Assessment of Ship Electric Power Consumption

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RESUMO

O principal objectivo deste trabalho é desenvolver um modelo numérico para estimar os principais consumidores eléctricos de um navio associados à superestrutura, casa de máquinas e convés em diferentes condições de operação do navio. Este modelo é desenvolvido de acordo com os parâmetros disponíveis na fase conceptual do navio. Portanto, a primeira vantagem é a sua aplicação em fases preliminares, fornecendo apoio à estimativa da potência total dos geradores auxiliares. A segunda abordagem complementa a primeira em que este modelo foi preparado para a análise do consumo eléctrico a bordo em diferentes condições de operação do navio, proporcionando vantagens tais como a avaliação das emissões durante uma viagem típica de navio, bem como a redução dos custos de operação do navio.

Este modelo foi desenvolvido com opções alternativas, tais como para sistemas de propulsão convencionais, máquinas a 2 tempos de baixa rotação e máquinas a 4 tempos de média rotação, e para o tipo de combustível, diesel e combustível intermédio. Foi também adaptado para estudar quatro tipos de navios, que representam a maioria da frota mundial: petroleiros, graneleiros, navios porta-contentores, e RoPax.

As equações resultantes do consumo de energia foram implementadas na ferramenta Excel VBA. A avaliação do consumo elétrico foi realizada para as condições de operação: na navegação, nas manobras, nas cargas e descargas, e no porto. Finalmente, é avaliado o nível de precisão do modelo com a sua aplicação a diferentes tipos de navios e configurações de motores. Posteriormente, são discutidos os respectivos resultados.

Palavras-Chave: Balanço Elétrico, Tabela de potência elétrica, Projecto de navio, Sistemas Auxiliares do Navio

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ABSTRACT

The main purpose of this work is to develop a numeric model to estimate the main electric loads of a ship associated with the superstructure, engine room, and deck in different ship operating conditions. This model is developed according to the parameters available in the ship conceptual stage. Therefore, the first advantage is its application in preliminary phases providing support for auxiliary generators' total power estimation. The second approach complements the first in which this model was prepared for the analysis of the electrical load on board in different operating conditions of the ship, providing advantages such as the evaluation of emissions during a typical ship voyage, as well as the reduction of ship operating costs.

This model was entirely developed with alternative options such as for conventional propulsion systems, i.e 2-stroke engines low speed and 4-stroke engines medium speed, and for fuel type, i.e diesel oil and intermediate fuel oil. It has also been adapted to study four ship types, which represent the majority of the world fleet: tankers, bulk carriers, container ships, and RoPax.

The resulting equations of the power consumption were implemented in the Excel VBA tool. The evaluation of the electrical loads was performed for the operating conditions: in navigation, maneuvering, loading and unloading, and in port. Finally, it is evaluated the level of accuracy of the model with its application to different ship types and engine configurations. Afterward, the respective results are presented and discussed.

Keywords: Electric Load Balance, Electric Power Table, Ship Design, Ship Auxiliary Systems

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CONTENTS

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LIST OF FIGURES

LIST OF TABLES

Nomenclature

Symbols

A_g	-	Area of windows or side scuttles	[m^2]
A_v	-	Area of surfaces excluding windows	[m^2]
$b_{Cylinder}$	-	Bore of the cylinders	[m]
B	-	Breadth of the ship	[m]
c	-	Air specific heat capacity	[kJ/kgK]
$C_{Powerpervolume}$	-	Coefficient applied to the superstructure volume for HVAC calculation	[kW/m^3]
$d_{Bilgepipe}$	-	Pipe diameter of bilge	[mm]
D	-	Depth of the ship	[m]
D0	-	Pipe diameter from ME to turbocharger	[mm]
D4	-	Pipe diameter of exhaust gas collector	[mm]
$D_{Anchorchain}$		Diameter of anchor chain	[mm]
$DFOC$		Daily of fuel oil consumption	[g/day]
E	-	Illuminance	[lux]
F_d	-	Depreciation Factor	[-]
F_u	-	Utilization Factor	[-]
g	-	Gravitational constant	[m/s^2]
G_s	-	Heat gain from glass surface	[W/m^2]
h_{Indoor}	-	Enthalpy related with air inside of accommodation spaces	[kJ/kg]
h_{Mix}	-	Enthalpy of air mixed	[kJ/kg]
$h_{Outdoor}$	-	Enthalpy of air from outside o	[kJ/kg]
H	-	Total Head	[mwc]
HCM	-	Total Heat Rejected by coolant	[kJ/kWh]
$HFOC$	-	Hourly Fuel Oil Consumption	[g/h]
k_g	-	Total heat transfer coefficient of windows or side scuttles	[W/m^{2}K]
k_L	-	Load Factor	[-]
k_s	-	Simultaneously Factor	[-]
k_v	-	Total heat transfer for surface areas	[W/m^{2}K]
L	-	Length of the ship	[m]
L_{ER}	-	Length of the engine room	[m]
L_{4-1}	-	Length of the horizontal exhaust gas collector	[m]
$L_{4-2.1}$	-	Length of the vertical exhaust gas pipe from engine top to main deck	[m]
$L_{4-2.2}$	-	Length of the vertical exhaust gas pipe corresponded of the superstructure	[m]

m	-	Mass	[kg]
$\dot{m}$	-	Mass flow	[kg/h]
m_{ad}	-	Air necessary for combustion of ME	[kg/kWs]
$\dot{m}_{Indoor}$	-	Mass flow circulating inside of the accommodation spaces	[kg/h]
$\dot{m}_{Outdoor}$	-	Mass flow from outside	[kg/h]
M_{max}	-	Maximum moment of steering gear	[Nm]
$n_{\ Cylinders}$	-	Number of engine cylinders	[-]
n_{Sewage}	-	Amount of sewage	[l/person/day]
N_{crew}	-	Number of crew	[-]
p	-	Pressure	[Pa]
ps	-	Pressure of exit	[kPa]
pe	-	Pressure of entrance	[kPa]
P_{AE}	-	Power of Auxiliary Engines	[kW]
P_{BWTS}	-	Power of ballast water treatment system	[kW]
$P_{compressor}$	-	Compressor Power	[kW]
$P_{Condition}$	-	Power consumption in each operating condition	[kW]
P_{dp}	-	Power of Main Engine	[kW]
P_{fan}	-	Fan Power	[kW]
$P_{FOcirculationpump}$	-	Power of fuel oil circulating pump	[kW]
$P_{FOPurifier}$	-	Fuel Oil purifier power	[kW]
$P_{FOPurifierfeedpump}$	-	Fuel Oil purifier feed pump power	[kW]
$P_{FOsupplypump}$	-	Power of fuel oil supply pump	[kW]
$P_{FOtransferpump}$	-	Power of fuel oil transfer pump	[kW]
P_{FWG}	-	Power of freshwater generator	[kW]
P_{HTpump}	-	Power of high-temperature pump	[kW]
$P_{illumination}$	-	Power requirement of illumination	[W]
$P_{LOmainpump}$	-	Power of lubrication oil main pump	[kW]
$P_{LOPurifier}$	-	Lubrication Oil purifier	[kW]
$P_{LOPurifierfeedpump}$	-	Lubrication Oil purifier feed pump power	[kW]
P_{LTpump}	-	Power of low-temperature pump	[kW]
P_{ME}	-	Power of Main Engine	[kW]
$PowerMCR$	-	Power of Main Engine in maximum continuous rate	[kW]
$P_{PTI(i)}$	-	Power of Shaft Motor	[kW]
$P_{Provisionplant}$	-	Power of provision plant equipment	[kW]
$P_{Purifiermotor}$	-	Purifier motor power	[kW]

P_{pump} - Pump Power [kW]
$P_{SteeringGear}$ - Power of steering gear [kW]
P_{STP} - Power of sewage treatment plant [kW]
$P_{TransverseThruster}$ - Power of transverse thruster [kW]
$P_{Winches}$ - Power of winches [kW]
$P_{Windlass}$ - Power of windlass [kW]
q_b - Airflow for combustion of boiler [m^3/s]
q_c - airflow necessary for combustion [m^3/s]
q_{dg} - airflow for combustion of Diesel-Generators [m^3/s]
q_{dp} - airflow for combustion of Main Engine [m^3/s]
q_h - airflow for evacuation of heat emission [m^3/s]
Q - Total airflow [m^3/s]
$\dot{Q}_{compressor}$ - Volumetric flow of compressor [m^3/h]
$\dot{Q}_{AverageWastewater}$ - Volumetric flow of wastewater [l/day]
$\dot{Q}_{Ballast}$ - Volumetric flow of ballast pump [m^3/h]
$\dot{Q}_{Bilge}$ - Volumetric flow of bilge pump [m^3/h]
$\dot{Q}_{Fire}$ - Volumetric flow of main fire pump [m^3/h]
$\dot{Q}_{pump}$ - Volumetric flow through the pump [m^3/s]
$\dot{Q}_{Transferpump}$ - Volumetric flow of FO transfer pump [m^3/h]
R - Specific gas constant [J/kgK]
S - Surface Area [m^2]
$t_{FOtransfer}$ - Time to transfer Fuel Oil [h]
$t_{Maneuver}$ - Time estimated to conclude the maneuver [s]
t_{Voyage} - Time of round voyage [days]
T - Temperature absolute [K]
T_{Air} - Temperature of the air [K]
T_{Indoor} - Temperature inside of accommodation spaces [K]
T_{Mix} - Temperature of mixture indoor air and and outdoor air [K]
$T_{Outdoor}$ - Temperature outside [K]
$\dot{v}$ - Volumetric flow through the fan [m^3/s]
V - Volume [m^3]
$V_{Oilywatertank}$ - Volume of oily water tank [m^3]
$\dot{V}_R$ - Standard flow of potable water in different service points [l/s]
$\dot{V}_S$ - Peak flow of potable water [l/s]
V_{ST} - Volume settling tank [m^3]

$V_{SewageTank}$ - Volume of sewage tank [m^3]
$V_{Sludgetank}$ - Volume of sludge tank [m^3]
$V_{Superstrucutre}$ - Volume of superstructure [m^3]
W_{Anchor} - Weight of anchor [kg]
$W_{Anchorchain}$ - Weight of anchor chain [kg]
$W_{Capacity}$ - Weight Capacity of the crane [ton]
W_{Total} - Total weight of anchor and anchor chain [kg]
Δ - Ship displacement [ton]
ηc - Efficiency of compressor [-]
η_{elect} - Electrical efficiency of the drive motor [-]
η_{lamp} - Efficiency of lamp [lm/W]
η_{mec} - Mechanical Efficiency of the pump [-]
ηv - Volumetric Efficiency of the fan [-]
$\theta_{initial}$ - Maximum angle initial of the maneuver [rad]
θ_{final} - Maximum angle final of the maneuver [rad]
ρ - Density [ton/m^3]
ρ_{35} - Air density at 35ºC [kg/m^3]
$\emptyset$ - Exhaust pipe diameter [mm]
$\emptyset V$ - Luminous flux [lm]
Δh_d - Heat Loss from ME [%]
$\varDelta p_{ref}$ - Pressure [kPa]
$\varDelta T$ - Mean temperature [K]
ΔT_r - Excess temperature caused by solar radiation [K]
ϕ - Heat loss or gain [W]
ϕ_s - Solar heat gain [W]
$\varPhi_{dp}$ - Heat emission from ME [kW]
$\varPhi_{dg}$ - Heat emission from DG [kW]
$\varPhi_{el}$ - Heat emission from electrical installations [kW]
$\varPhi_{ep}$ - Heat emission from exhaust pipes [kW]
$\varPhi_g$ - Heat emission from electrical alternator [kW]
$\varPhi_o$ - Heat emission from other components [kW]
$\varPhi_p$ - Heat emission from steam or condensate pipes [kW]
$\varPhi_t$ - Heat emission from hot tanks [kW]
$\varPhi_{tp}$ - Heat emission from boilers or heat exchangers [kW]
ω - Angular velocity [rad/s]

Abbreviations

AC - Air Conditioning [-]
BNAWS - Bridge Navigational Watch Alarm System [-]
BWTS - Ballast Water Treatment System [-]
CO_2 - Carbon Dioxide [-]
COP - Coefficient of Performance [-]
DDS - Design Data Sheet [-]
MDO - Marine Diesel Oil [-]
DG - Diesel Generator [-]
EEDI - Energy Efficiency Design Index [-]
EPLA - Electrical Power Load Analysis [-]
ER - Engine Room [-]
FEU - Forty Foot Equivalent Unit [-]
FO - Fuel Oil [-]
FW - Fresh Water [-]
GHG - Greenhouse Gas [-]
HVAC - Heating, Ventilation and Air Conditioning [-]
IEEE - Institute of Electrical and Electronics Engineers [-]
IFO - Intermediate Fuel Oil [-]
ISO - International Organization of Standardization [-]
LO - Lubrication Oil [-]
ME - Main Engine [kW]
MEPC - Marine Environment Protection Committee [-]
NAVSEA - Naval Sea Systems Command [-]
OWS - Oily Water Separator [-]
POB - People on Board [-]
RoPax - Roll-on Roll-off passengers [-]
SAE - Society of Automotive Engineers [-]
SFOC - Specific Fuel Oil Consumption [g/kWh]
SNAME - Society of Naval Architects and Marine Engineers [-]
STP - Sewage Treatment Plant [-]
SWBS - Ship Work Breakdown System [-]
TEU - Twenty Feet Equivalent Unit [-]

1. Introduction

1.1 Background and Motivation

The concept design stage of the ship design process is the phase where it is performed the first approach into technical ship characteristics. Preliminary studies and estimations of basic ship dimensions and powering arrangements are made. Being these decisions the most relevant in the ship's design, it will be therefore factual that this phase will have the largest impact in terms of ship costs.

On the other hand, all the alternative design solutions for the identification of the most cost-effective ship that fulfill the owner’s requirements should be explored at this stage, since during this stage the costs associated with the change of options will be lower than a later design stage where much more work is already developed.

The task of estimating an electrical load balance aims to determine the number and power of the generators sets required for the ship. According to (Taggart, 1980), the electric load balance is a process to be developed in the Contract Design phase when all list of the main equipment and components is sufficiently complete and comprehensive to enable an accurate estimation of the consumers on board. However, in an economical view, it is more reliable to estimate these characteristics associated with the power generation on board as soon as possible.

In the context of the global concern with the decarbonization and reduction of GHG emissions from ships and the request for the design of energy-efficient ships, it is also quite relevant to be able, at an earlier stage, to assess the electric power consumption of ships at different operating conditions. Being the source of the emissions strongly related to the fuel, the assessment of the total fuel consumption during the ship's typical voyage is very important to the knowledge of the ship's environmental impact and energy efficiency. However, this fuel consumption assessment will contribute also to the economical evaluation of the ship operation.

The fuel consumption on board is associated with propulsion and electric power generation. The estimate of the propulsive power during different operational conditions is a routine task in naval architecture and there are many semi-empirical methods available with a known level of accuracy. However, the estimation of the electric load is restricted to further phases of the ship design process or to a few empirical methods as a rough guide with a low degree of precision. Beyond the low accuracy, these few empirical methods are based on statistical data of the total power installed on board of ships and do not reflect the actual electric loads in operational conditions such as seagoing, maneuvering, and at the port.

The main objective of this work is to develop a numeric model to predict, at an early stage of the ship design, not only the electrical power generators to be installed on board, as well as the electrical loads of a ship when it is at sea, maneuvering, loading and unloading and in port. This model is to be parametric, and the parameters to be adopted shall be sufficient to describe and quantify alternative solutions for aspects such as the propulsion system, fuel type used, and maneuvering equipment. The development of numerical expressions shall be based on input data with a low level of knowledge about the characteristics of ships in which are available at this stage. Nevertheless, it is also intended that these expressions be equally flexible and generic to be applied to more conventional types of ships (bulk carriers, oil tankers, container ships, and RoPax ships).

In this manner, the methodology adopted in order to obtain improved forecasts and to circumvent the lack of detail in the provided information will be to use, whenever possible, physical principles. When it is impracticable to apply these principles, it will be performed a compilation of data provided by the main manufacturers of the respective equipment and extrapolated numerical functions based on curve-fitting methods.

1.2 Structure of the Thesis

The research is presented in five (5) chapters. The chapters are structured in a general form with an introduction, literature review, methodology, results and validation, and conclusion.

In Chapter 2 is introduced the literature review. A comprehensive literature review conducts to the knowledge of previous works developed and especially gives the scope for the basis of new model development. It is thus described procedures, methods and models developed in which it was considered directly or indirectly relevant to the thesis subject.

Chapter 3 corresponds to the chapter where the most relevant ship systems were described as well as the equipment and machinery on them that mostly contribute to the electrical consumption on board. Also, it is in this chapter that is described all procedures, assumptions, and the developed functions to predict the power requirement of each equipment proposed to model. At the end of this chapter, it is specified each proposed operating condition to analyze as well as explained the construction of the electric power table.

In Chapter 4 some comparisons of the model output with results from electric load balance estimate from different ship types and propulsion systems, to validate and determine the accuracy of the model.

Finally, Chapter 5 is presented the conclusions stating which objectives were achieved as well as a brief discussion with some conclusions according to these results. Also, it is identified and suggested some possible directions for future developments of the model presented and future research works.

2. State of the Art

The first historical record of electricity introduction on board was 1880 on the SS Columbia vessel with the installation of a lighting system (Skjong et al., 2015). Since then, the evolution of a vessel's systems has intensified the demand for electricity. On the other hand, this electrical demand is also directly proportional to the ship's main dimensions and characteristics such as speed and ship complexity (Patel, 2012).

The ship requires a large part of mechanical power for its propulsion and a small part of electrical power for service loads. Vassalos and Sfakianakis (2013), from an energy perspective, states that the percentage for generated energy for propulsion is around 80% to 85% and the generated energy for electrical services rounds 10%.

One of the fundamental tasks in the ship power systems design is to determine the required installed capacity of onboard power generators (Su and Liao, 2015). For this purpose, the total demand required by the machinery and its systems such as deck machinery, navigation equipment, hotel load, and cargo support shall be estimated (Rowen, 2003).

2.1 Electrical Load Analysis Methods

There are several approaches for the electric power systems estimate. An important reference is Doerry (2012) which classifies the estimating method types as follows:

1) Parametric evaluation

2) Load factor analysis

3) Zonal load factor analysis

4) Stochastic load analysis

5) Modeling/simulation load analysis.

One of the methods consists of previous experience with similar vessels which corresponds to the parametric evaluation (Wolfe, 2017; Doerry, 2012). An example of using this method is found in (Giernalczyk et al., 2010), where numerical equations are described and presented allowing the calculation and knowledge of the total power of the generators on board. These equations, differentiated by the type of vessel, have been obtained statistically, collecting power data from a list of reference vessels for several different capacities for the different types of vessels. Another similar example of a numerical expression deduced is found in (IMO, 2018). However, this type of analysis has not a high sensibility and intends to be only preliminary guidance.

The load factor analysis is a traditional method that is widely used in the shipbuilding industry due to its simplicity and rapidity of use. This traditional method consists of a list of loads defined in an early stage of ship design. The loads are subsequently tabulated, and a load factor is applied for each electrical consumer in each ship loading condition (Islam, 2011; Patel, 2012; Wolfe, 2017). The ship's power demand in the defined operating condition is calculated as the sum of each load consumer.

Two important references of guides based on traditional methods are the (Harrington, 1992), which is a guide directly for merchant vessels, and (Doerry, 2012), which is a guide conducted for naval vessels. These guides based on the traditional electrical power load analysis (EPLA), work well when there is a simple power system composed of non-variable loads or small loads. This occurs because the load factors provided are only scaled for some operating conditions that it is verified a constant load without large variation, such as seagoing and at port with a constant load. Therefore, although these guides provide sufficient information for the purpose of selecting the appropriate number and classification of generator sets, some caution should be taken in their use, especially in the first guide mentioned, which is the oldest, since the level of information is poor, and it can cause a false sense of accuracy resulting in oversizing or under-sizing of generators (Wolfe, 2013).

In accordance with this traditional method, there are some approaches with different objectives in the literature. In (Chin et al., 2016; Su and Liao, 2015) is developed an electrical load analysis for different operating conditions with the objective of sizing and reducing generators' costs of investment and also operating costs by reducing fuel consumption. Besides this traditional method, these same authors compare it with three other methods. One of these consists in specifying the electrical load required by pumps on board, since they represent 70% of the total consumption according to these authors. Another method advanced by them focuses on the efficiency that the generator set can achieve during its operation and for this, it was added the application of genetic algorithms. The last method consists of considering these last two methods in conjunction. One aspect that the traditional method cannot achieve directly is the optimizations. Normally combined with these optimizations other methods are added such as the use of genetic algorithms. One of these cases is observed in (Boveri et al., 2017a) that aggregates the algorithms to the electric balance process with the objective of optimizing operational costs.

A difficult aspect to estimate in this traditional method is the deterministic load factors or utilization factors. These deterministic factors, widely known as load or utilization factors, have been calculated as the average of the previously dated ship's electrical load balance (Wolfe, 2013). To facilitate the determination of these coefficients some documents supply predefined values for each equipment. In addition to the two guides mentioned above (Harrington, 1992; Doerry, 2012), also it can be found values for these coefficients in (Islam, 2011; Wolfe, 2013; Boveri et al. 2017b). Another case is (IMO, 2009a) that although being a guideline for the estimation of auxiliary cargo exclusively for passenger ships with the main purpose of being used in the EEDI calculation, it follows this traditional method and defines the various loading factors to be applied to each individual piece of equipment.

The improvement of numerical techniques and computational power has allowed an alternative path for the design and evaluation of the electric consumption of ships, optimizing the traditional method. Through the numerical modeling of onboard energy systems, the energy consumption of one or more systems can be evaluated at the earlier phases of ship design, providing not only the estimation of the power requirements as other useful information (Vassalos and Sfakianakis, 2013).

A methodology that allows having a power load estimation when no field data are available, as in the early stages of ship design, is achieved by the application of a probabilistic approach with Monte Carlo simulation. The first steps of this method are identical to traditional methods, where it is also identified the electrical loads or electrical loads groups and the operational scenarios (Doerry, 2012; Wolfe, 2013). This method is based on the assumption that it is possible to define a Probability Density Function (PDF) and a Cumulative Distribution Function (CDF) for each load installed on-board (Boveri et al., 2017b; Boveri et al. 2017c; Wolfe, 2017).

Boveri et al. (2019) with the objective to reduce the electrical power system costs in a short and long-term perspective uses the probabilistic method applied to EPLA load factors. Besides this method, these authors combine it with a stochastic process called Hidden Markov Model. This last process allowed them to translate information from other methods such as EPLA or experimental readings in the time domain.

It is important to simulate the different systems and machinery in order to understand the physical processes as well as the interaction between the systems involved (Krčum et al. 2018). The modeling and simulation method consists of using detailed models of the electrical components to simulate the performance of the electrical system during steady-state and dynamic events (Wolfe, 2017).

A well-known modeling and simulation program associated with complex ship systems, not only ship propulsion but also auxiliary systems, is *DNVGL COOSSMOS* (Dimopoulos et al., 2014). This program not only allows the user to analyze and evaluate emissions and fuel-saving but also allows the user to make a techno-economic comparison between different types of machinery configurations. A big advantage of this program compared to other methods developed and analyzed is the possibility of evaluating the operation performance, optimizing the systems in the different operating conditions of the ship (Zymaris et al., 2016). In the literature, there are several studies that utilize this program. What differentiates DNVGL COSSMOS approaches is that each one is dedicated to a specific type of analysis for a specific system/component. In (Zymaris et al., 2016) is used this program with the aim of increasing the efficiency associated with auxiliary systems in addition to a reliability study in a diesel-electric configuration.

Even though the modeling and simulation methods are very efficient, they are considerably more expensive (Wolfe, 2017). Two other major disadvantages are the fact that this type of method requires a large knowledge of the computational platforms to be used and also a high level of detail of the systems that are modeled, therefore, this method cannot be introduced in the early phases of the ship design.

2.2 Alternative Propulsion Systems

In the context of alternative propulsion systems, there has been an increase in the application of the electric propulsion concept on the ship, where the propeller is driven by an electric motor. This type of propulsion seeks to be more efficient and environmentally friendly. A new concept has been included, called All Electric Ship (AES). This concept includes the incorporation of several independent sources for power generation, being here included not only main but also auxiliary electrical consumers (Lim et al., 2019). This type of configuration is one of the aspects that traditional methods cannot achieve due to the large variable load in specific operating conditions, therefore, associated with this type of configuration are the statistical methods and especially the modeling and simulation methods (Swider and Pedersen, 2019). In this line of development, some studies were developed focusing on Electric Propulsion System (EPS).

Swider and Pedersen (2019) perform an operational profile analysis for the power system to facilitate the selection of the number and configuration of generators. This analysis, different from those observed so far, was carried out through real measures collected during one year from a PSV vessel in DP mode. From these measures, a statistical analysis was performed enabling the construction of a probability distribution function with the most common loads. Sofras and Prousalidis (2014) seek to present the advantages of this type of system (AES) for different types of ships, from an economic and efficiency point of view. These authors present a comparison between two solutions for propulsion (conventional and diesel-electric). One aspect considered in this comparison is the elaboration and analysis of an electrical load balance for the two alternatives of propulsion and for three operating conditions, sea-going, rest-in-port, and maneuvering condition. In (Bø et al., 2015) is introduced a simulator developed in MATLAB to be used especially for the marine vessels with electric propulsion in which the input is according to the design choices and the output is the study of the behavior of the ship electrical system. This simulator has the particularity of considering the positioning system and the power system combined while some others' simulators have into consideration the two systems separately. In (Balland et al., 2014) is present an optimized model developed in an integer linear programming model to select the main machinery systems aiming to increase the ship's efficiency and to reduce the emissions. However, this type of model developed is not only intended to reduce emissions. One of the common objectives of all optimization models to be implemented in the ship design process, to comply with the desires of the shipowner is the reduction of costs not only of investments but also of operation. Another example is found in Solem et al. (2015) where an optimization model of machinery systems for the diesel-electric configuration evaluated in different operating conditions that can be implemented in the early stage of ship design with the aim to minimize the investment and operational costs. An obvious aspect is that emissions and costs are two related concepts since reducing fuel consumption will consequently reduce costs and emissions. An example of this is found in Vásquez (2016) in which it studies the influence of different arrangements of diesel generator sets and energy storage devices to reduce the fuel consumption and costs, ensuring the same flexibility in providing electrical power for propulsion and auxiliary consumers. A different approach to this type of propulsion is found in (Sui et al., 2020) which is investigated the influence of the application of different fuels such as MDO, heavy fuel, and LNG in the ship propulsion and electric power generation as well as the implementation of the control systems to reduce the fuel consumption. This research is performed in different operating conditions.

As previously mentioned, this more complex type of configuration requires greater attention and more detailed and developed methods for the estimation and study of the electrical system. However, a simpler method for the study of electrical systems and consumers associated with the type of fully electrical configuration is presented in (Tsekouras et al., 2015). This method consists of numerical equations developed with almost zero computational requirements. These same authors compare this method with another dynamic programming.

Also, there are development studies of control systems associated with this type of configuration. Examples of these are (Kanellos et al., 2010), in which the main objective of to find a cost-effective solution, and (Kanellos et al., 2014) that seeks to develop a control system to minimize fuel consumption in a perspective of emission reduction associated with these power systems that operate either as a propulsion system or as an auxiliary power system.

Although all these studies are presented with the advantages of this type of configuration, a significant disadvantage is presented in (Zhemim and Yuxin, 2020). This disadvantage is the high cost associated with the construction of the ship since the electric propulsion system requires a large amount of investment in construction and installation.

2.3 Machinery Assessment

The onboard equipment and systems are the electrical consumers, and therefore there is research work that seeks to size and to optimize systems in order to reduce their consumption and consequently the power of the generators.

Pumps are probably the major group of electric power consumers on board a ship. An investigation performed in (Durmusoglu et al., 2020) states that among energy-consuming machines, pumps are accountable for 20% of energy. For this reason, these authors advanced with energy efficiency analysis focused on pumps. In its case, the study was conducted for the pumps of the ship's cooling water system of a container ship in three conditions: full-ahead, half-ahead and slow ahead. Evidently, this percentage distribution of electrical consumption in relation to the pumps on board depends on the type of ship. Remembering that in (Chin et al., 2016) it was advanced with the number of 70% in relation to these consumers.

In a more global approach and not so specific for given equipment, there are several studies that review system by system. Giannoutsos and Manias (2013) focus mainly on two engine room systems, the engine room ventilation, and the central cooling system. This ship energy efficiency system is implemented as an integrated process control involving the variable frequency control. This variable frequency control, in turn, is performed based on temperature and pressure feedback from the process. Variable-frequency-drive (VFD) applications are being gradually recognized by maritime industries as one of the most effective tools for energy savings (Su et al., 2014). These same authors applied this method for energy savings through control of the pump's speed in the ship's central cooling system however focusing on the seawater cooling system, calculating all power consumption with VFD driven associated to the pumps.

Another similar study conducted in an overview of the main engine systems such as lubrication system, cooling system, fuel system, and air system is present in (Nahim et al, 2015). The research was conducted through a simulator implemented in MATLAB in order to study the behavior of these systems as well as to increase their efficiency and subsequently reduce their associated electrical consumption.

A particular system of the engine room is studied in (Zhang et al., 2015) which consists of a simulation for ship oil purifier systems.

The electrical demand is also dependent on the type of ship, size, and mission of the ship. One example of this are the container ships that are usually equipped with some sockets for plugging in reefer containers. A study on the power associated with this type of equipment is made by Nicewicz (2009). Based on statistics, it obtained a correlation of the power to be installed on board a reference ship with the number of reefers containers.

In particular for passenger ships, there is a need to guarantee passenger comfort. Vassalos and Sfakianakis (2013) advances to a more uniform distribution among consumers associated with propulsion and consumers associated with passengers' hotel load. This author states that 1/3 of the total consumption corresponds to HVAC, 1/3 to consumers associated with propulsion, and the last 1/3 associated with the electrical consumption of the accommodations, such as lighting and other components. HVAC being a great consumer some energy studies have been conducted as present in (Pérez et al., 2008) where it is studied the cooling water system of the air condition system in which is composed by a centrifugal pump that supplies 21 fan coils. From this study, the authors intend to decrease the losses of the system in order to increase efficiency and consequently decrease the required power for the same system. Also, for HVAC dimensioning, Jaraba et al., (2008) performs a comparative study between the practices recommended by *SNAME* and the methodology of thermal charge developed by *ASHRAE*, attempting to understand which of the methods is approaching reality, thus preventing overdimension of this system and consequently higher electric consumption than necessary. In a perspective directed to the operation, to reduce energy consumed and costs, Lugo-Villalba et al. (2017) present an energy analysis. This consists of the implementation of a system that varies the load required by the HVAC on board according to its use during the day that consequently will vary the electrical power associated with the respective equipment.

In a more specific subject of consumers on board, Lin et al. (2013) seek for improved power options for lighting on a ship without ever excluding all the existing regulations on this subject.

2.4 Emissions

To achieve the power demand of a ship, the generator has the necessity to burn marine diesel fuel, contributing to air pollution (Koumentakos, 2019). On the other hand, it is verified a constant evolution of the ship’s stringent requirements regarding emissions.

The air pollution from auxiliary diesel generators can be mainly verified when the ship is moored at the berth. This occurs since it is in this condition that the ship is found with all main propulsion installation down with the exception of the auxiliary generators that will contribute to the normal operation of the ship at the port. In this context, some studies have been developed to understand how these generators' emissions contribute negatively to the environment. Examples of these studies are found in (Thuy et al.,2016; Rymaniak et al., 2018) which, despite conducting a NOx emission study aimed at all ship operations, focusing predominantly on emissions in port. A common aspect of these studies and also seen in reports from international organizations is the presentation of loading factors exclusively in port condition for different types of ships. However, these loading factors are usually collected from the ships' data, and therefore it is not a precise method. In response to this, Nicewicz and Tarnapowicz (2012) developed a method to determine the loading factors of auxiliary marine engines in ports in hotel mode for different types of ships, based on identical loading tests of marine electrical power systems.

In another perspective of emission reduction, there is a demand for technologies such as the use of a shaft generator and reduction of diesel generators on board. Thus, some ships have accomplished the main engine shaft, one shaft generator which supplies electricity on board the ship (Badea, 2015). From the point of view of comparisons between the price of the diesel generator set and the shaft generator, the cost per kW of electricity produced, the easy maintenance and especially the flexibility and reliability of the ship's machinery systems, Martinović et al. (2012) affirms that it is a reliable and safe auxiliary system that will serve the main propulsion. The big disadvantage of using shaft generators is that it can only be operated while the main engine is in operation, this means that it is difficult to obtain power in port. Some approaches were made in order to study the possibility of reconfiguring the installation in order to install a shaft generator and its advantages (Perez, 2020). The scheme proposed permits the operation of at its optimum fuel oil consumption point. The scheme considers the use of the shaft generator as a Power Take-Off (PTO) drive when the diesel engine operates below the optimum fuel oil consumption and as a Power Take In (PTI) when the diesel engine operates above the optimum fuel oil consumption point. The shaft generator, when operated as a PTO, can generate enough power to turn-off the generator set of the ship, decreasing in this manner the emissions emitted. However, the disadvantage presented before is not overcome. In addition, the second disadvantage of this system is presented by (Koumentakos, 2019) since the propulsion machinery could only operate at a constant speed in order to maintain the network frequency within limits when operating with a shaft generator accomplished. This barrier could be overcome by controlling the propulsion thrust and speed of the ship, by changing the pitch of the propeller. However, this operation could lead to a reduction in efficiency and an increase in CO_2 emissions which would be the greatest objective of this system.

3. Model Development

A vessel is composed by a large number of systems that ensure the vessel operation. In order to ensure the proper functioning of these systems, there are a considerable number of machines and equipment on board that require external energy to drive them. This auxiliary power can be obtained by two means: mechanical or electrical. Although there is some mechanically operated equipment, these are relatively few and therefore the major importance is directed to those requiring electric power. This electrical energy is obtained through power generators installed on board. As previously described, these power generators are determined by an electrical load balance in which it consists of a series of consumers that should be analyzed and modeled. In this present dissertation, it is proposed a tool developed through a numeric model implemented in Excel and using Visual Basic for Application tool. The numeric models are frequently adopted for different purposes in the marine world. The modeling language is a natural platform for this since it can be used to describe several different parameters using basic system elements as input and obtaining more complex elements as output. In this dissertation, it was considered as input to the models developed, easy and simplified parameters to estimate from the ship conceptual design. Throughout this chapter, it will be described the whole process of developing this thesis as well as all the modeled equipment and the necessary assumptions. The methodological approach proposed in this thesis is represented in a schematic diagram for a better perception (Figure 1).

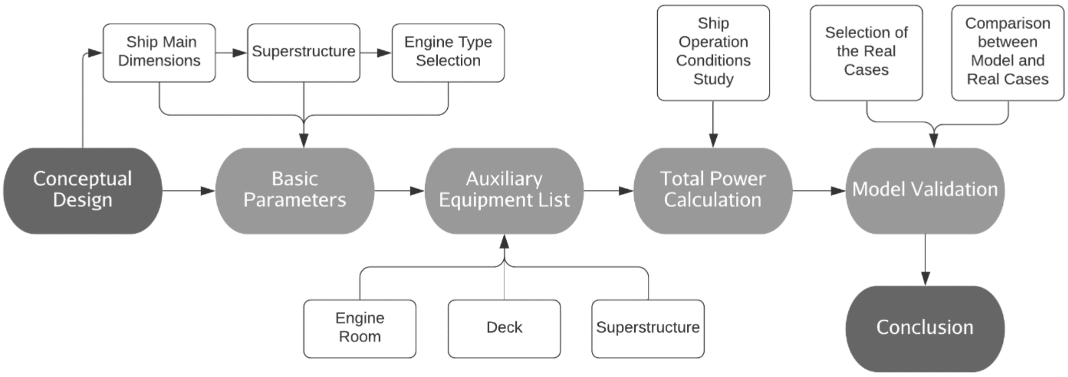

Figure 1 - Scheme of the proposed model

3.1 Description of the model

The process of electrical load analysis begins with the collection of data related to the electric consumption of each equipment installed and necessary on board. To facilitate the delineation of the ship's loads, it was opted to divide the load consumers into distinct groups. In this context, some documents and standards were analyzed in such a way as to find the most suitable grouping and the one that best adapts to the final objective of this thesis. (IMO, 2009a), in its document in consideration to the EEDI calculation provides a succinct division of the loads to define the auxiliary loads that will define the auxiliary power. This division is represented in Table 1.

Table 1 - Groups list definition (IMO,2009a)

Group	Designation	Group	Designation
A	Hull, Deck, Navigation and Safety Services	G	Galleys, refrigeration and laundries services
B	Propulsion services auxiliaries	H	Accommodation services
C	Auxiliary Engine and Main Engine Services	I	Lighting and socket services
D	Ship's General services	J	Entertainment services
E	Ventilation for ER, and Auxiliaries Room	K	Miscellaneous
F	Air Conditioning services		

The majority of the classification societies include in their regulation's documents which are related to electrical installations. Within these documents, the services are separated in essential, important, emergency and non-important, as it is possible to verify in (DNV GL, 2017). The essential services are those services needed to continuous operation of ship's maneuverability as propulsion equipment and steering equipment. The important services are considered continuous operation equipment, however only in ship's normal functions as anchor systems or transfer pumps. Non-important services are those services which are necessary in a ship, however not essential or important to the ship operation as for example superstructure interior illumination.

Although IEEE 45.1-2017 being a standard more directed to the recommendations for electrical installations on shipboard, it also makes a slight division of the consumers on board being these divided into groups as shown in Table 2.

Table 2 - Groups list definition (IEEE 45.1-2017)

Designation	Designation
Propulsion machinery	Hotel loads
Auxiliary machinery	Electronics
Cargo equipment	HVAC equipment
Deck machinery	
Propulsion machinery	

Some counties offer standards to facilitate the electrical load balance estimation, where each country standard contains a peculiarity. In (Doerry, 2012) is provided an electric load list with a different configuration, being each equipment defined by three digits, following the equipment location on the ship that is defined by digits as well.

Table 3 - Groups list definition (Doerry, 2012)

Group	Designation	Group	Designation
SWBS 2	Propulsion Plant	SWBS 5	Auxiliary Systems
SWBS 3	Electric Plant	SWBS 6	Outfit and Furnishings
SWBS 4	Command and Surveillance Services	SWBS 7	Armament

Another particularity of this standard are the load factors that are presented as a percentual period of time between 0 and 90%. The Brazilian standard NBR 7567:1982 was canceled in 2011, and not replaced for any other. This standard is especially interesting since organizes consumer's groups based on the type of service being presented as follows:

Table 4 - Groups list definition (NBR 7567:1982)

Group nº	Designation	Group nº	Designation
1	ER (continuous service)	8	Galley
2	ER (intermittent service)	9	Laundry
3	ER (miscellaneous)	10	Workshop
4	HVAC	11	Illumination
5	Provision Refrigeration	12	Navigation equipment
6	Cargo Refrigeration	13	Miscellaneous
7	Deck equipment		

In this thesis, the division of the electrical groups was based on this Brazilian standard. However, it was also adopted a division by areas according to the location on the ship: engine room, deck, and superstructure. The adopted division enables the omission of any group in case of the user's desire. Table 5 represents the electrical load groups division.

Table 5 - Power consumers groups list adopted

Electrical Load Groups					
Engine Room		**Deck**		**Superstructure**	
Group nº	**Designation**	**Group nº**	**Designation**	**Group nº**	**Designation**
1	Continuous Service	4	Cargo	6	Provision Refrigeration
2	Intermittent	5	Deck Equipment	7	HVAC
3	Miscellaneous			8	Workshop
				9	Laundry
				10	Bridge Equipment
				11	Illumination
				12	Galley

3.2 Description of the machinery analyzed

On board a ship it can be noted briefly that its auxiliary machinery is composed mainly by pumps, compressors, and fans. These three types of machinery are considered fluid machines that convert the energy of the fluid flowing inside into mechanical energy. Fluid machines can be classified according to the direction of energy exchange, type of flow, or operating principle. In terms of the operating principle, fluid machines can be divided into dynamic or positive displacement machines. Dynamic machines, also known as turbomachines, are characterized by the transfer of energy that occurs between a continuous flow and a rotor by the dynamic action of the blades. Thus, the flow is considered constant but will vary according to the amount of exchange energy. Positive displacement machines are characterized by the transfer of energy that occurs by a variation of fluid volume existing at each moment inside the machine. Thus, the flow, normally pulsatory, is independent of the energy. In order to enable this energy exchange, electrical energy is required, and the following section will present the basic numerical expressions applied to each type of machinery.

3.2.1 Pumps

Pumps are hydraulic machines with the capacity to transfer incompressible fluid. This means that the pump has the function of providing sufficient energy to the fluid to overcome hydraulic resistances with a given height. In this manner, this type of machinery must be selected according to the system capacity, fluid type and the system pressure or head. With these parameters, it is possible to know the electric power to drive the pump (equation (3.1)). Through the pressure indicated or estimated, it is easily converted into head in mwc.

$$P_{pump} = \frac{\dot{Q}_{pump} \times H \times \rho \times g}{\eta_{elect} \times \eta_{mec}} \tag{3.1}$$

In this equation P_{pump} is the pump power in kW, $\dot{Q}_{pump}$ is the flow rate in m^3/s, H is the total head in mwc, ρ is the density of liquid in ton/m^3, g is the gravitational constant in m/s^2, η_{mec} is the mechanical efficiency of the pump, and η_{elect} electrical efficiency of the drive motor.

The types of pumps used on board must be thoroughly selected according to the type of fluid. Within the dynamic type, the most used pumps are centrifuges. This type of pump is typically applied to the water. Within the positive displacement type, the most used pumps on a ship are screw and gear pumps. In this thesis, the type of pump utilized will define the respective efficiency (Table 6).

Table 6 - Mechanical Efficiency in function of pump type

Pump Type	Mechanical Efficiency
Centrifugal	0.70-0.85
Screw/Gear	0.65-0.70

3.2.2 Compressors

Compressors are required to compress matter in a gaseous state. In order to calculate parameters about compressor performance it is necessary methods to estimate the gas properties. When there are present changes in state of air in terms of thermodynamic, air can be regarded as perfect gas in the temperature and pressure intervals for compressed air. Thus, the simplest equation of state is the perfect gas law which relates the pressure, volume and temperature of a gas.

$$pV = mRT \tag{3.2}$$

Where p is the pressure in Pa, V is the volume in m^3, m is the mass of enclosed air in kg, R is the specific gas constant in J/kgK and T the temperature in K.

The work required per cycle or the power required to drive the compressor can be calculated based on several forms as for example from the pressure against volume diagram, enthalpy against entropy diagram or from the temperature that across the compressor. The compressor power estimation by the system enthalpy is represented in equation (3.3).

$$P_{compressor} = \dot{m} \times (hs - he) \tag{3.3}$$

In which $P_{compressor}$ is the power required for the compressor, $\dot{m}$ is the mass flow in kg/s, hs is the exit enthalpy in kJ/kg, and he is the entrance enthalpy in kJ/kg.

To simplify the power calculation of the compressor, in case of no possibility of having more accurate data of the thermodynamic parameters, some assumptions were made. It was considered an ideal cycle, which means that there is no heat transfer and perfect gas conditions. In this manner, the compression is isentropic, and then the discharge temperature can be calculated from pressure ratio and the suction temperature using the isentropic relationship. With some substitutions based on the adoptions mentioned, the compressor power can be computed by the equation (3.4).

$$P_{compressor} = \frac{p_e \times Q}{3{,}600 \times R} \times C_p \times \left[\frac{\left(\frac{ps}{pe}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} \right] \tag{3.4}$$

In which ps corresponds to the exist pressure of the fluid in kPa, p_e the entrance pressure in kPa, Q the air flow in m^3/h, R the gas constant in J/kgK, C_p is the specific heat in J/kgK, the γ is the isentropic coefficient, and η_c compressor efficiency.

The compressor efficiencies, as for pumps vary with type, size, and performance. An efficient compressor is the one which dislocates higher air quantity with a lower enforce. To determine the efficiency of a compressor is necessary a test, however the compressor manufacturers provide estimations that can be used as references for project calculations. The typical values used as efficiencies according to the compressor type are present in Table 7.

Table 7 - Typical efficiencies according with compressor type

Compressor Type	Efficiency
Centrifugal	0.70-0.85
Rotary Screw	0.65-0.75
High Speed Reciprocating	0.72-0.85
Low Speed Reciprocating	0.75-0.90

3.2.3 Fans

Fans are centrifugal machines in which the flow enters axially and leaves tangentially. The fans are mainly used for forced or natural air ventilation or extraction. To provide forced ventilation it is required that the fans are powered by electricity. The power required for fans can be calculated with the expression (3.5).

$$P_{fan} = \frac{\dot{v} \times \Delta p_{ref}}{\eta_v} \tag{3.5}$$

In equation (3.5), P_{fan} is the pump fan power in kW, $\dot{v}$ is the volumetric air flow m^3/s, Δp_{ref} represents the pressure in kPa, and η_v is the volumetric efficiency associated with the fan.

The reference absolute pressure which was taken into consideration for the calculation of the electric power associated with a fan was 70 mmwc which corresponds to 0.069 kPa (MAN, 2010).

3.3 Engine Room (Continuous Service)

Group 1 corresponds to the continuous service in the engine room (ER). This group is characterized by all services that must be in permanent operation, services provided without interruption, or those that are essential for the normal operation of the engine room machinery. The majority of ER machinery is directly related to the main engine auxiliary systems to guarantee its good functioning. The process of power estimate of these systems components begun by analyzing the project guides which most of the main engines (ME) manufacturers offer for the layout of marine propulsion plants. The collected parameters from these guides were essentially the flow rate and the pressure head suggested for each pump in each system. The engines data analyzed for 2-Stroke consists of 79 samples from (MAN, 2020a) with a range between 4,000 kW and 82,440 kW. For 4-Stroke engines data, it was analyzed 58 samples between 1,200 to 19,200 kW, from (MAK, 2020; Wärtsilä, 2020; Rolls-Royce, 2020; MAN, 2020b).

3.3.1 Fuel System

There are several types of fuel according to their degree of distillation. To comply with IMO legislation, it was considered that all engines studied are prepared to operate with two types of fuel. The ship's ME operates with intermediate fuel oil (IFO) in navigation time and with marine diesel oil (MDO) when it is in maneuvering and in port, this change of fuel is done when the ship is preparing to enter the port. In case the ship's ME only operates with MDO, the installation is simplified. Thus, in the model there is an input option to specify if the engine will work with both fuels or exclusively with MDO. The fuel system is composed of an internal circuit near the engine and an external circuit. Being the internal circuit mechanically driven, it was studied only the external circuit. The external fuel system can be divided into three sub-systems: transfer and storage, treatment, and supply system. In continuous service should be the supply system (Figure 2) and the treatment (Figure 3).

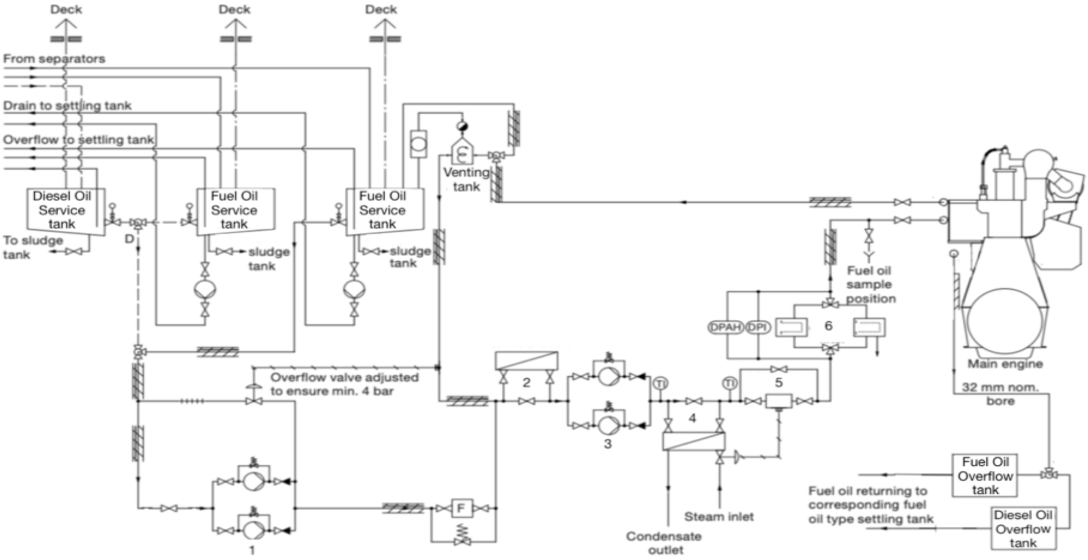

Figure 2 - Fuel supply system: single diagram (MAN,2020a)

The components of this system are described in Table 8.

Table 8 - Fuel supply system components

nº	Designation	nº	Designation	nº	Designation
1	Supply pumps	3	Circulating pumps	5	Viscosity sensor
2	MDO cooler (optional)	4	Pre-heater		

From the machinery presented in the single diagram of the Figure 2, it was studied the supply pumps and the circulating pumps, since the other components are small electrical consumers.

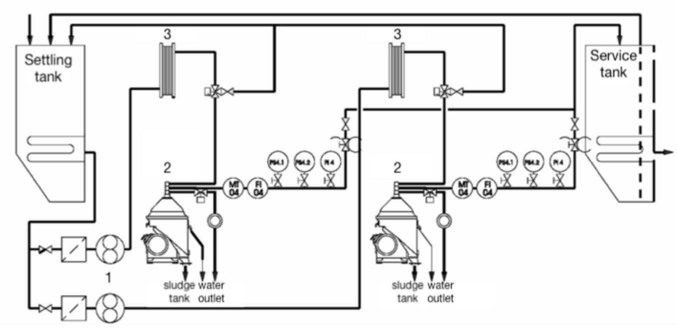

Figure 3 - Fuel treatment system: single diagram (MAN, 2020a)

The fuel treatment system components are shown in Table 9.

Table 9 - Fuel treatment system components

nº	Designation
1	Purifier feed pumps
2	Purifier
3	Pre-heaters

In this sub-system, all machinery was analyzed and implemented in the final model, with exception of the pre-heaters associated with the purifiers, since these are devices of small electrical consumption. Due to the type of fluid (IFO) used in this system, it was assumed screw or gear type for all pumps to be studied.

3.3.1.1 Fuel Oil Supply Pump

The fuel system includes two supply pumps which take suction from the service tanks and feed two circulating pumps. Knowing the capacity and pressure of the supply pumps, and assuming the fluid density as 0.991 which corresponds to the IFO density at a higher temperature, the power of each pump motor is computed by equation (3.1).

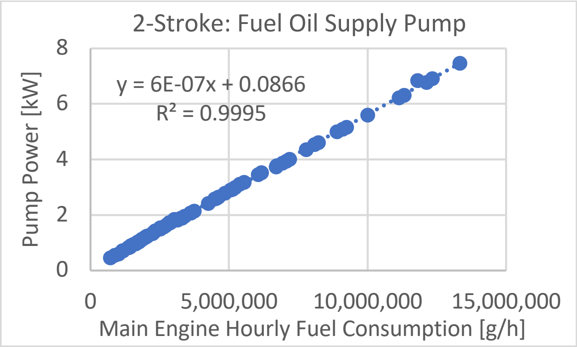

Figure 4 - Fuel oil supply pump for 2-Stroke engines

The parameter defined as independent variable to estimate the pump power was the main engine hourly fuel consumption (HFOC). This parameter is easily calculated with the ME power input and the corresponding ME specific fuel oil consumption (SFOC). The compiled results obtained in a graphical representation and the respective regression line obtained for 2-Stroke engines are present in Figure 4. The 2-Stroke fuel oil supply pump power consumption general equation obtained is shown in (3.6).

$$P_{FOsupplypump} = 6E - 07 \times HFOC + 0.0866 \tag{3.6}$$

Figure 5 is the resulting graphic referred to 4-Stroke engines fuel oil supply pump.

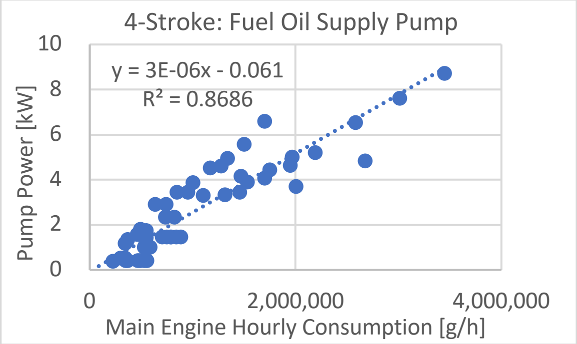

Figure 5 - Fuel oil supply pump for 4-Stroke engines

The respective equation obtained from linear regression performed is given in (3.7).

$$P_{FOsupplypump} = 3E - 06 \times HFOC - 0.061 \tag{3.7}$$

3.3.1.2 Fuel Oil Circulating Pump

The fuel supply system has also two circulating pumps that receive the fuel from the supply pumps and after passing through a heater and a viscosity regulator, the fuel is discharged in a common high-pressure collector and after directed for engine-driven fuel pumps. In the event of the fuel's viscosity grade being superior to the appropriate one, the fuel is recirculated through the heater until the appropriate temperature and viscosity conditions are verified in the viscosity regulator sensor. The same principle applied for supply pumps was applied for circulating pumps, resulting in Figure 6 graphic representation for 2-Stroke engines.

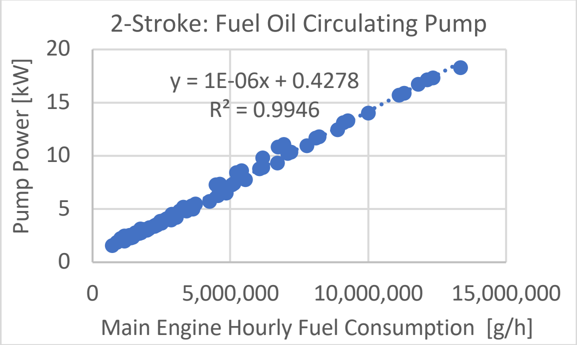

Figure 6 - Fuel oil circulating pump for 2-Stroke engines

The aggregated equation of the linear regression performed is shown in (3.8)

$$P_{FOcirculationpump} = 1E - 06 \times HFOC + 0.4278 \tag{3.8}$$

Figure 7 represents the fuel oil circulating pumps power consumption results for 4-Stroke engines.

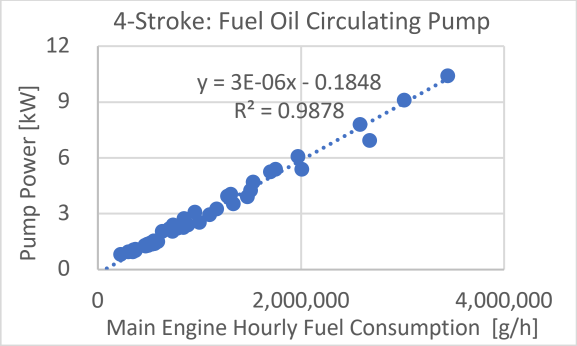

Figure 7 - Fuel oil circulating pump for 4-Stroke engines

The respective equation implemented on the model is shown in (3.9).

$$P_{FOcirculationpump} = 3E - 06 \times HFOC - 0.1848 \qquad (3.9)$$

3.3.1.3 Fuel Oil Purifier

The main function of the purifier is to separate the water and majority of particles from the fuel that passes through it. The process of separation is achieved by a centripetal force. The purifier receives the fuel from the settling tank by a feed pump and fills the service tank or simply recirculates the fuel, which the suction and the discharge are the service tanks. The separator is driven by an electric motor via a friction clutch and belt, and for this reason, must be considered in the electrical load balance model. The ME manufacturers provide the purifier capacity. Then, another study was conducted. It was analyzed the typical electrical consumptions for purifiers according to the capacity required, using catalogs. Figure 8 is the graphical representation of the (Mitsubishi, 2020) data collected.

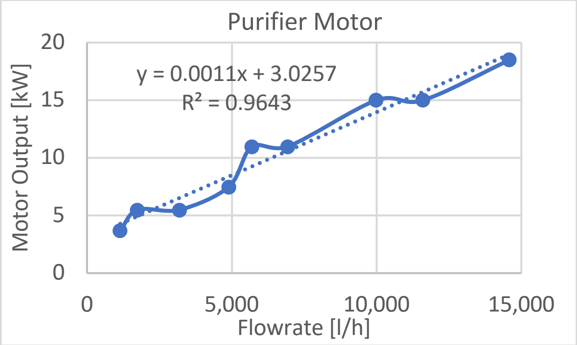

Figure 8 - Purifier motor power consumption (Mitsubishi, 2020)

The corresponding equation to be applied in each engine sample based on the engine purifier capacity given in engine project guides, is present in (3.10).

$$P_{Purifiermotor} = 0.0011 \times \dot{Q}_{Oil} + 3.0257 \qquad (3.10)$$

It was then possible to proceed with the prediction equation to be used in the final model. With all purifier motor consumption data calculated, and correlating with the HFOC parameter, the scatterplot result for 2- Stroke engines is presented in Figure 9.

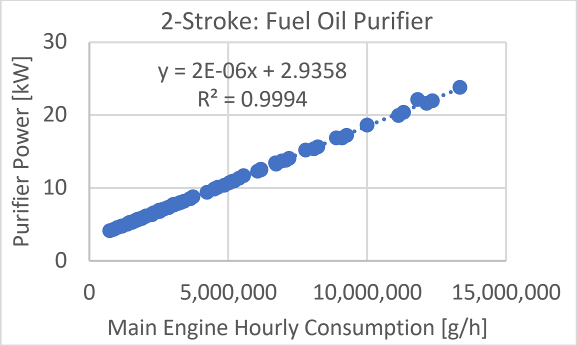

Figure 9 - Fuel oil purifier power for 2-Stroke engines

Where the resulting equation of the linear regression obtained from the graphic is the equation (3.11).

$$P_{FOPurifier} = 2E - 06 \times HFOC + 2.9358 \tag{3.11}$$

For 4-Stroke engines, the graphical representation result is shown in Figure 10.

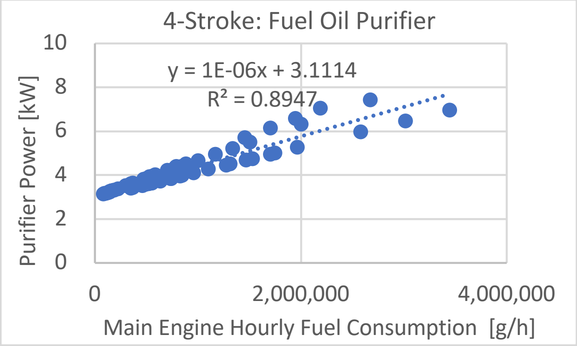

Figure 10 - Fuel oil purifier power for 4-Stroke engines

The corresponding equation obtained from the scatterplot regression line performed is shown in (3.12).

$$P_{FOPurifier} = 1E - 06 \times HFOC + 3.1114 \tag{3.12}$$

3.3.1.4 Fuel Oil Purifier Feed Pump

The untreated oil is continuously fed into the separator through a pump, that directs the oil from the service tank onto the purifier. For the calculation of the power of the feed pump, it was considered the same flow rate and pressure recommended in the guides for each engine purifier sample. After the power pump estimation and correlated with HFOC, the results achieved graphically are following shown. Figure 11 is the representation of the data calculated for 2-Stroke engines.

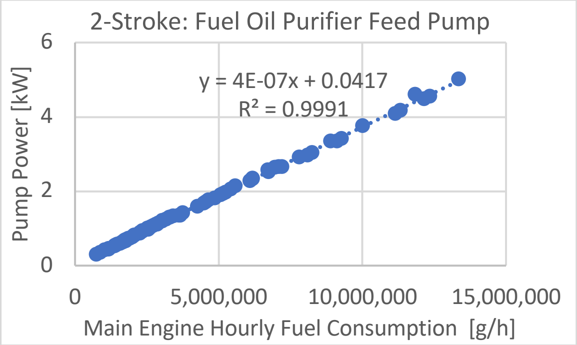

Figure 11 - Fuel oil purifier feed pump for 2-Stroke engines

The equation (3.13) is the equation implemented in the electrical balance model for 2-Stroke engines.

$$P_{Purifierfeedpump} = 4E - 07 \times HFOC + 0.0417 \tag{3.13}$$

For 4-Stroke engines, the results are shown in Figure 12.

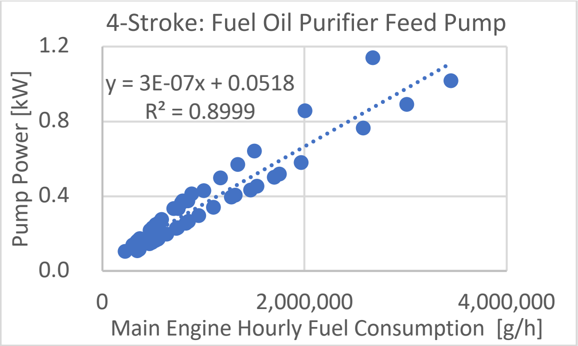

Figure 12 - Fuel oil purifier feed pump for 4-Stroke engines

The equation (3.14) is the result of the linear regression for 4-Stroke engines FO purifier feed pump.

$$P_{Purifierfeedpump} = 3E - 07 \times HCM + 0.0518 \tag{3.14}$$

3.3.1.5 Diesel Oil Supply and Circulating Pumps

Diesel is a fuel that can be used both in the ME and in the generators. It was not possible to estimate the consumption of the oil associated with these engines since there is no information about the generators at this stage. Thus, it was considered only pumps and MDO equipment exclusively for the ME. In addition, a dual fuel engine (IFO and MDO), normally uses the same supply and circulation pumps, and the change of fuel is done through a 3-way valve. For this reason, it was considered the same equations for the supply and circulating pumps in order to calculate the electrical consumption.

3.3.1.6 Diesel Oil Purifier and feed Pump

Once again, the DO purifier and the feed pump should be sized taking into consideration the diesel consumption of the generators. However, due to the reason previously described, also for the purifiers was only considered the main engine. This equipment was sized with the same equations used for fuel.

3.3.2 Lubrication System

The lubrication oil system has as mission the reduction of the friction between the main engine elements, the elimination of heat produced by friction, and also an anti-rust protection of the uncoated steel elements of the engine. To guarantee these functions, the system is divided into three sub-systems for transfer and storage, treatment and circulating (CIMAC, 2017). In this chapter will be analyzed the major parts of the system, which are the treatment and circulating service system. Figure 13 presents the circulating service loop where its principle will be explained forward.

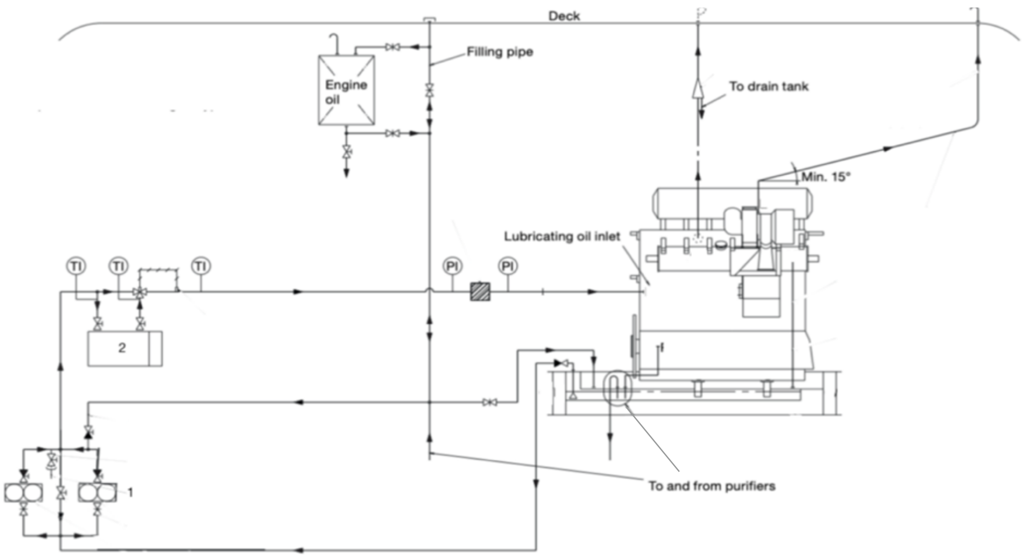

Figure 13 - Lubrication system: single diagram (MAN,2020a)

The main components of this sub-system are shown in Table 10.

Table 10 - Lubrication system components

nº	Designation
1	Lubricating oil pumps
2	Lubricating oil cooler

The machinery that will be further analyzed are the lubricating oil pumps.

3.3.2.1 System Lubrication oil pump

The lubrication oil (LO) is collected in a sump tank below the ME. Therefore, its movement mechanically propelled will lubricate the main bearings, crankpin, and crosshead in the case of 2-Stroke engines. After lubricating all components, oil discharge is done by gravity from the crankcase to the tank. The oil passing in all engine major interior components will consequently increase its temperature, as can also bring some impurities. For this reason, it is crucial to a constant circulation of this oil, as its treatment by a purifier. The circulating system contains two pumps that will conduct the oil from the sump tank, passing through the cooler when its temperature is above the ideal conditions, and also through a fine filter beforel entering in the sump tank. Despite a small consumption of main engine oil and small amounts lost by purifier discharges, this system has a constant flow. Therefore, it is estimated that the LO system is designed according to the ME displacement volume. So, it is estimated that if an engine is larger it will have a higher flow to lubricate all the components. Being the engine displacement volume an easy parameter to estimate, it was placed as input parameters of the model, the cylinder dimensions and the number of engine cylinders. For the power estimation associated with these pumps, it was considered the capacity mentioned in manufacturers' project guide. In addition to the capacity, it was assumed the density. The LO of this system has an SAE viscosity grade of 30, which corresponds to 0.89 kg/m^3 at 15ºC.

Implementing the same estimating process that has been developed until now, after pump power samples calculated, it was performed a scatter plot graphic in function of the displacement volume calculated for each engine. In this way, it was obtained for 2-Stroke the graphic of Figure 14.

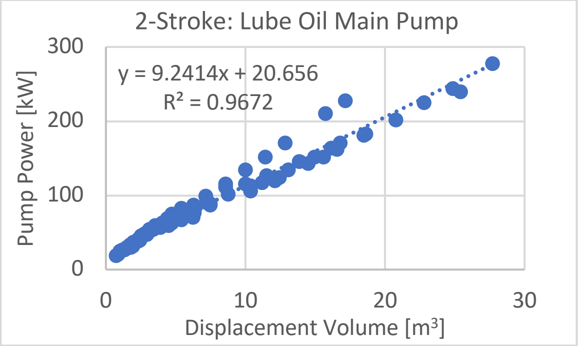

Figure 14 - Lubrication oil main pump power for 2-Stroke engines

The power consumption for LO system main pumps for 2-Stroke engines is calculated based on (3.15).

$$P_{LOmainpump} = 9.2414 \times V_d + 20.656 \tag{3.15}$$

The same principle was applied for 4-Stroke engines, obtaining the result shown in Figure 15 and Figure 16. After a verification of a big variance in the flow rate parameter in 4-Stroke engines with cylinders number lower than 12 and the remaining, and assuming that engines with more than 12 cylinders have a V-configuration, it was opted to divide into two possible configurations for 4-Stroke engines reducing the error previously found.

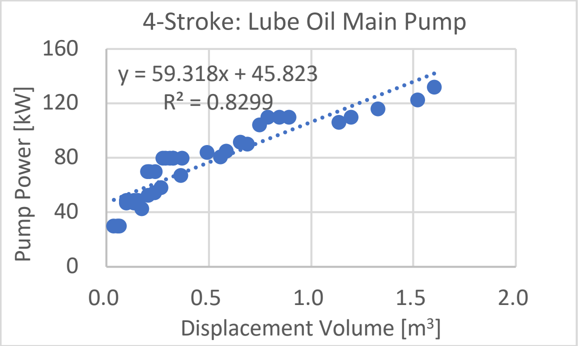

Figure 15 - Lubrication oil main pump power for 4-Stroke engines in line configuration

The power consumption equation for 4-Stroke engines lube oil main system pump is present in (3.16).

$$P_{LOmainpump} = 59.318 \times V_d + 45.823 \tag{3.16}$$

The graphic obtained for 4-Stroke engines in V configuration is shown in Figure 16.

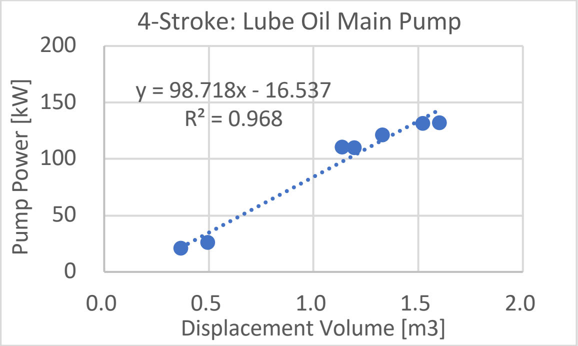

Figure 16 - Lubrication oil main pump power for 4-Stroke engines in V configuration

Where the corresponding equation of the regression achieved is following shown.

$$P_{LOmainpump} = 98.718 \times V_d - 16.537 \tag{3.17}$$

3.3.2.2 Cylinder Lubrication Oil Pump

For a 2-Stroke crosshead ME, normally, in addition to the general lubrication of the engine movements, there is an independent one for the cylinders. The cylinder LO will lubricate liners, pistons, and piston rings. This system is one of the most important systems since it should be prepared to deal with conditions of higher temperatures and combining with the acidity of the fuel. Normally this system can be pumped by a mechanical system that is actuated by the camshaft or can be introduced as an automatic system to dose the cylinder oil for each one. In this thesis it is considered as a mechanical system.

3.3.2.3 Lubrication Oil Purifier

The ME oil in its passage can be contaminated by small particles, combustion products, or water, for this reason, it is essential a purifier. The purifier capacity is recommended by the ME manufacturers. For the purifier power estimation, it was used the equation (3.10) and performed the analysis with the same variable V_d. The result of the analysis for 2-Stroke engines is shown in Figure 17.

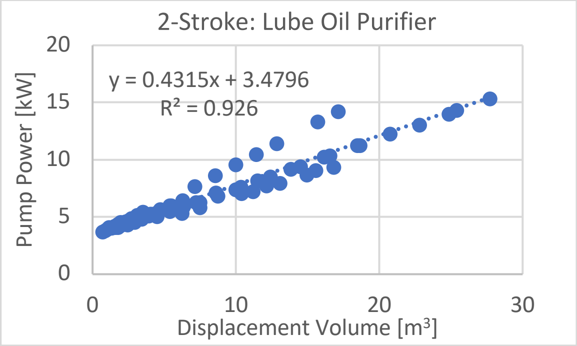

Figure 17 - Lube oil purifier for 2-Stroke engines

The power consumption of the LO purifier for 2-Stroke engines can be estimated with the equation (3.18).

$$P_{LOPurifier} = 0.4315 \times V_d + 3.4796 \tag{3.18}$$

After the same principle applied for 4-Stroke engines, it is obtained the result shown in Figure 18.

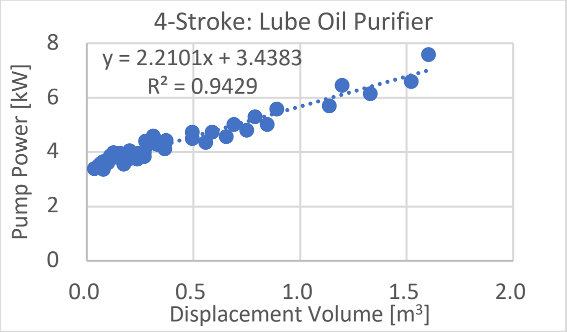

Figure 18 - Lube oil purifier for 4-Stroke engines

The corresponding equation obtained from the graphic regression curve is shown in (3.19).

$$P_{LOPurifier} = 2.2101 \times V_d + 3.4383 \tag{3.19}$$

3.3.2.4 Lubrication Oil Purifier Feed Pump

The LO purifier feed pump is part of the treatment sub-system. It has the same function as the FO purifier feed pump, to feed the purifier with a constant flow. The suction of this pump can be from the sump tank, occurring an oil recirculation to ensure the oil purity, or from the engine oil filling tank to guarantee the good quality of oil when it is supplied the small quantities necessary to the closed system. For the power consumption of these pumps, it was used the recommended values for purifier flow rate described on ME project guides. The independent basic design variable considered for the LO feed pump power estimation is the displacement volume. Figure 19 presents the scatter graphic then obtained for 2-Stroke engines.

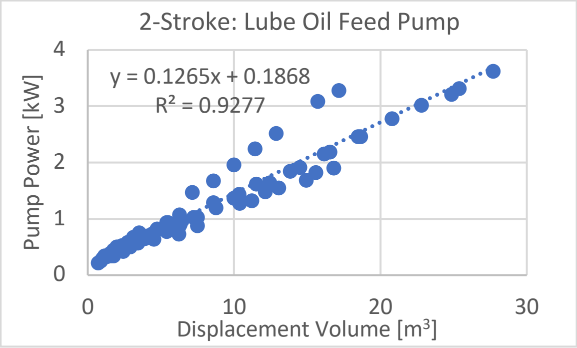

Figure 19 - Lubrication oil purifier feed pump for 2-Stroke engines

The power consumption equation implemented in the model for 2-Stroke engines, is the equation (3.20).

$$P_{LOPurifierfeedpump} = 0.1265 \times V_d + 0.1868 \tag{3.20}$$

For 4-Stroke engines the resulting graphic is present in Figure 20.

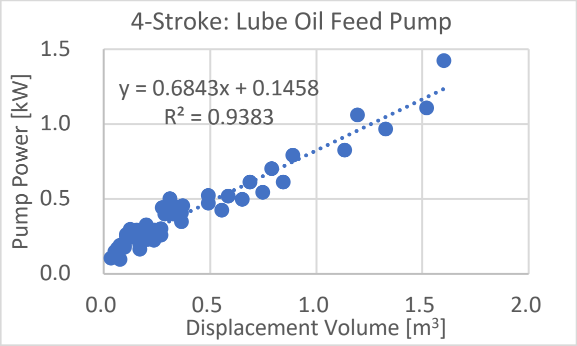

Figure 20 - Lube oil purifier feed pump for 4-Stroke engines

The resulting equation of the regression line performed is presented in (3.21).

$$P_{LOPurifierfeedpump} = 0.6843 \times V_d + 0.1458 \tag{3.21}$$

3.3.3 Cooling System

The main function of the cooling system is to maintain optimal operating temperatures, cooling down the engines and other equipment, and also it is by this system that much of the heat generated by friction is removed. To reduce the corrosion caused by seawater, usually, this system is divided into two subsystems: seawater, freshwater central cooling (low-temperature and high-temperature).

3.3.3.1 Freshwater Circulating High-Temperature Pump

The cylinder jacket and cylinder head water circulation are performed by FW. The thermal load of the engine is transmitted later and externally through an exchange for seawater.

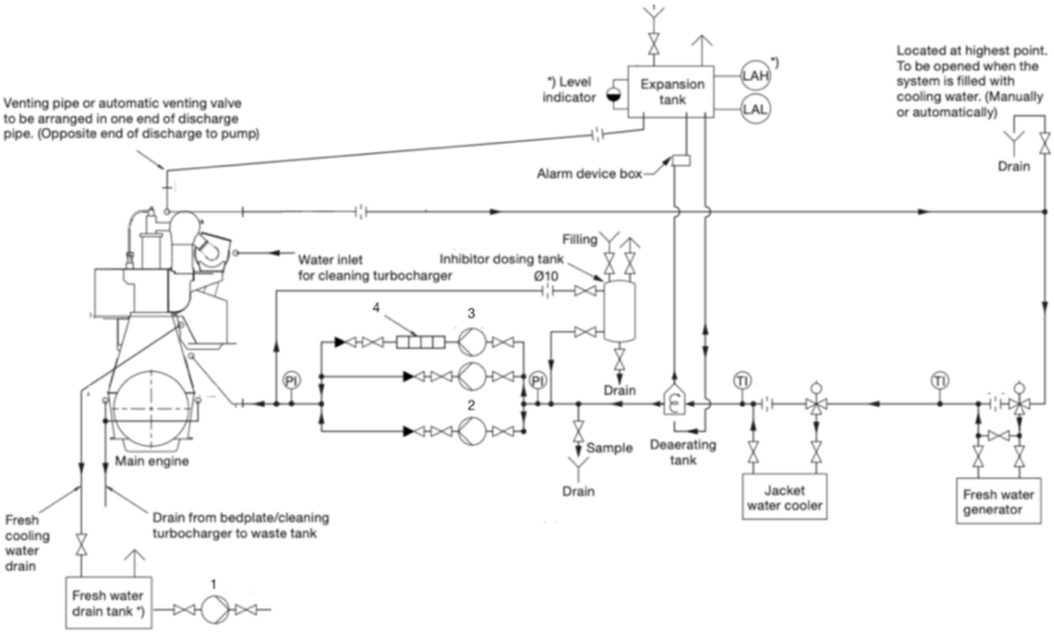

Figure 21 - High-Temperature water system: single-diagram (MAN, 2020a)

It is denominated as high-temperature system (Figure 21) since it is an internal circuit of the engine and the outlet water temperature is elevated (around 80ºC). After leaving the engine, the water temperature is controlled by a mixing control valve. This valve guarantees the ideal temperature, controlling the opening or closing at a higher or lower flow rate to a cooler. To allow the circulation, there is a necessity of pumps. The system components are described on Table 11.

Table 11 - High-Temperature water system components

nº	Designation	nº	Designation
1	Freshwater drain pump	3	Pre-heater pump
2	Jacket water pumps	4	Pre-heater

From the components present in the previous table, it was studied the jacket water pumps (HT centrifugal pumps). The parameters from the HT pumps are provided in ME project guides. Then it is calculated the power requirement for these pumps according to each engine sample with equation (3.1). After, it was sought a parameter easy to obtain through conceptual ship design to correlate the power of the HT pumps. Therefore, the parameter selected was the total heat rejected through water (Nitonye, 2017), which link the lower heating value of the fuel (constant value from the used fuel type) and its specific fuel oil consumption (SFOC). For each sample, the amount of heat rejected was calculated following the equation (3.22).

$$HCM = LHV \times (SFOC - 3600)[1 - ff] \tag{3.22}$$

In the equation (3.22), HCM is the total heat rejected by coolant in kJ/kWh, LHV is the lower heating value, equivalent to 42,700 kJ/kg for IFO fuel, $SFOC$ is the specific fuel oil consumption [g/kWh], and ff

is the fuel factor (for IFO =0.56). It is possible to see in Figure 22, the scatterplot and the respective regression curve obtained to estimate the power for 2-Stroke engine HT pump.

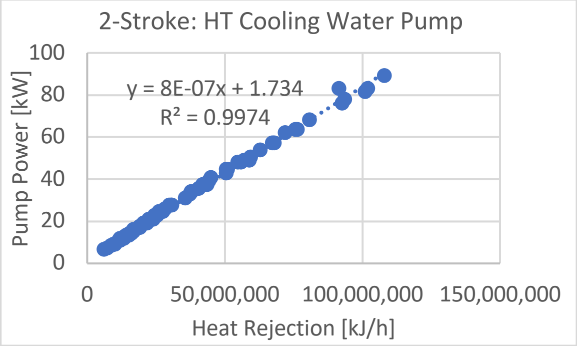

Figure 22 - HT pump power in function of heat rejection for 2-Stroke engines

The respective equation is shown in (3.23).

$$P_{HTpump} = 8E-07 \times HCM + 1.734 \tag{3.23}$$

For 4-Stroke engine HT pump result is shown in Figure 23.

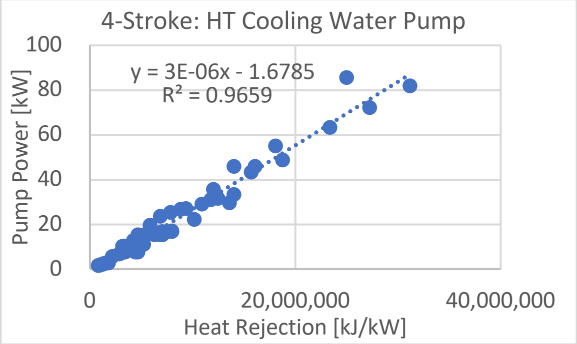

Figure 23 - HT pump power in function of heat rejection for 4-Stroke engines

The equation obtained from the regression line is shown in (3.24).

$$P_{HTpump} = 3E-06 \times HCM - 1.6785 \tag{3.24}$$

3.3.3.2 Freshwater Circulating Low-Temperature Pump

The low-temperature water (Figure 24) circulates all the heat exchangers such as the main exchanger heat (the one which circulates the high-temperature water), the lubrication oil cooler, main engine air cooler, and so on. Although it is not a circuit directly related to the ME, its pumps parameters are mentioned in ME project guides. Then the same principle was applied for low-temperature centrifugal pumps.

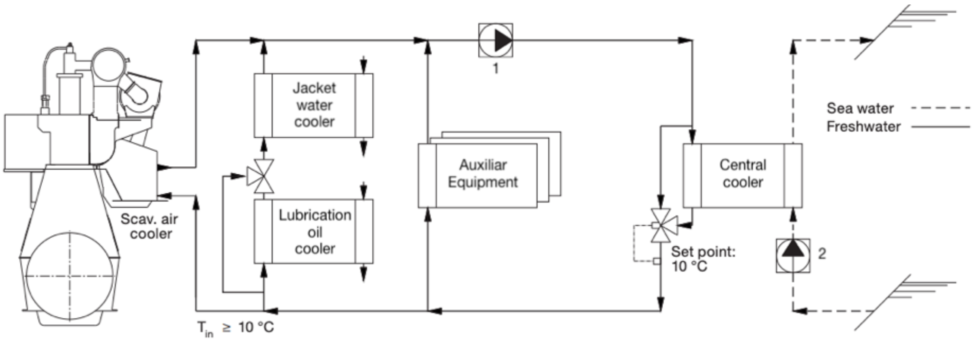

Figure 24 - Low-Temperature water system: single-diagram (MAN,2020a)

The system components are described in Table 12.

Table 12 - Low-Temperature water system components

nº	Designation
1	Central cooling pumps
2	Sea water pumps

Both pumps presented in Table 12 were considered. After all calculations were performed, it was obtained the graphic result of the LT cooling water pump for 2-Stroke engines, shown in Figure 25.

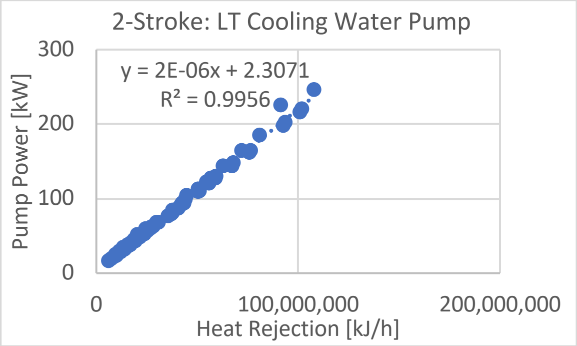

Figure 25 - LT pump power in function of heat rejection for 2-Stroke engines.

In this manner, the LT pump power consumption equation to be used in the case of 2-Stroke engines is the equation (3.25).

$$P_{LTpump} = 2E - 06 \times HCM + 2.3071 \tag{3.25}$$

For LT pumps in case of 4-Stroke engines, the result is shown in Figure 26.

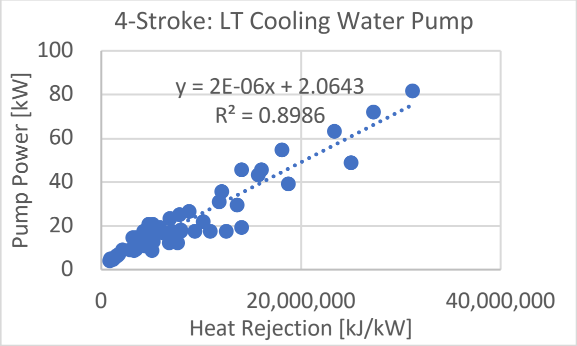

Figure 26 - LT pump power in function of heat rejection for 4-Stroke engines

The equation to be used in the power consumption estimation of this pump in case of the 4-Stroke engines is shown in equation (3.26).

$$P_{LTpump} = 2E - 06 \times HCM + 2.0643 \tag{3.26}$$

3.3.3.3 Freshwater Generator

Nowadays all ships are equipped with a freshwater generator (FWG). The FWG process consists of evaporate seawater using a heat source, separating thus the water, the salt and small particles, resulting in freshwater. The high-temperature water circuit that circulates through the ME, in its outlet will pass through the FW distiller acting as a heat source. The FWG is totally dependent on the freshwater consumption on board since if there is more consumption on board the distiller will have to increase the water production capacity to fulfill the requirements. The freshwater consumption is described in detail in section 3.5.5. Based on the daily consumption, the FWG manufacturers present the power consumption prediction. Thus, it was collected data from (Osmomar, 2020; Farad, 2020). Figure 27 represents the scatterplot obtained from the power consumption data collected in the function of the daily consumption on board. Also, it is presented the regression curve performed from the data.

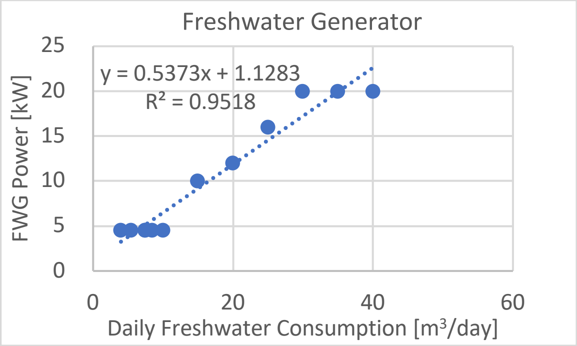

Figure 27 - Freshwater generator power in function of the daily freshwater consumption

The equation to be used to estimate the freshwater generator power consumption is the equation (3.27).

$$P_{FWG} = 0.5373 \times \dot{V}_S + 1.1283 \tag{3.27}$$

3.3.3.4 Seawater Circulating Pump

The seawater system is normally an open system that has as main objective the cooling of the FW closed system. Seawater (SW) is taken from the sea chest and pumped by electrically driven centrifugal pumps for the system, being first correctly filtrated by a strainer. The SW flows from pumps for several heat exchangers. After SW circulate through the equipment, it will return overboard. For this system, it was verified a high complexity to obtain a realistic estimation of all consumers using seawater in its cooling. For this reason and being the seawater pump parameters easy to estimate in the ship's conceptual design it was decided to introduce the flow and pressure related to the seawater system as input in the model, and then the model is capable to estimate the respective power consumption.

3.3.4 Steering Gear Unit

Two types can be distinguished for steering gear units, being these the ram-type electrohydraulic steering gear or rotary vane steering gear. Independently of the steering gear type, there is a necessity of a pumping unit to allow the oil movement on the steering gear mechanism. Normally two independent pumping units are provided which in cargo ships the two units work to provide a faster response and in passenger ships, only one unit works. To the unit power estimation, it was applied the equation (3.28), based on physical principles.

$$P_{Steeringgear} = \frac{M_{max} \times \omega}{\eta_{elect} \times \eta_{mec}} \tag{3.28}$$

In equation (3.28), $P_{SteeringGear}$ is the power required to drive the steering gear pumps in kW, M_{max} is the maximum moment exercised by steering gear in Nm, and ω the angular velocity in rad/s.

The rudder moment or torque is defined in several classification societies. It is a parameter that is in function of the maximum rudder force and other components and coefficients specific of each ships' rudder design. Due to this complexity and being these parameters known in conceptual phase of a ship it was added the maximum moment as an input value of the model. However, also an auxiliary tool is presented on the input spreadsheet which follows the (DNV GL, 2017) calculations of this parameter for a case of user's unawareness of the maximum moment parameter. Also, in (DNV GL, 2017) it is specified that the ship shall have the capacity to turn from 35º SB to 35º PS or the opposite in 28 seconds. In this way, it is easily calculated the maximum angular velocity to be exercised by the steering gear unit (3.29).

$$\omega = \frac{(\theta_{final} - \theta_{initial})}{t_{Maneuver}} \tag{3.29}$$

Where ω is the angular velocity in rad/s, θ is the maximum angle for each board in rad, and $t_{Maneuver}$ the estimated time to conclude the maneuver in s.

3.3.5 Ventilation System

The calculation of the power associated to the ER ventilation was performed using the equation (3.5). For the estimate of the airflow required in this equation it was followed the standard ISO 8861:1998 and the classification societies. Analyzing the standard ISO 8861:1998, it is specified the calculation method of the ER ventilation. The first step of the calculation is the knowledge of the total airflow (Q) necessary for engine combustion and for the evacuation of heat emission in the ER. The standard states that total airflow should be considered as the highest value between the following two conditions:

1) $\mathrm{Q} = q_c + q_h$

2) $\mathrm{Q} = 1.5 \times q_c$

In these conditions, Q is the total airflow in m^3/s, q_c the airflow necessary for combustion in m^3/s, q_h the airflow for evacuation of heat emission in m^3/s. Following the first condition previously presented 1), the airflow necessary for combustion is defined as:

$$q_c = q_{dp} + q_{dg} \tag{3.30}$$

Where, q_{dp} is the airflow for combustion of ME in m^3/s, q_{dg} airflow for combustion of DG in m^3/s.

The airflow necessary for combustion of the ME is calculated according to the next equation:

$$q_{dp} = \frac{P_{dp} \times m_{ad}}{\rho_{35}} \tag{3.31}$$

Where P_{dp} is the power of ME in kW, m_{ad} the air necessary for combustion of ME in kg/kWs, ρ_{35} corresponds to the air density at 35ºC, which is equivalent to 1.13 kg/m^3.

Table 13 - Typical values for air necessary for combustion of 2-Stroke and 4-Stroke engines

	m_{ad} [kg/kWs]
2- Stroke	0.0025
4- Stroke	0.002

The air necessary for combustion m_{ad} is provided as typical values in case of these values are not available (Table 13). The airflow for DG combustion considered uses the same equation (3.31) used for ME. However, the power to be considered is related to the DG. Since an electrical balance is being developed and in turn, the aim of this is to estimate the power required for the diesel-generators to install on board, the diesel-generators power was done with an approximation for necessary calculations. The approximation followed is provided in (IMO, 2018), in which is a guideline for EEDI estimation, however, provides reference equations for auxiliary engines power calculation in case of its unawareness. Then for ships in which total propulsion power is 10,000 kW or above, the equation to be used is (3.32).

$$P_{AE} = \left(0.025 \times \sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right) + 250 \tag{3.32}$$

In otherwise when the total propulsion power is below 10,000 kW the equation to be applied is (3.33).

$$P_{AE} = \left(0.05 \times \sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right) \tag{3.33}$$

Where is the MCR_{ME} the maximum continuous rate of ME in kW and $P_{PTI(i)}$ the power of the shaft motor in kW. The power of the shaft motor is not considered.

Also, in accordance with condition 1), q_h refers to airflow necessary to evacuation of heat emission and the respective equation for the calculation is present in (3.34).

$$q_h = \frac{\Phi_{dp} + \Phi_{dg} + \Phi_{tp} + \Phi_p + \Phi_g + \Phi_{el} + \Phi_{ep} + \Phi_t + \Phi_o}{\rho_{35} \times c \times \Delta T} - 0.4\left(q_{dp} + q_{dg}\right) - q_b \tag{3.34}$$

In equation (3.34), Φ_{dp} is the heat emission from ME in kW, Φ_{dg} the heat emission from DG in kW, Φ_{tp} the heat emission from boilers or heat exchangers in kW, the Φ_p is heat emission from steam or condensate pipes in kW, Φ_g the heat emission from electrical alternator in kW, Φ_{el} the heat emission from electrical installations in kW, Φ_{ep} the heat emission from exhaust pipes in kW, Φ_t the heat emission from hot tanks in kW, Φ_o the heat emission from other components in kW, ρ_{35} is the air density at 35ºC, equivalent to 1.13 in kg/m^3, c the air specific heat capacity, equivalent to 1.01 kJ/kgK, the ΔT corresponds to the mean temperature in ER, considered equal to 12.5 [K], q_{dp} the airflow for combustion of ME [m^3/s], q_{dg} the airflow for combustion of DG [m^3/s], and q_b the airflow for combustion of boiler [m^3/s].

The heat emitted by ME can be calculated with the follow equation:

$$\Phi_{dp} = \frac{P_{dp} \times \Delta h_d}{100} \tag{3.35}$$

Where P_{dp} is the power at maximum of ME in kW and Δh_d the heat loss from ME in %. For DG can be followed the same equation with the difference of the power and the heat loss to be related to DG.

For the heat loss, the ISO 8861:1998 presents two graphics which relates this parameter with the continuous power rate. Due to the difficult to obtain the desired points from these representations, it was opted to use the respective equations presented for 2 and 4-Stroke engines.

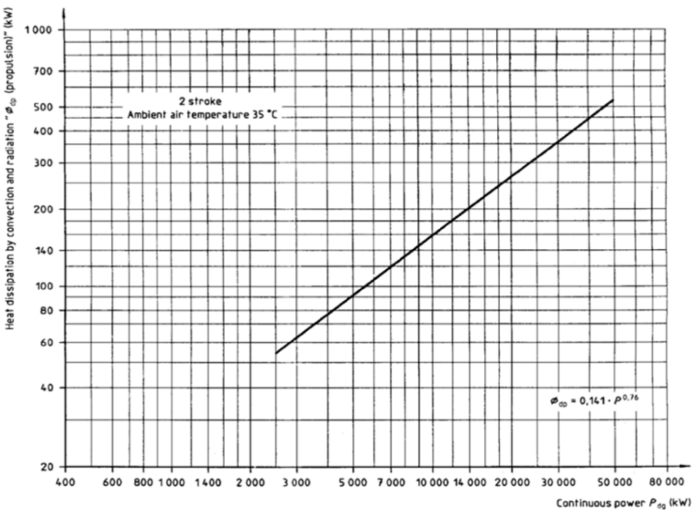

Figure 28 - Heat emission from 2-Stroke engines (ISO 8861:1998)

The respective equation for 2-Stroke engines is following present.

$$\Phi_{dp} = 0.141 \times P^{0.76} \tag{3.36}$$

The heat emission coefficient in a graphic representation for 4-Stroke engines is present in Figure 29.

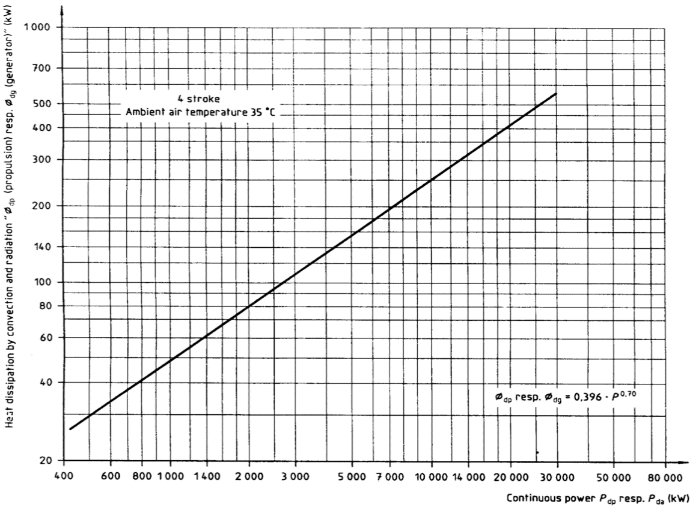

Figure 29 - Heat emission from 4-Stroke engines (ISO 8861:1998)

The equation applied for this parameter estimation in relation to the 4-Stroke engines is (3.37).

$$\Phi_{dg} = 0.396 \times P^{0.70} \tag{3.37}$$

To be noticed that the equation (3.37) can be applied not only for the heat loss from 4-Stroke propulsion engines but also for DG. Since the boiler is an equipment which is not considered in this thesis, the heat emission from boiler and thermal fluid heater Φ_{tp}, is neglected. The same is applied for Φ_{p}, the heat emitted from the steam and condensate pipes. The heat emission from alternator is calculated as follow:

$$\Phi_{g} = P_{g}(1 - \frac{\eta}{100}) \tag{3.38}$$

Where P_g is the power of generator installed in kW and η the generator efficiency equivalent to 94.5 %. The electrical installation heat emission is a parameter not available at this phase of ship design. In this case, the standard describes that should be considered 20% of the electrical apparatus power (DG). Regarding the heat emission from exhaust pipes, ISO 8861:1998 presents the following curves.

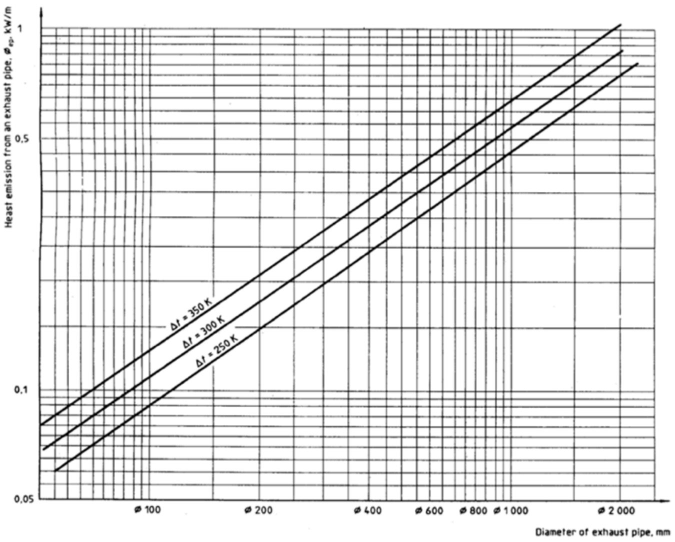

Figure 30 - Heat Loss in kW/m from exhaust pipes (ISO 8861:1998)

As it is possible to see, the heat emission is determined in function of the localized temperature, the exhaust pipe diameter and the length of each pipe section. The temperature was considered the suggested by the standard, $\Delta t = 250\ K$ for 2-Stroke engines and $\Delta t = 350\ K$ for 4-Stroke engines. To simplify obtaining the desired points, it was deducted equations from linear regressions performed from Figure 30 in function of the exhaust pipe diameter [mm].

For $\Delta t = 250\ K$:

$$\Phi_{ep} = 0.0003 \times \emptyset + 0.0918 \tag{3.39}$$

For $\Delta t = 300\ K$:

$$\Phi_{ep} = 0.0004 \times \emptyset + 0.1134 \tag{3.40}$$

For $\Delta t = 350\ K$:

$$\Phi_{ep} = 0.0005 \times \emptyset + 0.1237 \tag{3.41}$$

In relation to the exhaust pipe diameter variable, it was taken into consideration the diameter differences along of its length. After checking the project guides previously used in this thesis, it was found that the difference in diameters occurs at the exit of the engine as shown in Figure 31.

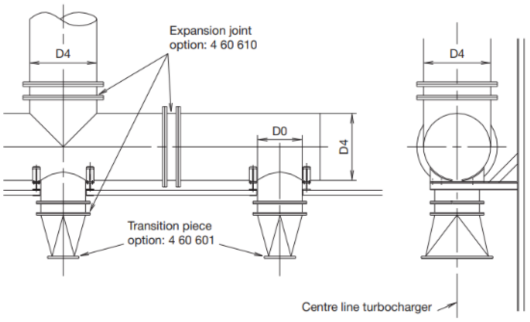

Figure 31 - Exhaust pipe system, with turbocharger located on engine side (MAN, 2020a)

It is then considered as D0 the pipe diameter which enters in the common exhaust gas collector and D4 the diameter of the common exhaust gas collector and also the remaining exhaust pipe length from the turbocharger outlet pipe. These two parameters were imposed as input of the model since it is an engine characteristic already known in the conceptual ship design. As mentioned above, the heat emission is a parameter provided in function of the pipe length. Therefore, it is required each sectional length of the exhaust pipe. On board, the exhaust pipe has both a horizontal and vertical orientation.

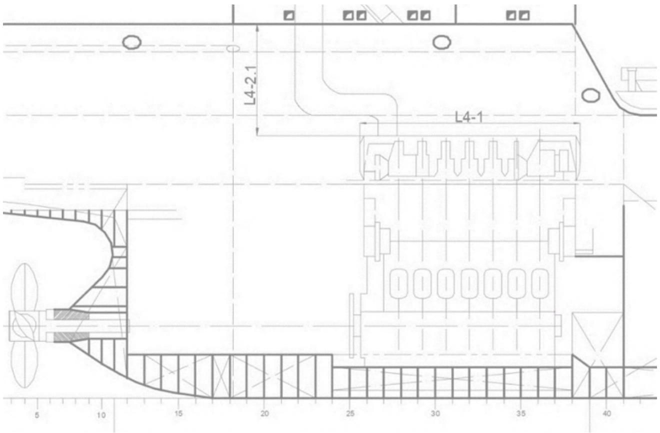

Figure 32 - Representation of exhaust pipe length in an engine room

Figure 32 is an example of the pipe configuration in an ER. L4-1 is considered the exhaust gas collector in position horizontally. To estimate this length, it is assumed the following equation:

$$L_{4-1} = b_{Cylinder} \times n_{\ Cylinders} + 0.01 \ \times (b_{Cylinder} \times n_{\ Cylinders}) \qquad (3.42)$$

Where L_{4-1} is the horizontal length of the exhaust gas collector in m, $b_{Cylinder}$ the bore of each cylinder in m as well, $n_{\ Cylinders}$ are the number of cylinders of the engine. In vertical orientation it is considered the length of the inlet pipe of the turbocharger as constant. In addition, it is considered the height of the pipe from the top of the engine to the main deck (L4-2.1). It was then necessary to have the ship depth as an independent variable and then assumed 1/3 of this value. From here, the pipe is considered in a vertical orientation through the entire height of the superstructure (L4-2.2). With this, another independent variable is the superstructure height with addition of 2.5 meters since the exhaust pipe is always higher than the superstructure. The total heat emission is considered as the sum of the sectional part calculated for the differences found on each variable (pipe diameter and pipe length). Regarding the emission from other components as compressors, reduction gears, separators, piping and hydraulic systems, it was assumed as 80% of the electrical apparatus power. After the calculation of total airflow from ISO 8861:1998, it was applied the requirement of (GL, 2016). This requirement specifies the ventilation for machinery rooms, indicating the air renovation of at least 30 times per hour in all space volume. Therewith, the total airflow considered for the power estimation is the sum of the highest value of the two conditions transcribed before with the airflow provided by air changes per hour method. Therefore, with the airflow calculated it is possible to use the fan power equation (3.5) and then the total power required for ER ventilation is estimated.

3.3.6 Scrubber

IMO (1978) sets limits for the Sulphur content existent on FO. This content was reduced by 0.5% in 2020. To comply with this regulation, there are two practical solution (Faber et al., 2020). To use an exhaust gas cleaning system (EGCS) in combination with FO which the sulphur content is verified higher than the maximum established, or to use FO with sulphur content of 0.5% or lower. Being a scrubber installation on board a possibility and there is an associated electrical consumption, it was modelled this equipment. The scrubber operation consists of the passage of gases through a liquid that will chemically react. The common liquids used can be treated freshwater or untreated seawater. Associated with the liquids to be used is the type of circuits that can be open-loop (OL) (Figure 33) and closed-loop (CL) (Figure 34). An OL scrubber uses seawater as the liquid which is supplied by an independent pump and after the process, this water mixture is directed to a wet sump at the scrubber bottom. This water is extracted from the bottom of the scrubber by a pump after passing through a deaerator, appropriately treated, and finally discharged overboard. A CL scrubber uses treated water circulating through the scrubber. This loop is similar to the OL in terms of the chemical process however the major difference between them is the fact of the FW recirculated inside of a closed system, properly treated after the scrubber exit, and also there is a necessity to have a circuit for cooling this water, which is normally used SW. In addition, there is the possibility of the conjunction of the two types of circuits being called hybrid, however, it is a circuit that requires much more space and is more complex. In this thesis, only the two separate loops are analyzed.

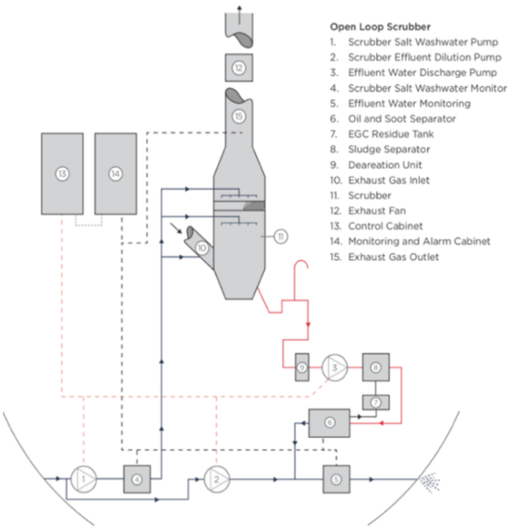

Figure 33 - Open loop scrubber (ABS, 2018)

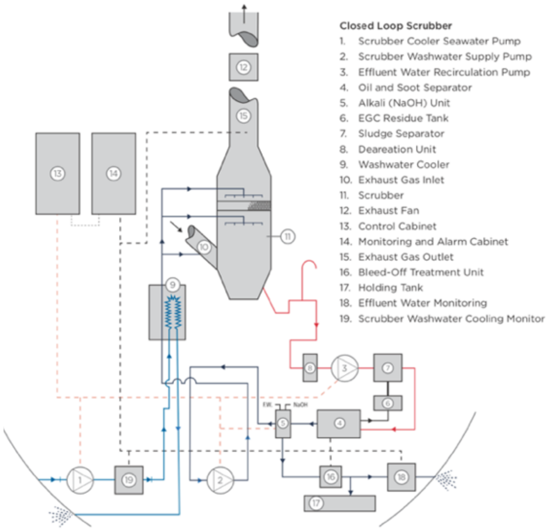

Figure 34 - Closed Loop Scrubber (ABS, 2018)

In terms of power consumption, as the CL is a circuit more complex with more auxiliary equipment associated, it is expected that its consumption be higher. It was opted to use the values from (ABS, 2018), which are presented in function of the engine size and the loop type chosen (Table 14). On the model it was introduced an option for CL or OL, and thus it will be estimated the respective scrubber consumption.

Table 14 - Wet scrubber samples in function of engine size (ABS, 2018)

Engine Size [MW]	**Electrical Load [kW]**	
	OL	**CL**
5	65	85
8	205	190
15	205	350
20	205	-
40	395	-

Note: in (ABS, 2018) these values assume that the scrubber is installed 20 m above the ship draft.

3.4 Engine Room (Intermittent Service)

Group 2 is the group which presents the services that are essential in ER, however not working continuously all the time.

3.4.1 Fuel System

The part of the fuel system which is verified an intermittent functioning is the transfer and storage sub-system that will be further studied in the following section.

3.4.1.1 Fuel Oil Transfer Pump

After pumping the FO into the ship, the fuel is stored in tanks that are classified as bunkers. In the next phase, the fuel oil should be pumped from bunkers to the settling tanks. For this to occur, it is necessary a pump. The FO transfer pump, as the others FO pumps, normally is screw-type. For the calculation of this pump power, it was necessary to estimate the volume of the settling tanks considering the equation (3.43).

$$V_{ST} = P_{ME} \times SFOC \times 24 \times 1.1023 \times 10^{-6} \tag{3.43}$$

In equation (3.43), V_{ST} is the volume of settling tank in m^3, the P_{ME} is the power of main engine in kW and the $SFOC$ the specific fuel oil consumption in g/kWh.

According to (DNV GL, 2017) the settling tanks should be capable of storing fuel for 24 hours of operation in maximum fuel consumption. To obtain the flow rate, it was then assumed between 4-6 hours to transfer fuel from any bunker to settling tank, this information was based on experience.

$$\dot{Q}_{Transferpump} = \frac{V_{ST}}{t_{FOtransfer}} \tag{3.44}$$

Where $\dot{Q}_{Transferpump}$ represents the flow rate of transfer pump in m^3/h, V_{ST} the volume of settling tank in m^3, and $t_{FOtransfer}$ the hours necessary to transfer FO in h.

The pressure for these pumps was considered 3 bar based on experience. After applied this concept to the project guides data collected it was obtained for 2-Stroke the graphic of Figure 35.

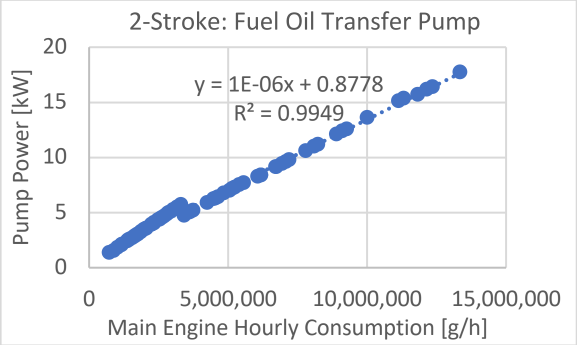

Figure 35 - FO transfer pump power in function of the daily ME consumption for 2 Stroke engines

The respective equation for 2-Stroke engines is shown below.

$$P_{FOtransferpump} = 1E - 06 \times HFOC + 0.8778 \tag{3.45}$$

The resulting scatterplot for 4-Stroke engines is shown in Figure 36.

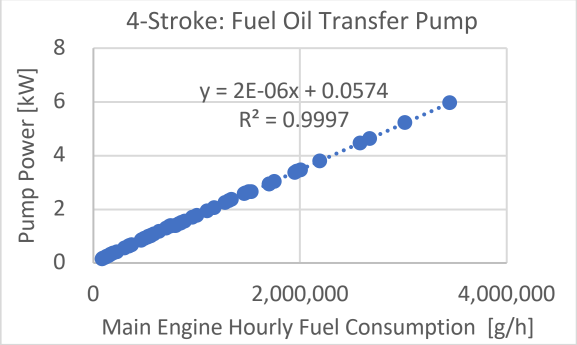

Figure 36 - FO transfer pump power in function of the daily ME consumption for 4 Stroke engines

The equation for 4-Stroke engines is shown in (3.46).

$$P_{FOtransferpump} = 2E - 06 \times HFOC + 0.0574 \qquad (3.46)$$

3.4.1.2 Diesel Oil Transfer Pump

The DO transfer pumps have the same function of the FO transfer pump. In similarity with the principle adopted for other FO pumps previously explained, it was also assumed for the DO transfer pumps the same equations derived for FO transfer pumps.

3.4.2 Lubrication System

In the lubrication system, the only pump which its functioning is intermittent is the transfer pump.

3.4.2.1 Lubrication Oil Transfer Pump

Similar to the FO system, there is the possibility of having a pump that transfers the lubricating oil from a storage tank to the LO feed system tank, or simply to transfer the oil to the onboard tank. Although of this possibility, due to the small consumption of the LO in the closed system, the oil feed is executed manually, by gravity, or by an external pump. To guarantee the lubricating oil properties, it is only from time-to-time that is replaced an oil total or partial load. However, this operation normally occurs during the ship's docking time, with external equipment.

3.4.3 Compressed Air System

There are three compressed air sub-systems on board, the main compressed air, general services compressed air, and compressed air for instrumentation as valve actuation or control air. Despite these three subsystems existence, the most important and significant is the main compressed air system that enables to start up the engines. The electrical consumption requirement of this system is mainly from the air compressors that will supply air at the required pressure.

3.4.3.1 Starting air system compressor

The main air compressor is part of the high-pressure compressed air system directed for main engines or the auxiliary engines starting. The purpose is to provide sufficient air at the required pressure for the receivers, for this reason, all compressors start and stop automatically according to the actual verified pressure on receivers. The operation of the starting air compressors consists of one compressor selected and another in parallel in stand-by, however, this one can be used in series to pressurize the receivers more rapidly or in case of failing the main one. The starting air pressure must be sufficient to provide enough speed to the piston that is in its expansion stroke in a progressive manner until the engine has enough inertia for its normal operation. This nominal pressure is 30 bar. The receiver's capacity should be estimated according to the engine size and type of engine. The classification societies require that for non-reversible engines the receivers should have the capacity for twelve starts, and for reversible engines requires a minimum of six starts. It is possible to estimate the receiver capacity based on the thermodynamic equation (3.2), and thus obtaining the equation (3.47). Afterward, the knowledge of the bottle capacity, (DNV GL, 2017), describes that the total reservoir capacity should be charged by two or more compressors where this reservoir capacity shall be shared between the compressors. Assuming that for its total filling it is necessary 1 hour as described in (DNV GL, 2017), it is then possible to obtain the necessary flow for the calculation of the electric consumption of the compressors (equation (3.4)). This compressor will compress the atmosphere air to the 30 bar pressure required.

$$\dot{Q}_{compressor} = \frac{30 \times \ V_d \times n_{Starts}}{2} \tag{3.47}$$

In which V_d is the displacement volume in m^3 and n_{Starts} the number of starts required according to engine reversibility. For non-reversible engines $n_{Starts} = 12$, for reversible engines $n_{Starts} = 6$. To assume a compressor efficiency, it was assumed based on experience that this compressors type is reciprocating high-speed.

3.4.3.2 Service Air Compressor

Depending on the requirements on board, this system may have its own compressor and bottle. However, it can be supplied from the starting air system with a pressure reducing valve from 30 to 7 bar. This system has a compressed air manifold that will feed all consumers both in the engine room and on deck, such as hoses for tool connection, a supply of pneumatic motors, cleaning filters or filling of pressurized tanks.

3.5 Engine Room (Miscellaneous)

The miscellaneous group are all systems which are significant to the ship integrity, people on board protection or engine residue discharges. They are mainly found in the engine room.

3.5.1 Bilge System

The main function of the bilge system is to remove water from watertight compartments. Some ships have the ballast and bilge systems linked with the same pump for both systems, however, it was considered pumps separately. The bilge system is available to clear oil/water leakage from machinery space or in another space such as water from some ship hold washes. These pumps should be provided with the capability to pump in emergence. For the purpose of calculating the power of these pumps, it had into consideration the regulations about the bilge system. Following (DNV GL, 2017), it is detailed the arrangement of the bilge system. To estimate the capacity of each pump, it was first necessary to calculate the pipe diameter. For cargo ships and passenger ships, it was considered the equation corresponding to all ship space bilge.

$$d_{Bilgepipe} = 1.68 \times \sqrt{L \times (B + D)} + 25 \tag{3.48}$$

For tanker ships, it was considered the equation (3.49), since the bilge pumps are used to drain only machinery space, or in this case considered only the ER.

$$d_{Bilgepipe} = 2.15 \times \sqrt{L_{ER} \times (B + D)} + 25 \tag{3.49}$$

In equation (3.48), $d_{Bilgepipe}$ is the diameter of main bilge pipe in mm, L is the length of ship in m, B the breadth of ship in m, and D is the depth of the ship in m. In equation (3.49), L_{ER} is the ER length in m. The pump minimum capacity of deliver is calculated using the next equation:

$$\dot{Q}_{Bilge} = \frac{5.75 \times {d_{Bilgepipe}}^2}{10^3} \tag{3.50}$$

The $\dot{Q}_{Bilge}$ is the representation of the bilge pump capacity in m^3/h. The pressure recommended, present in the (DNV GL, 2017) is 4 bar. With these parameters it is possible to use the equation (3.1) , obtaining the power consumption of these pumps.

3.5.2 Ballast System

This system ensures the trim and the stability desired on the ship directing water from any ballast tank or the sea and discharging into another ballast tank or the sea. To guarantee this water circulation, there is a necessity for the existence of pumps in the system.

3.5.2.1 Ballast Pump

The ballast pump capacity is a difficult parameter to estimate for the model, however it is an easy parameter known from the conceptual ship design. For this reason, the ballast pump capacity is calculated based on total ballast water volume inputted on the model dividing by a desired time inputted on the model by user as well.

3.5.2.2 Ballast Water Treatment System

To estimate the power required for BWTS, it was verified (UniBallast, 2020) which provides information from several BWTS manufacturers. It was the considered all the different treatments, processes and the lowest energy consumptions, and therefore, collected all corresponded data. Below it is possible to see the scatter plot with all collected data.

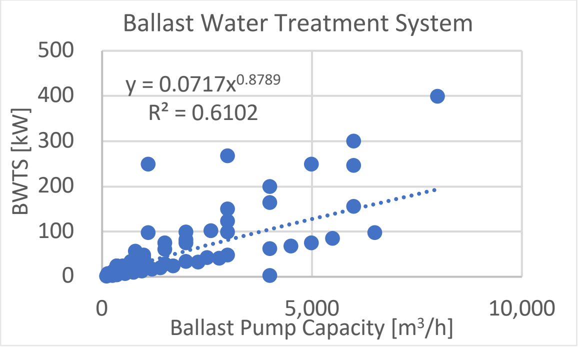

Figure 37 - Analysis BWTS power requirement

The equation result of this analysis is given in (3.51).

$$P_{BWTS} = 0.0717 \times \dot{Q}_{Ballast}{}^{0.8789} \tag{3.51}$$

The regression line performed has not the same strongness as the others verified in this thesis. This occurs since the data were collected from different manufacturers and each one has the own power consumption for the same capacity required.

3.5.3 Fire System

The fire system has the ability to distribute seawater in a controlled manner to any point of the ship for firefighting. The fire system consumers are the fire water main pumps and the emergence of fire water pumps. This machinery will be described in the following sections.

3.5.3.1 Main Fire Water Pump

IMO (1974) establish the necessary requirements for the installation of the fire system. The fire system is basically divided into three main stages: Fire protection, Fire detection, and Fire extinction. Focusing on firefighting, it is referred, besides the fire extinguishers, the supply water for firefighting. Besides all the accessories that a fire system must have, it must be equipped with pumps. These pumps are mainly electrically driven. To estimate the power associated with these pumps, it was checked the minimum pressure to be maintained at the hydrants in (IMO, 1974) being differentiating for ship types (Table 15).

Table 15 - The minimum pressure of fire system (IMO, 1974)

Passenger Ships	
Gross Tonnage	Pressure [N/mm²]
≥ 4,000	0.40
< 4,000	0.30
Cargo Ships	
Gross Tonnage	Pressure [N/mm²]
≥ 6,000	0.27
< 1,000	0.25

Having in count these minimum values and based on experience on board, it was adopted for constant pressure value in this model equal to 9 bar. (IMO, 1974) establish the number of pumps required on board, according to the ship type as well.

Table 16 - Number of main fire pumps required for fire system (IMO, 1974)

Passenger Ships	
Gross Tonnage	Number of Pumps
≥ 4,000	At least 3
< 4,000	At least 2
Cargo Ships	
Gross Tonnage	Number of Pumps
≥ 1,000	At least 2
< 1,000	At least 2, with one independently powered

The values used in the model corresponds with these minimum numbers of pumps required. Thus, the required fire pumps shall be capable of delivering for fire-fighting purposes the following amount of water. If it is a case of a passenger ships should be used the equation (3.52).

$$\dot{Q}_{Fire} \geq \frac{2}{3} \times \dot{Q}_{Bilge} \tag{3.52}$$

In case of cargo ships the equation to be applied is (3.53).

$$\dot{Q}_{Fire} \geq \frac{4}{3} \times \dot{Q}_{Bilge} \tag{3.53}$$

Another condition established in (IMO, 1974) and implemented on the model is the capacity of each pump should not be inferior to 80% of the total capacity required dividing by the minimum number of pumps required or inferior to 25 m^3/h.

3.5.3.2 Emergence Fire Water Pump

Cargo ships and passenger ships are usually supplied with emergency fire pumps located outside of the ER because a fire in the ER could put all other pumps out of action. This emergency fire pump should attend with (IMO, 2015) which mention that the capacity for these pumps should be bigger than 40% of the total capacity of the main fire pumps and never with capacity lower than 25 m^3/h. It was considered in the model 60% of the main fire pumps total capacity. The pressure was considered the same as for main fire pumps.

3.5.4 Sewage System

In (IMO, 1978) it is described the ships requirements necessary to avoid sea pollution by sewage.

3.5.4.1 Sewage Pump

Sewage in definition is the wastewater from water closets, urinals, bidets, and washing basins, and other water sources (IMO, 1978). This wastewater can be divided into two categories: blackwater and greywater. Blackwater is considered all the waste produced by drainage from toilets, washbasins, or wash tubs. Greywater is produced by a dishwasher, washing machines, cabin showers, or from the air conditioner condensates. The sewage is directly associated with the people on board (POB). It is expected that if the POB increases the sewage capacity should be increased as well. To estimate the wastewater, it was verified the ISO 15749-1:2004. This standard concerns the system design of sanitary drainage, this means the drainage system to evacuate wastewater from the accommodation areas on ships. The minimum values of the amount of wastewater referred in this standard for a plant with vacuum are:

Table 17 - Minimum amount of black and grey water according with ship type (ISO 15749-1:2004)

Ship Type	Black and grey water [l/person/day]
Passenger Ships	185
Cargo-Ships	135

The minimum values presented in Table 17, mention the average minimum values generated by each person on board and per day. This value was then used to estimate the volume of the tank (holding tank), using the equation (3.54) and added a percentage fraction to comply with reality. For cargo ships, being the number of POB the same as the crew, and considering one cabin per crew member, it is easy to estimate. However, a 10% margin was added for possible losses of the system and other support toilets on board. For passenger ships, it is a little more difficult to estimate the number of onboard bathrooms. Therefore, it was considered all crew members and applied 50% as margin which corresponds to passenger toilets.

$$V_{SewageTank} = 0.001 \times n_{Sewage} \times N_{Crew} \times t_{Voyage} \tag{3.54}$$

Where $V_{SewageTank}$ is the sewage volume tank in m^3, n_{Sewage} the sewage amount in l/person/day, the N_{Crew} corresponds to the number of crew in person, and t_{Voyage} the time of voyage in days.

It is assumed that to drain the full tank it is necessary 3 hours. With this assumption, it is possible to know the sewage pump capacity, dividing the sewage tank volume by the estimated hours to drain the tank. The assumed pressure was 5 bar. After it is proceeded the respective estimation of the pump power requirement.

3.5.4.2 Sewage Treatment Plant

The sewage treatment analyzed was the most common, the biological treatment plant which uses a tank divided into three watertight compartments: an aeration compartment, settling compartment and a chlorine compartment. As is possible to understand this plant necessitates a pump that can drive the fluid to the compartments and an auxiliary compressor to the first compartment (aeration process). This type of equipment is achieved on the market as a single module that is directly mounted on the ship. To estimate the required power associated with STP, it was analyzed data from various models of (HiSeaMarine, 2020). The manufacturer provides the power estimation according to load peak or to the average. The available values of produced sewage on board are the values from Table 17, then it was collected the manufacturer data in function of average [l/day]. The same principle used for sewage pumps was adopted for the STP, it was considered the respective values for different ship types, multiplied by the number of crew members, and applying the percentages to achieve more realistic values. Figure 38 presents the scatterplot graphic obtained, associating the power consumption with the sewage water amount average produced per day.

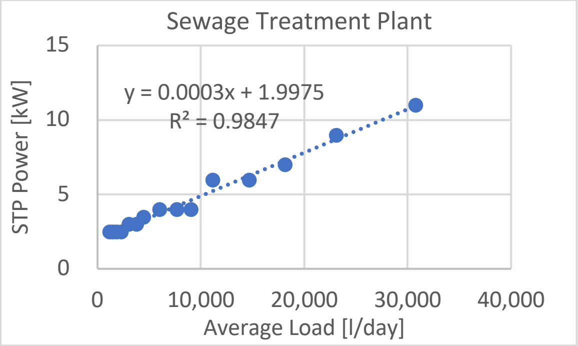

Figure 38 - Sewage Treatment Plant power regression in function of average flow

A linear regression has been performed and the respective equation is presented in (3.55).

$$P_{STP} = 0.0003 \times \dot{Q}_{AverageWastewater} + 1.9975 \tag{3.55}$$

3.5.5 Potable Water System

The potable water system on board of the ships is regulated by the international standard ISO 15748:2002. ISO 15748:2002 is composed into two parts where only part 2 was considered since it corresponds to the calculation method for the several components of this system. In this system the energy expenditure is on the pump drive and the heater required for hot water.

3.5.5.1 Hydrophore Feed Pumps

Following 15748-2:2002, it can be noted the requirements and a guide about how to determine the water consumption on a ship based on the POB, ship type, and days on board. The potable water consumption is the parameter that will determine the pump delivery flow required. Table 18 refers the guide for minimum values of potable water consumption which is present in liters per second.

Table 18 - Standard flow of potable service points (ISO 15748-2:2002)

Potable Water Service Point			
	$\dot{V}_R$Cold [l/s]	$\dot{V}_R$Warm [l/s]	$\dot{V}_R$Mixed [l/s]
Cabin Bathroom			
Washbasin	0.07	0.07	
Toilet Valve for flushing			1
Shower	0.15	0.15	
Galley			
Kitchen sink	0.07	0.07	
Dish Wash Machine			0.15
Extra Valve			0.3
Laundry			
Washing Machine			0.25
Extra Valve			0.3
Extra Bathroom			
Washbasin	0.07	0.07	
Toilet Valve for flushing			1

For cold water it is considered 15ºC and for hot water 60ºC as described on the original standard table.

It is considered that each cabin on board has its own bathroom. furnished with a toilet, shower and a lavatory. This means that these spaces are directly proportional with POB. For laundry, it is considered the washing machines and an extra valve. In order to estimate the number of existing washing machines on board it was used in the equation (3.80) and divided by the assumed average of 4 kW power consumption of each one. For the galley, it was accounted a kitchen sink, the dish wash machine (following the same principle of washing machines), and an extra valve used for an extra lavatory or auxiliary on the galley cleaning. Finally, it was contemplated 5% more of the POB for extra toilets determination. These extra toilets normally serve to support the engine room workers, bridge, and deck. The total flow is the result of all the unit's sum considered the cold, warm, and mixed water. The pump should have the capacity to support the peak flow, and the ISO 15748-2:2002 has a logarithm graphical representation of two curves in which the peak flow is set as a function of the total flow rate for passengers' ships and for cargo ships. These graphics were represented in such a way as to obtain the equation corresponding to each curve to implement in the model, since it is not mentioned in the standard.

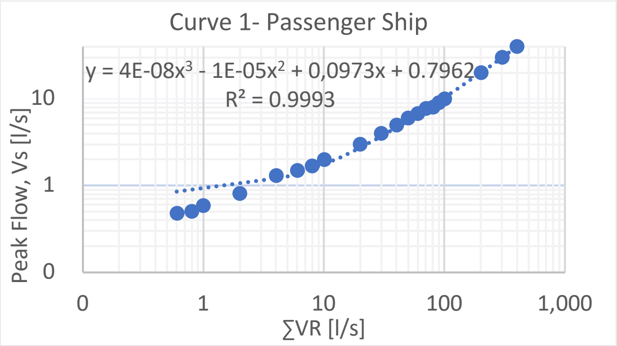

Figure 39 - Passenger Ship: peak flow in function of the sum flow (ISO 15748-2:2002)

The resulting equation of the regression curve performed for passenger ships is the equation (3.56).

$$\dot{V}_S = 4E - 08 \times \sum \dot{V}_R^{\ 3} - 1E - 05 \times \sum \dot{V}_R^{\ 2} + 0.0973 \times \sum \dot{V}_R + 0.7962 \tag{3.56}$$

Figure 40 represents the curve for cargo ships.

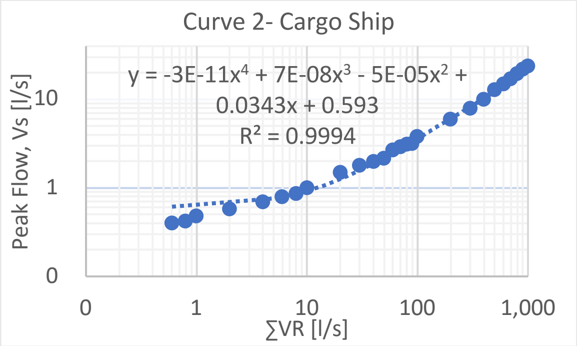

Figure 40 - Cargo Ship: peak flow in function of the sum flow (ISO 15748-2:2002)

The equation to be used to calculate the peak flow for cargo ships, is the equation (3.57).

$$\begin{gathered}\dot{V}_S = -3E - 11 \times \sum \dot{V}_R^{\ 4} + 7E - 08 \times \sum \dot{V}_R^{\ 3} - 5E - 05 \times \sum \dot{V}_R^{\ 2} \\ + 0.0343 \times \sum \dot{V}_R + 0.593\end{gathered} \tag{3.57}$$

In addition, it was also considered plus 10% of $\dot{V_S}$ as recommended in the standard for centrifugal pumps. For pressure, it was verified some feed pumps pressure and it was noted that the pressure rounds 4 bar.

3.5.5.2 Water Heater

For the heater power determination connected with the hydrophore, it was following the same standard and represented in Table 19.

Table 19 - Heater power in function of POB (ISO 15748-2:2004)

Number of persons	Heater Power [kW]
1 < POB < 10	15
11 < POB < 20	30
21 < POB < 30	40
31 < POB < 50	40
51 < POB < 75	80
76 < POB < 100	80
101 < POB <150	100
151 < POB < 200	160
201 < POB < 300	200
301 < POB < 500	300
501 < POB < 700	400
701 < POB < 1000	550

3.5.6 Sludge System

Sludge system consists of a system which is a result of waste oil products. According to the viscosity level and water content, it is possible to divide into two types: sludge and oily products.

3.5.6.1 Sludge Pump

Sludge is the denomination for residual waste oil products generated from the equipment operation on board, such as the fuel or lubricating purifiers discharges, waste lubricating oils or hydraulic or leakages. (IMO, 1978) establish that every ship with 400 GT and above should be provided with tanks with adequate capacity to store sludge. All residues stored in a sludge tank should be directly discharged ashore via a pump. These types of pumps, in similarity with the others of the FO system, should have a good capacity to handle high viscosity matter due to the fluid viscosity. To estimate the power consumption associated with these pumps, it is necessary to estimate the flow rate. In turn, to know the flow rate it is necessary to estimate the tank capacity which the pump should drain. The sludge tank capacity, following (GL, 2016), is related to the daily fuel oil consumption on board, and the duration of the voyage as it is possible to see in equation (3.58):

$$V_{Sludgetank} = k_{IFO} \times DFOC \times t_{voyage} \tag{3.58}$$

Where $DFOC$ is the daily fuel oil consumption in m^3/day, t_{voyage} is the voyage time in days, and k_{IFO} is the coefficient applied due to the fuel used, for IFO is equivalent to 0.015.

Assuming 4 hours to drain the full tank, the capacity of the pump is easily obtained. The pressure was considered constant equals 4 bar. To the power consumption estimation, it is used the equation (3.1).

3.5.6.2 Stripping Pump

In addition to the sludge, as described before, there is a residue with a lower level of viscosity denominated oily bilge water. Oily bilge water is water that can be contaminated by oil resulting from leakages or maintenance work. This means that it is necessary a tank to collect and store oily water before its treatment or discharge. The same principle used for sludge pump capacity estimation was performed for stripping pumps. To calculate the capacity of stripping pumps is divided the tank capacity by the estimated time to empty the tank. In turn, the oily bilge tank capacity is also described in (GL, 2016).

With ME Power < 1000 kW:

$$V_{Oilywatertank} = 4 \tag{3.59}$$

With 1000 kW < ME Power < 20000 kW:

$$V_{Oilywatertank} = \frac{PowerMCR}{250} \tag{3.60}$$

With ME Power > 20000 kW:

$$V_{Oilywatertank} = \frac{PowerMCR}{500} + 40 \tag{3.61}$$

With the tank capacity known it is assumed 1 hour and a half as the time to drain all the tank. Also, assuming a pressure of 1 bar, it is possible to know the stripping pumps electrical consumption.

3.5.6.3 Oily Water Separator

OWS is an equipment that allows to separate the oil from bilge water and then the water can be discharged overboard. (IMO, 1978) establishes the maximum content of oil that the bilge water should contain before being discharged overboard. For this reason, OWS should be equipped with an oil content detector in addition to the pump which sucks from the oily water tank. To estimate the electrical consumption associated with the OWS it was followed (Wärtsilä, 2015) that provides the power consumption for OWS according to the maximum capacity. In turn the maximum capacity of the OWS equipment is regulated in (GL, 2016) in function of the ship gross tonnage (Table 20).

Table 20 - Oily water separator capacity (GL, 2016)

Gross Tonnage	OWS capacity [m3/h]
GT < 400	0.25
401 < GT < 1600	0.5
1601 < GT < 4000	1
4001 < GT < 15000	2.5
GT > 15000	5

The power consumption according to the equipment capacity is given in Table 21.

Table 21 - Oily water separator power consumption (Wärtsilä, 2015)

OWS capacity [m³/h]	OWS power [kW]
≤ 2.5	3
5	6

3.6 Deck

On the ship deck it is possible to find different types of equipment and machinery to be used in exterior space. The various items of machinery and equipment will be described next.

3.6.1 Deck Equipment

This section will present the main machinery and equipment used in the deck area according to ship type. Then, it was attempted to include the largest consumers within the types of ships selected for the analysis.

3.6.1.1 Anchoring equipment

The anchoring and mooring system can be categorized in terms of their drive type which can be steam, hydraulic or electrical. It was assumed, for the development of this model, the drive as electrical. In this manner, it is expected that these units have a high electrical consumption. The windlass is the machine that handles the anchors on board. These machines can be used as a separated one for each anchor or only one for the two anchors. In this thesis, it was considered two windlass units, one for each anchor. The windlass is composed by a horizontal cylinder that is rotated by an axis. This simple operating mechanism allows to calculate the respective power consumption based on the physical principle of a force multiplying by a velocity. In addition, it was imposed the mechanical efficiency and the electrical efficiency related to the equipment in question (3.62).

$$P_{Windlass} = \frac{W_{Total} \times g \times v}{1{,}000 \times \eta_{elect} \times \eta_{mec}} \tag{3.62}$$

Where W_{Total} is defined by equation (3.63) given in kg, g the gravitational acceleration in m/s^2, v the velocity of handling in m/s.

The equipment number (EN) established by classification societies is a parameter known in conceptual design. Associated with this EN are the main characteristics of, and anchor chain, the anchor such as anchor weight, chain length requirement, and chain diameter. Through these characteristics as input, it is possible to estimate the weight to be moved by the windlass (3.63).

$$W_{Total} = W_{Anchor} + 0.85 \times W_{Anchorchain} \tag{3.63}$$

The total weight is considered the anchor weight and the weight of 85% of the anchor chain since it is assumed that 15% of the chain segment corresponds to the segment which is inside of the chain locker and the remaining length between the chain locker and the windlass. On the other hand, the chain weight is a characteristic not directly referred to by the classification societies. For the chain weight estimation, it was collected data from (SOTRA, 2020) where it is specified characteristics as the chain weight in function of the diameter and chain length. Assuming a chain intermediary steel grade 2, the data collected, and the regression performed is present in Figure 41.

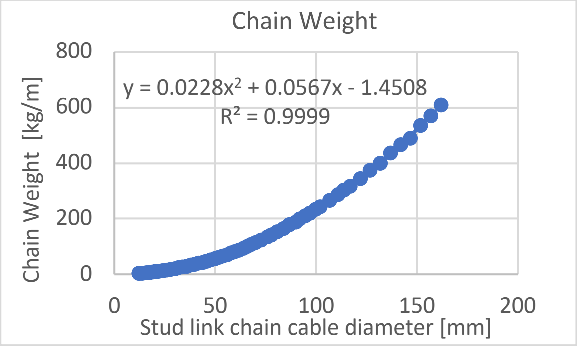

Figure 41 - Anchor chain weight per length in function of chain diameter

The respective equation from the curve fitting performed is shown in (3.64).

$$W_{Anchorchain} = 0.0228 \times D_{Anchorchain}{}^{2} + 0.0567 \times D_{Anchorchain} - 1.4508 \qquad (3.64)$$

In this equation $W_{Anchorchain}$ is given in kg/m, which in and was further multiplied by chain length.

IACS (2019) specify some requirements for design and test of ship windlass such as the hoisting velocity, being the minimum defined as 0.15 m/sec. In the model was assumed as one chain segment per minute, this means 27.5 m/min, or 0.45 m/sec.

3.6.1.2 Mooring equipment

Winches are the equipment that support the mooring lines in the ship. To calculate the respective power consumption of the electric mooring winch, there is a need to specify a few main specifications such as rope diameter, nominal speed and rope capacity (3.65). These characteristics are already known in conceptual design since they are specified through the EN described by classification society in similarity with anchor windlass. Thus, with the input of the known parameters, the model will produce the unit power consumption. It was assumed that for each cable there would exist one winch, thus it is also necessary to know the minimum number of cables as a model input characteristic as well.

$$P_{Winches} = \frac{T \times v_s}{60 \times \eta_{elect} \times \eta_{mec}} \qquad (3.65)$$

Where T is the hauling tension in kN, v_s is the velocity required in m/min, η_{elect} the electrical efficiency assumed for winch motor, and η_{mec} the mechanical efficiency assumed for winch. The maximum hauling tension which can be applied corresponds to 1/3 times of the rope's breaking strength (DNV, 2010). The velocity was assumed as constant 15 m/min.

3.6.1.3 Cranes

Shipboard cranes can be of various types and capacities. Some of them are directly connected with the safety equipment such as cranes for lifeboat or rescue boats. Others are simpler and used for example to move the gangway. However, these cranes are considered of small consumption and difficult to estimate. In relation to the deck cranes, it was assumed the provision crane and cargo cranes. It is expected that these are part of a group with a large influence in an electric balance, in case of existence on board. The cranes power estimation follows the physical principle of equation (3.62), where, in this case, the cargo weight capacity desired is an input parameter to be specified by the user. However, this equation was applied only for weights until 40 tons. Regarding the provision crane, it was assumed a constant weight of 1 ton, based on experience. For the assumption of an average of handling velocity, it was verified (MacGregor, 2020), being mentioned 25 m/min for cargo cranes and 13 m/min for provision cranes. In case of heavy lift cranes, it was followed (TTS, 2020) where it is specified the power consumption according to the weight capacity (Table 22).

Table 22 - Heavy lift cranes power consumption

Crane Weight Capacity [ton]	Power consumption [kW]
40 < $W_{Capacity}$ < 150	160
150 < $W_{Capacity}$ < 250	180
250 < $W_{Capacity}$ < 400	320
$W_{Capacity}$ > 400	360

3.6.1.4 RoPax Ramp and lift elevator

RoPax is one of the ships' types taken into consideration. One of the main ship particularities in comparison with the others is the fact of carry passengers and roll-on and roll-off cargo. In order to load and unload the vehicles it is used ramps that can be positioned at the ship stern, side or bow. Due to the difficulty encountered in sizing this equipment, it was opted not to estimate it. However, in addition to the external access equipment, on board RoPax there are internal accesses which allow transferring vehicles for different decks taking advantage of the cargo space. It was contemplated as an individual car lift with constant power consumption. For the calculation of this consumer, it was considered that it should be capable of lifting a TIR truck. For this reason, the weight considered was 25 ton added with 1 ton weight of the platform and a height of 4.5 meters in 2 minutes. With these characteristics, the power consumption is easily estimated following the physics concept, resulting in a constant value of 11.9 kW.

3.6.1.5 Hatch Cover

Hatch covers can have several designs according to the ship's particularities. However, three types are the basic: lift-away hatch cover, side-rolling, and the folding hatch cover. Two drives types can be associated with this equipment: hydraulic cylinders in which it will necessitate energy from an electric motor in order to boost the movement of the oil and cylinder actuation, or a system powered by direct electrical energy. Typically, the lift away and folding type is combined with the hydraulic system and it is a difficult process to predict. Therefore, it was only modeled the power associated with the side rolling type using equation (3.62). It was considered a coefficient of 0.02 ton/m^2 (Tawfik et al., 2017), which multiplied by the corresponding area it is possible to know the weight of the hatch covers. The rolling displacement was considered equal to the half breadth of the ship for each side in 3 minutes.

3.6.2 Cargo Refrigeration and Ventilation

In this section will be described the refrigeration and ventilation systems which cargo should be subject. These systems are essential to avoid cargo damage during the ship voyage, as well as to ensure a clean and safe atmosphere in the holds or spaces where it is transported.

3.6.2.1 Refrigerated Containers

Refrigerated containers are a large part of the energy consumption on board a ship since the cargo must be refrigerated 24 hours a day during all navigation time to maintain the desired temperature and avoid spoiling the cargo. In such a way to estimate the power associated with the reefers, it was necessary to know the number of refrigerated containers on board. Due to the difficulty of knowing the exact value, it was needed to consider a percentage concerning the total capacity of containers on board. Following (Krefft, 2015), it is possible to see an estimation performed in terms of the reefer percentage on board of the container's ships and its power demand as well. The same author states that the number of reefer containers is 5% up to 20% of the total ship's containers from an analysis performed by him. In this thesis an average of these values was considered, corresponding to 12%. This means that 12% of container capacity will be reefers. After the contemplation exposed before, (GL, 2016) presents a guide for the reefer's containers on board ships with the power requirement for each reefer container according to the cargo type inside of them. Although this guide presents values for TEU and FEU, it was chosen to consider that all reefers to be transported are FEU for the simplicity of the calculation and for their consumption as FEU will be higher, consequently, this estimate will always be over-dimensioned.

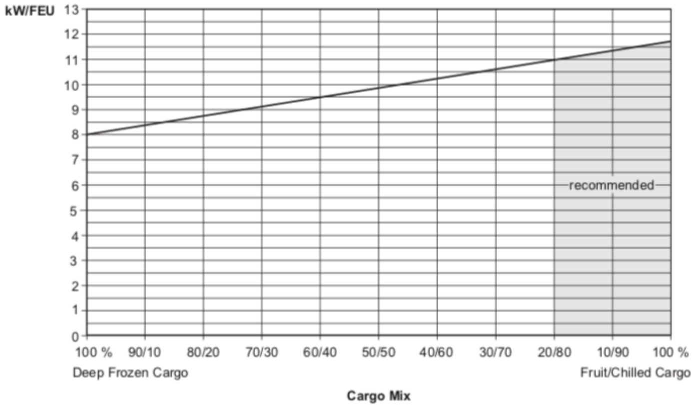

Figure 42 - Power consumption of FEU reefer container (GL, 2016)

As it is visible, the cargo is exposed along an axis by a percentage of the freezing level it is at, being on the left side, the cargo in which is totally frozen, and on the right side only refrigerated. For our model, it was considered cargo within the recommended limits of fruit/chilled cargo with the consumption higher value, which gave us a value of 12 kW for each FEU reefer loaded.

3.6.2.2 Cargo Space Ventilation

Beyond the ER ventilation, the cargo space shall be properly ventilated. This ventilation will prevent the damage of cargo due to the cargo sweat or vessel sweat, supply fresh air to the cargo, remove some smell of the older cargo, and more importantly, prevent the accumulation of harmful gases. The ventilation power consumption was divided for cargo ships and for RoPax ships. As RoPax ships transport vehicles in which emit gases due to their internal combustion engines require a little more attention in this subject of ventilation. The ISO 9785:2002 standard is specific to this ship type and gives a guide for the calculation of the airflow required for vehicles cargo spaces, however, presents a higher detail degree about the vehicles that are transported such as the gases emitted. Also, in (GL, 2016) it is presented data about the required ventilation, and it was opted to use these values due to the simplicity of the method. In the case of RoPax ships, the classification society requires that in the case of the operating condition in which vehicles are being loaded or unloaded (roll-on, roll-off) the ventilation must have the capacity for at least 20 renovations per hour, and during navigation, this value decreases to 10 renovations. For the other cargo ships, it was assumed 10 renovations per hour in any ship operating condition. Therefore, in addition to the cargo space volume as input, these values were used to calculate the airflow and the respective fan power in relation to the specific ship type.

3.6.2.3 Inert Gas System

According to (IMO, 1974), all ships over 8,000 DWT carrying hydrocarbon cargo must supply inert gas to create a non-explosive atmosphere. This is achieved by reducing the oxygen level below 8% and establishing positive pressure in cargo tanks. The inert gas system (IGS) consists of fans that, through pipelines, supply the gas to each cargo tank. The IGS operates during the discharge time of the cargo and is directly connected to the quantity of cargo discharged. According to the classification societies, it is defined that this system must have sufficient capacity to supply a volume of gas equivalent to 125% of the capacity of the cargo discharge pumps when they are operating simultaneously. Thus, for the calculation of fan capacity, the (3.66) equation was used.

$$\dot{V}_{fan} = 1.25 \times \dot{V}_{Cargopumps} \times nr_{Cargopumps} \tag{3.66}$$

Where $\dot{V}_{fan}$ is the fan flow rate in m^3/h, $\dot{V}_{Cargopumps}$ is the cargo pumps flow rate in m^3/h, and $nr_{Cargopumps}$ the number of cargo pumps.

The calculation of the electrical consumption of these two fans required by (IMO, 1974) was performed using the (3.5) equation, considering a pressure of 0.2 bar as referred to in this same source as well. Inert gas in this system derives from two sources: boiler exhaust gases or an autonomous inert gas generator. If it comes from a boiler, this gas must be cleaned and cooled by a scrubber. In the case of an inert gas generator, an electrical consumption is added. For this reason, in addition to the fans previously mentioned, the option of having an inert gas generator was also considered. To calculate the electrical consumption associated with this equipment, the values of electrical consumption provided by the Survitec manufacturer were used. It was then performed a linear regression of these points (Figure 43).

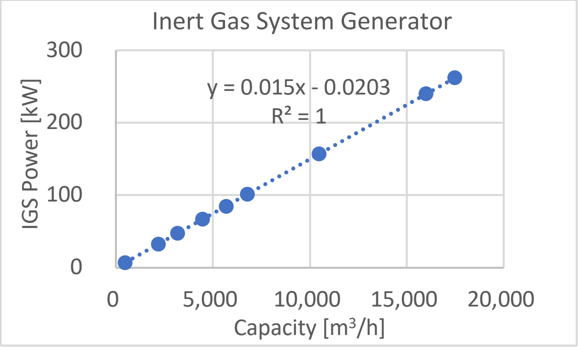

Figure 43 - Inert Gas Generator power consumption

The equation of the linear regression performed is shown in (3.67) equation and it was then applied in the model.

$$P_{IGSgenerator} = 0.015 \times \dot{V}_{IGS} - 0.0203 \tag{3.67}$$

The $\dot{V}_{IGS}$ is the total capacity of the inert gas system defined by the equation of IGS fan flow rate (3.66).

3.6.3 Deck Maneuvering

The maneuvering equipment is located along the ship. This is not part of the deck equipment. However, it is not logical to consider this equipment as belonging to the superstructure or the engine room. Then, a subsection is created within the deck section exclusively for the maneuvering equipment.

3.6.3.1 Side Thrusters

In this work, it is considered that the quantity of side thrusters is an input as well as its existence. The power associated with these equipment does not follow a direct equation. Normally, it is decided the size of a transverse propulsion unit and the most appropriated power for the unit chosen inside of a range given by manufacturers.

The size of transverse propulsion can be determined by two methods. One consists of a rigorous calculation performed in model tests sob all adverse weather and sea conditions. The second option is following empirical numerical expressions based on the experience of similar ships. Some investigation of empirical equations led to the realization that they all needed more detail than was available at this stage of the ship design. Therefore, for the estimation of the power associated with a transverse thruster, it was followed (Ozdemir, 2008) where it provides an empirical equation for the power calculation that depends on the driving force. It also provides several coefficients according to the type of ship that simulates this driving force per water line lateral area (Table 23).

The equation used and the coefficients according to the type of vessel are following transcribed.

$$P_{TransverseThruster} = k \times \Delta^{\frac{2}{3}} \tag{3.68}$$

Where $P_{TransverseThruster}$ is the power required to drive a transversal thruster, k coefficient associated to driving force (Table 23), and Δ is the ship displacement in ton.

Table 23 - Coefficient required for transversal thruster equation (Ozdemir, 2008)

Ship Type	k
Tanker/Bulk Carrier	0.60
Container Ship	0.70
RoPax	1.35

In addition to the equation (3.68), it was applied the mechanical and electrical efficiency.

3.7 Superstructure

3.7.1 HVAC

ILO (1970) recommends that all ships with 1,000 GT or more should be equipped with air conditioning (AC). This system should be distributed to all accommodation spaces. In the case of the control rooms of the ER there is also AC however it is an independent system that will not only for the crew comfort but also for the electronic equipment cooling in this space. There are several methods for the AC design, some of them simpler, others more detailed, being some examples (ASHRAE, 2015; Awwad, 2015), norms as ISO 7547:2002 for the ship accommodations AC design or more specific, ISO 8864:2001 for wheelhouse on board, and ISO 9943:2009 for galleys and pantries. Regardless of the design method chosen, the design conditions to comply are the same, being these described on Table 24 (ISO 7547:2002).

Table 24 - Design conditions for HVAC project (ISO 7547:2002)

Summer Condition	
Outdoor Air [Temperature and Humidity]	+35 ºC and 70% humidity
Indoor Air [Temperature and Humidity]	+27 ºC and 50% humidity
Winter Condition	
Outdoor Air [Temperature]	- 20ºC*
Indoor Air [Temperature]	+22ºC

* The winter outdoor air in the norm considers a negative temperature that in reality does not make sense since ships would have to navigate in very extreme conditions. Then, the temperature of the outside air considered for this study was 3ºC.

Since a HVAC detailed model is a very complex process to be used in current electrical load balance model, it was decided to develop coefficients that enable to know the HVAC power consumption in function of the superstructure volume. For this, a simplified model for a specific ship was performed with 3 different design methods and then compared the respective values with the known ship real value. The vessel analyzed is a container feeder ship with 17 persons on board with singular cabins for all persons.

3.7.1.1 Compartment Equipment List

First, it was compiled a list of all compartments to be analyzed. These compartments were analyzed by decks, along the superstructure. The list grouped results in: Cabins, Laundry, Offices, Hospital, Mess, Pantry and Bridge. Then, each compartment is divided by surfaces, a surface turned to the bow, surface turned to the stern, surface corresponding to portside and starboard, the top, and the floor, then it is possible to analyze each surface and the adjacent surfaces. It was measured all surface areas, including the windows or scuttles areas, and stipulated which are the adjacent surfaces for each one.

3.7.1.2 Method of Heating and Cooling Load Calculations

The first method applied consists in a heat load balance following (ISO 7547:2002; Awwad, 2015). This method consists of the heat transmission calculation for the two seasons previously described. For each season heat transmission calculation, it is considered all the heat gain or loss due to the temperature differential crossing the boundary surfaces, using the equation given on ISO 7547:2002:

$$\phi_{season} = \sum \Delta T \times (k_v \times A_v) + (k_g \times A_g) \tag{3.69}$$

In equation (3.69), ϕ_{season} is the heat loss or gain in the space in W, ΔT is the difference in air temperature in K, k_v is the total heat transfer coefficient for surface in W/m^{2}K, A_v corresponds to the surface area excluding windows or side scuttles in m^2, k_g is the total heat transfer coefficient for windows or side scuttles in W/m^{2}K, and A_g the area of windows or side scuttles in m^2. In Table 25 it is possible to see these temperature differences between the adjacent spaces for summer and winter based on ISO 7547:2002.

Table 25 - Temperature differences between surfaces (ISO 7547:2002)

Deck or Bulkhead	Temperature Difference [K]	
	Summer	**Winter**
Against to exterior	15	8
Against laundry	11	17
Against non-air conditioning space	18	17
Against cargo spaces or non-heated tanks or other spaces	13	42
Against boiler-room	28	17

Between the air conditioning spaces the temperature is 0, since it is supposed to be at the same temperature. The heat transfer coefficient is a quantitative parameter of convective heat transfer defined by the material properties such as the thermal conductivity, thermal insulation between different layers of material, type of insulation, and the thickness of material. Due to the lack of the material information, it was decided to use values described in the same standard.

Table 26 - Total heat transfer coefficient (ISO 7547:2002)

Surfaces	Total heat transfer coefficient [kW/m^{2}K]
Weather deck not exposed to sun's radiation and ship side or external bulkheads	0.9
Deck and bulkhead against ER, cargo space or non-air-conditioned spaces	0.8
Deck and bulkhead against boiler-room or boiler in ER	0.7
Deck against open air or weather deck exposed to sun's radiation and deck against hot tanks	0.6
Side scuttles and rectangular windows, single glazing	6.5
Side scuttles and rectangular windows, double glazing	3.5
Bulkhead against alleyway non-sound reducing	2.4

Another heat gain that affects the temperatures inside of a space is the heat gained from surface exposure to the sun. The solar heat gain is calculated by a derivation of equation (3.69) and is presented below.

$$\phi_s = \sum \Delta T_r \times (k_v \times A_v) + \sum (G_s \times A_g) \tag{3.70}$$

Where ϕ_s is the solar heat gain in W, A_v the surface exposed to solar radiation in m^2 excluding windows or side scuttles, k_v the heat transfer coefficient in accordance with Table 26 and the surface exposed to the sun in kW/m^{2}K, ΔT_r is the excess temperature caused by solar radiation on surfaces in K, considering vertical light surfaces (superstructure painted white) this excess is 12 K, A_g is the area corresponded to the existing windows or side scuttles in m^2, and G_s the heat gain from glass surface which was considered clear glass surfaces and for this is equivalent to 350 W/ m^2.

All persons emit heat through their body. The values of sensible and latent heat emitted, considering a temperature of 27ºC indoor and the exercise type are shown below.

Table 27 - Heat gain from persons (ISO 7547:2002)

Activity	Emission (sensible heat + latent heat) [W]
Seat at rest	120
Medium or heavy work	235

As the AC was being designed for accommodation spaces, the heat emission assumed was when persons are resting. All the spaces are provided with lighting and light causes energy emission in heat form. Assuming incandescent light, the heat gain per m^2 is shown in Table 28.

Table 28 – Heat gain from light

Space	Heat gain from general lighting [W/m^2]
Cabins	15
Mess or dining-rooms	20
Gymnasiums	40

It is only considered the lights heat gain for the top surface, since this is where the lamps are located. After the heat loads calculated and summed, the volumetric flow calculation is performed for winter and for summer based on equation (3.34) given in ISO 8861:1998.

3.7.1.3 Method of Air Changes

The second method applied consists of air renovations per hour within each space.

Table 29 - Air renovations rates for supply air (GL, 2016)

Space	Supply air [ren/h]
Cabins	6
Mess, dining-rooms or offices	12
Hospitals	12
Galley	40
Pantries	15
Dry provision room	5
Laundries	15
Bridge	18

It was used the values from (GL, 2016), in which are present on (Table 29). For cabins with sanitary which is the case of this ship, (GL, 2016) specify that should be supplied 10% more incoming air, for this reason, the value assumed for cabins is 6.6 renovations/h. Then, it was applied these numbers to the corresponding volume of each space resulting in individual volumetric flow rates. The third method consists of a second method simplified derivation. This is the simplest method of the three reviewed. The assumption adopted was to apply a constant number of renovations per hour in all habited spaces referred to before. For this, it was applied a constant value of 10 renovations per hour advanced in (Frijters, 2017). This value is a conservative approach to the result obtained using the standard ISO 7547:2002 and based on the author's practical experience in RH Marine.

3.7.1.4 Thermodynamic System Analysis

In ISO 7547:2002, it is mentioned that of the defined volumetric flow rate 40% is fresh outdoor air and 60% is reused indoor air. For a better comprehension, a schematic representation of the system is shown in Figure 44.

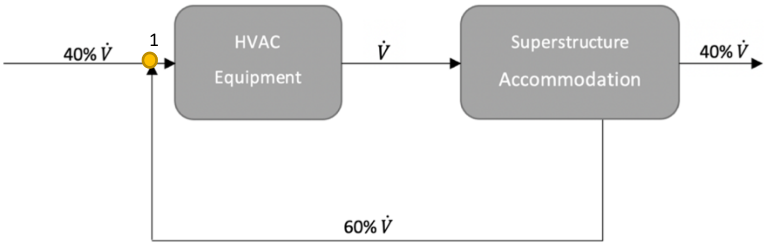

Figure 44 - Schematic volumetric flow for HVAC system

The required cooling power for the two different seasons is performed through the equation (3.3) that adjusting to this case, h_s is the h_{indoor} and h_e is the h_{Mix} in kJ/kg. The mass flow that should be in kg/s corresponds to the volumetric flow estimated in the different methods previously described. So, first it was calculated the mass air flow of the outdoor and indoor. The temperature of these flows corresponds to the design conditions established in Table 24 and due to the temperature difference, the respective density will be different. For the density calculation, the following equation is applied.

$$\rho = \frac{p}{R \times T_{Air}} \tag{3.71}$$

Where ρ is the density at specific temperature in kg/m^3, p is the atmospheric pressure, equivalent to 101,325 Pa, R the specific gas constant for dry air, equivalent to 287.058 J/kgK, and T_{Air} the air temperature in K. With the density defined, it is calculated the mass flow required for power calculation. This can be done with equation (3.72).

$$\dot{m} = \rho \times \dot{V} \tag{3.72}$$

In equation (3.72) $\dot{m}$ is the mass flow in kg/h, and $\dot{V}$ the volumetric flow in m^3/h. As the indoor flow and outdoor at a certain point are mixed (point 1), this mixed air in the system entrance will have a different temperature, enthalpy, and humidity ratio. Denominating as mix temperature as T_{Mix}, it can be calculated using equation (3.73).

$$T_{Mix} = \frac{\dot{m}_{Indoor} \times T_{Indoor} + \dot{m}_{Outdoor} \times T_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \tag{3.73}$$

The temperature of the mixture, T_{Mix} is given in K, $\dot{m}_{Indoor}$ is the mass flow circulating from indoor in kg/h, T_{Indoor} is the corresponded temperature inside of the accommodation spaces in K, $\dot{m}_{Outdoor}$ the mass flow from outside in kg/h, and $T_{Outdoor}$ the outside temperature in K. The determination of the enthalpy is achieved through the psychrometric chart (Annex A). The psychrometric chart is a graphic representation of the relationship between the air temperature and enthalpy according to the humidity present on air. In accordance with Table 24 conditions, the relative humidity ration for winter is considered 0. However, for summer it is not zero. For this reason, it is necessary to have the humidity in consideration on the psychrometric chart, and the mixture enthalpy can be done with the equation (3.74).

$$h_{Mix} = \frac{\dot{m}_{Indoor} \times h_{Indoor} + \dot{m}_{Outdoor} \times h_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \tag{3.74}$$

The cooling is done with auxiliary coolant. Associated to this coolant there is a coefficient of performance associated, COP. Being this parameter the relation between the cooling power and the compressor power and considering the R407C gas as coolant, the COP rounds between 2 and 3 for different types of compressors. For the calculations it was assumed an average, this means equivalent to 2.5. This means that the HVAC power requirement is lower than the cooling power requirement. The final power considered was an average between winter and summer seasons for the first method.

3.7.1.5 Final Results

After the three methods have been estimated for the different superstructure spaces, the final results are compiled into a table for a better understanding and comparison between the methods:

Table 30 - Final results for methods comparison

	First Method	Second Method	Third Method
Total Power Result [kW]	34.29	33.74	38.28

Analyzing the electrical load balance of the real ship studied, the power required for the AC system is 22 kW. It is perceptible in Table 30 that the approximated value to the real corresponds to the second method, although the first is relatively close to the second. For this reason, it was chosen to use the second method to obtain coefficients to be applied in the electric balance load model estimation, since this is not only the closest value but also a simpler method than the first one.

The coefficients to be implemented in the model was defined by the relationship presented in (3.75).

$$C_{Powerpervolume} = \frac{P_{Space}}{V_{Superstrucutre}} \tag{3.75}$$

$C_{Powerpervolume}$ is the coefficient associated with the determined space in kW/m^3, P_{Space} the specific power calculated for each space of the ship analyzed in kW, and $V_{Superstrucutre}$ the total volume of the superstructure in m^3. Table 31 presents the different coefficients calculated. Thus, for each accommodation space, it is possible to estimate the corresponded power required in function of the superstructure volume parameter. This input value can be easily obtained on ship conceptual design.

Table 31 - AC system power coefficients in function of the superstructure volume

Space	$C_{Powerpervolume}$ [kW/m^3]
Cabins	0.00466
Mess, dining-rooms or offices	0.005133
Hospitals	0.000522
Pantry	0.000673
Dry provision room	0.000633
Laundry	0.00055
Bridge	0.002705

For the total required power is performed a sum of all singular powers calculated.

3.7.1.6 Supply and Exhaust System

As previously mentioned, in combination with the AC system designed for accommodation areas, there must be an onboard ventilation system for all superstructure areas, whether working or rest areas. This ventilation system consists of a set of fans and exhausts fans. Since the air conditioning is already dimensioned taking into account the necessary ventilation inside these spaces, only it is required exhausts that force the air to be expelled to the outside. For the majority of work areas, the ventilation occurs in natural form. For this reason, only exhaust fans were dimensioned, with the exception of the galley. The galley is an area extremely regimented by maritime rules since it is a work area with a higher number of electrical equipment which function is to produce heat. The rules focus not only on fire protection but to create good work conditions as well. For this reason, both the ISO 9943:2009 and the (GL, 2016) describe the requirement for a mechanical fan that supplies air in large quantities to its interior and an exhaust fan to remove the air. In addition, (GL, 2016) presents the minimum values for exhaust air, which are represented in Table 32, following the same grouping of areas as previously conducted.

Table 32 - Air renovations rates for exhaust air

Space	Exhaust air [ren/h]
Cabins	0
Mess, dining-rooms or offices	12
Hospitals	12
Galley	40
Pantry	15
Dry provision room	5
Laundries	15
Bridge	18
Extra Bathroom	15
HVAC Room	30
Deck Stores, workshops or spare rooms	10

To perform the conversion of these values for flow rates, it was necessary to know the volumes obtained from the real ship model developed. Knowing the flow rates associated with the ventilated spaces it is applied the power fan equation (3.5). Following the same principle used in (3.75), it is possible to have the power coefficients in function of the superstructure volume. Table 33 presents the coefficients summary in relation of supply and exhaust system to be applied in the main electrical balance model.

Table 33 - Supply and exhaust power system coefficients in function of the superstructure volume

Space	Fan $C_{Powerpervolume}$ [kW/m^3]	Exhaust fan $C_{Powerpervolume}$ [kW/m^3]
Cabins	-	-
Mess/Dining-rooms/Offices	-	0.0007750
Hospitals	-	0.0000788
Galley	0.000482	0.0004820
Pantry	-	0.0001020
Dry provision room	-	0.0000955
Laundries	-	0.0001250
Bridge	-	0.0004400
Extra Bathroom	-	0.00000105
HVAC Room	-	0.00023500
Deck stores/Workshops/Spare	-	0.00023500

The extra bathrooms are spaces with some difficulty to estimate, for this reason this specific coefficient is in function of the POB as well. As mentioned, this HVAC model was developed based on a cargo ship and it is intended that this model will also be applied on RoPax ships. For this purpose, it was required to differentiate the volume to be applied to these coefficients. This occurs since in this type of specific ship, the cargo space is also counted in the volume of the superstructure. Thus, for a RoPax ship the volume of the superstructure is deducted from the cargo space.

3.7.2 Provision Refrigeration and Ventilation

The provision rooms on board are normally composed into three rooms, where which one corresponds to a food type at a given temperature. For this reason, it was considered the three following rooms: The dry provision room, which was considered 15ºC as interior temperature, the cooling provision room with a temperature of 0ºC, and the freezing provision room with a temperature equal to -20ºC. The most appropriate method to power requirement calculation is based on a thermal balance. This means that should be take into account all the heat sources that may be involved around the installation, including the thermal materials to be used in the rooms, the spaces adjacent to the rooms, the heat emission by people and lights inside the rooms, and the ventilation and air renovation requirement. Normally, the provision store installation is located near the galley or at least with easy access. However, at this design phase, it is difficult to know the details such as the adjacent spaces that the provision installation will have to share boundaries. The only available and easiest parameter to estimate at this project stage is the total volume of the cold storage rooms since this is related to the POB and navigation time. To simplify all the questions and details of the installation and to be able to reach the objective of the associated power calculation, it was used an auxiliary software provided in (INTARCON, 2012), assuming that each room is a modular room already in the market. Important to inform that the cooling calculator comprises an advanced calculation method for the cooling system, based on the component simulation rules proposed by (ASHRAE, 2015), coolant properties calculated by NIST REFPROP, and updated thermodynamic correlations for the calculation of heat exchange. This software presents the temperature for the three rooms assumed (15ºC, 0ºC, and -20ºC). Then, it was collected data for room volume between 6 m^3 and 80 m^3. As ambient temperature, it was considered 25ºC. All the thermodynamic values, such as insulation thickness, goods properties (as water percentage and transpiration heat), was considered by default already in the program. Concerning external heat loads, it was contemplated that a person will enter a total of 2 hour per day. Switching to the program results tab, it was added a 10% safety margin and estimated 22 hours per day of the room's operation. After all results collected, it was executed a sum between the three rooms with the same volume. This was another assumption executed to facilitate the calculations. Then, a regression was performed in order to have an equation which correlates the provision plant power consumption and the provision plant volume, parameter that should be inputted on the model (Figure 45).

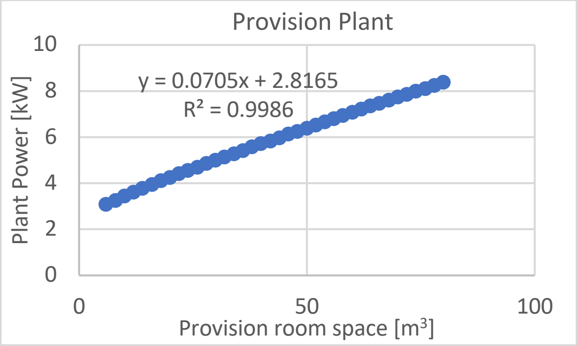

Figure 45 - Provision plant consumption

The equation obtained from the regression curve performed it shown in (3.76).

$$P_{Provisionplant} = 0.0705 \times V_{Provisionplant} + 2.8165 \tag{3.76}$$

Where $P_{Provisionplant}$ is the power associated to the provision plant on board in kW, and $V_{Provisionplant}$ is the volume of all provision rooms in m^3.

3.7.3 Illumination

In this section it is present the illumination consumption on board of a ship. It was considered the interior illumination, the exterior illumination, and the navigation light.

3.7.3.1 Interior Illumination

For the interior illumination estimative, it is considered the superstructure and the ER. Before going into detail, it will then be described how the lighting power was calculated (3.77).

$$P_{illumination} = \frac{\emptyset V}{\eta_{lamp}} \tag{3.77}$$

Where $P_{illumination}$ is the power required for illumination in W, $\emptyset V$ the luminous flux in lm, and η_{lamp} the luminous efficacy of a lamp in lm/W. The luminous flux is defined as the total amount of light emitted from a luminaire in all directions, for this reason, it cannot be measured directly. Then, there is a necessity to apply two main concepts: illuminance and the luminance. With these two concepts it is possible to know the luminous flux in a determined zone or area. The luminous flux is then given in equation (3.78).

$$\emptyset V = E \times S \times \frac{F_d}{F_u} \tag{3.78}$$

The parameters of the equation presented above are E as the illuminance in lux, S the surface area in m^2, F_d the depreciation factor, and F_u the utilization factor. The illuminance permits to know the amount of light on a surface, and in its turn, luminance is the amount of light reflected by the surface. It is the luminance that is seen by a person in the vessel interior. However, for the luminance knowledge it is necessary to know the illuminance. The illuminance is provided by levels of general lighting or task lighting as it is possible to see in criterion from (ABS, 2016), which is based on ISO 8895-1:2002 and focuses on lighting specifically on vessels. (ABS, 2016) describes the illuminance level according to the space to illuminate.

Table 34 presents these guide values summarized in space groups.

Table 34 - Illuminance level criteria based on (ABS,2016)

Space	**Illuminance level [lux]**
Accommodations	
Cabins	150
Bathroom	200
Service	
Galley	500
Pantries	300
Dry provision room	200
Laundries	300
Common	
Mess and Recreation Spaces	300
Gymnasiums	300
Access and Passageways	100
Hospital	150
Changing Rooms	200
Operating and Maintenance	
Control rooms and offices	300
Workshops and chemical rooms	300
Auxiliary equipment rooms	200
Bridge	300

At this ship design phase, it is relatively challenging to provide an estimation of the specific areas for each compartment inside a superstructure. For this reason, it was elaborated a model that enable the areas estimation for each illuminated onboard space according to ship type and conceptual ship design parameters. The first step of this area model was to select ships general arrangements covering several ship types such as tanker, bulk carrier ship, container ship, and also two RoPax. From these ships types it were grouped in cargo ships and RoPax, however, a same principle was applied for all ships analyzed. The second step consisted in to measure all the accommodation areas. The last step was to correlate these areas with conceptual design parameters such as superstructure total area, number of crew members, number of passengers and POB. From this point, it was conducted on an average for the cargo ships group and for the RoPax ships group, since it was verified the same magnitude order. Table 35 presents the final coefficients achieved for cargo ships and for RoPax with the respective units, grouped by spaces.

Table 35 - Area coefficients developed in a model for cargo ships and RoPax ships

Space	$C_{Cargoshipsarea}$		$C_{Ropaxshipsarea}$	
Accommodations				
First Officers Accommodation	0.00277	m^2/ crew	0.00044250	m^2/ crew
Officers Accommodations	0.00376	m^2/ crew	0.00016190	m^2/ crew
Ratings Accommodations	0.00594	m^2/ crew	0.00039640	m^2/ crew
Hotel Crew Accommodations	-		0.001137 or 0.00079530	m^2/ crew
Service				
Galley	0.00095	m^2/ crew	0.102900	m^2/ POB
Pantries	0.00036	m^2/ crew	0.000340	m^2/ crew
Dry provision room	0.00174	m^2/ crew	1.11E-05	m^2/ POB
Laundries	0.01208	m^2	0.0027936	m^2
Common				
Mess and Recreation Spaces	0.00342	m^2/ crew	0.0002384	m^2/ crew
Access and Passageways	0.09497	m^2	0.0431108	m^2
Hospital	0.01632	m^2	0.0040339	m^2
Changing Rooms	0.03254	m^2	-	
Operating and Maintenance				
Control rooms and offices	0.05887	m^2	0.0044776	m^2
Workshops and chemical	0.02208	m^2	-	
Auxiliary equipment rooms	0.05768	m^2	0.0220603	m^2
Bridge	0.06829	m^2	0.0228080	
Passenger zone				
Accommodations	-		0.00192738 or 0.000615098	m^2/Passengers
Recreation	-		1.24550	m^2/Passengers
Bar	-		0.02036	m^2
Restaurant	-		0.07925	m^2/Passengers
Bathroom	-		2.53E-05	

Although the areas' model is an approximation, it was tried to achieve the most accurate estimates. Therefore, some options are available on the electrical load balance input spreadsheet. Two of them are related to the RoPax ships in which the user can choose the hotel crew sharing a single or double cabin. The same occurs for passengers, it was considered an option for passengers to share double or four-persons cabins. By the equation (3.78), it is possible to understand that two factors are considered. The depreciation factor is defined by the dirt that accumulates inside and outside of refractors, reflectors, and lamps, resulting in reduction of lumen output. This factor rounds between 1.25 and 2.5 depending on the space clean level. This thesis considers an average of 1.75 which is the middle of the range present before. In turn, the utilization factor is defined by the incidence of lighting, i.e., whether the light is direct or indirect, in this thesis was considered 0.55 as direct light in all spaces. Luminous efficacy is the rate of the lamp total luminous flux to the total electric power consumed by the lamp (Choudhury, 2014). This means that the luminous efficacy shows how the light source can produce visible light in a space. The luminous efficacy is directly related with the types of lamps, since each lamp has its own efficacy in a space. (Choudhury, 2014), specify some of these values for different lamps which were compiled in Table 36.

Table 36 - Luminous efficacy according to lamp type

Lamps Type	Luminous Efficacy [lm/W]
Incandescent Tungsten	45
Fluorescent tube	60
Halogen	20
LED	120

It was decided to use fluorescent tube lamps, being these the most common onboard lamps. For the ER, the same principle was applied, and the same lamp type was assumed. The ER illumination is then calculated in function of ER area, parameter inputted on the model.

3.7.3.2 Navigation and exterior illumination

In addition to the interior lighting, a ship also has exterior lighting and navigation lights. (IMO, 1972) states the visibility of the navigation lights in terms of range and the light arc that every light shall have. These light characteristics are significant to know the associated power consumption. On the other hand, it was also considered signalization lights such as for ship mooring and without propulsion or not under command. Following these requirements, it was collected data from manufacturers catalogs. Assuming these consumptions as constant, an average was performed, and the resulting values present in Table 37.

Table 37 - Navigation lights power consumption

Light Designation	Number of Lights	Angle[º]	Visibility Range	Power [W]
Masthead Light	2	225	6	85
Sidelights	2	112.5	3	55
Stern light	2	135	3	75
Towing Light	2	135	3	110
All round Light	2	360	3	55
Flashing Light	1	135	3	55
Signalization Lights	4	-	-	60

In addition to these navigation lights, it was considered 10 kW extra for exterior light on superstructure and deck. This value is an average of several examples analyzed.

3.7.4 Laundry

A laundry room on a ship is necessary to wash and dry work and normal crew clothes. It is as important as washing machines as dryer machines to decrease the time spent on natural dry. Depending on the POB, the number of machines required will vary. To estimate the power associated with the ship laundry, it was analyzed manufacturers catalogs and three ship known electrical load balances. This last analysis allowed us to obtain the coefficients present on equation (3.79) and (3.80), since it was divided the machines total power data by the corresponding POB of each ship, obtaining a coefficient in kW/person.

$$P_{Dryermachine} = 0.3816 \times POB \tag{3.79}$$

Where $P_{Dryermachine}$ is the total power associated to dryer machines in kW, and POB the people on board.

$$P_{Washingmachine} = 0.3032 \times POB \tag{3.80}$$

Where $P_{Washingmachine}$is the total power associated with the washing machines in kW, and POB the people on board. These equations estimate the total power associated to the dry and wash machines without the knowledge of the number of machines.

3.7.5 Workshop

A ship can navigate for a few days or months. For this reason, it is essential not only to have spare parts on board for the several machineries but also equipment to patch up some possible damages due to the operation or even for the manufacture of small parts, or tools for the crew's handling during navigation time. After some research, it was chosen the basic equipment inside of a workshop to be considered in the thesis model, being these a double grinder that allows to remove undesired edges from metal, a drilling machine normally used to cut a cylindrical hole in a solid material, a lathe to be used for manufacturing, or shaping different spares and welding machine which permits melting the metal. To the power estimation, it was collected consumptions from manufactures catalogs. After the data collected, it was performed an average for each machine and assumed as constant consumption (Table 38).

Table 38 - Workshop machinery power consumption

Machinery Designation	Power [kW]
Double Grinder	1.0
Drilling Machine	1.5
Lathe	6.0
Welding Transformer	13.5

3.7.6 Bridge Equipment

Nowadays, the bridge of a ship is equipped with a large amount of maritime navigation equipment. The advance of technology requires that today's seafarers are properly trained to understand the operation of all modern navigation equipment that has made navigation safer.

3.7.6.1 Navigation Equipment

Navigation workstation is properly prepared to the navigators' command, in this way, allow the monitoring of the route, survey traffic, course, or speed alterations. To ensure this, some instruments and specialized equipment are needed. (IMO,1974) state the minimum navigation equipment which all ships shall be equipped with. For this thesis, it was considered the most common and that required to be electrically powered. The gyrocompass is a form of gyroscope used on ships to find the right direction. The electronic chart display and information system (ECDIS) is a technologic equipment that presents visually the navigational chart. The speed equipment is the equipment used to measure the speed and the distance which will allow to adjust the ship ETA to any port. Echo sounder is the equipment that is used to measure the water depth below the ship's bottom through emitted sound waves and the echo returned. Radar is used for identifying, tracking and positioning of ships, including the own ship, and permits the ship to navigate safely from one point to another, but not only in navigation time, it is also important on port for the traffic monitorization of the authorities. The recorder is a crucial instrument installed on a ship which records continuously at least 12 hours all operation, voices and movements inside of a bridge, containing thus vital information in case of accidents on board. The BNAWS (Bridge Navigational Watch Alarm System) is an alarm system with aim to increase the ship during navigation, avoiding accidents caused by crew distractions. This alarm consists of a bottom that should be pressed along all navigation time in period to period by the officer navigation watch. Finally, the satellite navigation equipment shows the ship's location with help of a receiver from a satellite in the earth's orbit. After the electrical consumers' equipment list defined, it was searched for the respective electrical power consumption from manufacturers catalogs and also, it was analyzed two ships known electrical balances, performing then an average and resulting in the constant values of Table 39.

Table 39 - Navigation equipment power consumption

Designation	Power [kW]
Gyrocompass	0.38
ECDIS	0.16
Speed Equipment	0.46
Echo Sounder	0.24
Radar	2.37
Recorder	0.11
BNAWS	0.08
Satellite Navigation Equipment	0.34

3.7.6.2 Communication Equipment

Communications are the equipment group used on maritime platforms to communicate among themselves and with land stations. The communication equipment can be divided into internal communication or exterior communication. To have the knowledge of the equipment's existence on board it was followed (IMO, 1974). In specific for exterior communications, it followed the global maritime distress and safety systems (GMDSS) equipment that is internationally agreed. Being part of this equipment the NAVTEX receiver which receives maritime safety information as weather forecast and warnings or search and rescue notices, and INMARSAT communication which provides telex between ship-to-ship or ship-shore with priority for rescue centers. In addition, it was also considered VHF and an internal telephone that allows direct communication between people who are in separate locations.

Table 40 - Communication equipment power consumption

Designation	Power [kW]
NAVTEX Receiver	0.14
INMARSAT communication	0.97
VHF	0.28
Internal telephone	0.35

3.7.6.3 Others Equipment

Other small consumers were considered based on other ship's electrical balance, as for example the batteries chargers, clear view screen, and the horn or whistle.

Table 41 - Miscellaneous bridge equipment power consumption

Designation	Power [kW]
Batteries Chargers	1.00
Clear View Screen	0.62
Horn/Whistle	5.53

3.7.7 Galley

The galley of a ship is an area where all the food for POB is prepared. To enable this there is an equipment requirement for food preparation. After a small list of the most common ship's galley household appliances established, it was collected the electrical consumptions which some of them were taken as unique and constant and others sized in the function of the POB. Table 42 shows the machines considered as well as the functions used for power calculation or the constant values. All these values were obtained by collecting typical values associated with each equipment. This collection was carried out from manufacturers catalogs and also from ship known electrical balances, and thus was subsequently placed according to the POB.

Table 42 - Galley equipment list and respective power consumption calculation

Machines Designation	Power demand [kW]
Dish Wash Machine	0.275×POB
Electric Range	9.70
Garbage Grinder	1.02
Hot Plate	1.40
Refrigerator	0.0175×POB
Microwaves	0.09875×POB
Electric Frying	4.87

3.8 Electrical Load Balance Development

Afterward the electrical consumers list concluded as well as the nominal power for each consumer modeled, the electrical load balance is structured. For this purpose, the ship operating conditions were defined, carrying out an electrical analysis according to each operational condition of the vessel. It was considered the following operating conditions:

1- Navigation: condition in which the ship navigates full ahead at its service speed. In this condition, it is included all auxiliary services necessary to the normal navigation operation of the ship, and superstructure crew facilities.

2- Maneuvering: condition since a ship reduces the rated speed to enter in port until the mooring is complete and the main engine stop. It is included all the consumers necessary for the normal navigation condition (at different regime), superstructure crew facilities, maneuvering auxiliary equipment, and deck equipment such as winches.

3- Loading and Unloading: condition in which are considered all consumers necessary to the normal operation of the ship at port and deck auxiliary equipment for cargo movement (load and unload).

4- Port: condition in which all machinery solely required for propulsion is stopped with exception of fuel recirculation systems. It is only considered the essentials consumers to the ship moored at the port, as superstructure crew facilities.

These 4 operational conditions chosen are the basic conditions that any electrical load balance shall cover and enable the derivation of any other desired. The electrical load balance model was then constructed following the next organization. It was first described the groups and consumers, after it was defined the number of units installed on board and the number of units in service and finally the power of the consumer according to each operating condition.

To estimate the equipment power consumption in each condition it was used the equation (3.81).

$$P_{Condition} = P_{Nominal} \times nr_{Service} \times k_L \times k_s \tag{3.81}$$

Where $P_{Nominal}$ is the nominal power calculated for each equipment list in kW, $nr_{Service}$ is the amount of equipment in service, k_L is the load factor, and k_s is the simultaneity factor.

The amount of equipment in service is directly connected with the number of installed on board and the operating condition. The majority of engine auxiliary systems shall be arranged with redundancy. Redundancy is a secondary component or system that ensures the corresponded system does not suffer any loss in case of primary equipment failure. In this manner, for the most pumps and compressors, it was considered that are installed 2 and in service 1 remaining the other in standby. Some exceptions were carried out such as for the fuel pumps, being then considered 2 per engine. In case there are 2 engines installed, each one is fitted with a group of 2 fuel pumps. On the other hand, for the deck equipment, the number of the equipment is established by the user of the model as input data. For all the other equipment, by default, it was considered installed only 1, and the same in operation. As it is possible to observe in (3.81), the operating condition power is defined by the amount of equipment in service and the two factors considered the load or utility factor (k_L) and the simultaneity factor. Following (Pater, 2012), the utility factor is defined as the average power during the operation period of time divided by the peak power of the equipment. This means that for an equipment continuously on load, the k_L will be 1, if the equipment as an intermittent operation, this factor will be lower than 1 and if the equipment is in stand-by the k_L will be 0. Following this definition, for each equipment list described on the model, the equation used is equation (3.82).

$$k_L = \frac{\%Powerload \times t_{operation}}{100 \times\ 24} \tag{3.82}$$

The peak load is defined by the nominal power of the equipment functioning in 24 hours. $\%Powerload$ is the percentage of the power which is in load, and $t_{operation}$ is the equipment operation time in hours. Both the load percentage and the time of operation were factors assumed according to the experience of operating a ship, according to each device modelled. Some exceptions to this equation were carried out after checking the large difference in values used in the model and in real electrical power tables. In these cases, the load factor was adjusted to approximate the actual and most common value used. For a better perception of the coefficients considered, an example was attached (Annex B). The simultaneity factor is defined by the percentage of consumers that are driving at same time. It is difficult to estimate which are the consumers that will work at the same time. For this reason, it was followed the standard NBR 7567:1982 that provides standard values to be used in electrical load balance estimation, according to the electrical consumers group. These values are applied not for each equipment as usually seen but in group. Adapting the table presented on the standard to this thesis consumers list, it was obtained the followed tables. The simultaneity coefficient to be applied in the engine room group is shown in Table 43.

Table 43 - Simultaneity coefficient applied to Engine Room groups (NBR 7567:1982)

Engine Room					
Group	Designation	Navigation	Maneuvering	Loading/Unloading	At Port
1	Continuous Service	1	1	1	1
2	Intermittent Service	0.5	0.6	0.5	0.5
3	Miscellaneous	0.4	0.4	0.4	0.4

Table 44 represents the simultaneity coefficient to be used in deck groups.

Table 44 - Simultaneity coefficient applied to Deck groups (NBR 7567: 1982)

Deck					
Group	Designation	Navigation	Maneuvering	Loading/Unloading	At Port
4	Cargo Refrigeration	1	1	1	1
5	Deck Equipment	0.4	0.8	1	1

In spite of the simultaneity coefficient of the deck equipment presents 1 for “At port” condition, the load factor for this auxiliary machinery is zero with exception of the winches, since it is always necessary adjust cables in port due to tidal variation, and the provision cranes in case of its existence.

Finally, for the superstructure groups it was followed the coefficients present on Table 45.

Table 45 - Simultaneity coefficient applied to Superstructure groups (NBR 7567: 1982)

Superstructure					
Group	Designation	Navigation	Maneuvering	Loading/Unloading	At Port
6	Provision	1	1	1	1
7	HVAC	1	1	1	0.7
8	Workshop	0.4	0.4	0.4	0.4
9	Laundry	0.5	0.5	0.5	0.5
10	Bridge Navigation Equip.	0.8	0.8	0.8	0.8
11	Illumination	0.7	0.7	0.7	0.5
12	Galley	0.5	0.5	0.5	0.5

4. Results Validation

In this chapter it will be validate the model derived in the previous section and analyzing the results of a parametric study for different cases. This study will verify the veracity of the modelled equations in order to be applied in a more realist way to other ships. Two types of validation were performed. One of them consists of a global validation. This validation is based on the collection of all vessels parameters necessary for the functioning of the model from Significant Ships database. Afterward, the different operating conditions of the ship were compared with the total installed power value on board, also reported in these technical journals. The second method consists in a detailed validation. The detailed validation was achieved by comparing each vessel operating condition values acquired by the model and the known ships' electric load balance values. In this manner, all parametric input values for the model were collected through the general arrangements and ship specifications. In order to provide consistent validation, the different options for ship propulsion systems were analyzed, as well as the 4 proposed options for ship types to be modeled in the numerical tool.

4.1 Conventional 2-Stroke engines

4.1.1 Global Validation

For the global validation in which the parametric model will be applied, two reference ships were selected. For 2-Stroke engines, it was selected a tanker product carrier (Ship nº 1) and a bulk carrier (Ship nº 2). The ship particularities are verified mainly on deck equipment. The specific equipment that a tanker is equipped with in comparison to the other types analyzed are the cargo pumping system. On the other hand, the bulk carrier ships are vessels more simplified in terms of cargo equipment. The reference ship number 1 is a coastal tanker with one 2-Stroke-engine dual fuel with 11,060 kW. This ship is equipped with 12 cargo pumps, each one with 600 m^3/h of capacity, one bow thruster, and a crane with 5 ton of capacity. The ship number 2 is a capesize bulk carrier of 87,000 DWT with one 2-Stroke-engine dual fuel with 10,500 kW. This ship is equipped with side-rolling hatch covers and for this reason, it was possible to estimate the corresponded power associated. In addition to these bigger consumers mentioned in the technical journals, it is considered the scrubber installed on board these ships since 2-Stroke engines operate with IFO and MDO.

It was then verified the condition which presents a bigger value of electrical demand and compared with the power installed on board. The Table 46 shows the model values compared to the electrical power installed in each ship and the corresponding error associated.

Table 46 - Global validation 2-Stroke engines

Ship nº	Real Values [kW]	Model Values [kW]	Error [%]
1	3,120	2,879	-8
2	1,900	1,717	-10

In the case of ship number 1 it is verified that the highest electric demand occurs in unloading condition. This is justifiable since it is in this condition that the cargo pumps are in operation. It is important to refer that it was considered that the pumps are not all operating at the same time with the same load and therefore a load coefficient equivalent to 0.6 was attributed. It is possible to conclude that the model provides a good estimative of the total power required for this tanker ship. In the ship nº 2, it was verified the highest value of power consumption in maneuvering condition. The numerical model produces also a good estimate for this ship since the error is verified 10%.

4.1.2 Detailed Validation

The second type of validation performed has great relevance since it enables to understand where there are greater discrepancies of values in the model and thus be properly corrected. As previously mentioned, the load factor and the simultaneity factor can be calculated in many different ways. Due to the lack of knowledge of the method used in each real electrical balance analyzed and to maintain the level of truthfulness of the calculated errors, instead of the values of electrical consumption in the different operating conditions, it will be examined the nominal power of each equipment.

The two detailed validations performed for 2-Stroke engines were conducted based on oil tanker ships. The first aframax tanker ship is powered by a reversible 2-Stroke engine with 10,760 kW. The cargo system of this ship is equipped with 3 pumps where each pump has the capacity of 2,500 m^3/h at 16 bar. Nonetheless, these pumps are not electrically drive but steam drive. The superstructure is arranged to be the accommodation of 45 crew persons. Afterward all the data inputted on the first spreadsheet of this model, the main results are shown in Table 47.

Table 47 - Groups Power Consumption, 2-Stroke engines: Ship number 1

Group nº	Real Values [kW]	Model Values [kW]	Error [%]
1	243	256	+5
2	49	54	+9
3	85	71	-16
4	65	65	0
5	6	5	-11
6	6	6	+6
7	99	107	-8
8	8	9	+9
9	18	17	-5
10	22	13	-42
11	71	64	-9
12	70	35	-51

Comparing the values of this table some observations can be noted. The third group is one of the groups which presents a difference higher than 10%. This occurs mainly due to the difference in the fire pump values of this ship. As it is possible to see in Table 48 the consumption of the main fire pump on the model is lower than the real value in 23%.

The most discrepant percentage errors between the model and the known ship are found in groups 10 and 12 with about 40 to 50 %. Since these groups are mainly composed of constants, it is normal to verify differences. These differences occur due to the fact of the minimum equipment considered in the thesis may not correspond to the exact number that the ship actually has. The most important aspect to retain is that these groups are not influential since corresponds about 2% of the total power which is a small impact on the final results.

Table 48 - Detailed Validation, 2-Stroke engines: Ship number 1, group 3

Group nº3	Real Values [kW]	Model Values [kW]	Error [%]
Bilge Pump	28	28	0
Main Fire Pump	50	38	-23

Since it is not possible to compare the cargo pumps consumption due to these pumps be steam drive, it was opted to present a specific equipment associated with the cargo equipment of a tanker ship. Thus Table 49 shows the inert gas fan power consumption.

Table 49 - Detailed Validation, 2-Stroke engines: Ship number 1, group 4

Group nº4	Real Values [kW]	Model Values [kW]	Error [%]
Inert Gas Fans	65	65	0

From this table, it is possible to see that there is no difference between the power consumption of inert gas fans.

The second ship analyzed is a handysize tanker powered by a reversible 2-Stroke engine with 9,600 kW. The ship cargo system consists of 4 pumps in which capacity was considered as 2,700 m^3/h at 14 bar based on a similar ship from Ship Significant journals. Differently from the previous tanker ship, these pumps are electrically driven. In addition to deck auxiliary equipment, this ship has one deck crane of 7 ton to auxiliar the maneuver of the cargo hoses. Also, it is furnished with an inert gas generation system in addition to the respective fans. The accommodation is prepared for 36 crew persons. Table 50 details the values obtained for each group modelled.

Table 50 - Groups Power Consumption, 2-Stroke engines: Ship number 2

Group nº	Real Values [kW]	Model Values [kW]	Error [%]
1	312	332	+6
2	100	81	-18
3	231	227	-2
4	138	252	+82
5	1,593	1,699	+6
6	14	12	-11
7	77	70	-9
8	20	8	-57
9	27	24	-6
10	14	13	-7
11	43	40	-8
12	38	31	-18

Analyzing this table, some points can be denoted. The worst numbers are founded in group 2, 4, 8 and 12. The discrepant values identified in group 2 focus on transfer pumps. The reason for this discrepancy could be the assumed number of hours to transfer. Remembering that for this thesis a constant value of 6 hours was considered. A lower value of transfer hours may have been considered in the design of these pumps, specifically for this ship. In turn, the main compressor, also a constituent of this group has a percentage error of only 2%. The large difference in group 4 is due to the inert gas generator. However, there is no possibility to have a conclusion about this equipment due to lack of information such as the own existence of this equipment and the real value of the pump’s capacity, remembering that it was used a value of a similar ship. In turn, the inert gas fans were compared, and it was noticed an error of 10%.

Table 51 - Detailed Validation, 2-Stroke engines: Ship number 2, group 4

Group nº4	**Real Values [kW]**	**Model Values [kW]**	**Error [%]**
Inert Gas Fans	104	94	-10

Again, the Group 8 and Group 12 show values higher than 10 % of error. However, these groups have a weight lower than 1% of the total power consumption.

Table 52 reveals the total values corresponding to the ship's operating conditions for the two tanker ships previously presented.

Table 52 - Ship operating conditions analysis for 2-Stroke engines

	Tanker 1			**Tanker 2**		
Ship Condition	Real [kW]	Estimated [kW]	Error [%]	Real [kW]	Estimated [kW]	Error [%]
1	542	491	-9	545*	523	-4
2	763	804	+5	974*	936	-4
3	-	-	-	2,071	1,970	-5
4	-	-	-	617	675	+9

1- Normal Navigation, 2- Maneuvering, 3-Unloading, 4- Port

*These numbers correspond to the real electrical load balance with exception of all associated thermal oil boiler equipment, electrical heating, incinerator, fans of the specific ship type such as inert gas room fan and cargo pump room fan.

The first tanker has an auxiliary boiler. With this boiler are associated the equipment and auxiliary machinery for its good functioning. This equipment includes an exclusive fan for the boiler area, the burner, fuel pumps to feed the boiler, and water feed pumps. Also ships fitted with boilers, take advantage of this steam to drive various equipment instead of being driven electrically. For these reasons, it was decided not to compare the values of those conditions where there is a higher demand from the boiler. These conditions refer to when the vessel navigates with all the tanks heating service and when the ship is unloading its cargo. The condition of the ship in port is not presented in the electrical balance and therefore it is not possible to compare. Consequently, for this ship, it was possible to verify the values of the ship navigating without heating load. This difference being below 10%, it is stated that it is a valid estimative. Similarly analyzed for the ship in maneuver there is a percentage difference of 5%. Therefore, it is also affirmed that the model performs a good assessment for this ship in these two operating conditions.

In the second tanker study, it was checked all the equipment not contemplated in the model to ensure a plausible validation. It was conclusive that most of the equipment not modelled are directly related to this type of ship. For this reason, the power consumption of those unmodelled equipment was deducted from the actual values presented in the tanker's electric balance for navigation and maneuvering conditions. Observing Table 52 it is factual that all percentage errors are under 10%.

4.2 Conventional 4-Stroke engines

4.2.1 Global Validation

For 4-Stroke engines, the same process as shown for 2-Stroke engines was performed. The ships chosen to analyze were then an oil tanker (Ship nº1), a multipurpose heavy-lift ship (Ship nº2), and a RoPax (Ship nº3). The tanker selected is a coastal tanker with a complement of 17 persons and equipped with a 4-Stroke engine of 4,500 kW of power. Associated with the engine it is considered a scrubber for exhaust gas treatment when it works with IFO. This tanker ship has 12 cargo pumps of about 600 m^3/h each. Besides these pumps, it is also equipped with a 5 ton crane on deck and a bow thruster. The multipurpose ship is prepared to handle containers as well as bulk cargo, however, this ship is arranged to transport heavy cargo. This is the reason for this reference ship choice since on this deck there are 2 cranes of 60 ton of capacity. In this manner, this ship is considered a container feeder ship type with a capacity of 516 TEU. On board can be accommodated 19 persons as crew. The engine is a 4-Stroke with 5,400 kW of power and can operate with dual-fuel. In addition, this ship has one bow thruster to account for the electrical load balance. The third ship considered is a RoPax which can transport 600 passengers and 45 persons as crew. This ship is equipped with 2 main-engines with 4,500 kW each one and exclusively operates with MDO. This means that it should be considered auxiliary diesel-oil machinery for each engine. In addition, two bow thrusters are installed on board to facilitate the ship maneuvers.

After applied all the vessels characteristics on the model, the results are shown in Table 53.

Table 53 - Global validation for 4-Stroke engines

Ship nº	Real Values [kW]	Model Values [kW]	Error [%]
1	2,040	1,612	-20
2	1,576	1,486	-6
3	4,080	3,907	-4

The global validation for 4-Stroke engines indicates that the model is able to perform a reliable estimation for the multipurpose ship and RoPax ship in terms of generator power estimation. The vessel number 1 analyzed is a tanker that transports asphalt. This means that it requires a large heating installation in order to unload the cargo. As mentioned in detail in section 4.1.2, no boiler has been estimated or modeled, and therefore this percentual difference verified can be justified by the lack of estimation of the heating equipment.

4.2.2 Detailed Validation

For ships furnished with 4-Stroke engines validation, 3 ships were analyzed being one feeder container ship, and two RoPax ships.

The first ship analyzed is a feeder container ship, powered by a 6,000 kW engine. This ship is capable of handling 610 TEU and it is prepared to accommodate 17 crew members. As extra deck and maneuvering equipment, two 25 ton cranes provide self-unloading in smaller ports and two bow-thrusters as well. After the input data imposed, the groups consumption values corresponding to this ship are shown in Table 54.

Table 54 - Groups Power Consumption, 4-Stroke engines: Ship number 1

Group nº	Real Values [kW]	Model Values [kW]	Error [%]
1	271	270	-0.5
2	11	13	+27
3	111	123	+11
4	1,026	924	-10
5	580	607	+5
6	-	4	-
7	55	52	+6
8	20	22	+10
9	18	12	+30
10	4	13	+259
11	26	26	-3
12	30	24	-18

Another analysis was performed. It was verified that the larger groups consumers are the group 1 with 13% of the total electrical demand, the group 4 representing 48%, and group 5 which represents 25% of the total. Therefore, it is possible to analyze the general table (Table 54), verifying the worst values corresponded to the group 2, group 9, group 10 and group 12. Although the group 2 reports a high percentage error, this translates in 2 kW which is not significant. The remaining groups are the groups corresponding to those composed mostly by constants. It is important to have in consideration in this analysis the magnitude order which is not guaranteed by this percentual error. A clear example of this occurs for group 10 that is verified a difference of 9 kW. This difference does not have a significant effect on the total. Following it is possible to see a detailed analysis in particular to the groups which were verified higher consumptions. For the first group (Engine Room-Continuous Service) it was analyzed the higher consumers and compiled in Table 55.

Table 55 - Detailed Validation, 4-Stroke engines: Ship number 1, group 1

Group nº1	Real Values [kW]	Model Values [kW]	Error [%]
LO main Pump	75	72	-4
SW Pump	37	40	+8
FW circulating Central Pump	22	21	-4
FW HT pump	22	19	-12
Steering Gear Unit	26	22	-16
ER Ventilation	61	62	+1
TOTAL	271	270	-0.5

As it is possible to verify, the percentage error values of the largest individual consumers are small with exception of the steering gear where it is verified a percentage error of 16%. However, in a total of small and large consumers, the error is almost null, so it is considered that this group is well dimensioned. Another weighted group in the total electrical load balance is the cargo refrigeration. As a ship container is being evaluated, this group has a high consumption due to the quantity of refrigerated containers on board.

Table 56 - Detailed Validation, 4-Stroke engines: Ship number 1, group 4

Group nº4	Real Values [kW]	Model Values [kW]	Error [%]
Reefer containers	960	878	-9
TOTAL	1,026	924	-10

The error verified in this group is lower than 10% and for this reason is considered that the model provides a cargo refrigeration and ventilation good estimation. Group 5 corresponds to the deck and maneuvering auxiliary equipment, where in specific for this ship will have a high importance due to the equipment installed. In this manner, it was analyzed the individual values of nominal power of the cargo cranes and bow thruster.

Table 57 - Detailed Validation, 4-Stroke engines: Ship number 1, group 5

Group nº5	Real Values [kW]	Model Values [kW]	Error [%]
Cargo Cranes	128	128	0
Bow Thrusters	420	428	+2
TOTAL	580	607	+5

Following Table 57, it is demonstrated a lower error percentage individually and also in the total group value. Although the group number 11 does not present the higher consumption in total electrical load balance, it was opted to present since it represents a large consumer of the superstructure.

Table 58 - Detailed Validation, 4-Stroke engines: Ship number 1, group 11

Group nº11	Real Values [kW]	Model Values [kW]	Error [%]
Superstructure Illumination	8	9	-17
Engine Room Illumination	4	5	+28
Navigation Light and Exterior	14	11	-23
TOTAL	26	25	-3

Despite the individual values presenting high percentage errors, in the group total, it is possible to notice that the percentage error is small. This is justified by the fact that the power distribution associated with lighting is carried out differently however in the final result it has the same value.

The second ship is a RoPax propelled by two 4-Stroke engines with 9280 kW each one. This RoPax is prepared to transport around 700 persons including crew members. In addition, two bow thrusters are installed. Similar to the previous cases study, the table of electrical consumption per group of this ship is presented in Table 59.

Table 59 - Groups Power Consumption, 4-Stroke engines: Ship number 2

Group nº	Real Values [kW]	Model Values [kW]	Error [%]
1	308	306	-0.5
2	32	25	-23
3	187	182	-3
4	60	59	-2
5	961	986	-3
6	20	19	-6
7	226	275	+12
8	31	22	-29
9	40	39	-1
10	26	13	-50
11	106	97	-9
12	115	125	+9

The groups with larger significance in terms of consumption on the total electrical balance are the group 1, representing 19% of the total, the group 5 which is 64% of the total, the HVAC group (group nº 7) with a weight of 8% of the total. All the other groups present a 10% part of the total electrical consumption estimated. Group 7 corresponds to the HVAC, however the authors of the electrical balance of this ship only inform the power value referring to the air conditioning of the superstructure, and in the model developed for the equipment associated with air conditioning is also dimensioned ventilation values for different areas of the superstructure such as the galley. This may explain why the dimensioned value is higher than the actual value presented. Comparing the values of the AC unit, it is verified that the real consumption value is 186 kW, and, in the model, it is estimated a value of 166 kW, then resulting in an error of 10%. Group 8 presents a difference of 9 kW which it is not a considerable value comparing in a total. Group 10 is again a group with discrepant values. However, for this ship it is verified that the ship consumes more in this group than that estimated in the model. This occurs since as a RoPax ship perhaps it has the necessity of more equipment associated with the bridge. The Table 60 presents the continuous service machinery, and as conducted for the previous ship the main consumers are present on this table, observing that these are the same as in the previous ship.

Table 60 - Detailed Validation, 4-Stroke engines: Ship number 2, group 1

Group nº1	Real Values [kW]	Model Values [kW]	Error [%]
LO main Pump	35	35	0
SW Pump	40	43	+7
FW circulating Central	30	33	+9
FW HT pump	30	31	+2
Steering Gear Unit	18	22	+20
ER Ventilation	97	92	-5
TOTAL	308	306	-0.6

Analyzing the table, it is verified again lower errors in percentage for the bigger consumers of this group, being the steering gear the worst case. As the container ship, the higher consumption for the steering gear can be justified by the approximation used to calculate the torque as input parameter of the model. In the total set of small and large electrical consumers, it is concluded that the model provides a good prediction. The cargo space in this ship particularly has a big importance as described in 3.6.2.1 due to the vehicle's emissions. Although it was not noticed that it is one of the biggest consumers, it was decided to present and calculate the model error in this particular equipment for this type of ships.

Table 61 - Detailed Validation, 4-Stroke engines: Ship number 2, group 4

Group nº4	Real Values [kW]	Model Values [kW]	Error [%]
Cargo Space Ventilation	60	59	-2

Examining this table, it is possible to conclude that the cargo space ventilation estimation by the model has a low error. The major percentage of electrical consumption on board is associated with the maneuvering equipment and deck equipment. These include bow thrusters, or the lifts typically used by these ships. As can be seen in Table 62 the real and modelled power ratings are similar.

Table 62 - Detailed Validation, 4-Stroke engines: Ship number 2, group 5

Group nº5	Real Values [kW]	Model Values [kW]	Error [%]
Bow Thruster	900	905	+1
RoPax lift	11	12	+9
TOTAL	961	986	-3

The third ship is a RoPax with capacity to transport 700 persons including the crew members, and around 150 cars. This ship is equipped with two engines of 9,600 kW each one. As maneuvering equipment, this ship has two bow thrusters. Table 63 presents the individual nominal power groups comparison between the real values presented on the electrical balance of this ship and the modelled values.

Table 63 - Groups Power Consumption, 4-Stroke engines: Ship number 3

Group nº	Real Values [kW]	Model Values [kW]	Error [%]
1	287	283	-1
2	26	24	-6
3	252	212	-16
4	-	107	-
5	1,036	1,020	-3
6	19	17	-9
7	550	641	-17
8	30	22	-27
9	-	27	-
10	15	13	-13
11	90	104	+16
12	140	125	-11

In similarity with the previously RoPax analyzed the three main groups are the group 1 with 17% of the total electrical consumption, group 5 with 51% and group 7 representing 21% of the total. The group 7 presents a higher percentual error. However, in similarity to the explanation described in the previous ship presented, the ship's electrical load balance only presents values for the AC unit, thus the value of the model is oversized compared to the same group. Comparing the AC unit, it was verified the value of 550 kW in reality and 511 kW estimated by the model, then corresponding to an error of 7%. In this ship it is verified that the value associated with the equipment present in the ship bridge differs only 2kW from the real value presented. Following a detailed examination within the higher groups' consumption, the first group has the higher error percentage present on the fresh water low temperature pump with 16% of error. However, this percentual error corresponds to only 6 kW. Once again, the total error of this group is small.

Table 64 - Detailed Validation, 4-Stroke engines: Ship number 3, group 1

Group nº1	**Real Values [kW]**	**Model Values [kW]**	**Error [%]**
LO main Pump	35	35	0
SW Pump	45	44	-3
FW circulating Central Pump	37	31	-16
Steering Gear Unit	37	36	-3
ER Ventilation	96	96	0
TOTAL	287	283	-1

The group number 5 has exactly the same values that presented on the previous ship. For this reason, it is not present here.

Extending for a global analysis of each of the ships studied, it is possible to compare the operating condition. In such a way that a proper comparison can be carried out in all the operating conditions proposed in this thesis, it was necessary to verify the specific equipment which was not modelled in this thesis.

Table 65 - Ship operating conditions analysis for 4-Stroke engines

	Container Ship			**RoPax 1**			**RoPax 2**		
Ship Condition	Real [kW]	Estimated [kW]	Error [%]	Real [kW]	Estimated [kW]	Error [%]	Real [kW]	Estimated [kW]	Error [%]
1	905	920	+2	901	864	-4	1,237	1,364	+6
2	1,471	1,413	+4	2,635*	2,499	-7	3,095	2,864	-8
3	467	474	+2	784*	712	-9	1,237	1,133	-10
4	176	181	+2	442	461	+4	764	702	-8

1-Navigation; 2-Maneuvering; 3-Load and Unloading; 4-Port

*This specific ship electrical load balance presents values for stern ramps and pilot ramps, hydraulic system, stabilizers, passenger elevators. Thus, the total resulted in 167 kW for maneuvering condition and 84kW for loading/unloading condition. These consumers were deducted to the corresponding presented values of these two operating conditions.

In the container ship real electrical load balance it is performed 3 types of analysis for maneuvering condition depending on the number of refrigerated containers considered and the number of bow thrusters in functioning. The real value present corresponds to its maximum load, which corresponds to half of the maximum reefers' containers loaded on board and two bow thrusters in functioning. This is the condition that resembles the maneuver condition analyzed in this model. As expected, comparing all the ships studied for 4-Stroke engines, the operating condition which is verified the higher power is in maneuvering condition. This is expected since it is in this condition that operates the higher consumers of these ships, the bow thrusters. The worst case can be noted in loading and unloading condition of

RoPax number 2. In this ship exist some ship type specific consumers that were not modelled to compare in this model as specified for RoPax number 1. However, it can be perceived that the power model estimation for this ship is closer to the real electrical balance, the percentage error being inferior to 10%. This occurs since for this ship it does not include the same equipment that is counted in the electrical balance of ship 1. The stern ramp is the most distinctive equipment of this type of ship; thus, a small comparison was conducted. Having this vessel's ramp, a consumption of 50 kW and is mainly used in the third condition, the percentage error value decreases to 7%.

Comparing the 3 tables referring to the 3 ships (Table 54,Table 59, and Table 63), it can be assessed a common error to the 3 ships. This error focuses on those groups that are composed mostly by constants. These being the groups 8, 10 and 12. Although it is also conclusive that these errors and these groups do not have a large impact in the final evaluation of the electric balance. Despite these small differences found, it can be seen in Table 65, that most conditions possess errors of lower than 10%, for this reason it is considered a good result for 4-Stroke engines.

5. Conclusions and Further Work

5.1 Conclusions

This thesis proposes a numerical model developed based on the conceptual ship design phase parameters in order to estimate the electrical demand of a ship in different operating conditions such as navigation, maneuvering, loading and unloading, and in port. Through this model, it is possible to estimate not only the power associated with the generators in preliminary phases of the project which has associated cost advantages but also to have an estimation of the various conditions for fuel consumption assessments which may provide advantages such as cost and emissions evaluations. This numerical model was implemented in Excel with the Visual Basic for Applications (VBA) auxiliary tool.

The whole research began by collecting and defining those systems and equipment that are essential to the proper functioning of the main engine, those that ensure comfort and conditions in the accommodations, that improve better maneuverability of the ship and those that are part of the deck support. Although all models are an approximation, it was tried to ensure that no system or essential component in the ship's equipment was excluded at this stage of listing.

After the definition of all systems, correlations were found with basic parameters of the ship's conceptual design. To achieve this, a bridge was established between theory and practice, therefore, physical principles were followed whenever possible and when not, data from manufacturers were collected. Also, it was necessary to follow some assumptions to overcome the lack of detail in this ship design phase. Some of these assumptions are related to the physical characteristics associated with each machinery such as the manometric height and system pressure. On the other hand, the most complex systems required greater consideration in the assumptions made, such as the air conditioning system where a specific model for a ship was developed and then it was deducted coefficients to be applied in a generalized form in the electrical load balance numerical model. Another case was the model developed for the superstructure compartment areas estimation in order to have the power consumption of the superstructure interior lighting.

The final model developed consists of 67 input basic parameters, classified into five groups: ship dimensions, main engine, engine room dimensions, superstructure dimensions, and deck equipment characteristics. This results in 82 output data in the form of nominal powers. These nominal power values are grouped into 12 groups according to machine function and then analyzed in 4 operating conditions of the vessel.

After the development of the model the next step was the validation of the results. Due to the difficulty in obtaining reference data from known existing ships, the validation was carried out in two stages. The first validation was more generic, and the principal purpose was to compare the total power of generators installed on board with the values obtained from the parametric model. For this purpose, were selected two ships with 2-Stroke engine propulsion system (a tanker and a bulk carrier) and three ships with 4-Stroke engine propulsion system (a tanker, a multipurpose vessel and RoPax). In these comparisons the differences found were less than 10%.

The second validation was done using reference values from five ships with a known electrical load balance calculation. In this process, not only can be compared partial values from groups of consumers but also values from different operating conditions. From the five ships analyzed, two (tankers) have 2-Stroke main engines and three (a container carrier and two RoPax) have 4-Stroke main engines. In these comparisons the differences found were less than 10%.

5.2 Paths for Future Work

Over the course of the study, several aspects were noticed that could improve the results of this research, if the research would be repeated or a similar study would be carried out in the future. From the validations, it is possible to affirm that within the equipment modeled and proposed, the numerical model can achieve a satisfactory final estimate. However, there were some common aspects observed in all validations. The largest error remains in those groups that are considered constant, which are mainly group 8 associated with the ship's workshop, group 10 associated with navigation bridge equipment, and group 12 with equipment associated with the galley. Despite the attempt to approximate to the reality, this type of equipment was estimated considering only the minimum required in each area. This type of equipment is designated and estimated by the designer in a further phase of the ship design in order to have the exact idea of the equipment to be installed on board and the respective number necessary. This type of information depends on the ship type. One of the suggested improvements would be a better investigation of these groups of constants, performing a deeper investigation and even specifying for each type of ship.

It was also mentioned that no model was developed about heating required on board, boilers and their auxiliaries, and due to this failure, it was found that they would have a considerable weight in the electrical balance in specifically for tankers carrying oil or asphalt. Therefore, it is also suggested as future work that a thermal energy analysis be conducted on board. With this analysis it will then be possible to estimate the necessary thermal load on a ship and the respective power calculation associated with the heat generation equipment. Finally, another interesting point to be developed focuses on equipment that is driven by hydraulic systems. Examples of these are hatches, ramps, valve actuation and propeller pitch maneuvering. Although they are specific to each ship's project, it would be interesting to be able to size this equipment and their associated power.

In a broader perspective instead of improvement, this model could be extended to more types of ships as tugs or dredgers and even to different propulsion configurations as diesel-electric.

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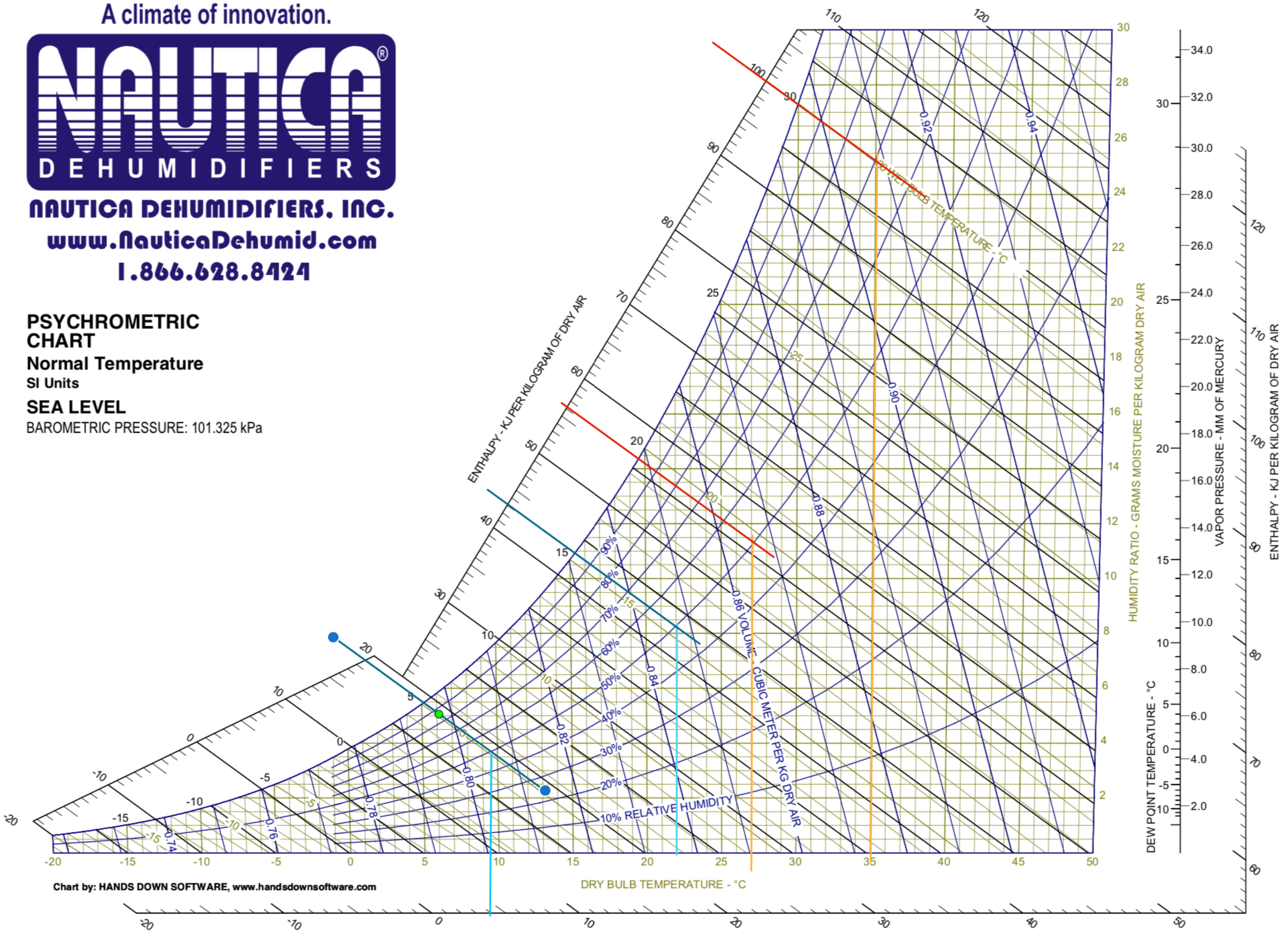
Annex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VOLUME - CUBIC METER PER KG DRY AIR
10% RELATIVE HUMIDITY
20%
30%
40%
50%
60%
70%
80%
90%
0.74
0.76
0.78
0.80
0.82
0.84
0.86
0.88
0.90
0.92
0.94
DRY BULB TEMPERATURE - °C
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45
50
HUMIDITY RATIO - GRAMS MOISTURE PER KILOGRAM DRY AIR
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
DEW POINT TEMPERATURE - °C
VAPOR PRESSURE - MM OF MERCURY
ENTHALPY - KJ PER KILOGRAM OF DRY AIR
Chart by: HANDS DOWN SOFTWARE, www.handsdownsoftware.com

Annex B - Example of Validation

					Seagoing			Maneuvering			Loading and Unloading			At Port		
Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
1.Engine Room(Continuous Service)	1	Fuel Oil Purifier Feed Pump	0.35	2	1	1	0.35	1	1	0.35	1	1	0.35	1	1	0.35
	2	Fuel Oil Circulating Pump	2.81	2	1	1	2.81	1	1	2.81	1	1	2.81	1	1	2.81
	3	Fuel Oil Supply Pump	2.94	2	1	1	2.94	1	1	2.94	0	0	0.00	0	0	0.00
	4	Fuel Oil Purifier	4.11	2	1	1	4.11	1	1	4.11	1	1	4.11	1	1	4.11
	5	Diesel Oil Purifier Feed Pump	0.35	1	0	0	0.00	1	1	0.35	1	1	0.35	1	1	0.35
	6	Diesel Oil Purifier	4.11	1	0	0	0.00	1	1	4.11	1	1	4.11	1	1	4.11
	7	System Lube Oil Pump	72.35	2	1	1	72.35	1	1	72.35	0	0	0.00	0	0	0.00
	8	Lube Oil Purifier Feed Pump	0.51	1	1	1	0.51	1	1	0.51	1	1	0.51	1	1	0.51
	9	Lube Oil Purifier	4.61	1	1	1	4.61	1	1	4.61	1	1	4.61	1	1	4.61
	10	SW Circulating Pump	61.03	1	1	1	61.03	1	1	61.03	1	1	61.03	1	1	61.03
	11	FreshWater Circulating Central Pump	19.17	2	1	1	19.17	1	1	19.17	0	0	0.00	0	0	0.00
	12	FreshWater Circulating Jacket Pump	17.34	2	1	1	17.34	1	1	17.34	0	0	0.00	0	0	0.00
	13	Fresh Water Generator	18.25	2	1	1	18.25	1	0	0.00	0	0	0.00	0	0	0.00
	14	Scrubber	337.5	1	1	1	337.50	1	1	337.50	0	0	0.00	0	0	0.00
	15	Steering Gear Unit	19.33	2	2	0.5	19.33	2	0.5	19.33	0	0	0.00	0	0	0.00
	16	Sewage Treatment Plant	2.84	1	1	1	2.84	1	1	2.84	1	1	2.84	1	1	2.84
	17	ER Ventilation	56.02	1	1	1	56.02	1	1	56.02	1	0.6	33.61	1	0.6	33.61
Kl [Concurrency Factor]							1			1			1			1
TOTAL POWER TO CONSIDER [kW]							619.17			605.38			114.35			114.35
Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
2.Engine Room (Intermintent Service)	18	Fuel Oil Transfer Pump	2.06	2	1	0.23	0.47	1	0.23	0.47	0	0.23	0.00	0	0.23	0.00
	19	Diesel Oil Transfer Pump	2.06	1	1	0.15	0.30	1	0.15	0.30	1	0.15	0.30	1	0.15	0.30
	20	Main Air Compressor	8.98	2	1	0.42	3.74	1	0.08	0.75	1	0.17	1.50	1	0.17	1.50
Kl [Concurrency Factor]							0.50			0.6			0.5			0.5
TOTAL POWER TO CONSIDER [kW]							2.26			0.91			0.90			0.90
Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
3.Engine Room (Miscelaniuos)	21	Bilge Pump	26.84	2	0	0	0.00	1	1	26.84	1	1	26.84	1	1	26.84
	22	Ballast Pump	38.60	2	0	0	0.00	1	1	38.60	1	1	38.60	1	1	38.60
	23	Ballast Water Treatment System	6.41	1	0	0	0.00	1	1	6.41	1	1	6.41	1	1	6.41
	24	ER Stripping Pump	0.84	2	1	1	0.84	2	1	1.67	2	1	1.67	2	1	1.67
	25	Oily Water Separator	3.00	1	1	1	3.00	1	0	0.00	1	0	0.00	1	0	0.00
	26	Sludge Pump	0.44	1	0	0	0.00	0	0	0.00	1	0.24	0.11	1	0.24	0.11
	27	Main Fire Pump	37.14	2	0	0	0.00	0	0	0.00	1	0	0.00	1	0	0.00
	28	Emergence Fire pump	27.85	1	0	0	0.00	0	0	0.00	1	0	0.00	1	0	0.00
	29	Fresh Water Hydrophore Water pumps	1.41	2	1	1	1.41	1	1	1.41	1	1	1.41	1	1	1.41
	30	Hydrophore Heater	15	1	1	1	15.00	1	1	15.00	1	1	15.00	1	1	15.00
	31	Sewage Pump	4.2	1	1	0.21	0.87	0	0	0.00	1	0	0.00	1	0	0.00
Kl [Concurrency Factor]							0.40			0.4			0.4			0.4
TOTAL POWER TO CONSIDER [kW]							8.45			35.97			36.01			36.01
Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
4.Deck (Cargo Refrigeration)	32	Reefer Containers	743.04	1	1	0.6	445.82	1	0.25	185.76	0	0	0.00	0	0	0.00
	33	Cargo Ventilation	50.49	1	1	0.5	25.24	1	1	50.49	0	0	0.00	0	0	0.00
	34	Inert Gas Fan	0.00	2	1	0.2	0.00	2	1	0.00	2	1	0.00	2	1	0.00
	35	Inert Gas Generator	0.00	1	1	0.05	0.00	1	0.4	0.00	1	1	0.00	1	1	0.00
Kl [Concurrency Factor]							1.00			1			1			1
TOTAL POWER TO CONSIDER [kW]							471.07			236.25			0.00			0.00
Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
5.Deck (Equipment)	36	Windlass	352.24	2	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00
	37	Winches	45.38	4	0	0	0.00	4	0.08	15.13	4	0.025	4.54	4	0.025	4.54
	38	Hatch Cover	0.00	8	0	0	0.00	8	0.00	0.00	8	0.5	0.00	8	0.5	0.00
	39	Cargo Cranes	160	2	0	0	0.00	0	0	0.00	2	1.00	320.00	0.00	1.00	0.00
	40	Cargo Pumps	0	0	0	0	0.00	0	0	0.00	0	0.60	0.00	0	0.60	0.00
	41	RoPax Ramp	0	0	0	0	0.00	0	0	0.00	0	1.00	0.00	0.00	1.00	0.00
	42	RoPax Lift	0.0	1	0	0	0.00	0	0	0.00	1	1.00	0.00	0	1.00	0.00
	43	Bow Thruster	420	2	0	0	0.00	2	1.00	839.10	0	0	0.00	0	0	0.00
	44	Provision Crane	5.31	1	0	0	0.00	0	0	0.00	1	0.17	0.89	1	0.17	0.89
Kl [Concurrency Factor]							0.40			0.6			1			1
TOTAL POWER TO CONSIDER [kW]							0			512.53			325.42			5.42

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
6.Superstructure (Provision Refrigeration)	45	Provision Plant System	6.694	1	1	1	6.69	1	1	6.69	1	1	6.69	1	1	6.69
Kl [Concurrency Factor]							1.00			1			1			1
TOTAL POWER TO CONSIDER [kW]							6.69			6.69			6.69			6.69

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
7.Superstructure (HVAC)	46	Air Conditioning Superstructure	52.07	1	1	0.9	46.86	1	0.9	46.86	1	0.9	46.86	1	0.5	26.03
	47	Superstructure Exhaust	5.66	1	1	1	5.66	1	1	5.66	1	1	5.66	1	1	5.66
	48	Galley Ventilation Fan /Exhaust	3.37	1	1	1	3.37	1	1	3.37	1	1	3.37	1	1	3.37
	49	WC Extra	0.07	1	1	1	0.07	1	1	0.07	1	1	0.07	1	1	0.07
	50	HVAC Exhaust	0.82	1	1	1	0.82	1	1	0.82	1	1	0.82	1	1	0.82
	51	Deck Stores and Workshop Exhaust	0.81	1	1	1	0.81	1	1	0.81	1	1	0.81	1	1	0.81
Kl [Concurrency Factor]							1.00			1			1			0.7
TOTAL POWER TO CONSIDER [kW]							57.60			57.60			57.60			25.74

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
8.Superstructure (Workshop)	52	Double Grinder	1	1	1	0.03	0.03	0	0	0.00	1	0.08	0.08	1	0.08	0.08
	53	Drilling Machine	1.5	1	1	0.03	0.04	0	0	0.00	1	0.08	0.11	1	0.08	0.11
	54	Lathe	6	1	1	0.03	0.15	0	0	0.00	1	0.08	0.45	1	0.08	0.45
	55	Welding Transformer	13.5	1	1	0.03	0.34	0	0	0.00	1	0.08	1.01	1	0.08	1.01
Kl [Concurrency Factor]							0.40			0.4			0.4			0.4
TOTAL POWER TO CONSIDER [kW]							0.22			0.00			0.66			0.66

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
9.Superstructure (Laundry)	56	Dryer Machine	5.76	2	2	0.5	5.76	0	0	0.00	2	0.5	5.76	2	0.5	5.76
	57	Washing Machine	7.25	2	2	0.5	7.25	0	0	0.00	2	0.5	7.25	2	0.5	7.25
Kl [Concurrency Factor]							0.50			0.5			0.5			0.5
TOTAL POWER TO CONSIDER [kW]							6.51			0.00			6.51			6.51

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
10.Superstructure(Bridge Navigation Equipment)		**Navigation Equipment**														
	58	Girocompass	0.38	1	1	1.0	0.38	1	1.0	0.38	1	0.6	0.22	1	0.6	0.22
	59	ECDIS	0.16	1	1	1.0	0.16	1	1.0	0.16	1	0.6	0.09	1	0.6	0.09
	60	Speed Equipment	0.46	1	1	1.0	0.46	1	1.0	0.46	1	0.6	0.27	1	0.6	0.27
	61	Echo Sounder	0.24	1	1	1.0	0.24	1	1.0	0.24	1	0.6	0.14	1	0.6	0.14
	62	Radar	2.37	1	1	1.0	2.37	1	1.0	2.37	1	0.6	1.38	1	0.6	1.38
	63	Recorder	0.11	1	1	1.0	0.11	1	1.0	0.11	1	0.6	0.06	1	0.6	0.06
	64	BNAWS (Bridge Navigational Watch Alarm System)	0.08	1	1	1.0	0.08	1	1.0	0.08	1	1.0	0.08	1	1.0	0.08
	65	Satelite Nav.Equipm	0.34	1	1	1.0	0.34	1	1.0	0.34	1	0.6	0.20	1	0.6	0.20
		Comunication Equipment														
	66	Navtex Receiver	0.14	1	1	1	0.14	1	1	0.14	1	1	0.14	1	1	0.14
	67	INMARSAT communication	0.97	1	1	1	0.97	1	1	0.97	1	1	0.97	1	1	0.97
	68	VHF	0.28	1	1	1	0.28	1	1	0.28	1	1	0.28	1	1	0.28
	69	Internal Telephone	0.35	1	1	1	0.35	1	1	0.35	1	1	0.35	1	1	0.35
		Others Equipments														
	70	Batteries Chargers	1.00	1	1	1	1.00	1	1	1.00	1	1	1.00	1	1	1.00
	71	Clear Viewr Sreen	0.63	1	1	0.2	0.11	1	0.2	0.11	1	0.2	0.11	1	0.2	0.11
	72	Horn/Whistle	5.53	1	1	0.02	0.12	1	0.02	0.12	1	0.02	0.12	1	0.02	0.12
Kl [Concurrency Factor]							0.80			0.8			0.8			0.8
TOTAL POWER TO CONSIDER [kW]							5.67			5.67			4.32			4.32

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
11.Superstructure(Illumination)	73	Superstructure Illumination	9.62	1	1	1	9.62	1	1	9.62	1	1	9.62	1	1	9.62
	74	Engine Room Illumination	4.28	1	1	1	4.28	1	1	4.28	1	1	4.28	1	1	4.28
	75	Navigation Light & Exterior Light	11.06	1	1	1	11.06	1	1	11.06	1	1	11.06	1	0.5	5.53
Kl [Concurrency Factor]							0.70			0.7			0.7			0.5
TOTAL POWER TO CONSIDER [kW]							17.47			17.47			17.46869446			9.7138889

Group	Item Nr.	Description	Nominal Power [kW]	Nr. Installed	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]	Nr. Service	Kl [Load Factor]	ABSORBED POWER [kW]
12.Superstructure(Galley)	76	Dish Wash Machine	5.225	1	1	0.5	2.61	1	0.5	2.61	1	0.5	2.61	1	0.5	2.61
	77	Electric Range	9.7	1	1	0.5	4.85	1	0.5	4.85	1	0.5	4.85	1	0.5	4.85
	78	Garbage Grinder	1.025	1	1	0.5	0.51	1	0.5	0.51	1	0.5	0.51	1	0.5	0.51
	79	Hot Plate	1.4	1	1	1	1.40	1	1	1.40	1	1	1.40	1	1	1.40
	80	Refrigerator	0.3325	1	1	0.5	0.17	1	0.5	0.17	1	0.5	0.17	1	0.5	0.17
	81	Microwaves	1.87625	1	1	0.5	0.94	1	0.5	0.94	1	0.5	0.94	1	0.5	0.94
	82	Electric Frying	4.87	1	1	0.5	2.44	1	0.5	2.44	1	0.5	2.44	1	0.5	2.44
Kl [Concurrency Factor]							0.50			0.6			0.5			0.5
TOTAL POWER TO CONSIDER [kW]							6.46			7.75			6.46			6.46
TOTAL POWER TO CONSIDER FOR EACH CONDITION							1202			1487			577			217