Assessment of Ship Electric Power Consumption

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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

1. Introduction

The concept design stage of the ship design process represents 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 onboard. 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 for the economical evaluation of the ship operation. The fuel consumption onboard 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.

2. Model Development

The process of electrical load analysis begins with the information collected related to the electric consumption of each equipment installed and necessary onboard for the proper functioning of the vessel as her operation. In order to facilitate the delineation of the ship's loads, it was decided to divide the load consumers into distinct groups. In this work, the division of the electrical groups was based on the Brazilian standard NBR 7567:1982. However, it was also adopted a division by areas according to the location on the ship: Engine room, deck, and superstructure. The adopted division enable the omission of any group in case of the user's desire. Table 1 represents the electrical load groups division adopted.

Table 1 - 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 Refrigeration	6	Provision Refrigeration
2	Intermittent Service	5	Deck Equipment	7	HVAC
3	Miscellaneous			8	Workshop
				9	Laundry
				10	Bridge Equipment
				11	Illumination
				12	Galley

Organizing all auxiliary equipment, it is possible to verify that can be summarized in pumps, compressors and fans. Below it is presented the corresponded power equations used for each of these machineries during the development of this research.

It is denominated as pumps, all hydraulic machines with the capacity of incompressible fluid transfer. This means that the pump has the function of providing to the fluid a determined energy quantity (by a drive motor) which enables it to overcome hydraulic resistances with a given height.

$$P_{pump} = \frac{\dot{Q}_{pump} \times H \times \rho \times g}{\eta_{elect} \times \eta_{mec}} \quad (1)$$

For mechanical efficiency, two types were distinguished, for centrifugal pumps is considered a mechanical efficiency between 0.7 and 0.85. For screw or gear pumps this efficiency decreases for 0.65-0.70.

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. The compressor cycle was considered with no heat transfer and with a perfect gas, this means that was considered an ideal cycle which indicates that the compression is isentropic then the discharge temperature can be calculated from pressure ratio and the suction temperature using the isentropic relationship. The compressor power equation used is present in (2).

$$P_{compressor} = \frac{p_e \times Q}{3{,}600 \times R} \times C_p \times \left[\frac{\left(\frac{ps}{pe}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta c} \right] \quad (2)$$

Associated to this formula, there is a compressor efficiency. This efficiency as for pumps, varies with type, size and performance. In this research it was considered for centrifugal compressors that its efficiency varies between 0.70 and 0.85 For rotary screw type, this efficiency is founded between 0.65 and 0.75. For high-speed reciprocating speed compressors have efficiencies between 0.72 and 0.85. For low-speed this efficiency increase for 0.75-0.90.

Fans are centrifugal machines in which the flow enters axially and leaves tangentially. To provide the forced ventilation is necessary that it be powered by energy. To calculate the power required for fans is followed the numerical expression (3).

$$P_{fan} = \frac{\dot{v} \times \Delta p_{ref}}{\eta_v} \quad (3)$$

Therefore, first of all, data was collected regarding the auxiliary systems for main engine. The collected data from manufacturer project guides were essentially the flow rate and the pressure head suggested for each pump in each system. The pressure provided in bar can be easily converted to head in meters. The engine 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 consists of 58 samples between 1,200 to 19,200 kW, from (MAK, 2020; MAN, 2020b).

2.1. Engine Room: Continuous Service

2.1.1.Fuel System

The fuel oil system consists in to supply clean fuel with correct pressure and viscosity uninterruptedly. Typical fuels are light fuel oil (LFO), intermediate fuel oil (IFO), heavy fuel oil (HFO), or a combination of two of them. IFO and diesel oil are the fuel considered in this research for 2-Stroke engines and for 4-Stroke engines as well.

The first pumps analyzed of this system are the supply pumps. These pumps are used to guarantee the fuel oil continuous flow at a correct pressure supplied for main engines. Its suction is from the service tanks and routed for the two circulating pumps located forward. Afterward be collected the data regarding engine supply pumps capacity and pressure was estimated the power for each engine sample using the equation (1). In the case of the fuel system, the basic design parameter assumed to relates the corresponded consumption power was the main engine hourly fuel consumption (HFOC). This parameter is easily calculated with the main engine (ME) power input and the corresponded ME specific fuel oil consumption (SFOC). The general equations obtained are following presented. For 2-Stroke fuel oil supply pump consumption, the general equation implemented is (4).

$$P_{FOsupplypump} = 6E-07 \times HFOC + 0.0866 \quad (4)$$

For 4-Stroke engines, the equation is (5).

$$P_{FOsupplypump} = 3E - 06 \times HFOC - 0.061 \quad (5)$$

In case of the vessel main engine uses only diesel oil or when changed the fuel to enter in port, the same equations are considered since there are the same pumps working.

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 it is directed for engine-driven fuel pumps. The same principle applied for supply pumps was applied for circulating pumps, resulting in two equations for 2-Stroke and 4-Stroke engines. For 2-Stroke engines:

$$P_{FOcirculationpump} = 1E - 06 \times HFOC + 0.427 \quad (6)$$

For 4-Stroke engines:

$$P_{FOcirculationpump} = 3E - 06 \times HFOC - 0.184 \quad (7)$$

The same equations were considered for DO operation as well.

The main function of the purifier is to separate the water and particles majority from the fuel that passes through it. The engine manufacturers provide the purifier capacity. With this parameter, another study was conducted. The purifiers are driven by an auxiliary electric motor, for this reason, it was collected data from the typical electrical consumptions for (Mitsubishi, 2020) purifiers according to the capacity required. The corresponded equation to be applied in each engine sample basing on the engine purifier capacity given in engine project guides is equation (8).

$$P_{Purifiermotor} = 0.0011 \times \dot{Q}_{Oil} + 3.0257 \quad (8)$$

Then, it was possible to proceed with the obtaining process of the prediction equation to be used in the final model. With all purifier motor consumption data calculated, and placing in function of the variable HFOC, the resulting equations for 2-Stroke engines is shown in (9).

$$P_{FOPurifier} = 2E - 06 \times HFOC + 2.9358 \quad (9)$$

In turn of 4-Stroke engines, the equation is (10).

$$P_{FOPurifier} = 1E - 06 \times HFOC + 3.1114 \quad (10)$$

2.1.2.Lubrication Oil 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. The lubrication oil (LO) is collected in a sump tank below the main engine. 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 before enters in the sump tank. To estimate the power associated with these pumps, consideration was given to the capacity mentioned in manufacturers' project guide. In addition to the capacity, it is necessary to assume the density. The density is an oil property that has a variation with the viscosity grade. The lubrication oil of the main lubrication oil system has an SAE viscosity grade of 30, which corresponds to 0.89 kg/m3 at 15ºC. With these assumptions and after the utilization of the equation (1), it was obtained for 2-Stroke engines the equation (11).

$$P_{LOmainpump} = 9.2414 \times V_d + 20.656 \quad (11)$$

It was verified a big variance in the flow rate capacity parameter in 4-Stroke engines with cylinder number lower than 12 and the remaining. Then it was opted to use two different equations for 4-Stroke engines with cylinders number lower than 12.

$$P_{LOmainpump} = 59.318 \times V_d + 45.823 \quad (12)$$

And for cylinders number higher than 12.

$$P_{LOmainpump} = 98.718 \times V_d - 16.537 \quad (13)$$

The main engine oil in its passage can be contaminated by small particles, combustion products, or water. For purifiers the result for 2-Stroke engines is shown in (14).

$$P_{LOPurifier} = 0.4315 \times V_d + 3.4796 \quad (14)$$

For 4-Stroke engines is shown in (15).

$$P_{LOPurifier} = 2.2101 \times V_d + 3.4383 \quad (15)$$

2.1.3.Cooling System

The cylinder jacket and cylinder head water circulation are performed by freshwater. The thermal load of the engine is transmitted later and externally through an exchange for seawater. It is denominated as high-temperature (HT) since is an internal circuit of the engine and as expected the outlet water temperature is elevated (around 80ºC). The parameter selected was the total heat rejected through water, which relates to the lower heating value of the fuel (constant value from the used fuel) and its specific fuel oil consumption, which is a parameter from the basic design.

$$HCM = LHV \times (SFOC - 3600)[1 - ff] \quad (16)$$

Then, with the same principle adopted for the others pumps, it was obtained for 2-Stroke engines HT pump the next equation.

$$P_{HTpump} = 8E - 07 \times HCM + 1.734 \quad (17)$$

For 4-Stroke engines HT pump is shown in (18).

$$P_{HTpump} = 3E - 06 \times HCM + 1.679 \quad (18)$$

In turn for LT cooling water pump, the equation obtained for 2-Stroke engines is shown in (19).

$$P_{LTpump} = 2E - 06 \times HCM + 2.3071 \quad (19)$$

And the equation for 4-Stroke engines is present in (20).

$$P_{LTpump} = 2E - 06 \times HCM + 2.0643 \quad (20)$$

Nowadays all ships are equipped with a freshwater generator (FWG). FWG is a device that converts seawater into freshwater. The process is simple: seawater is evaporated using a heat source, separating the water and the salt or small particles as sediments. Based on the daily consumption, the FWG manufacturers present the power consumption prediction. It was collected data from two manufacturers (Osmomar, 2020; Farad, 2020) and correlated with the peak daily consumption. The resulting equation is following present.

$$P_{FWG} = 0.5373 \times \dot{V_S} + 1.1283 \tag{21}$$

2.1.4.Ventilation

The engine room is a space which requires a large amount of air as result of its large size, the air consumed by machinery. Thus, for the total airflow estimation, it was followed the standard ISO 8861:1998 and the classification societies. The standard states that total airflow should be considered as the highest value between the following two conditions:

1) $Q = q_c + q_h$
2) $Q = 1.5 \times q_c$

Therewith, the total airflow considered for power estimation is the sum of the highest value of the two conditions transcribed before with the airflow provided by air changes per hour in the space volume required equal to 30 ren /h. Then it was used the equation (3) for power estimation.

2.1.5.Scrubber

The possibility of a scrubber installation onboard in the near future is higher compared to the utilization of other alternative fuels. Although, there is an associated electrical consumption that should be accounted for electrical balance. There are two types that can be considered according to circuit type: open-loop (OL) and closed-loop (CL). (ABS, 2018) presents the following table for the power estimation of the scrubber.

Table 2 - 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	-

2.1.6.Steering Gear unit

The steering gear provides the rudder movement in the response of the bridge control under normal operating conditions the pumps are the equipment which allows the movement of the total unit, for that it is necessary a power supply in order to drive theses pumps. The classification societies specify 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. In addition, with the maximum torque input on model the power required can be estimated.

$$P_{Steeringgear} = \frac{M_{max} \times \omega}{\eta_{elect} \times \eta_{mec}} \tag{22}$$

2.2. Engine Room: Intermittent Service

2.2.1.Fuel System

The fuel oil transfer pump, as the other fuel oil pumps, normally is screw-type due to the high viscosity. After the fuel oil pumped 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. According to (DNV GL, 2017), the settling tanks should be capable to store fuel for 24 hours of operation in maximum fuel consumption. To obtain the flow, it was then assumed between 4 and 6 hours to transfer fuel from any bunker to settling tank, this information was based on experience. Afterward the capacity estimated, the procedure to obtain the relation between the power estimation in function of a basic parameter performed was the same as the one carried out so far. For 2-Stroke engines, the resulting equation is (23).

$$P_{FOtransferpump} = 1E - 06 \times HFOC + 0.877 \tag{23}$$

The resulting equation for 4-Stroke engines is (24).

$$P_{FOtransferpump} = 2E - 06 \times HFOC + 0.057 \tag{24}$$

Also, it is considered DO transfer pumps in which its power consumption estimation uses these same equations presented.

2.2.2.Starting air

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 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. In this way it is possible to estimate the receiver capacity based on the thermodynamic equation, thus obtaining the equation (25).

$$\dot{Q}_{compressor} = \frac{30 \times V_d \times n}{2} \tag{25}$$

Where n is =12 or 6 depending on the engine type. 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 (2)).

2.3. Engine Room: Miscellaneous

2.3.1.Fire System

Following (IMO, 1974) in order to estimate the power associated with main fire water pumps, the minimum pressure to be maintained at the hydrants was checked for different ship types. Having in count these pressure values and based on experience onboard, it was adopted for constant pressure value in this model equal to 9 bar. Thus, the required fire pumps shall be capable of delivering for fire-fighting purposes the following amount of water.

$$\dot{Q}_{Fire} \geq \frac{4}{3} \times \dot{Q}_{Bilge} \tag{26}$$

Afterward the capacity estimation and pressure assumption, it is possible to estimate the power requirement by equation (1).

2.3.2.Potable Water system

The potable water system onboard ships is also regulated by the international standard ISO 15748-2:2002. For hydrophore feed pumps it was followed the referring standard. 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. The minimum values guide for potable water consumption are presented below in liters per second.

Table 3 - 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 WC			
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 WC			
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 onboard has its own W.C. 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. One curve corresponds for passenger ships and the other for cargo ships. From these curves result two regression equations that is presented following. For passenger ships, the equation to be used is (27).

$$\dot{V}_S = 4E-08 \times \sum \dot{V}_R^{\,3} - 1E-05 \times \sum \dot{V}_R^{\,2} + 0.0973 \times \sum \dot{V}_R + 0.7962 \tag{27}$$

It is represented for cargo ships in equation (28).

$$\dot{V}_S = -3E-11 \times \sum \dot{V}_R^{\,4} + 7E-08 \times \sum \dot{V}_R^{\,3} + 5E-05 \times \sum \dot{V}_R^{\,2} + 0.0343 \times \sum \dot{V}_R + 0.593 \tag{28}$$

For heater power determination connected with the hydrophore, it was following the table present in the same standard which relates the heater power with number of people on board.

2.3.3.Sludge system

Sludge is the denomination for residual waste oil products generated from the equipment operation onboard, as for example from the fuel or lubricating purifiers, waste lubricating oils or hydraulic or leakages. (IMO, 1978) establish that every ship with 400 of GT and above should be provided with tanks with adequate capacity to store sludge. In turn the sludge tank capacity was estimated based on 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 (29).

$$V_{Sludgetank} = k_{IFO} \times DFOC \times t_{voyage} \tag{29}$$

All residues stored in a sludge tank should be directly discharged ashore via a pump. Assuming 4 hours to drain the full tank, the capacity of the pump is easily obtained. The pressure was considered constant equals 4 bar. It is then possible to know the power consumption of these pumps, using the equation (1). Also, the Oily Water Separator (OWS) is a piece of shipboard equipment that requires attention since, on the one hand, it is mandatory for almost all ships to have, and on the other hand, its design must be followed under the rules, mainly the MARPOL convention. In turn the maximum capacity of the OWS equipment is regulated by the classification societies in function of the ship gross tonnage. It was collected the power consumption for OWS according to the maximum capacity established by classification societies from a manufacturer.

2.3.4.Sewage System

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. As it is possible to note the sewage is directly associated with the people onboard. It is expected that if the POB increases the sewage capacity should be increased as well. In order to estimate the wastewater, it was verified the international standard ISO 15749-1:2004. From this standard it is established that for passenger ships it is wasted 185 l/person/day and for cargo ships 135 l/person/day. In addition to these values, it was added 10% for possible losses of the system. Then, the sewage tank volume estimation follows the equation (30).

$$V_{SewageTank} = 0.001 \times n_{Sewage} \times N_{Crew} \times t_{Voyage} \tag{30}$$

For passenger ships, the number of crew onboard (Ncrew), was considered a 50% margin added in consideration to the passenger toilets. It is then assumed that to drain the full tank it is necessary 3 hours. With this assumption, it is achievable the sewage pump capacity, dividing the volume of the sewage tank by the estimated hours to drain the tank. The assumed pressure was 5 bar.

For the Sewage treatment plant (STP) it is considered the numbers previously referred and performed a linear regression with power values provided by HiSeaMarine manufacturer. Resulting then in equation (31).

$$P_{STP} = 0.0003 \times \dot{Q}_{AverageWastewater} + 1.9975 \tag{31}$$

2.3.5.Bilge System

The bilge system is available to clear oil/water leakage from machinery space or in another space for example from some wash in the holds of a merchant's vessel. For this to succeed, pumps are needed. 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 firstly calculated the pipe diameter. For cargo ships and passenger ships, it was considered the equation corresponding to all ship space bilge (32).

$$d_{Bilgepipe} = 1.68 \times \sqrt{L \times (B + D)} + 25 \tag{32}$$

For tanker ships, it was considered the equation (33), since the bilge pumps are used to drain only machinery space, or in this case considered only the engine room.

$$d_{Bilgepipe} = 2.15 \times \sqrt{L_{ER} \times (B + D)} + 25 \tag{33}$$

The pump minimum capacity of deliver is calculated using the next equation provided in (DNV GL, 2017) as well.

$$\dot{Q}_{Bilge} = \frac{5.75 \times d_{Bilgepipe}{}^2}{10^3} \tag{34}$$

The pressure recommended, present in the same rule is 4 bar. With these parameters it is possible to use the equation (1) to obtain the respective associated electrical consumption.

2.3.6.Ballast System

The ballast pump capacity is calculated based on a volume of water that has to be discharged in a given time. As the ballast tanks volume is an already known value of the conceptual project, it is easily assumed a time to discharge and then calculated the pump capacity. The pressure for this system was assumed as 4 bar.

To estimate the power required for the Ballast Water Treatment System (BWTS), it was verified various models from a variety of manufacturers. All the different treatments, processes and the lowest energy consumptions were then considered and collected all corresponded data. Below it is possible to see the resulting equation from the scatter plot with all collected data.

$$P_{BWTS} = 0.0717 \times \dot{Q}_{Ballast}{}^{0.8789} \tag{35}$$

2.4. Deck

2.4.1.Cargo Refrigeration and Ventilation

Refrigerated containers are a large part of the energy consumption on board of a container ship since the cargo must be refrigerated 24 hours a day during all navigation time, in order 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 an estimation through a percentage concerning the total capacity of containers on board. In (Krefft, 2015), it is performed an estimation in terms of the percentage of reefers containers on board of the container's ships. This estimation was conducted based on several ships and analyzing the refers percentage of each one. For this research an average of this table was considered, corresponding to 12%. This means that 12% of container ship capacity in study will be reefers. In (GL, 2016) is presented a guide for the reefer's containers onboard ships. After the contemplation exposed before, it was chosen to consider that all reefers to be transported are FEU to simplify the calculation and in other hand their consumption as FEU will be higher, consequently, this estimation will be always over-dimensioned. From the respective table presented on (GL, 2016), it was considered cargo within the recommended limits of fruit/chilled cargo with the consumption higher value, which results in a value of 12 kW for each FEU reefer loaded.

Beyond the engine room ventilation, the cargo space shall be properly ventilated. The ventilation power consumption model estimation was divided for Cargo ships and for RoPax ships In (GL, 2016) is presented data about the required ventilation, and due to the simplicity of the method, it was opted to use these values. 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.

2.4.2.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. 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 (36).

$$\dot{V}_{fan} = 1.25 \times \dot{V}_{Cargopumps} \times nr_{Cargopumps} \tag{36}$$

The calculation of the electrical consumption of these two fans required by (IMO, 1974) was performed using the equation (3), 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.

$$P_{IGSgenerator} = 0.015 \times \dot{V}_{IGS} - 0.0203 \tag{37}$$

2.4.3.Deck Anchoring Equipment

The windlass can be utilized as a separated one for each anchor or only one for the two anchors. In this research, it was considered two windlass units, one for each anchor.

$$P_{Windlass} = \frac{W_{Total} \times g \times v}{1{,}000 \times \eta_{elect} \times \eta_{mec}} \tag{38}$$

The equipment number established by classification societies is a parameter already known in conceptual design. Associated with this EN are the main characteristics of the anchor, and anchor chain such as the anchor weight, the required chain length, and the chain diameter. With these two last parameters can be calculated chain weight. And then the total weight to input in equation (38). (IACS, 2019) specify 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.

2.4.4.Deck Mooring Equipment

Winches are the equipment that support the mooring lines in the ship. In order to calculate the respective power consumption of the electric mooring winch, there are a few main specifications that are necessary to specify, as it is possible to see in equation (39), including rope diameter, nominal speed and rope capacity. These characteristics are already known in conceptual design since they are specified through the EN described by classification society. It was assumed that for each cable there would exist one winch, thus it is necessary to know the minimum number of cables as a model input characteristic as well.

$$P_{Winches} = \frac{T \times v_s}{60 \times \eta_{elect} \times \eta_{mec}} \tag{39}$$

The maximum hauling tension which can be applied corresponds to 1/3 times of the rope's breaking strength. The velocity was assumed as constant 15 m/min.

2.4.5.Cranes

Shipboard cranes can be of various types and capacities. 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 onboard. The estimation of the power associated with the cranes follows the equation (38), where, in this case, the cargo weight capacity desired is an input parameter to be specified by the user in ton, for each cargo crane. However, this equation was applied only for weights until 40 tons. About the provision crane, it was assumed the weight was constant 1 ton, based on experience. The average velocity of handling assumed, following MacGregor manufacturer, was 25 m/min for cargo cranes and 13 m/min for provision cranes. In case of heavy lift cranes (more than 40 ton), a TTS catalogue was followed where specifies the power consumption according to the weight capacity desired.

2.4.6.RoPax lift elevator

In a RoPax there are internal accesses which allow transferring vehicles for different decks taking advantage of the cargo space. As follows, it was contemplated as an individual car lift with constant power consumption. For the calculation of this consumer was considered that should be capable of lifting a TIR truck in which the weight considered was 25 ton added with 1 ton weight of the platform. Also, it was considered a height of 4.5 meters and a velocity to lift equals to 2 minutes.

2.4.7.Hatch cover

Hatch cover is a fundamental part of ships since it is used to close the opening of the ship cargo hatch protecting the cargo inside of the holds. Various designs can be applied depending on the ship's particularities. However, in this research only one is considered side-rolling since its drive is more probable to be fully electric and not driven by hydraulics as is the case with other types of covers. For this estimation, it was used the equation(38). For the hatch cover weight was considered the coefficient equal 0.02 ton/m^2, which multiplied by the corresponded area, it is possible to have the knowledge of the hatch cover weight. For the rolling displacement it was considered equal to the half breadth of the ship for each side.

2.4.8.Deck Maneuvering

Many owners opted to have transverse thrusters in their vessels. This allows the vessels a superior maneuvering capability in confined waters as well as often dispense with assistance from other vessels such as tugboats, at their berths in ports. Therefore, for the estimation of the power associated with a transverse thruster, it was followed (Ozdemir, 2008) where it provides us with an empirical equation for the power calculation that depends on the driving force. It also provides a table where it presents several coefficients according to the type of ship that simulates this driving force per water line lateral area. The equation used and the coefficients according to the type of vessel are transcribed below.

$$P_{TransverseThruster} = k \times \Delta^{\frac{2}{3}} \tag{40}$$

In which k is coefficient associated to driving force. This coefficient is also defined on the same document being presented in the next table.

Table 4 – 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(40), it was applied the mechanical and electrical efficiency.

2.5. Superstructure

The forecast for provision plant electrical power consumption was performed with an auxiliary software from a manufacturer. It was assumed that each room corresponds to a modular room already in the market. In this present research, 3 modular room are considered in which each one corresponds to one temperature (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. Following all results collected, it was performed a sum between the three rooms with the same volume. Then, a regression was performed.

$$P_{Provisionplant} = 0.0705 \times V_{Provisionplant} + 2.8165 \tag{41}$$

2.5.1.HVAC

This first step consists in knowing the outside conditions in which the ship will be exposed to, and the interior conditions that should be guaranteed. For this purpose, the international standard regarding HVAC was analyzed in the accommodation spaces on ships (ISO 7547:2002). Then, the design conditions for indoor air are +27ºC and 50% humidity for Summer and +22ºC in Winter, the outdoor air condition for Summer is +35ºC and 70% of humidity and 3ºC for Winter.

With the knowledge of the conditions which should be applied in the HVAC calculation, it was opted to follow the method of the air changes, which the minimum requirements are specified in (GL, 2016).

Table 5 - Air renovations rates for supply air

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

For cabins with sanitary, which is the case, (GL, 2016) specify that should be supplied 10% more incoming air, for this reason, the value assumed for cabins is 6.6 renovations/h. The air changes multiplied by the corresponding volume results in a volumetric flow rate. After all individual flow rates obtained it was applied the heating and cooling analysis which define the thermodynamic parameters according to the desired conditions previously explained and then it is possible to calculate the mass flow rate and the enthalpies necessary to the compressor power calculation.

$$P_{compressor} = \frac{\dot{m} \times (hs - he)}{COP} \tag{42}$$

Where hs is the exit enthalpy of the compressor in kJ/kg and he is the entrance enthalpy. However due to the gas coolant which circulates inside of a refrigeration cycle, there is an associated coefficient of performance (COP) which in this work was considered 2.5. The coefficients to be implemented in the model are defined by the relationship presented in (43).

$$C_{Powerpervolume} = \frac{P_{Space}}{V_{Superstrucutre}} \tag{43}$$

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 6 - AC power coefficients in function of the superstructure volume

Space	$C_{Powerpervolume}$ [kW/m3]
Cabins	0.004660
Mess, dining-rooms or offices	0.005133
Hospitals	0.000522
Pantry	0.000673
Dry provision room	0.000633
Laundry	0.000550
Bridge	0.002705

In addition to the AC system, there is a necessity for the accommodations ventilation. As the method used already has in consideration the supply air, the only supply fan to be dimensioned is the galley fan. However, it is necessary to model the exhaust fans for all accommodation spaces. In this way, in (GL, 2016) it is presented the minimum values for exhaust air which are presented in next table.

Table 7 - 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 WC	15
HVAC Room	30
Deck Stores, workshops or spare rooms	10

Applying the same principle that applied for supply air, it is obtained the volumetric flowrates of the fans. To estimate the power, it is then applied equation (3) for each space flowrate. Then it is possible to calculate the coefficients associated to these fans using equation (43).

2.5.2.Workshop

A workshop on board is an essential space. To estimate the power consumption, it was opted to collect some data from manufacturers, performing then an average between the values collected. It was then considered a constant value of 22 kW in total of these consumers.

2.5.3.Laundry

To provide a method to estimate the power associated with the ship laundry, it was analyzed some catalogs from common manufacturers, and ship electrical balances. This last analysis allowed us to estimate a power required in the function of each person on board, resulting in the following coefficients that can be applied to the POB and obtained the total power of the respective machine type. For dry machines it was implemented equation (44) in the model.

$$P_{Dryermachine} = 0.3816 \times POB \tag{44}$$

For washing machines, it was followed equation (45).

$$P_{Washingmachine} = 0.3032 \times POB \tag{45}$$

2.5.4.Bridge equipment

After collecting the minimum electrical consumers' equipment list, it was searched for the respective electrical power consumption from manufacturers catalogs. Also, it was analyzed two electrical balances of real ships. It was then performed an average between the constant values, resulting in a total constant of 5.9 kW of power consumption.

2.5.5.Illumination

The lighting power was calculated following equation (46).

$$P_{illumination} = \frac{\emptyset V}{\eta_{lamp}} \tag{46}$$

Where $\emptyset V$ is the luminous flux in lm. 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 by the following equation.

$$\emptyset V = E \times S \times \frac{F_d}{F_u} \tag{47}$$

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 is provided by levels of general lighting or task lighting. It is possible to find an illuminance level criterion in (ABS, 2016), which is based on ISO 8895-1:2002 and focuses on lighting specifically on vessels. 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 areas 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. After the areas' definition and the illuminance level established, it is lacking the factors to be applied in equation (47). 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 model 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 work was considered 0.55 as direct light in all spaces. Thus, based on experience onboard it was opted to use fluorescent tube lamps, since they are the most common lamps onboard in all locales. With 60 lm/W.

2.5.6.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 analyzed. For this purpose, the ship operating conditions were defined, carrying out an electrical analysis for 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 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 operating 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 with each operating condition.

To estimate the equipment power consumption in each operating condition it was used the equation (48).

$$P_{Condition} = P_{Nominal} \times nr_{Service} \times k_L \times k_s \qquad (48)$$

The equipment in service is a dependent variable of the number of installed equipment and the operating condition. In this work it was considered redundancy system for all engine auxiliary machinery as pumps and compressors, this means that there are 2 installed but only one operates, with exception for fuel pumps. For these pumps are considered installed 2 per engine. In relation to the deck equipment, the installed equipment is defined by the model user and the same equipment is considered in service. The remaining equipment installed is considered as 1 and the same in operation. Following (Pater, 2012), the utility factor is defined as the average power during the operation period of time dividing by the peak power of the equipment.

$$k_L = \frac{\%Powerload \times t_{operation}}{100 \times 24} \qquad (49)$$

The simultaneity factor is defined by the percentage of consumers that are drive at same time. For this factor definition, it was followed the standard NBR 7567:1982 that provides standard values to be used in electrical load balance estimation, according with the electrical consumers group: Engine Room, Deck and Superstructure.

3. Model Validation

Two types of validation were applied on the model. One of them consists of a global validation. This validation is based on the ships database, where all the vessels parameters necessary for the functioning of the model were collected. 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.

3.1. 2-Stroke Engines

For the global validation in which the parametric model was applied, two reference ships were selected. The ships choice consists in differing the ship type for a better consolidation of the obtained model result. For 2-Stroke engines, it was selected a product carrier tanker ship and a bulk carrier. The observed errors are -8% for tanker ship and -10% for bulk carrier. The two detailed validations performed for 2-Stroke engine was conducted with two oil tanker ships. The first is aframax tanker ship powered by 10760 kW and the second ship is a handysize tanker with 9600 kW. Table 8 reveals the total values corresponding to the ship's operating conditions for the two tanker ships previously presented.

Table 8 - 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

*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 is equipped with an auxiliary boiler for the respective heating system of the cargo. This system consumption is more evident in the loading and unloading condition and for this reason it was decided to not compare. The fourth condition is not present in the known ship electrical balance and thus it is not possible to compare values.

3.2. 4-Stroke Engines

The global validation for 4-Stroke engines was performed with an oil tanker, a multipurpose heavy-lift ship and a RoPax. From these validations, it was observed that the worst case is the tanker ship with -20% of error. The second and third ship have errors of -6 and -4 %. The oil tanker presents worst number since is a ship that requires a large heating installation to unload the cargo. This heating installation was not modelled in this model. For ships with 4-Stroke engines, the detailed validation was performed for one feeder container ship, and two RoPax ships. The results are shown in Table 9 for the container ship.

Table 9 - Ship operating conditions analysis for 4-Stroke engines

Container Ship			
Ship Condition	Real [kW]	Estimated [kW]	Error [%]
1	905	920	+2
2	1,471	1,413	+4
3	467	474	+2
4	176	181	+2

The resulting values for the two RoPax are shown in Table 10

Table 10 - Ship operating conditions analysis for 4-Stroke engines

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

*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. 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.

4. Conclusions

This work proposes a numerical model developed based on the concept ship design variables that allow estimating not only the power of the generators on board as well as to estimate the different electrical load demand in four different operating conditions: navigation, maneuvering, loading and unloading and in port. This numerical model was implemented in Excel with the auxiliary tool Visual Basic for Applications (VBA). 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. 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 onboard with the values obtained from the parametric model. For this purpose, were selected two ships with 2-Stroke engine and three ships with 4-Stroke engine. 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. From the five ships analyzed, two have 2-Stroke main engines and three have 4 Stroke main engines. In these comparisons, the differences found were less than 10%.

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