one engine (in other words when the requested power is equal or lower than the power that one engine can supply at full load), it's more convenient working with only one main engine: indeed, Table 14 shows a lower total annual consumption compared to the one achieved in the load following configuration.

Considerations about thermal power are the same described in the load following configuration, however the production of thermal power by the exhaust boilers is lower.
In the cases in which the load can be provided by only one engine, in the two shift configuration there is only one engine working, while in load following both the engines are running. At lower load, the temperature after turbine increases and the sum of the fuel mass flow of the two engines is higher than the fuel mass flow that one single engine at higher load would consume [13]. This fact leads to a higher production of thermal power by the exhaust boilers in the load following configuration compared to the two shifts one. Anyway, the thermal request is satisfied also in this case, always except for the BAL phase. From the thermal point of view, the convenience in adopting the load following configuration may be evident through the use of the thermal energy storage: this fact is going to be treated in the next chapter.

5.3.4 Minimal consumption

In the "minimal consumption" configuration, the curve of the specific fuel consumption of the two main engines is studied in order to find for every request of power the configuration that guarantees the minimal consumption of fuel. The results of this analysis are:

1. If the requested power is lower than the power that one single engine can produce at 100% of load (in this case 3840 kW), the best configuration states that the second engine must be switched off;
2. If the requested power is between 3840 kW and 4346,67 kW, the best solution is working with one main engine at full load (100%) and one main engine at the load necessary to provide the remaining power;
3. If the requested power is higher than 4346,67 kW, the best configuration is working with two main engines at the same load.

As the results show, the minimal consumption configuration (Table 15) is the same of the two shifts one, except for the introduction of the second point. The difference is almost negligible.

Table 15: Fuel annual consumption of the Main Engines – Minimal consumption

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
3856,05	366,94	150,99	0	4373,98

From thermal point of view, there is no significant variation with the two shifts configuration. The thermal power produced by the exhaust boilers is always lower than the one produced in the load following configuration. In the chapter of thermal energy storage, the advantages or disadvantages of using the load following configuration (higher fuel consumption for mechanical and electrical power, lower fuel consumption for the thermal one) instead of two-shifts/minimal configuration (lower fuel consumption for mechanical and electrical power, higher fuel consumption for the thermal one) are going to be discussed.

5.3.5 Comparison of Results

Table 16 shows a comparison, in terms of fuel consumption, between the three configurations adopted for the two main engines.

Table 16: Fuel annual consumption of the Main Engines – comparison

Configuration	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
Load following	3905,11	368,31	162,67	0	4436,10
Two Shifts	3860,95	367,89	150,99	0	4379,83
Minimal	3856,05	366,94	150,99	0	4373,98

As Table 16 proves, the minimal consumption configuration is the best, which is very similar to the two shifts one. Results evince that working always with two engines at the same load is expensive in terms of fuel consumption: this fact coincides with a higher outlay of money and with a greater emission of gas in the atmosphere.

However, the difference between the "load following" configuration and the "two shifts" one is small. The reason is that the curve of specific consumption is pretty "flat", so working at lower loads doesn't produce a significant increase in terms of fuel consumption.

5.4 Auxiliary Engines

5.4.1 Available Data

Auxiliary engines are used during the WAI phase, while the main engines are off. They don't produce mechanical power (there is no need during the waiting in port): when they are on, they drive the auxiliary generator that provides the electrical power. No exhaust gas is recuperated, hence thermal power is supplied by the auxiliary boilers [6].
The only one available data of the auxiliary engines is the specific consumption of fuel in design conditions (the load is assumed to be 85%, like the case of the main engines) [10]. The curve of specific fuel consumption is estimated following the same trend of the curve of the main engines. This is an assumption that doesn't reflect exactly the reality: smaller engines, in fact, usually have a "less flat" curve of specific fuel consumption than the bigger ones. This fact produces an underestimation of the consumption of the auxiliary engines: this outcome is going to be discussed afterwards.
Table 17 summarizes specific fuel consumption data obtained for the auxiliary engines.

Table 17: Specific Fuel consumption of the Auxiliary Engines

Power (kW)	Load (%)	Specific fuel consumption (g/kWh)
750	110	197
682	100	195
580	85	193
341	50	203

It's necessary interpolating these data in order to estimate the specific consumption for all the punctual value of requested power.
Figure 33 shows specific fuel consumption of the auxiliary engines.

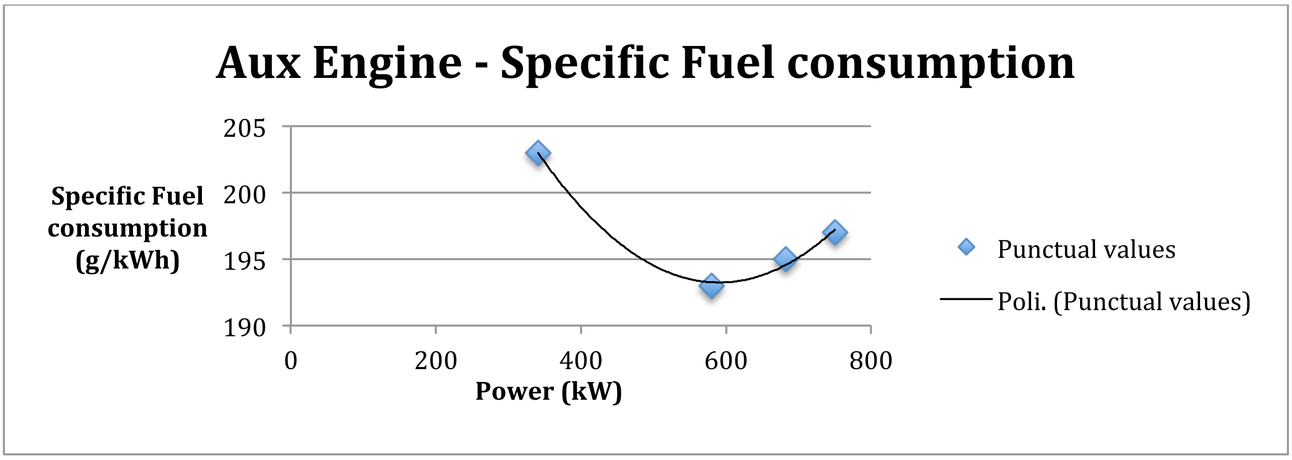

Figure 33: Specific Fuel consumption of the Auxiliary Engines

Figure 33 shows a typical trend of a Diesel engine. However, as previously said, the curve is too much flat for engines of that size: usually, the decrease of power demand produces a faster increase in specific fuel consumption than the one considered in this study.
The specific fuel consumption, also in this case, permits the calculation of the total consumption of fuel and allows the comparison between the consumptions obtained through different repartition of the load between the two engines.
Electrical values of power, after being incremented by considering the efficiency mentioned above, are the only input because no mechanical power is needed.
After these considerations, the two auxiliary engines are going to be studied following the same three configurations treated for the main engines: load following, two shifts and minimal consumption.

5.4.2 Load Following

In the "load following" configuration both the auxiliary engines are always on: the electrical load is shared equally between them, even if this load is lower than the load that can be provided by only one engine.
There is no production of thermal power, which is supplied by the auxiliary boilers.
Through the interpolations of the curves previously described, it's possible evaluating the total annual consumption of fuel of the auxiliary engines (Table 18).

Table 18: Fuel annual consumption of the Auxiliary Engines – Load Following

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	0	0	262,47	262,47

5.4.3 Two Shifts

In the "two shifts" configuration, if the electrical load is equal or lower than the power that one single engine can provide, one of the two auxiliary engines is switched off. On the other hand, if this load is higher than the power that one single engine can supply, the load is shared equally between the two engines. Results are shown in Table 19.

Table 19: Fuel annual consumption of the Auxiliary Engines – Two Shifts

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	0	0	253,16	253,16

The difference with the previous configuration is the use of one single engine instead of two when the request of power can be provided by only one of them. Looking at the curve (Figure 33), the specific consumption increases with the decrease of the engine's load: hence, even in this case, it's convenient working with one engine at high load than two at low load.
Table 19 shows a lower total annual consumption compared to the one achieved in the load following configuration.

5.4.4 Minimal consumption

In the "minimal consumption" configuration, the curve of the specific fuel consumption of the two auxiliary engines is studied in order to find for every request of power the configuration that guarantees the minimal consumption of fuel. The results of this analysis are:

1. If the requested power is lower than the power that one single engine can produce at full load (in this case 682 kW), the best configuration states that the second engine must be switched off;
2. If the requested power is between 682 kW and 1160 kW, the best solution is working with one auxiliary engine at design conditions (85%) and one auxiliary engine at the load necessary to provide the remaining power;
3. If the requested power is higher than 1160 kW, the best configuration is working with two auxiliary engines at the same load.

As the results show, the minimal consumption configuration (Table 20) is very similar to the two shifts one. The difference is almost negligible.

Table 20: Fuel annual consumption of the Auxiliary Engines – Minimal consumption

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	0	0	253,10	253,10

5.4.5 Comparison of Results

Table 21 shows a comparison, in terms of fuel consumption, between the three configurations adopted for the two auxiliary engines.

Table 21: Fuel annual consumption of the Auxiliary Engines – comparison

Configuration	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
Load following	0	0	0	262,47	262,47
Two Shifts	0	0	0	253,16	253,16
Minimal	0	0	0	253,10	253,10

Looking at the punctual request of electrical power during the WAI phase, it's important saying that it's almost always lower than 682 kW [7], so it's possible working with only one auxiliary engine practically at all time. This fact is confirmed by the negligible difference between the "two shifts" configuration and the "minimal consumption" one: this latter works almost always following the first point previously mentioned, that coincides with the logic adopted by the two shifts configuration.
These considerations suggest that, during the WAI phase, it could be possible working with one auxiliary engine, using the second one only in cases of maintenances and failures and when there is a particular request that overcomes the maximum power that one engine can provide.
Results evince again that working always with two engines at the same load is expensive in terms of fuel consumption: this fact coincides with a higher outlay of money and with a greater emission of gas in the atmosphere. However, the difference between the "load following" configuration and the "two shifts" one is small. The reason is that the curve of specific consumption is pretty "flat", so working at lower loads doesn't produce a significant increase in terms of fuel consumption; therefore, the adopted curve approximation reduces the difference between the two configurations (in particular it underestimates the consumption in load following).

5.5 Auxiliary Boilers

5.5.1 Available Data

Auxiliary boilers are used during the BAL and the WAI phase. In the first one they help the exhaust boilers, providing the missing thermal power; in the second one, no exhaust gas is recuperated, hence thermal power is entirely supplied by the auxiliary boilers [9]. The only one helpful data is the maximum amount of steam per hour that each boiler can produce [6]:

- 28 000 kg of steam / hour (2 x 14000) at 14 bar

After some conversions and considering saturated steam at 14 bar, the maximum power produced by each auxiliary boiler at full load (100%) is equal to 7613,28 kW.
No data are available concerning the consumption of fuel, so the curve of specific fuel consumption is estimated following the typical trend of a boiler curve:

- At full load (100%) the efficiency is equal to 90%;
- At half load (50%) the efficiency is equal to 80%.

Table 22 summarizes specific fuel consumption data estimated for the auxiliary boilers.

Table 22: Specific Fuel consumption of the Auxiliary Boilers

Power (kW)	Load (%)	Specific fuel consumption (g/kWh)
7613,28	100	99,01
3806,64	50	111,39

It's necessary interpolating these data in order to estimate the specific consumption for all the punctual value of requested power. The assessed curve is shown in Figure 34. Below the curve, the equation that interpolates the punctual values is represented.

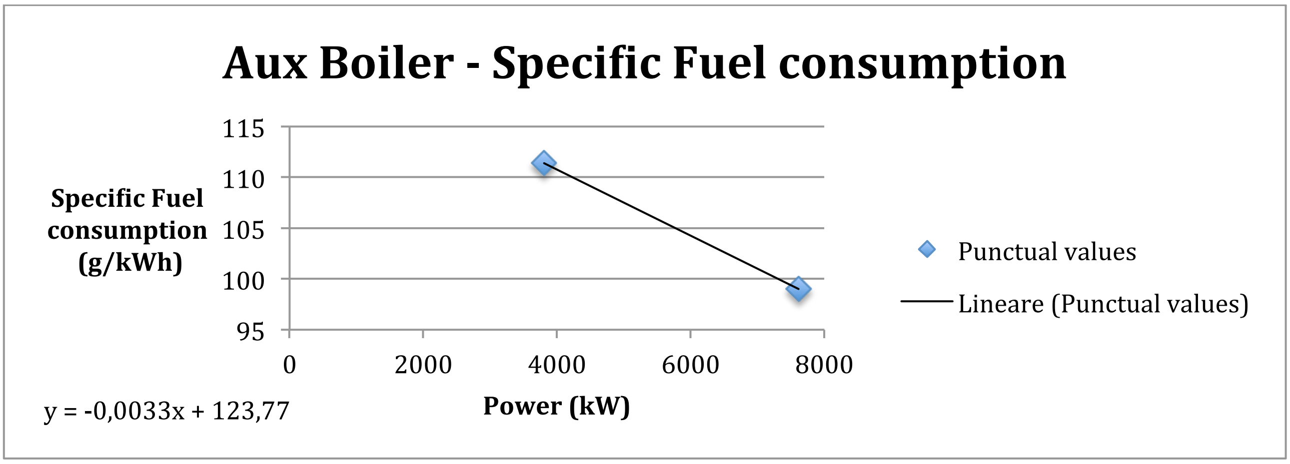

Figure 34: Specific Fuel consumption of the Auxiliary Boilers

The specific fuel consumption, also in this case, permits the calculation of the total consumption of fuel and allows the comparison between the consumptions obtained through different repartition of the load between the two boilers.
The input of thermal power, in the WAI phase, is represented by the total request of thermal power every hour; instead, in the BAL phase, the input of thermal power is the difference between the total request every hour and the amount of power that the exhaust boilers can provide [6].
After these considerations, the two auxiliary boilers are going to be studied following the same three configurations treated for the main and auxiliary engines: load following, two shifts and minimal consumption.

5.5.2 Load Following

In the "load following" configuration both the auxiliary boilers are always on: the thermal load is shared equally between them, even if this load is lower than the load that can be provided by only one boiler.
Through the interpolations of the curve previously described, it's possible evaluating the total annual consumption of fuel of the auxiliary boilers (Table 23).

Table 23: Fuel annual consumption of the Auxiliary Boilers – Load Following

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	40,79	0	114,51	155,30

During the BAL phase, also the main engines follow the load following configuration. It's important to state that the amount of thermal power produced by the exhaust boilers in load following is different than the thermal power produced if the main engines are in two shifts, as it is said in the chapter of the main engines. So, changing the configuration of the main engines, thermal power produced by the exhaust boilers changes and then the missing thermal power that the auxiliary boilers must provide changes as well. Ultimately, in this case both auxiliary boilers and main engines are considered in load following.
During the WAI phase this fact is not relevant, because there is no thermal power production, so the auxiliary boilers must provide the total thermal power requested every hour.

5.5.3 Two Shifts

In the "two shifts" configuration, if thermal load is equal or lower than the power that one single boiler can supply, one of the two auxiliary boilers is switched off. On the other hand, if this load is higher than the power that one single boiler can provide, the load is shared equally between the two boilers. Results are shown in Table 24.

Table 24: Fuel annual consumption of the Auxiliary Engines – Two Shifts

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	41,51	0	114,10	155,61

During the BAL phase, also the main engines follow the two shifts configuration. It's important to state that, due to the reasons previously explained in the load following section.
The difference with the preceding configuration is the use of one single boiler instead of two when the request of power can be provided by only one of them. Looking at the curve (Figures 34), the specific consumption increases with the decrease of the boiler's load: hence, even in this case, it should be convenient working with one boiler at high load than two at low load. However, in the "two shifts" configuration the total consumption of fuel is very slightly higher than the one obtained in "load following". These results are going to be analysed.
In the WAI phase the consumption is lower following the two shifts configuration: this is explained by the fact that in this phase there is no recuperation of thermal power, so the request of thermal power is the same in both the configurations. Hence, always referring to the curve (Figure 34), it's convenient working with one boiler at high load than two at low load.
In the BAL phase the consumption in two shifts is higher than the one in load following. This is due to the higher production of thermal power by the exhaust boilers in load following than the one produced in two shifts: the auxiliary boilers must provide more power in this latter configuration, so they consume more.
The sum of consumptions reveals that load following is slightly better than two shifts. However, working in load following with the main engines is less convenient than working in two shifts: for

this reason it's necessary finding a trade off that can achieve the minimal consumption of the auxiliary boilers together with the minimal consumption of the main engines.
In conclusion there is an important consideration to say. Both in WAI and BAL phases, the request of thermal power is much lower than the maximum power that a single auxiliary boiler can provide. This fact leads to three consequences:

1. Only one auxiliary boiler works, the second one is always switched off except in cases of maintenance and failure;
2. These auxiliary boilers are oversized and they could become even more oversized if a thermal energy storage system was put into account;
3. The differences in consumption between the two configurations is always very low, because the boiler, in both the cases, works more or less at the same efficiency (70-75%), so the specific consumptions are almost the same.

5.5.4 Minimal consumption

The goal is to find the configuration that guarantees the minimal consumption of fuel for both the auxiliary boilers and the main engines. The results of this analysis are:

1. In the WAI phase, the minimal consumption is the one obtained in "two shifts";
2. In the BAL phase, the minimal consumption is the one obtained in "two shifts" for both the auxiliary boilers and the main engines, except in the case when the total amount of mechanical and electrical requested power can be supplied by only one main engine. In this case, it's more convenient working with two main engines at the same load (load following configuration) and always following the two shifts configuration for the auxiliary boilers.

Table 25 explains point 2. The particular case under study is when the sum of mechanical and electrical loads is lower than the power that one engine can provide at full load (3840 kW). With main engines in load following (both working) the consumption is higher than the one obtained in two shifts configuration (only one working). However, in load following the production of thermal power is higher than the one produced in the two shifts configuration, so the auxiliary boilers consume more in two shifts than in load following. Table 25 shows that the sum of consumptions of the main engines and auxiliary boilers is higher in two shifts, so in this particular case is convenient the load following configuration.
Table 25 considers a punctual request of power in BAL phase as example.

Table 25: Comparison between load following and two shifts

Configuration	Main Engines consumption (ton)	Auxiliary Boilers consumption (ton)	Total consumption (ton)
Load following	0,674	0,079	0,753
Two shifts	0,631	0,200	0,831

Table 26 shows the results obtained following the "minimal consumption" configuration for the auxiliary boilers.

Table 26: Fuel annual consumption of the Auxiliary Boilers – Minimal consumption

FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
0	40,27	0	114,10	154,38

5.5.5 Comparison of Results

Table 27 shows a comparison, in terms of fuel consumption, between the three configurations adopted for the two auxiliary boilers.

Table 27: Fuel annual consumption of the Auxiliary Boilers – comparison

Configuration	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
Load following	0	40,79	0	114,51	155,30
Two Shifts	0	41,51	0	114,10	155,61
Minimal	0	40,27	0	114,10	154,38

As Table 27 suggests, the differences in total consumption are negligible. The meaning of the difference between load following and two shifts has been discussed above. The "minimal consumption" configuration is simply obtained putting into account the considerations debated in the previous section.

5.6 Results

5.6.1 Discussion and comparison with Real consumption

It's possible summarizing all the obtained results in a single table, in order to have a general overview of the achieved outcomes, which are compared with the real consumption of the tanker. Table 28 shows the situation. "Minimal consumption" is the best configuration for all the three devices from the energy point of view.

Table 28: Fuel annual consumption of the tanker – comparison with Real consumption

Device	Config.	FUL cons. (ton)	BAL cons. (ton)	CAR cons. (ton)	WAI cons. (ton)	Total cons. (ton)	Real cons. (ton)
Main Engines	Load F.	3905,11	368,31	162,67	0	4436,10	4583
	2 Shifts	3860,95	367,89	150,99	0	4379,83	
	Min	3856,05	366,94	150,99	0	4373,98	
Aux. Engines	Load F.	0	0	0	262,47	262,47	423
	2 Shifts	0	0	0	253,16	253,16	
	Min	0	0	0	253,10	253,10	
Aux. Boilers	Load F.	0	40,79	0	114,51	155,30	214
	2 Shifts	0	41,51	0	114,10	155,61	
	Min	0	40,27	0	114,10	154,38	

The last column shows the real consumption of the tanker during one particular operational year [6]. The configuration adopted for the devices is unknown, however it's possible to make the assumption that all the engines and boilers are in "load following" configuration [6]. Table 29 proves the difference between real values of consumption and values obtained in load following calculations.

Table 29: Differences between Real consumption and Load Following calculations

Configuration	Total consumption ME (ton)	Difference ME (%)	Total consumption AE (ton)	Difference AE (%)	Total consumption AB (ton)	Difference AB (%)
Load following	4436,10	3,2	262,47	38	155,30	27,4
Real	4583		423		214	

The difference is very small regarding the main engines; on the other hand, calculations on auxiliary engines and boilers show a lower similarity compared to reality. One important fact is that real consumptions are always higher than the estimated ones: during this study, many considerations have been neglected and these approximations inevitably lead to lower consumptions than real ones. There are many factors that may produce differences between calculations and real data. These factors are divided into two different groups: the first one refers to general factors; the second one refers to those approximations made due to missing data.

General factors include all the approximations made neglecting efficiencies and real behaviours of the devices that would have complicated the study without any great advantage from the accuracy point of view [15]. There are many general factors that may be listed; the principal ones are:

1. The ambient temperature changes and then it modifies the engines and boilers' performance;
2. Maintenances, failures and malfunctions influence the performance as well;
3. Load's regulation produces a higher consumption: calculations don't put into account this factor;
4. Also start-up transients influence the real consumption: they are not considered into this study;
5. Filters clogging is a real problem, difficult to be debated and modelled;
6. There are many other efficiencies that for simplicity are neglected, but in reality they influence the general behaviour of the device.

The second group is made by all the missing data that led to approximations that most of the times don't represent the real situation. In this study, the most important missing data are:

1. Real consumptions during tank cleaning, which represent the greatest thermal consumption;
2. Curves of specific fuel consumption of the auxiliary engines and boilers.

Main engines are influenced only by the first group of factors, because many data have been available for these devices. The gap between estimated consumptions and real ones is almost negligible. This fact demonstrates that all the significant considerations have been put into account.
Auxiliary engines and boilers are influenced by both the first and the second groups. In this case, the difference between real data and estimated ones is higher: this fact proves that missing information represents a great threat to the results of this study. In particular, the curve of specific consumption of the auxiliary engines is too much "flat" for engines of that size: having the real curve would have reduced the gap with real data. The same goes for the curve of specific consumption of the auxiliary boilers, which seems to be estimated in a better way, together with the evaluation of the tank-cleaning request of power.

5.6.2 Cost Savings and Environmental Impacts

After this optimization analysis, it's time to estimate the economical and environmental advantages that this study can lead. The comparison is made between the real situation and the three analysed configurations (load following, two shifts and minimal consumption). The outcomes of this evaluation are influenced by all the factors previously discussed (groups 1 and 2), so they don't reflect the exact saving that can be achieved, but they give an idea of the improvement's order of magnitude that this optimization can obtain.

From the economical point of view, it's necessary finding a reference price of the fuel oil used on the tanker. The cost of fuel varies from day to day, and especially from place to place. Today, the indicative price of fuel oil for marine engines is between 500 and 700 U.S. dollars/ton [6]. For instance, the price ranges from 612 U.S. dollars/ton in Singapore up to 755 U.S. dollars/ton in Valparaiso [6]. When ships are sailing in emission controlled areas (North American territorial waters, Baltic Sea, North Sea) they should use a better fuel, called MGO (Marine Gas Oil), which price, instead, fluctuates between 900 and 1100 U.S. dollars/ton [6]. Due to lack of information regarding the places in which the tanker refuels and regarding how many times the ship sails in emission controlled areas, an average fuel price is put into account in this economical analysis. The chosen value is 800 U.S. dollars/ton of fuel oil.

From the environmental point of view, CO_2 and NO_x emissions are considered. In the combustion of fuel oil, the reference value for CO_2 emissions (complete combustion) is 3,148 ton CO_2/ton of fuel [1]; instead for NO_x emissions, the reference value of the engines on board is 1,687 ton NO_x/ton of fuel [13].

Table 30 and 31 show the economical and environmental advantages obtained through the hypothesis just explained. The last column describes the difference between the configuration under observation and the previous one.

Table 30: Annual Cost Savings compared to the Real expense

Configuration	Saved money Main Engines (U.S. dollars)	Saved money Aux Engines (U.S. dollars)	Saved money Aux Boilers (U.S. dollars)	Total Saving (U.S. dollars)	Saving compared with the previous configuration (U.S. dollars)
Real	**0**	**0**	**0**	**0**	**0**
Load following	**117 519**	**128 424**	**46 962**	**292 905**	**292 905**
Two Shifts	**162 535**	**135 872**	**46 708**	**345 115**	**52 210**
Minimal	**167 213**	**135 923**	**47 698**	**350 834**	**5 719**

Table 31: Annual reduction of CO_2 and NO_x Emissions compared to the Real emissions

Configuration	Emission Reduction Main Engines (ton)		Emission Reduction Aux Engines (ton)		Emission Reduction Aux Boilers (ton)		Total Emission Reduction (ton)		Emission Reduction compared with the previous configuration (ton)	
Compound	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x
Real	0	0	0	0	0	0	0	0	0	0
Load following	462	248	505	271	185	99	1153	618	1153	618
Two Shifts	640	343	535	287	184	98	1358	728	205	110
Minimal	658	353	535	287	188	101	1381	740	23	12

Tables 30 and 31 show the overall situation putting into account the hypothesis explained up to now. The user can change these assumptions into the spread sheet in order to modify the results automatically. This tool can be adapted to many ships and tankers, giving the possibility to obtain a fast and accurate outcome. The more data are available on the devices on board, the more the optimization study is precise.

Looking at Tables 30 and 31, the difference between "load following" configuration and the other two is one order of magnitude greater than the difference between "minimal consumption" configuration and "two shifts" one for both emissions and money.
The greatest gap is between the three configurations and real data, but this difference is mostly due to all the factors previously discussed into the section 5.6.1.
The "two shifts" configuration (the same is valid for the "minimal consumption" one) seems to be better than load following one. However, the number of switching on and off is higher during one year, because of the logic that "two shifts" and "minimal consumption" configurations adopt. This means higher consumption due to all the factors previously mentioned in the group 1 into the section 5.6.1, but these factors are not considered in this optimization study. The owner of the ship have to evaluate the maximum number of switching on and off beyond which is no more convenient following the "two shifts" or "minimal consumption" logic instead of the "load following" one.
Considering the "load following" configuration as the worst from the energy point of view, it's possible calculating the relative saving achieved with the other two configurations.
Table 32 explains the situation.

Table 32: Absolute and Relative savings compared to "Load Following" configuration

Configuration	Absolute saving compared with load following (U.S. dollars)	Relative saving compared with load following (%)
Two shifts	**52 210**	**1,34**
Minimal consumption	**57 929**	**1,49**

Table 32 proves that relative savings are low: during one operational year, through this energy optimization, is possible to save about 1,5% of the total economical expense for fuel. However, reduction in CO_2 and NO_x emissions is a further point that must be considered as positive result in this analysis. It's difficult evaluating emissions in terms of saved money but this fact must not lead to an underestimation of this problem. Saving money could be classified as short-term problem; on the other hand, emissions are a long-term trouble that must be solved since now in order to avoid that the situation became unsustainable for next generations.

The presented optimization regarded exclusively the energy system on board. A subsequent investigation may suggest the introduction of a thermal energy storage system that could permit to save energy and money, together with a further reduction of emissions.
This system is going to be discussed in the next chapter: advantages, disadvantages and comparisons between different solutions are going to be debated and presented, together with final results that are going to clarify if the system could be considered a convenient improvement of the energy system on board.

6. Introduction of a Thermal Energy storage System

6.1 Importance of a Thermal Energy storage System

In general, energy storage systems are important means that permit the exploitation of energy that would be wasted. The feasibility of such a system must be evaluated considering two particular guidelines together [16]:

1. The size of the storage system;
2. The convenience to accumulate energy, in terms of money and emissions.

It's not always possible to have available space to store energy, just think about the automotive case. Furthermore, a trade off between size and convenience must be achieved, otherwise the design of a storage system results not feasible.
In the chemical tanker case, the available space is not considered a problem: this is a reasonable assumption due to the large size of the ship [6].
Moreover, as previously discussed, excess steam is produced and wasted in the FUL and CAR phases. However, during the BAL and WAI phases, auxiliary boilers are switched on in order to supply the missing thermal power [6]. Therefore, the goal is to accumulate thermal energy wasted in FUL and CAR and afterwards exploiting it in BAL and WAI, reducing and maybe avoiding the use of auxiliary boilers. In this study three solutions are presented and discussed:

1. A storage tank able to accumulate 80000 kWh (more or less equal to the energy provided by one auxiliary boiler at full load working for 10 hours);
2. A storage tank able to accumulate 40000 kWh (more or less equal to the energy provided by one auxiliary boiler at full load working for 5 hours);
3. A storage tank able to accumulate 8000 kWh (more or less equal to the energy provided by one auxiliary boiler at full load working for 1 hours);

The adopted sequence of phases is reported below; its choice is now discriminating:

1. WAI
2. CAR
3. BAL
4. CAR
5. FUL

This sequence repeats 10 times over one year. The accumulation starts with the first CAR phase, because main engines are off during the first waiting in port so exhaust boilers don't produce thermal energy, thus auxiliary boilers are on. The accumulated thermal energy during CAR and FUL is the difference between the energy produced by the exhaust boilers and the one exploited due to the request of thermal power. Every hour of CAR and FUL, the excess of energy is stored and summed to the amount of energy stored until the previous hour. This sum proceeds up to the saturation of the tank's capacity.
Looking at the adopted sequence, the accumulation starts with the first CAR phase; afterwards, the tank begins to empty during the BAL phase, due to the high request of thermal power (which overcomes the produced one). After that, another phase of CAR allows to accumulate energy, followed by the FUL phase, which contributes as well to the storage. Finally the sequence restarts, but now there is a certain amount of stored energy that can be exploited during the WAI phase.
In all the cases the stored energy is lower than the requested one, an auxiliary boiler must be switched on in order to supply the missing energy.
In the preceding chapters it's explained that the exhaust boilers, depending on the configuration of the main engines, produce a different amount of thermal energy. For instance, in "load following" the production of thermal energy is higher than the one in "two shifts": for this reason, the energy storage system is studied depending on the configuration of the main engines. The optimization, in this case, must put into account also the consumption of the main engines. The three configurations are always the same:

- "Load following" configuration;
- "Two shifts" configuration;
- "Minimal consumption" configuration.

6.2 Load Following

The main engines are in "load following". The situation is studied considering the three tank's capacities listed above. Table 33 shows the annual consumption.

Table 33: Fuel annual consumption of Auxiliary Boilers with storage – Load Following

Tank capacity (kWh)	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
80 000	0	0	0	15,80	15,80
40 000	0	0	0	65,24	65,24
8 000	0	31,66	0	104,49	136,15

Obviously, decreasing tank's capacity total consumption increases. Considering the chosen sequence of phases, consumption in BAL is equal to zero with a capacity of 80000 and 40000 kWh.

6.3 Two shifts

The main engines are in "two shifts". The situation is studied considering the three tank's capacities listed above. Table 34 shows the annual consumption.

Table 34: Fuel annual consumption of Auxiliary Boilers with storage – Two shifts

Tank capacity (kWh)	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
80 000	0	23,01	0	15,80	38,81
40 000	0	23,01	0	65,24	88,24
8 000	0	32,90	0	104,49	137,39

Due to lower production of thermal energy by the exhaust boilers in "two shifts" configuration, consumption in BAL is never equal to zero. Consumption in WAI is equal to the one in "load following" because in this phase there is no production of thermal energy by the exhaust boilers because main engines are off.

6.4 Minimal consumption

Table 33 and 34 show that load following is more convenient than two shifts regarding the consumption of the auxiliary boilers; on the other hand, load following is less convenient than two shifts concerning the consumption of the main engines. Table 35 considers both the consumptions and it reveals what is the best configuration between them.

Table 35: Comparison between Load Following and Two Shifts annual consumptions

Tank capacity (kWh)	Configuration	Main Engines consumption (ton)	Auxiliary Boilers consumption – with storage (ton)	Total consumption (ton)
80 000	Load Following	4436,10	15,80	4451,90
	Two shifts	4379,83	38,81	4418,64
40 000	Load Following	4436,10	65,24	4501,34
	Two shifts	4379,83	88,24	4468,08
8 000	Load Following	4436,10	136,15	4572,25
	Two shifts	4379,83	137,39	4517,22

"Two shifts" configuration turns out to be always the best and it must be considered as the base to calculate the minimal thermal consumption obtainable through the use of a storage system.
The minimal consumption approach starts from the "two shifts" one and it tries to improve this latter.
In the WAI phase, load following and two shifts configurations are exactly the same, always due to the fact that main engines are off: there is no way to reduce consumptions in this case.
In the BAL phase, the only one difference between load following and two shifts is represented by a particular situation, that is when the sum of mechanical and electrical loads is lower than the power that one engine can provide at full load (3840 kW). With main engines in load following (both working) the consumption is higher than the one obtained in two shifts configuration (only one working). However, in load following the production of thermal power is higher than the one produced in the two shifts configuration, so the auxiliary boilers consume more in two shifts than in load following. As mentioned in a previous chapter, in this particular case is convenient the load following configuration of the main engines. This is the only one modification that can improve the two shifts configuration. Adopting the load following out from this exception, it leads to higher total consumptions, as Table 35 proves.
Table 36 shows the annual consumption of auxiliary boilers with a storage system, following the "minimal consumption" configuration just explained.

Table 36: Fuel annual consumption of Auxiliary Boilers with storage – Minimal cons.

Tank capacity (kWh)	FUL consumption (ton)	BAL consumption (ton)	CAR consumption (ton)	WAI consumption (ton)	Total consumption (ton)
80 000	**0**	**21,77**	**0**	**15,80**	**37,57**
40 000	**0**	**21,77**	**0**	**65,24**	**87,01**
8 000	**0**	**31,66**	**0**	**104,49**	**136,15**

6.5 Results and Discussions

Table 37 shows total consumptions obtained with the three configurations, varying tank capacity. It summarizes results obtained in Tables 33-34-36.
Hence it's possible to have an overview of the results obtained with a thermal energy storage system on board. "Minimal consumption" configuration is the best because of the just explained reasons.

Table 37: Fuel annual consumption of Auxiliary Boilers with storage – Overview

Tank capacity (kWh)	Load Following consumption (ton)	Two Shifts consumption (ton)	Minimal consumption (ton)
80 000	15,80	38,81	37,57
40 000	65,24	88,24	87,01
8 000	136,15	137,39	136,15

Table 38 reveals absolute and relative savings obtained comparing the situations with and without the energy storage. The last column shows relative thermal saving considering the total annual consumption of the tanker.
Considering the first two columns, Table 38 shows that thermal energy storage system is much convenient. In the minimal consumption configuration, with a tank able to store 80.000 kWh, the system allows to save almost 76% of the total thermal energy requested. However, the relative thermal saving considering the whole annual consumption of the tanker is low (2,44%): this is due to the fact that consumptions for thermal energy represent the 3,22% of the total consumptions, so the room for improvement is low.

Table 38: Absolute and Relative Savings

Tank capacity (kWh)	Configuration	Absolute thermal energy saving compared with the same configuration without storage (U.S. dollars)	Relative thermal energy saving compared with the same configuration without storage (%)	Relative thermal saving considering the total annual consumption of the tanker (%)
80 000	Load Following	111 600	89,83	2,87
	Two shifts	93 446	75,06	2,44
	Minimal	93 446	75,66	2,44
40 000	Load Following	72 050	57,99	1,86
	Two shifts	53 896	43,29	1,41
	Minimal	53 896	43,64	1,41
8 000	Load Following	15 319	12,33	0,39
	Two shifts	14 583	11,71	0,38
	Minimal	14 583	11,81	0,48

Table 39 shows the same situation, but now regarding the emissions reduction. Load following is the best from the thermal point of view, but Table 35 proves that in general it's less convenient due to higher consumption of the main engines. Therefore, "minimal consumption" configuration comes from the "two shifts" one and it makes use of the load following configuration of the main engines when the sum of mechanical and electrical load is lower than 3840 kW (full load of one main engine).

Table 39: Annual Emissions Reduction obtained with a Thermal Energy Storage System

Tank capacity (kWh)	Configuration	Reduction compared with the same configuration without storage (ton)		Reduction compared with Real data (ton)		Reduction compared with the previous configuration (ton)	
	Compound	CO_2	NO_x	CO_2	NO_x	CO_2	NO_x
80 000	Real	0	0	0	0	0	0
	Load Following	439	235	624	334	624	334
	Two shifts	368	197	552	296	-72	-38
	Minimal	368	197	555	298	3	2
40 000	Real	0	0	0	0	0	0
	Load Following	284	152	468	251	468	251
	Two shifts	212	114	396	212	-72	-39
	Minimal	212	114	400	214	4	2
8 000	Real	0	0	0	0	0	0
	Load Following	60	32	245	131	245	131
	Two shifts	57	31	241	129	-4	-2
	Minimal	57	31	245	131	4	2

At the end of this analysis it's important understanding the size of the tank that allows working with auxiliary boilers always off. Table 40 shows the results of this study. A tank capacity of 92.900 kWh permits the auxiliary boilers switching off in load following configuration; on the contrary, auxiliary boilers are always off in "two shifts" and "minimal consumption" if the size of the tank is respectively of 111.150 and 110.100 kWh.

Table 40: Tank size in order to have Auxiliary Boilers always off

Configuration	Tank size in order to have Auxiliary Boilers always off (kWh)
Load following	**92 900**
Two shifts	**111 150**
Minimal consumption	**110 100**

Conclusion

At the end of this study, it's very important providing the recapitulation of the achieved results. Here, only the "minimal consumption" configuration is represented, which has proved to be the best one from the optimization analysis. Load following configuration is always considered the worst from the energy point of view [6], so real consumptions are assumed to coincide with load following ones.
Figure 35 shows the relative thermal energy saving that can be obtained through "minimal consumption" configuration, varying tank's capacity of the energy storage system. With no storage, the saving is almost equal to zero (0,59%); on the other hand, a capacity of 110.000 kWh assure to save the 100% of the fuel consumed by auxiliary boilers (considering the adopted alternation of the phases). The relative saving is obtained comparing "minimal consumption" configuration with the real one (load following values).
Figure 35 proves that energy storage can be of significant importance; obviously, economic analysis should be performed in order to find the tank's capacity that may guarantee the maximum profit.

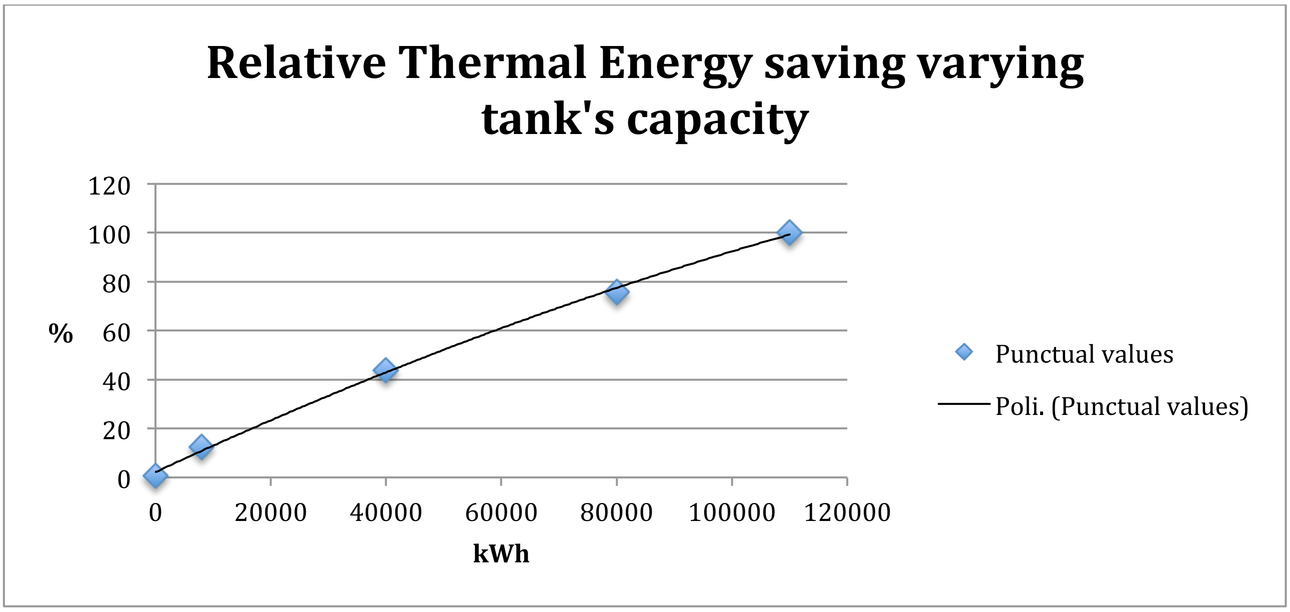

Figure 35: Relative Thermal Energy saving varying tank's capacity

Figure 36 shows instead the relative energy saving that can be obtained through "minimal consumption" configuration, varying tank's capacity of the energy storage system. Therefore, in this case the attention is focussed on the total relative saving that can be achieved through "minimal consumption" configuration, comparing it with real situation (load following values).

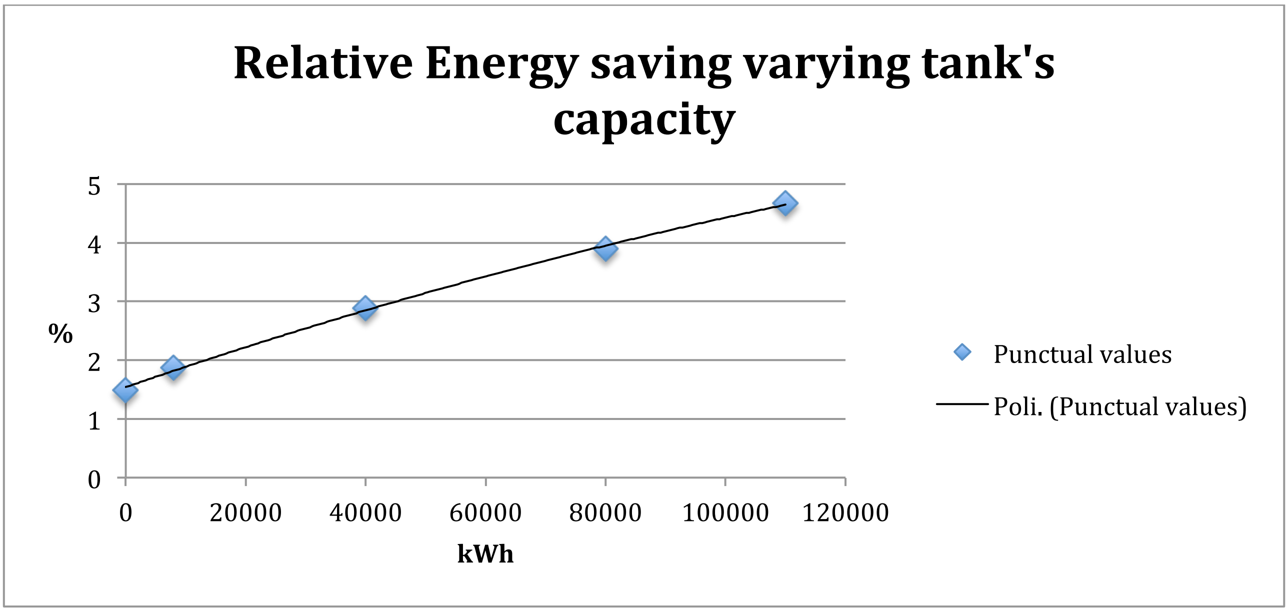

Figure 36: Relative Energy saving varying tank's capacity

With no storage, the saving is 1,49%; on the other hand, a capacity of 110.000 kWh assure to save 4,67% of the total fuel consumed by the ship during one operational year (considering the adopted alternation of the phases).

Both Figures 35 and 36 are summarized in Table 41.

Table 41: Relative Energy saving (thermal and total) varying tank's capacity

Tank capacity (kWh)	Relative Thermal Energy saving (%)	Relative Energy saving (%)
110 000	100	4,67
80 000	75,81	3,90
40 000	43,97	2,88
8 000	12,33	1,87
0	0,59	1,49

Following the "minimal consumption" configuration, the two main results are underlined in Table 41.

With no thermal energy storage system, the relative total saving is not so high (1,49%), however this saving is completely "free" because it can be achieved only by following some simple rules in energy management. Thinking in absolute terms, it's possible to save 72 tons/year of fuel, corresponding to about 58.000 U.S. Dollars/year (Table 42). This is certainly a great result and it must be a sort of stimulus to efficiency.

On the other hand, with a thermal energy storage system of 110.000 kWh it's possible saving 4,67% of the total fuel consumption over one operational year. In this case the cost of this system must be put into account and through economic analysis the size of the tank that ensures the minimal expense have to be found. In absolute terms it's possible to save 227 tons/year of fuel, corresponding to about 180.000 U.S. Dollars/year (Table 42).

Table 42 shows the absolute savings in terms of tons/year and U.S. Dollars/year achieved through the "minimal consumption" configuration, varying tank's capacity.

Table 42: Absolute Energy saving varying tank's capacity

Tank capacity (kWh)	Absolute Energy saving (ton/year)	Absolute Energy saving (U.S. Dollars/year)
110 000	**227**	**181 431**
80 000	**189**	**151 375**
40 000	**140**	**111 825**
8 000	**91**	**72 512**
0	**72**	**57 929**

The introduction of a new system on board proves the increase of efficiency and reduction of costs and emissions. This study works on the energy system already installed on board, optimizing its configuration and trying to add some elements that can improve energy exploitation. However no mention has been made about the idea of a new energy system, different from the actual ones based on diesel engines. This fact would be a revolution in the business world, but nowadays researchers are not still ready to put into the market a revolutionary energy system that is able to ensure higher efficiency at the same reliability of the actual ones. Further investigations are taking place to find innovative solutions, which may open new ways and new currents of thought on the use of natural resources available on the planet and on their exploitation.

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