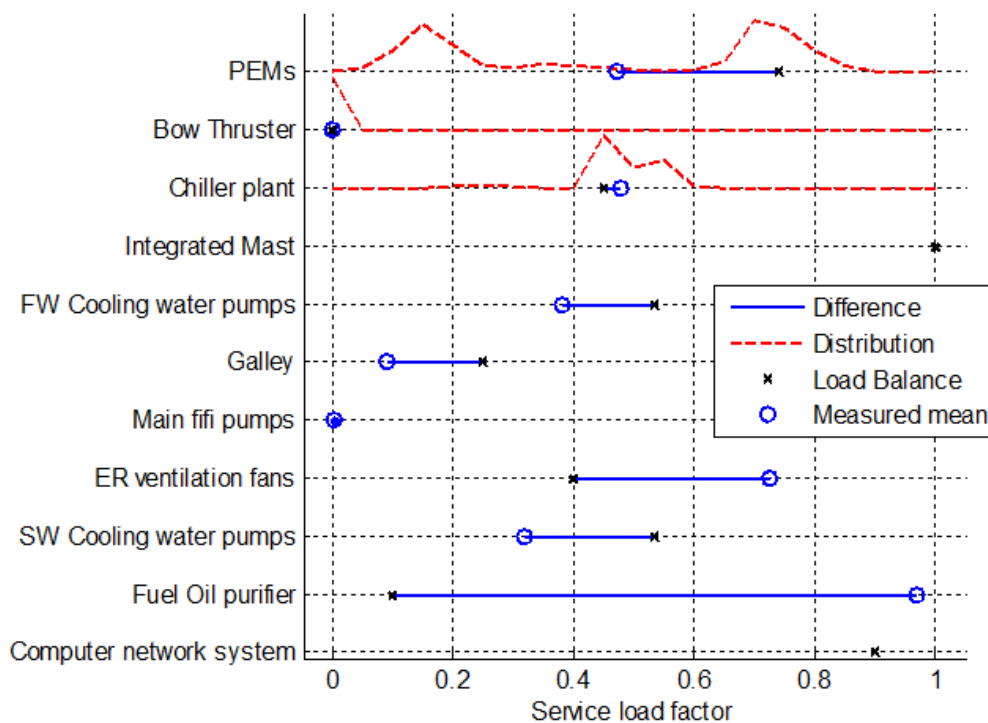


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# Improvements to the design process of the energy distribution system

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*A comparison between operational use of the energy distribution system of a naval ship and its expected use during the design phase*



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TU Delft student number: 1360671, report number: SDPO.15.019.m

Delft, July 20, 2015

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Version 1

*Some content in this document is omitted due to its confidential nature. The full document is can be requested at the research department of Damen Schelde Naval Shipbuilding BV.*

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# Abstract

After a ship is delivered from a shipyard to a customer, its operational use is not yet structurally compared to its expected use. This lack of structural comparison results in limited verification and self-evaluation of the design process. The objective of this research is therefore to develop a method to analyze operational data and apply this operational data analysis method to the Royal Netherlands Navy Holland class Oceangoing Patrol Vessels (OPVs). These vessels use Combined Diesel Electric or Diesel (CODELOD) propulsion. The data analysis focuses on the electrical energy distribution system, because this determines a large portion of the total fuel consumption of the ships. Operational data from these ships was collected from the Integrated Platform Management System, which is installed on the OPVs.

By applying the operational data analysis on the Holland class OPVs, the generator plant setup is evaluated. Based on the results from this analysis, a father-son generator setup is proposed, consisting of two 835 ekW gensets and two 475 ekW gensets. This setup has better redundancy, less fuel consumption, and a lower total installed power, compared to the three currently installed 920 ekW generators. The proposed father-son alternative setup reduces the total installed electric power by 5.1%, and saves 0.4% to 2.4% fuel consumption for electricity generation. To obtain an accurate calculation of fuel consumption for widely distributed power consumption profiles, a power consumption distribution must be used instead of an average value.

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# Preface

This report is the result of a lot of time spent and sweat produced over the course of nine months. It is the pinnacle of my education as a Master of Science in Mechanical Engineering studying at the Delft University of Technology, where I was allowed to study during my education as an engineering officer in the Royal Netherlands Navy. I will start my operational naval career soon after the completion of this Master of Science. The results of this thesis should prove useful to designers and ship operators alike.

I would like to thank everyone who has helped me over the course of the past nine months. Special thanks go out to my supervisors: Kasper de Ruyck at Damen Schelde Naval Shipbuilding, and Milinko Godjevac at TU Delft. I would also like to thank Arthur Vrijdag and Toine Cleophas of Damen Shipyards Gorinchem for their insights, ideas and discussions during my time spent there. They all helped me tremendously in different parts of the process.

Delft, July 20, 2015

Michael Smith

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## List of abbreviations

CPP:	Controllable Pitch Propeller
CODELOD:	Combined Diesel-Electric or Diesel
ELB:	Electric Load Balance
FPP:	Fixed Pitch Propeller
Genset:	Generator set
HNLMS:	His Netherlands Majesty's Ship
HVAC:	Heating, Ventilation and Air Conditioning
I/O:	Input/Output
I-MAST:	Integrated Mast
IPMS:	Integrated Platform Management System
LTO:	Landing & Takeoff
OPV:	Oceangoing Patrol Vessel
SFOC:	Specific Fuel Oil Consumption

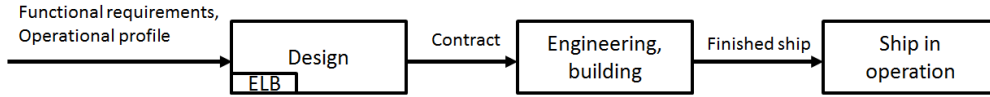
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# 1 Introduction

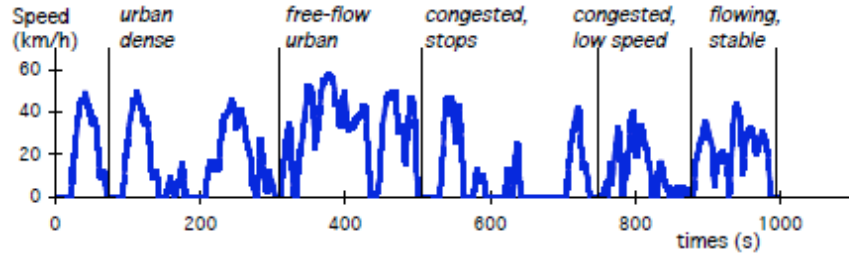
## 1.1 Background



**Figure 1:** The typical process of building a transportation vehicle is one-way traffic. Arrows indicate products, while blocks represent processes.

The process from requirements to operational use of any customly designed transportation vehicle follows more or less the same route, regardless of its field of application, see Figure 1. The customer decides the functional requirements that the vehicle should have. These requirements reflect the customers expectation of the operation of the platform. This includes various parameters, such as maximum speed, environmental extremes that the vehicle can still operate in, reliability and availability. A set of some of these requirements is called the operational profile. The representation of the operational profile and its practical use differs per mode of transportation.

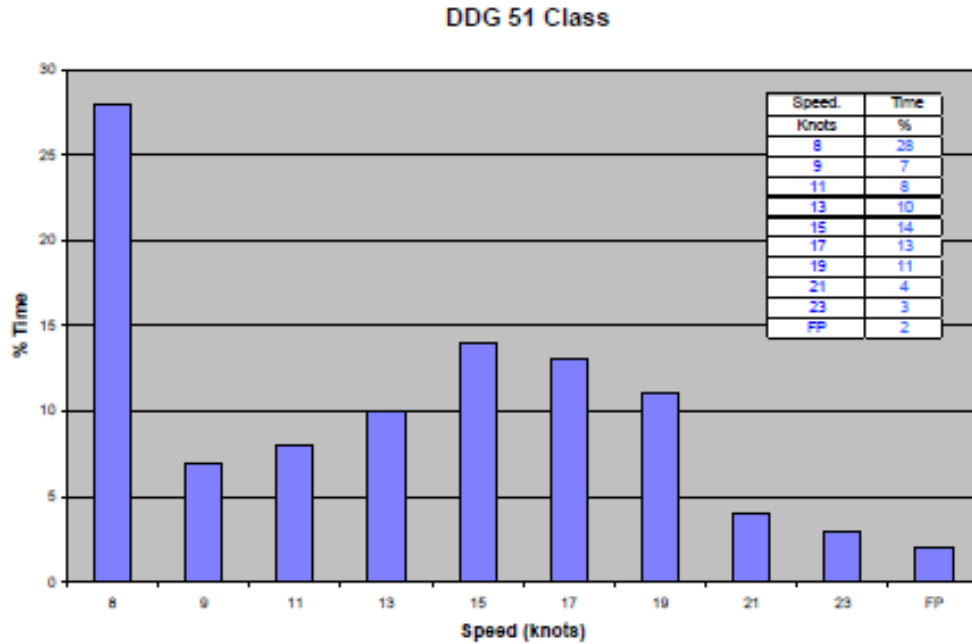
For a road vehicle, the typical operational use of the system is given in the form of a time-speed driving cycle and driving patterns, as seen in Figure 2a. Airplane designers commonly use Landing & Takeoff (LTO) Cycles to determine the dominant part of gaseous emissions up to 3000 ft above ground, as seen in Figure 2b. In ship design, a speed-time histogram representation is often used together with a distribution of operational modes. An example of such a profile is shown in Figure 2c.



(a) The operational profile of a road vehicle is given as a speed-time curve with predetermined driving patterns [1].

Operating Mode	Thrust setting	Time in operating mode, minutes
Take-off	100 % $F_{oo}$	0.7
Climb	85 % $F_{oo}$	2.2
Approach	30 % $F_{oo}$	4.0
Taxi/ground idle	7 % $F_{oo}$	26.0

(b) The operational profile of an airplane is dominated by Landing and Take-off (LTO) cycles [2].



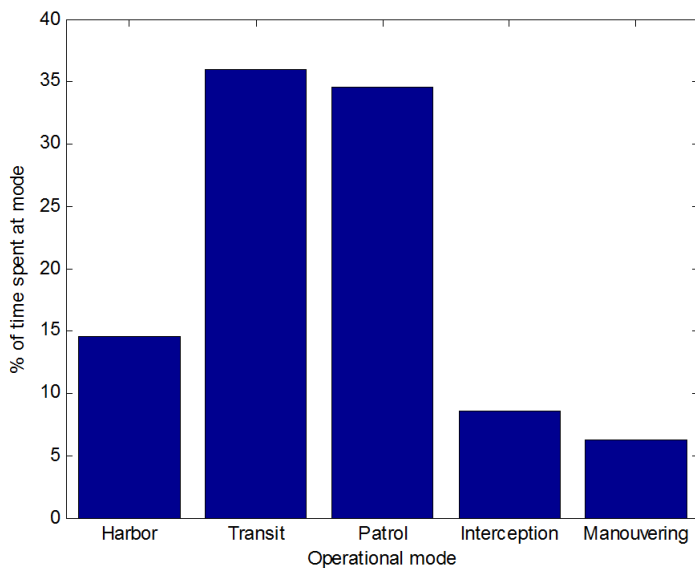
(c) An important part of the operational profile of a ship is the speed-time distribution [3].

**Figure 2:** Operational profiles are represented in different ways for different types of vehicles.

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Operational profiles for a large part determine how the vehicle is designed. For road vehicles and airplanes, research has been performed to determine realistic operational profiles, based on measured data [1] [2]. For ships however, little research has been performed. These profiles are in practice estimated based on experience, not based on measured data. The United States Navy has performed research on the Arleigh-Burke class destroyers, which concluded that the speed profile used in the design process was outdated and should be updated to more accurately represent the actual use of a warship in modern times [3]. This research is based on written ship logbooks, however, not based on digital information. This results in a limited resolution of logging and the possibility of human error. Higher resolution information may lead to better results.

Another part of the operational profile of a ship, along with the speed-time distribution, is the Electric Load Balance (ELB), usually represented on a spreadsheet. In the ELB, all electric consumers are listed along with their service load factor  $k_s$ , which represents the long-term average operating power level as a fraction of the component's rated load. This fraction is dependent on the ships operational mode, multiplication gives an estimate of the average power drawn per consumer over a long period.



**Figure 3:** An example of a distribution of operational modes, which influences the electrical load of a naval patrol vessel.

The operational modes are represented in a similar way as the speed-time distribution, as seen in Figure 3. An operational mode is typically characterized by a certain speed range and key electrical consumers. With the operational modes and the corresponding service load factor values, the ELB gives a first estimate of sizing of electric power generation machinery. Because of time limitations and marginal influences of smaller consumers, only the largest consumers are taken into consideration in the early design phases. Designers focus on the

DESCRIPTION	INSTALLED			HARBOR		TRANSIT		PATROL		INTERCEPTION		MANOUEVERING	
	Nr. inst.	P inst. each kW	P kW	ks	P kW	ks	P kW	load fact.	P kW	ks	P kW	ks	P kW
Propulsion Electric motor	2	400	800	0	0	0	0	0.6	480	0	0	0.3	240
Bow Thruster	1	350	350	0	0	0	0	0	0	0	0	0.8	280
Firefighting pumps	3	45	135	0.1	13.5	0.4	54	0.3	40.5	0.3	40.5	0.4	54
HVAC compressors	2	50	100	0.2	20	0.5	50	0.4	40	0.4	40	0.5	50
Cooling water chiller	2	60	120	0.4	48	0.4	48	0.2	24	0.2	24	0.4	48
Integrated mast	1	70	70	0.5	35	0.3	21	0.2	14	0.2	14	0.3	21
FW Cooling water pump	2	50	100	0.15	15	0.4	40	0.3	30	0.3	30	0.4	40
Rotating crane	1	90	90	0.2	18	0.1	9	0.2	18	0.2	18	0.1	9
<b>Total power</b>			1765		149.5		222		646.5		166.5		742

**Figure 4:** The Electric Load Balance gives an early estimate of the electrical load per operational mode.

dominant users on a ship using the Pareto principle, which indicates that 20% of the consumers use 80% of the total electrical power [4]. An example of a simplified electric load balance is shown in Figure 4, the service load factor  $k_s$  is given per electric consumer per mode. The ELB results in an estimate of the maximum expected power consumption while the ship is in a specified mode. A more detailed description of the energy distribution system design of a ship is given in chapter 2

Life Cycle Costs of the electric energy distribution system are calculated by combining two pieces of information: the distribution of operational modes, and the distribution of electrical power consumption per operational mode. The electrical power consumption distribution is only used to calculate fuel consumption, not maintenance costs, in this report.

## 1.2 Research motivation

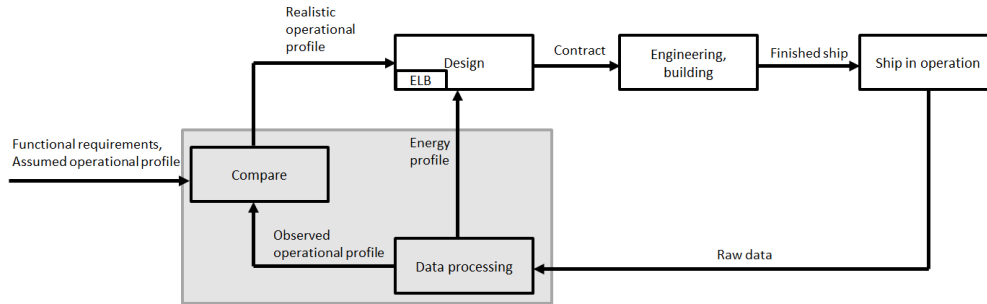
The actual use of a ship and its equipment is rarely compared to design considerations, assumptions and estimates made during the design process. An obvious exception to this is when machinery is drastically lacking and requires a modification. In the case of the energy distribution system, a modification is usually performed only when for example a generator set can not handle the load, and therefore a more powerful generator set is required. On the other hand, when a generator is too large for its average load, there is always sufficient power available for all of the electrical consumers on board, but the gensets are running with partload. Even though low loaded diesel engines require more maintenance, have an increased chance of failure, and have a higher specific fuel consumption, these factors rarely financially justify a large modification such as engine replacement. The ship operator will generally not report information about the low loaded gensets to the ship designer. The ship designer therefore misses out on valuable information that might be used to improve the design of future ships. These possible improvements to ship design are the ultimate goal of this research.

Additionally, detailed information about how a ships energy distribution system is used, is rarely gathered. Low resolution information, such as average



generator load, is sometimes used, but is limited in its applicability in the improvement of design of new ships. More information about the operational use of ship systems leads to better ship design by enabling a better verification of design considerations. Systematic design evaluation gives the opportunity to obtain a better fit between vessel design and vessel operation of future ships.

### 1.3 Goal and scope



**Figure 5:** Feedback from operational use of a ship improves the design process. Arrows indicate products, while blocks represent processes.

Damen Schelde Naval Shipbuilding (DSNS) recognizes the problem of limited verification of design considerations and has the desire to tackle this. By implementing feedback from operational use of ships, Damen aims to improve ship design. The feedback from ship use to design is shown in Figure 5. Damen has placed data collection means on board of all four Holland class Oceangoing Patrol Vessels (OPVs), starting in May of 2014. However, neither a tool nor a methodology of analysis have been developed yet.

The focus of this thesis is depicted as the grey area in Figure 5, and consists of three parts. First, a data handling and analysis method must be developed. Secondly, this analysis must be applied to the Holland class-OPVs. The analysis must yield an energy and operational profile of the ship. The energy profile is effectively a detailed ELB with service load factors of dominant consumers, while the operational profile includes the ships operational mode distribution and speed distribution. Thirdly, the results of this analysis must be used to give advice to the ship designers. The main objective of this research is therefore:

**Propose improvements to the design process of the energy distribution system of a naval ship by comparing actual use of the energy distribution system of the Holland class Oceangoing Patrol Vessel to its expected use.**

In order to achieve the main objective, a number of sub-questions are identified. Question one and two concern the development of the data-analysis method. Question three and four concern the application of the method to a set of available operational data. Question five concerns the interpretation and practical consequences of the results.

- 
1. How is the energy distribution system of a ship designed in general and of the Holland Class OPV is particular?
  2. Which methods of analysis of operational data are available and what are their advantages and disadvantages?
  3. How were the dominant parts of the energy distribution system of the Holland class Oceangoing Patrol Vessel used during the research period?
  4. What are the differences and similarities between the actual use of the energy distribution system compared to its expected use during the design phase?
  5. How should the design methodology of the energy distribution system be improved, based on the observed differences and similarities?

The scope of this research is chosen such that only the most important consumers are considered, in order to improve clarity of the research as a whole. This research is therefore limited in the following ways:

- Only consider the dominant electrical consumers instead of all electrical consumers, using the Pareto Principle
- Focus on data from the Holland class OPV only

## 1.4 Report structure

As the main objective of this report is to improve the design process of a ships energy distribution system, chapter Two describes how the energy distribution system on board of a ship is designed. This is described both in the general case, as well as for the Holland class Oceangoing Patrol Vessel in particular. From this description, a list of information required by the designer is presented.

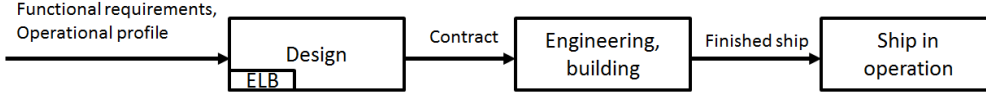
Two methods of data analysis are described in chapter Three. In order to acquire the best possible results from the analysis, the choice of analysis method is based on the available data and the desired results.

In chapter Four, the chosen method of data analysis is applied on the available operational data. The produced results are compared to the estimates from the design phase. Based on these results, an alternative generator plant setup is described.

All available data is subject to uncertainties due to, for example, sensor imperfections, processing and conversion from analog to digital signals. Chapter Five describes the sensitivity and uncertainty analysis of the results.

Lastly, chapter Six concludes the report with proposed improvements to the design process of naval ships, and suggestions for further research.

## 2 Design of the energy distribution system

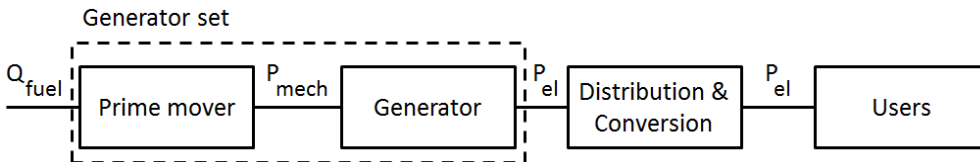


**Figure 6:** The typical process of designing a ship has several stages that determine the final product. Arrows indicate products, while blocks represent processes.

As illustrated in Figure 6, there are four main stages from the specification of functional requirements to an operational ship. This chapter focuses on the design process of the energy distribution system. A definition of operational modes by the ship designers represents expected typical power consumption configurations. These operational modes are based on the functional requirements and experiences with previous ships. Each operational mode has a number of dominant consumers, which have their respective service load factors. Based on the rated power and service load factor of the dominant consumers, an estimation of the required power per operational mode is obtained. Different power requirements have different optimal power plant setups, so tradeoff studies can be facilitated with the operational power requirements. A common method of making this calculation is the Electric Load Balance (ELB), which is a spreadsheet containing operational modes, electrical consumers and their service load factor  $k_s$ . A goal of this spreadsheet is to make the choice of generator configuration, early in the design process.

This chapter describes the process from functional requirements to the generator setup selection in the general case, as well as for the Holland class Oceangoing Patrol Vessels specifically. This chapter finishes with a list of items that needs to be produced by the operational data analysis, such that designers can use this information to finetune their assumptions and considerations.

### 2.1 Energy distribution system design in general



**Figure 7:** The main components of an electric power distribution system [6].

As seen in Figure 7, the prime mover is the machine that converts chemical energy from fuel into mechanical energy. A diesel engine is commonly used

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to drive the generator. The generator converts mechanical energy to electric energy. The combination of prime mover and generator is commonly referred to as *generator set* (or *genset* for short). The distribution and conversion of electric power to the electric users is done through switchboards and converters. The main switchboards distributes electric energy either directly to electrical systems, or via smaller switchboards. Large loads, such as the frequency drivers of propulsion motors and bow thrusters, are usually fed directly from the main switchboard [6]. The electrical consumers ultimately determine the load of the electric power plant.

### 2.1.1 Functional requirements

The functional requirements of a ship are specified by the customer in consultation with the ship designer. These requirements specify items such as speed, robustness, emission levels, operational conditions, noise and vibration levels, operational range, Dynamic Positioning class, etcetera. The design of the ship as a whole must be such that the specified functional requirements are met.

Depending on the type of ship being designed, different operational modes are identified that are used by the ship operator. For example, typical modes for an offshore support vessel are dynamic positioning (DP), transit, shore connection and maneuvering. Operational modes for a naval vessel on the other hand often include maneuvering, shore connection, combat, transit, replenishment at sea (RAS) and patrol.

### 2.1.2 Dominant consumers

Each operational mode has its dominant electrical consumers. For example, when a ship is in “Maneuvering” mode, the bow thruster and steering pumps will consume a large amount of power while the electric propulsion motors will consume a relatively small amount of power. Similarly, during “Transit” mode the bow thruster is not in use and therefore will consume little to no power, while the electric propulsion motors will consume most of the ships power. In most ships, the dominant users are propulsion electric motors (if installed), heating, ventilation and air conditioning (HVAC), chillers, bow thruster, cooling water pumps and fire fighting pumps [5].

The operational mode of the ship is only one of various operational conditions. Others include climate, sea state and the type of mission of a ship. Firstly, if a ship is in a warm or cold climate, HVAC will consume more power as the incoming fresh air will require more heating or cooling than when the ship is in a moderate climate. Some installations use sea water to provide a part of the required machinery cooling, the rest being provided by chillers. Secondly, if a ship has some form of active motion control, this installation will consume more power as the sea gets rougher.

---

### 2.1.3 Service load factor determination

To quickly get an indication of a ships electric power requirement in a specified operational mode, designers often use experience-based estimates. These estimates are often split into two parts; a load fraction  $k_1$  and a simultaneity fraction  $k_2$ .

$$P_{E,total} = \sum_{i=1}^n k_{s,i} \times P_{nom,i} \quad (1)$$

$$k_s = k_1 \times k_2 \quad (2)$$

$$k_1 = \frac{\text{Average power consumption when switched on}}{\text{Rated power consumption}} \quad (3)$$

$$k_2 = \frac{\text{Time in operation}}{\text{Total time}} \quad (4)$$

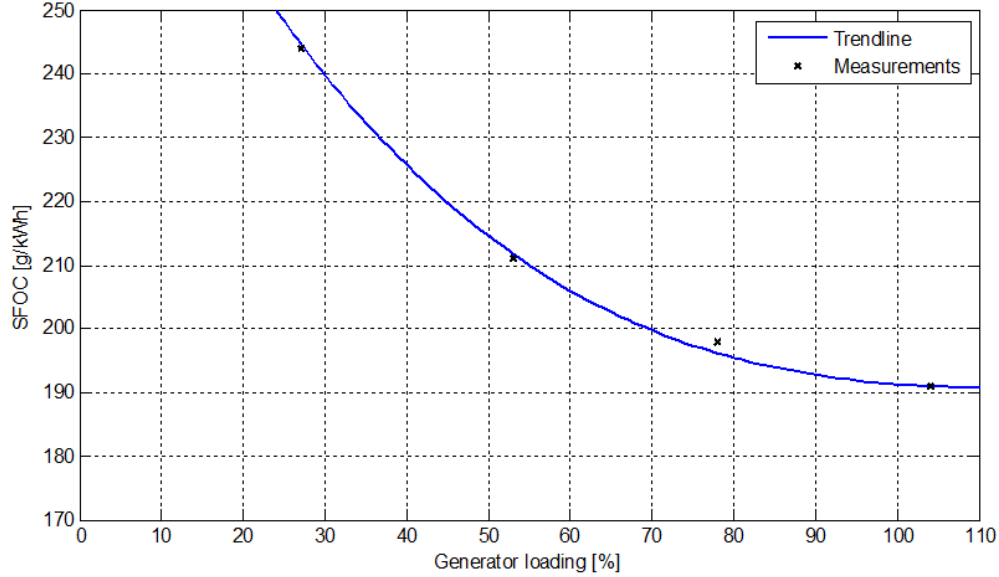
The average electrical power consumption per operational mode is the sum of the average powers of all individual electrical consumers, see equation (1). The service load factor  $k_s$  is the product of the load factor  $k_1$  and the simultaneity factor  $k_2$ , see equation (2). The load factor  $k_1$  is the ratio between average consumed power of an electrical consumer to its rated power, while the simultaneity factor  $k_2$  indicates the fact that not all consumers are engaged simultaneously, see equations (3) and (4). In this research,  $k_2$  is interpreted as the time fraction of operation [3]. These factors are determined by the operational mode of a ship, as described in section 2.1.2.

According to subject matter experts, the service load factors  $k_s$  are mostly based on experience with other ships and, effectively, estimates of the designers. The maximum required power of consumer groups (such as HVAC and pumps) is based on their models or ISO-norms applicable to these consumers.

The Electric Load Balance of similar vessels, of which the gensets were found to be satisfactory, serve as reference material for the design of new ships. However, operational information is not systematically used to validate the ELB, despite their use as reference material. Safety factors and conservative estimation are precautions taken to reduce the possibility that undersized generators are selected for new ships.

### 2.1.4 Generator setup selection

To operate a ships energy distribution system as energy efficient as possible, it is important that the right power plant setup is chosen. As shown in Figure 8, the specific fuel oil consumption (SFOC) of a generator set reduces with increasing load. The specific emissions have a similar characteristic as the specific fuel consumption [6]. This means that the energy generation is operated with maximum efficiency when the chosen generator sets are such that they are



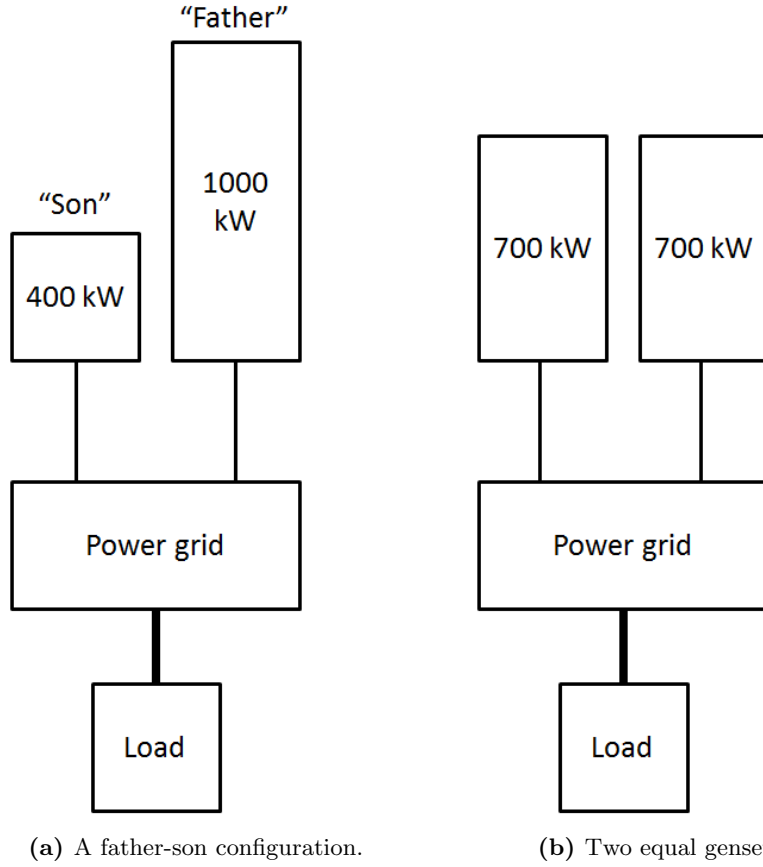
**Figure 8:** Specific fuel oil consumption versus generator loading, as measured by DSNS. A higher generator loading results in lower specific fuel oil consumption.

loaded above 70% of its rated load. Safety factors and conservative estimation of load factors, as explained in section 2.1.3, can easily result in the selection of an oversized generator set, which is operated at relatively low load most of the time. The operational costs and the specific emissions, such as  $\text{NO}_x$  and particulate matter, are therefore decreased when the power plant is chosen wisely.

The required electric power is dependent on the ships operational mode, as described in section 2.1.2. This means that for every operational mode, there is an optimal generator rated power. For example, if a ship spends 90% of its operational time in three modes with significantly different power requirements, it might be worth applying a father-son type power plant setup. In contrast, when a ship is in one operational mode with practically constant power requirement most of the time, a father-son type configuration is likely not the best option.

For example, suppose a ship has three operational modes which require 350 kW, 900 kW or 1250 kW. A father-son type configuration or two gensets of the same power are considered, as seen in Figure 9. Both configurations have similar initial costs and spare parts, therefore the only factors that play a role in the total lifecycle costs are the fuel consumption and maintenance requirements of the power plant. Lower loading of a genset usually results in higher maintenance costs [7]. To get an indication of the fuel consumption per genset, suppose that all gensets have a SFOC characteristic as seen in Figure 8.

The “*Load*” column in Table 1 indicates the portion of rated power, as supplied by one or both of the gensets. As seen in Table 1, the father-son configuration uses less fuel than the configuration with two identical gensets in the low and medium power modes. The fuel savings depend on the mode distribution, as



**Figure 9:** Two power plant setups with the same total power, but different setups

the difference between the father-son configuration and the two identical gensets is larger when the consumed power is lower. The more time spent in the 350 kW or 900 kW mode, the larger the fuel saving is. For example, if the mode distribution is 50%, 25% and 25% for the 350 kW, 900 kW and 1250 kW modes respectively, the father-son configuration will consume only 91% of the fuel consumed by the two identical gensets. In contrast, if the mode distribution is 25%, 25% and 50%, then the father-son configuration will consume 96% of the fuel consumed by the two identical gensets.

## 2.2 Particulars regarding the design of the Holland class system

As this research has the Holland class Oceangoing Patrol Vessel as a case study, it is important to know how this ship was designed and why it was designed in this way. Certain functional requirements, political considerations or external influences can lead to the decision to make a sub-optimal, less fuel-efficient or technically worse design.

---

**Table 1:** Fuel consumption per configuration in different operational modes.

Power [kW]	Config	Load [%]	SFOC [g/kWh]	Fuel rate [kg/h]
350	Father-son	87.5	240	72
350	Identicals	50	300	105
900	Father-son	90	240	216
900	Identicals	64.3	260	234
1250	Father-son	89.3	240	300
1250	Identicals	89.3	240	300

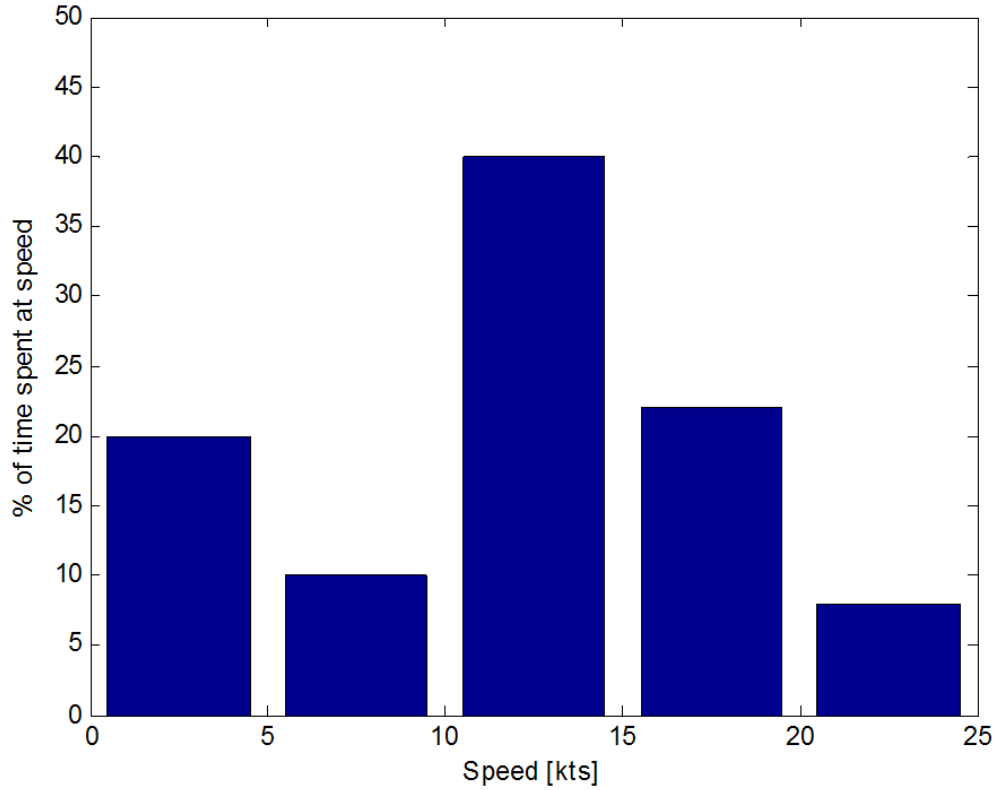
The Holland class OPV is a Combined Diesel-Electric or Diesel (CODELOD) ship, designed for a specific mission profile. According to the specifications and conditions, three mission types are defined: Guard ship Netherlands, Station ship Caribbean area and Expeditionary deployment. In the first two mission types, the ship mainly performs coast guard duties and maritime safety tasks in the Dutch or Caribbean waters, respectively. During expeditionary deployment, the ship performs maritime safety tasks varying from maritime presence to maritime interdiction operations. This type of ship is designed for the lower end of the violence spectrum, as it only has light to medium armaments on board. The largest weapon on board is a 76 mm cannon, which is relatively small compared to missiles and the 127 mm cannon that are present on the Royal Netherlands Navy frigates.

### 2.2.1 Functional requirements of the OPVs

Important functional requirements of the Holland class Oceangoing Patrol Vessel include items such as a certain action radius at a certain propulsive power, maximum speed, and the so-called  $N - 1$  redundancy requirement for certain key pieces of equipment. This requirement is one of the most important requirements for this type of ship. The  $N - 1$  requirement has a strong influence on ship design, as it specifies that a system must still be operable without reduced performance if one of its components fails. This results in a 100% redundancy of some important components and systems, such as two chiller compressors where one might suffice for normal operation. This requirement comes from the high level of reliability that the Royal Netherlands Navy demands from its ships. Even though this requirement results in a high reliability of the ship as a whole, it brings forth technical limits to the designer. For example, a father-son type generator configuration will be more difficult to realise, as the system will have drastically reduced performance if the father generator fails.

Another important design consideration is the speed profile of the ship, as shown in Figure 10. This is not so much a functional requirement as it is a prediction of the operation of the ship, based on the mission profile for which the ship was designed. The Propulsion Electric Motors (PEMs) are dimensioned, such that they can provide enough propulsion power to attain a speed of up to 10 knots. To attain speeds above 10 knots, the diesel engines are required. This means





**Figure 10:** In the design phase of the Holland class OPV, 5 speed windows are identified by the Royal Netherlands Navy. This information is taken from the (confidential) design specifications.

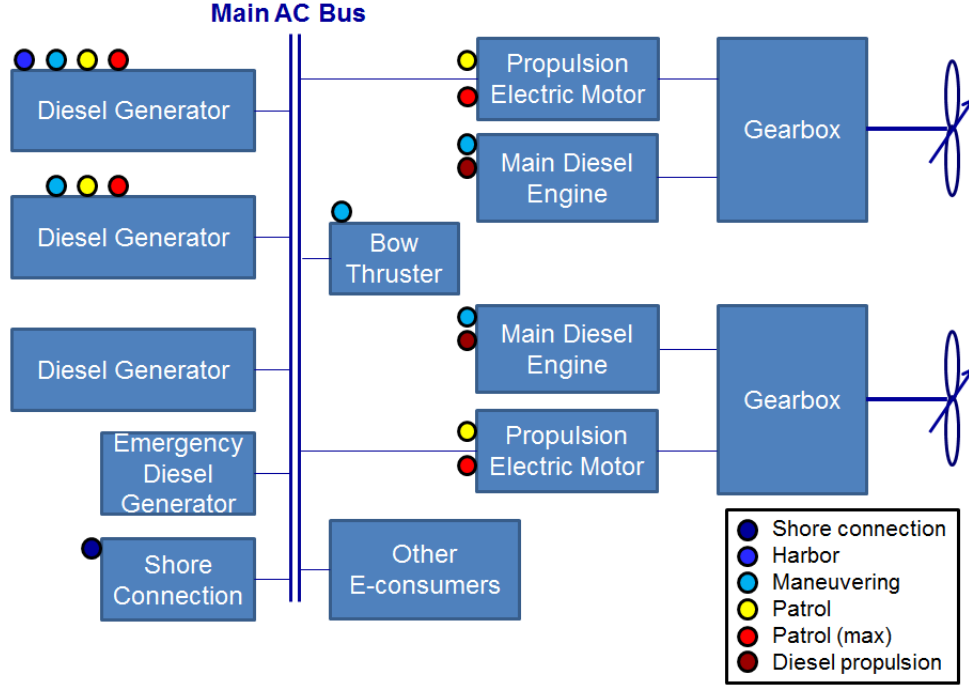
that it is expected that the PEMs provide the ship propulsion power for 30% of the time that the ship is sailing, while the diesel engines provide propulsion power for 70% of the time, see Figure 10.

### 2.2.2 Operational modes of the OPVs

A number of operational modes have been identified based on the mission profile of the ship and experience with previous vessels. To make a reliable estimation of the range, endurance, required power and fuel consumption of the ship, it is important to know the time distribution and the power consumption per mode. The operational modes, as identified by the designers, are as follows:

- Shore connection
- Harbour (Own electric energy generation)
- Maneuvering
- Transit
- Interception

- Patrol (E-propulsion)
- Patrol (Maximum E-propulsion)



**Figure 11:** The propulsion configuration of the OPVs in the defined operational modes. The colors indicate which components are used in which operational mode.

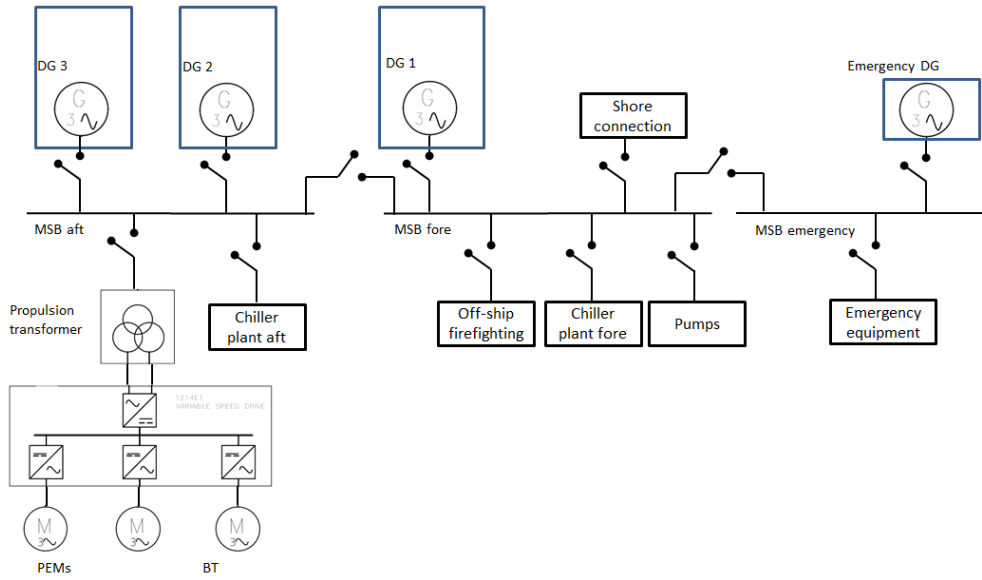
As far as the ELB is concerned, the two modes “Transit” and “Interception” are identified and use equal amounts of electric power. The only difference is in the ship speed, but as the diesel engines provide propulsion power in both modes, this has little to no influence on the electric power consumption. This report focuses on the electric power consumption, so these modes are grouped and referred to as “Diesel propulsion”. Figure 11 shows the propulsion and power generation configuration in each operational mode, as indicated by different colors.

### 2.2.3 Dominant consumers of the OPVs

During the design phase, a number of dominant consumers have been identified per operational mode as described in section 2.2.2. In all defined operational modes, dominant electrical consumers on the Oceangoing Patrol Vessels include: Air Conditioning compressor plants, the Integrated Mast (I-MAST), fresh water cooling pumps and the computer network. Together with the rest of the dominant consumers, they consume 500 to 700 ekW. In the Patrol modes, the propulsion electric motors consume a large fraction of the ships total electric power, which increases with ship speed. In Manoeuvring mode, the bow thruster requires a large amount of available power. The Electric Load Balance is included in Appendix A for reference.

## 2.2.4 Generator setup selection of the OPVs

According to subject matter experts, 3 options were considered during the power plant selection process. The first option was using 3 equal gensets, the second option was using 2 large gensets and 1 small genset, and the third option was using 1 large genset and 2 smaller gensets. The first option was ultimately chosen. Important determining factors in the decision process included: vulnerability characteristics,  $N - 1$  or  $N$  philosophy, space requirements, ease of maintainability and generator load during the identified operational modes.



**Figure 12:** A simplified Single Line Diagram of the Holland class OPVs. Three equal generator sets are used to provide electric power.

When different options all comply to the functional requirements, the choice only comes down to purchase and operational costs. Different brands and sizes were considered to make the best selection. In order to realise the lowest operational costs, it is beneficial to have equal spare parts for all gensets and to load the gensets as high as possible, as described in section 2.1.4.

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## 2.3 Designer requirements

To analyze the available data in a meaningful way, the desired products must first be known. Useful operational information, which provides feedback to the designers of the ship, includes at least the following items:

- Power consumption distribution per operational mode
- Operational mode distribution
- Service load factors  $k_s$  of dominant consumers [8]
- Variables that have a significant influence on ship power consumption

The power consumption and operational mode distributions are required to dimension the generator sets and to estimate the total lifecycle costs of a ship. Fuel consumption and maintenance costs are both dependent on the load distribution of the generator sets.

The observed service load factors are used to verify design assumptions and tune the ELB. Results from this research can also be used to better estimate service load factors of future ships.

Identification of variables that have a significant impact of the total electric power consumption are important because these determine the amount of variables that need to be taken into account during the early stages of ship design.

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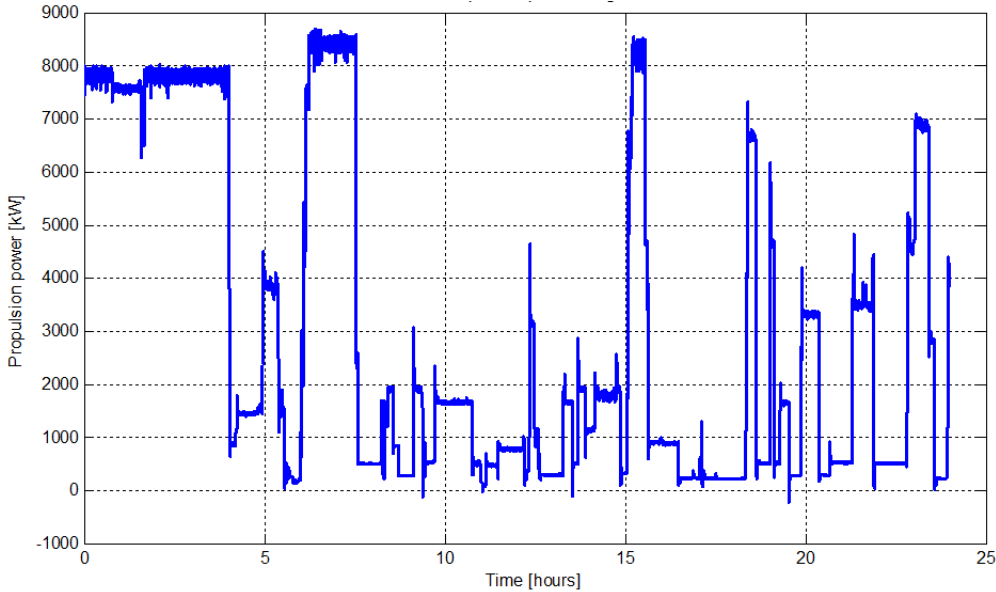
## 3 Data analysis methods

In order to properly analyze a set of data, an understanding of the different possibilities and their advantages and disadvantages is required. This chapter therefore describes two possibilities of data analysis: one that requires knowledge of the originally conceived operational modes, and one that does not require such knowledge. The applicability of any analysis method depends on the availability of operational data, therefore this chapter starts with a description of the ideal data set. This description can act as a guideline for the installation of shipboard sensors, if shipbuilders want to apply similar methods as presented in this thesis to improve their own design strategy.

The second paragraph of this chapter then describes the choice for one of the described analysis methods, based on the availability of operational data and the desired result of this research.

### 3.1 Possibilities of data analysis

#### 3.1.1 Ideal data set



**Figure 13:** The ideal set of data consists of power-time profiles of all consumers, similar to this propulsion power-time profile.

The difficulty of determining the operational mode depends on the available data set. In the simplest case, there is a signal that directly specifies when the ship is in which mode. Additionally, the power consumed by each consumer is available at all times, as illustrated in Figure 13. If these signals are available, the service load factors  $k_s$  are easily determined per operational mode by

calculating the average power consumed by each consumer. Depending on the available data, it is possible to determine  $k_1$  and  $k_2$  individually, only one of the two or only their product  $k_s$ .

**Table 2:** Data availability of three types of signals, from best-case scenario to worst-case scenario.

Operational mode	Dominant consumers	Other consumers
Direct	Power-time	Power-time
Indirect	Power-time	Power-time
Direct	Power-time	On/off
Indirect	Power-time	On/off
Indirect	On/off	On/off

If the mode signal is absent, the operational mode must be determined indirectly, based on other signals. This increases the difficulty of the data-analysis and decreases its accuracy, as it increases the number of assumptions that must be made in the process. Another possibility of decreased utility of the data-analysis is determined by the quality of the available signals. For example, if only an on-off signal is available, only the simultaneity factor  $k_2$  can be determined. Some combinations of different kinds of signals are listed in Table 2, from the most to the least useful combinations. “Other consumers” are consumers that do not fall into the “dominating consumers” category, as described in section 2.1.2. Power consumption is ideally specified per individual consumer, but realistically consumers are often grouped to reduce the number of sensors.

### 3.1.2 A priori knowledge

**Table 3:** The operational mode of the Holland class patrol ship is identified by a yes-no structure.

Operational mode	$P_{shore}$	$> 1$ DG	PEMs clutched	Main Diesels clutched	Maneuvering switch
Shore connection	Yes	No	Any	Any	Any
Harbour	No	Any	No	No	Any
Maneuvering	No	Yes	No	Yes	Yes
Patrol	No	Yes	Yes, $P < 0.85P_{max}$	No	Any
Patrol (max)	No	Yes	Yes, $P > 0.85P_{max}$	No	Any
Diesel	No	Any	No	Yes	No

In most cases, when a comparison is made between actual use of a ship and

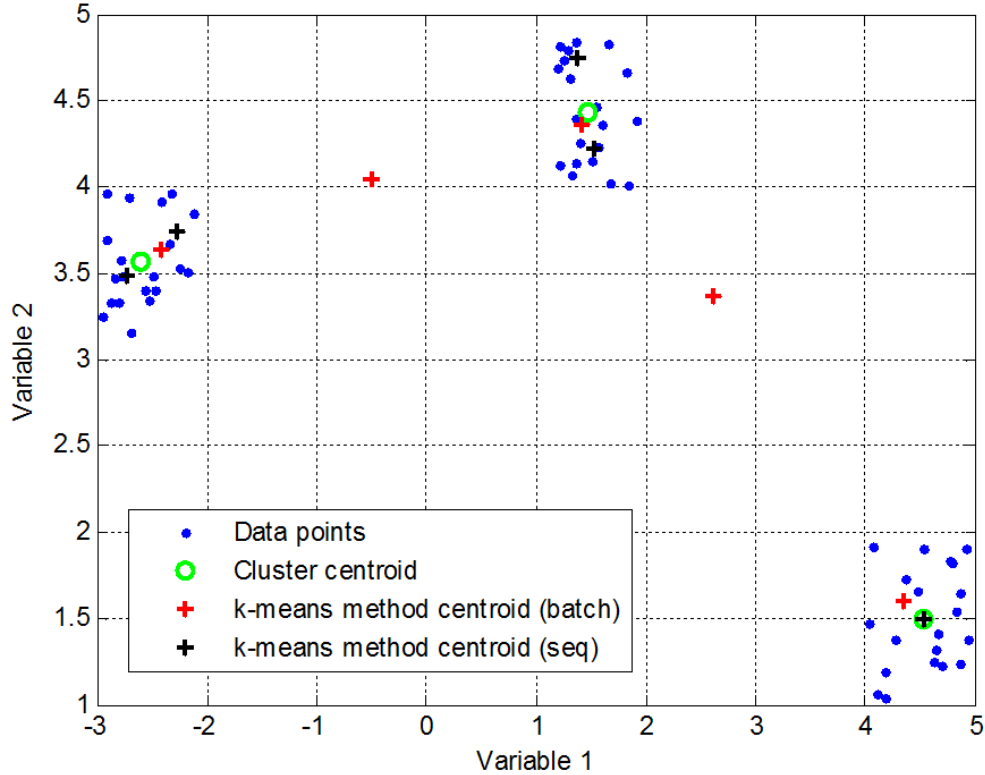
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its design considerations, the Electric Load Balance as described in chapter 2 is available. Each operational mode has a number of defining properties, such as ship speed and the use of certain pieces of equipment. In the case of the Holland class OPV, Table 3 provides one of the possibilities to determine the operational mode with a yes/no structure. This operational data analysis method is referred to as *A priori method* in this report. A table such as Table 3 requires knowledge of how the ship designers defined the operational modes, which is not always well-documented or unambiguous.

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### 3.1.3 Cluster analysis

Another possibility of determining ship operational modes is the use of clustering algorithms. Clustering algorithms are used to combine large collections of data points into groups with similar properties. Data points are combined in such a way that objects in the same group are more similar to each other than to those in other groups. Different methods of clustering are possible, including the k-means method and Self-Organizing Maps (SOM).



**Figure 14:** An example of concentrations of data points. The cluster centroids are found differently using different clustering algorithms.

Figure 14 shows a custom data sample used to test clustering algorithms, as well as centroids calculated by these algorithms. The blue points represent the data sample, while the green circles show the geometric mean of the sample data, and the red and black plus-signs show centroids calculated using batch and sequential k-means algorithms, respectively. “Sequential” and “batch” refer to the way in which the training vector is processed [9]. The sequential method yields better results than the batch method, as all centroids calculated by the sequential method are inside the blue clusters. Some centroids calculated by the batch method lie outside of the blue clusters. However, the batch method requires significantly less calculation time than the sequential method [10], see Appendix B.



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The used freeware clustering algorithm can be applied in two ways. The first way is to let the algorithm determine the optimal number of clusters, based on the spreading of datapoints in the dataset. In this way, the algorithm operates unbiased, possibly finding operational modes that were neglected or not considered in the design phase. The number of dimensions of the dataset plays a role in the calculated optimal number of cluster centroids. The second way is to manually specify the number of clusters, and let the algorithm determine only the cluster centroids. Specifying the number of clusters allows for a more fair comparison to the Electric Load Balance, because the number of clusters can be forced to equal the number of predefined operational modes. Cluster analysis is mainly useful to analyze data from a large number of ships, while having reduced utility in analyzing operational data from a few ships. Additionally, cluster analysis can be used exclusively on variables which have a continuous, non-boolean domain.

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## 3.2 Available data

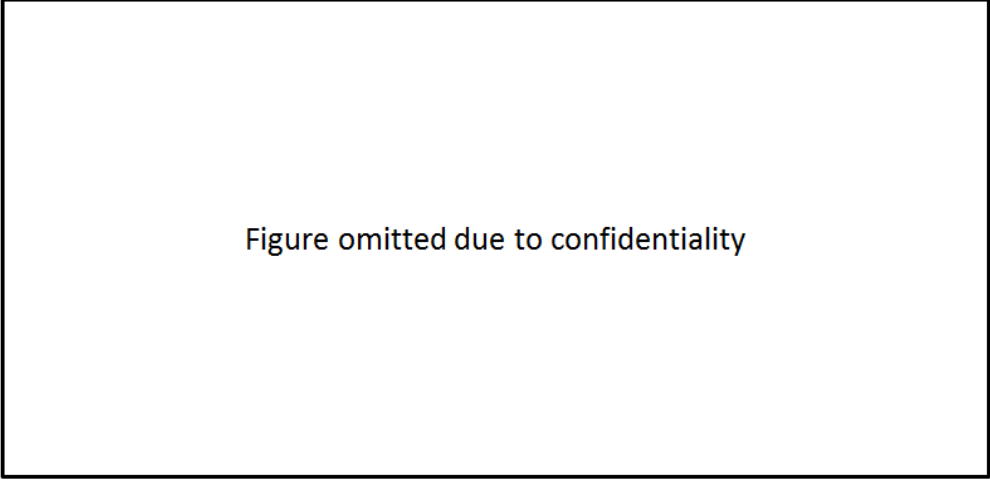


Figure omitted due to confidentiality

(a) Two types of signals are logged: “Switch” signals and “Value” signals.

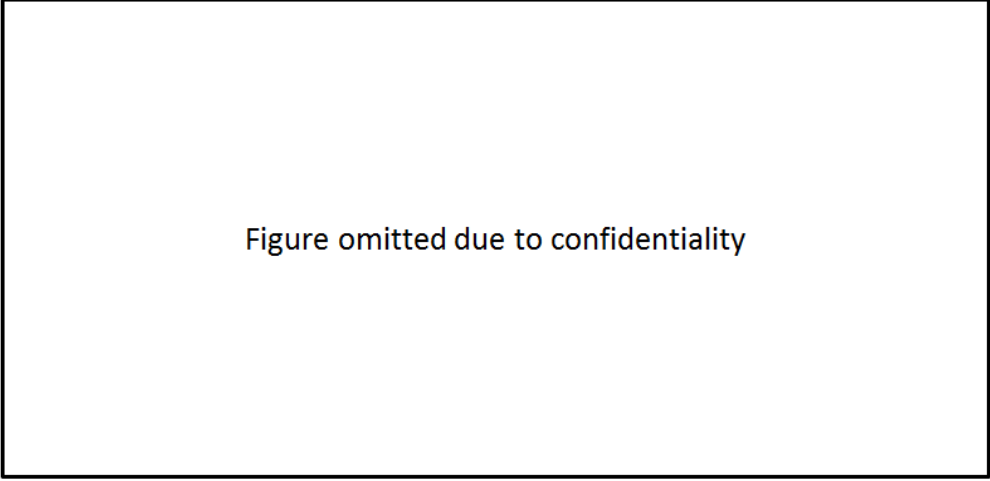
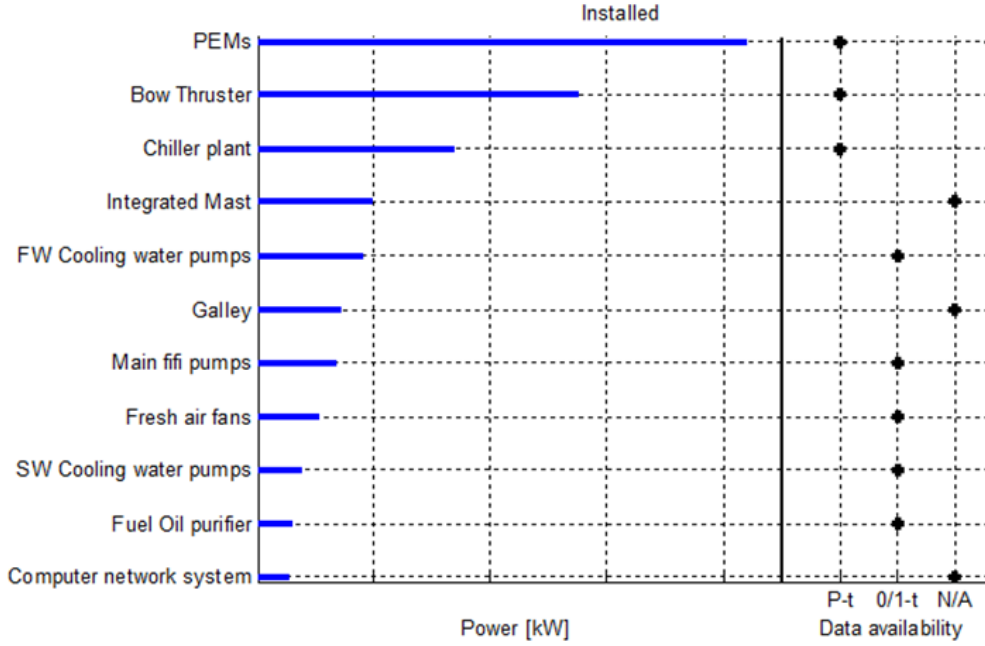


Figure omitted due to confidentiality

(b) The signals are logged in Comma Separated Value (CSV) files with a logging frequency of  $1/3$  Hz.

**Figure 15:** The available data come directly from the on-board Integrated Platform Management System (IPMS). No additional sensors are installed solely for the purpose of this research.

In order to determine which method of analysis is best for this research, it is important to describe which data are available. There are two types of signals: value signals and switch signals. Value signals are collected with a frequency of  $1/3$  Hz and contain information regarding items such as shaft torque and rotational speed, PEM power consumption and generator power production. Switch signals are collected every hour and anytime they change and contain information regarding the state (on, off, standby, etc.) of certain components, such as pumps, compressors, breakers and valves. Figure 15 shows a sample of the on-board IPMS and a sample of logged values. Figure 16 shows some of the



**Figure 16:** The installed power per consumer (group) and the availability of data. Some large users have no data available.

largest electric consumers and their data availability.

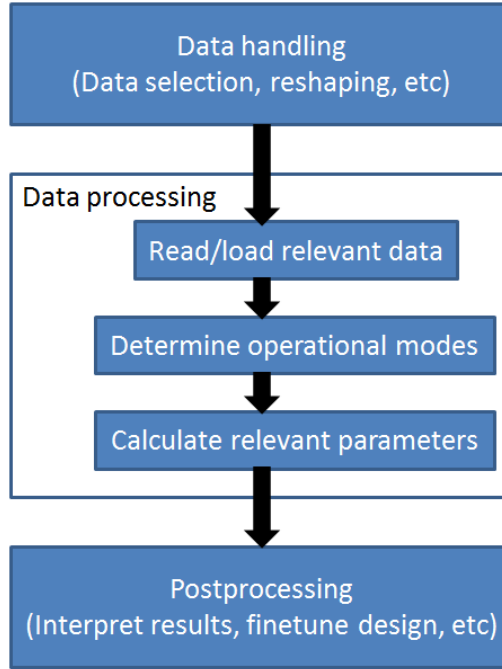
The operational use of an electric consumer is summarized in the service load factor  $k_s$ , as described in section 2.1.3. When the power consumption of a consumer is known, as is the case with for example the PEMs, the service load factor  $k_s$  is determined per operational mode. When only an on-off signal is available, as is the case with for example the Fuel Oil purifier, only the simultaneity factor  $k_2$  is directly determined. The load factor  $k_1$  can be determined indirectly, by observing the difference in total power consumption at the moment that the consumer is switched on or off. However, this indirect determination of  $k_1$  can be unreliable, because several consumers may be switched simultaneously and therefore distort the power estimation of individual electric consumers.

To solve the problem of indirect determination of the power consumption of certain consumers, additional measurements have been performed. Appendix C describes the method and results of these additional measurements. Measurements have been performed on the Zeeland while she was in the Carribean, performing duties as Station Ship Caribbean. Measurements were performed on four consumers: Chiller plant, Galley, Main firefighting pumps and Sea Water cooling water pumps. Besides physical measurements, interaction with the ships crew has given additional insights as to how the ship is used operationally. This information was used to improve the used algorithms and helps interpret results, which are discussed in Chapter 4.

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### 3.3 Selection of analysis method

The power-time data is available of some of the ships dominant consumers, but not of some smaller but still dominant consumers, as shown in Figure 16. Also, there is no signal that directly specifies the operational mode of the ship. Therefore the operational mode of the ship will have to be determined based on other signals, see section 3.1.2. This means that, in terms of Table 2, the data is such that fourth-best row applies.

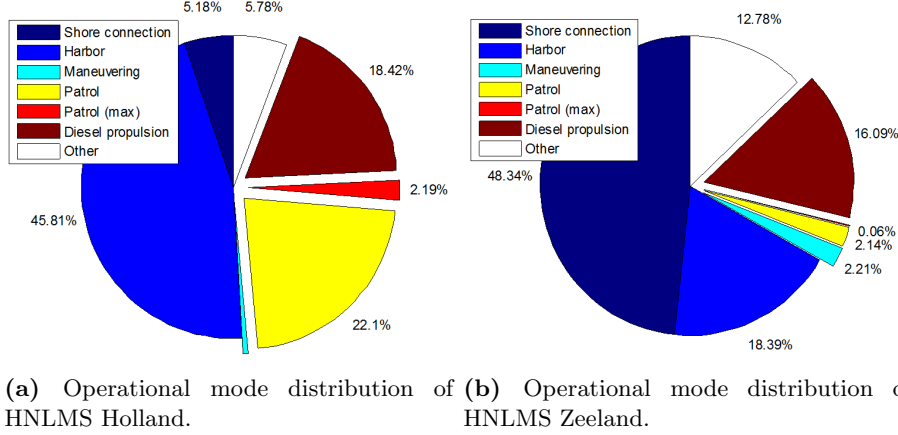


**Figure 17:** The data-analysis method used in this research consists of three steps.

Figure 17 shows the method of data-analysis used in this research. Firstly, the large datasets are organized and structured such that the processing tool can read the data properly. Then, the tool goes through its algorithms to read and analyse the data. This produces relevant parameters, in this research those parameters are the service load factors  $k_s$  of dominant consumers. Thirdly, a person must interpret the results to finetune the design of future ships. This process allows a shipyard to better design ships for their operational use, or *design for service*.

Considering the desired results, scope of this research and available dataset, the *A priori* method of analysis is used extensively. The clustering method is used in a small way, to demonstrate its use with a limited number of dataset dimensions and to compare the results of the clustering method to the *A priori* method.

## 4 Observed operational profile



**Figure 18:** The operational mode distribution of two OPVs. HNLMS Holland was used more outside of the harbour than the Zeeland in the analyzed research period.

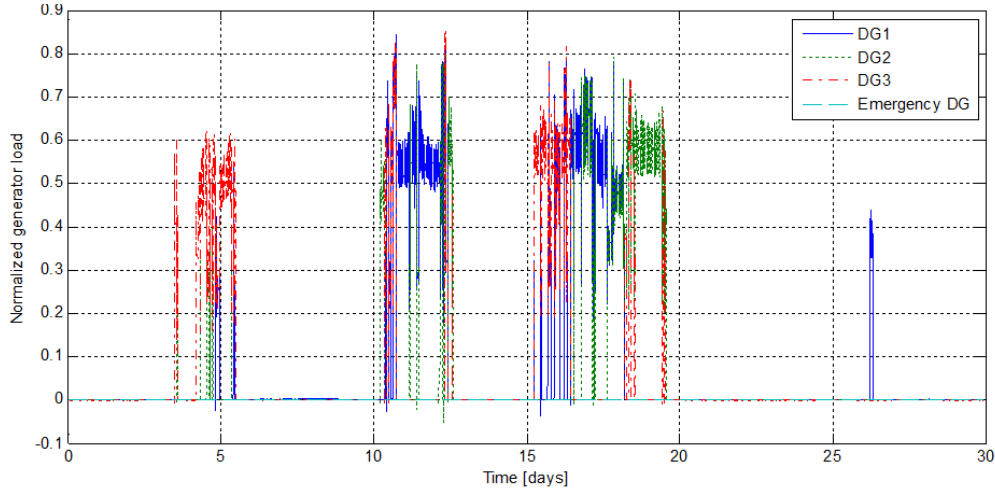
This chapter describes the operational use of the Holland class Oceangoing Patrol Vessel. Figure 18 shows the operational mode distribution of HNLMS Holland and HNLMS Zeeland over the entire set of available data. During the period outside of the harbor, HNLMS Holland sailed on its electric motors (*Patrol* and *Patrol (max)* modes) for more than 50% of the time, while the Zeeland sailed almost exclusively using its Diesel engines.

This chapter reviews five parts of the data-analysis. The first four parts concern the analysis of the available data using the “A priori” (i.e. using logic) analysis method. Firstly, the generator load during a typical month is described. Secondly, the operational use of selected large electric consumers, i.e. the dominating consumers, is described. Thirdly, the use of propulsion machinery is described. The propulsion machinery only has a significant influence on the electric energy consumption when the propulsion electric motors (PEMs) are used. Then, some variables that are expected to have a significant influence on the ships electric power consumption are discussed. Finally, the same set of operational data is analyzed using the “A posteriori” (i.e. using a clustering algorithm) method of analysis.

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## 4.1 Generator load

### 4.1.1 Observation

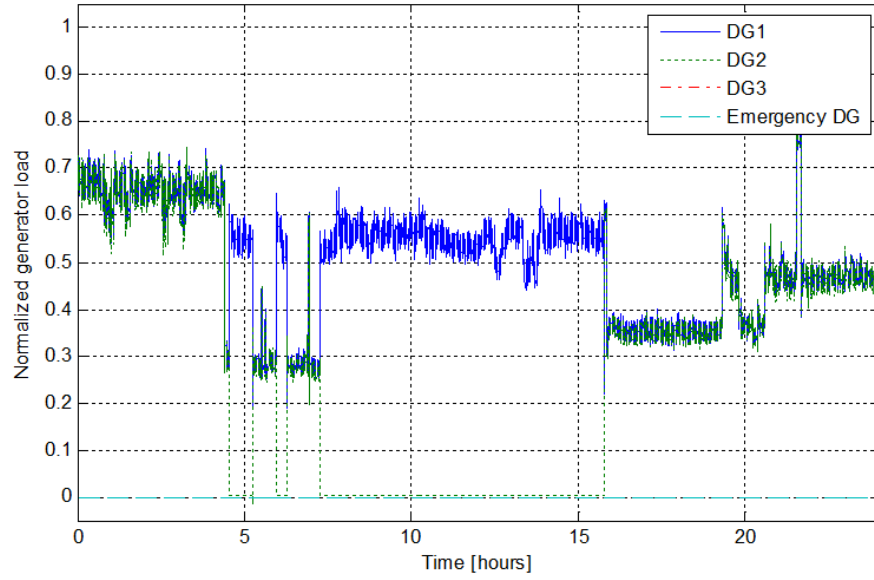


**Figure 19:** Typical generator load in a month of sailing of HNLMS Holland. One genset is often enough to handle the entire electric load, while sometimes two gensets are required.

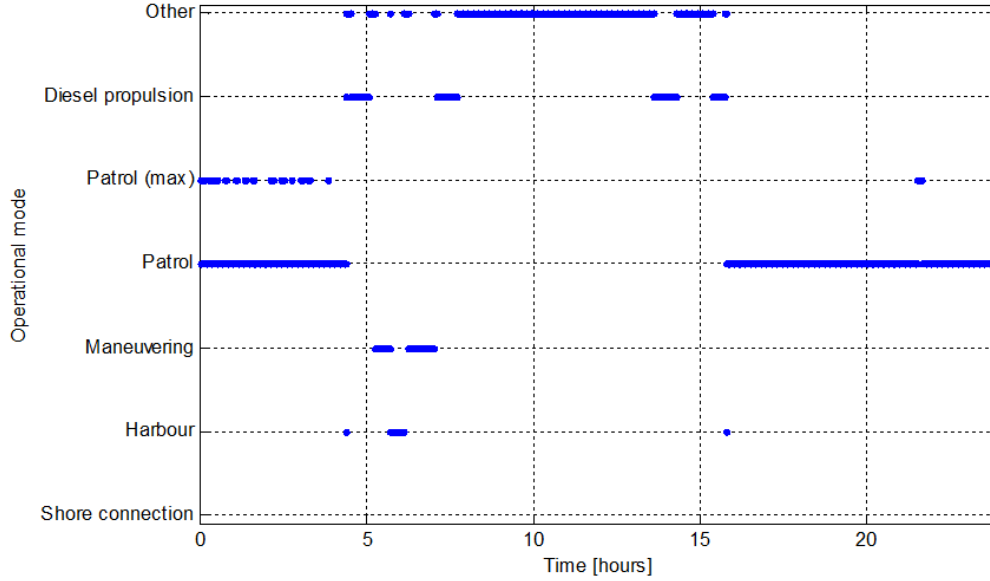
Figure 19 shows the electric load on the different gensets during a typical month of operation. This month includes some time spent in a harbour where a shore connection was available. During the largest part of the time when the ship does not use shore power, the entire electric load is covered with only one genset. The observed maximum load on a generator is around 85% of its rated load, while the observed average load during operation is around 50%. The fluctuations result from what the ship is doing; for example, when the PEMs are used or the chillers are heavily loaded, more electric power is required.

Figure 20a is comparable to Figure 19, only zoomed in when two generators are required simultaneously, on day 18. Figure 20b shows the operational mode of the ship during day 18. It can be seen that during the “Patrol” and “Patrol (max)” modes, two generators are engaged simultaneously, because the PEMs consume a large amount of electric power. Two generators are required during the first four hours of the day, as both generators are loaded above 50% of their rated load.

From hour 16 until hour 19, one genset would have sufficed to provide all required electric power. However, two gensets are engaged simultaneously and are loaded between 30 and 40%. The reason for this is possibly that the captain wanted to be able to quickly react to any situation. This situation seems to arise at hour 19, where the load of the gensets rapidly increases to above 50%. If a second genset would have to be started, the reaction time would significantly increase.



(a) Normalized generator load of HNLMS Holland on a day, when two gensets were simultaneously required.



(b) The operational modes of HNLMS Holland on a day when two generators were simultaneously required.

**Figure 20:** The operational mode of the ship influences the number of generators that are engaged simultaneously.

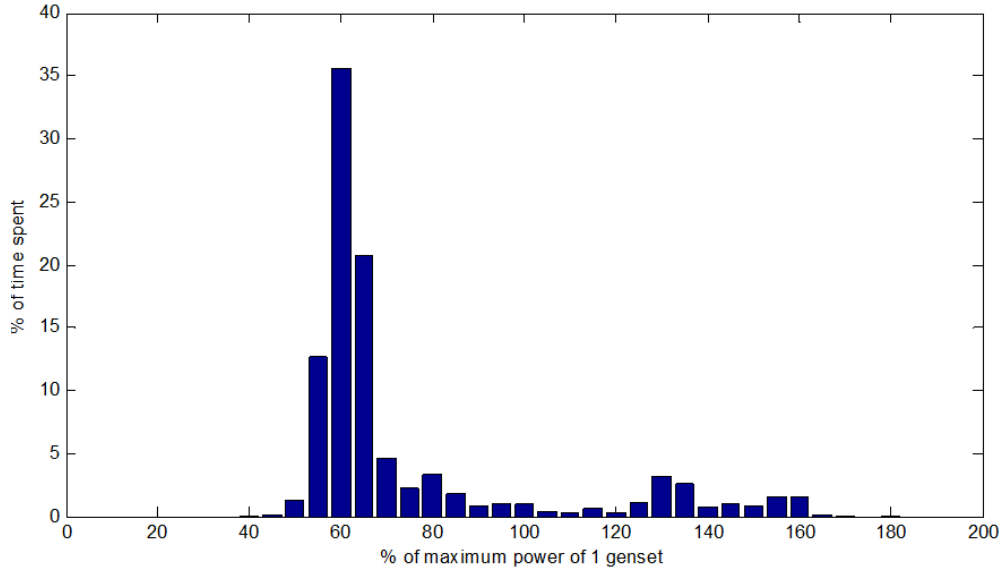
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Where the decision for engaging two gensets simultaneously during “Patrol” and “Patrol (max)” modes is quite straightforward, this decision is also made elsewhere. Two gensets are also simultaneously engaged while the ship uses diesel propulsion, intermittently between hours 5 and 8. Looking at Figure 20b, the ship is in “Maneuvering” operational mode some of this time. The captain likely anticipated that the ships bow thruster, a significant electric consumer, might be required during a longer period of time. This is a possible explanation for the fact that the generators are loaded at around 30% of their rated load for most of the time, while having peaks of 45% and 60% at hours 6 and 7 respectively.

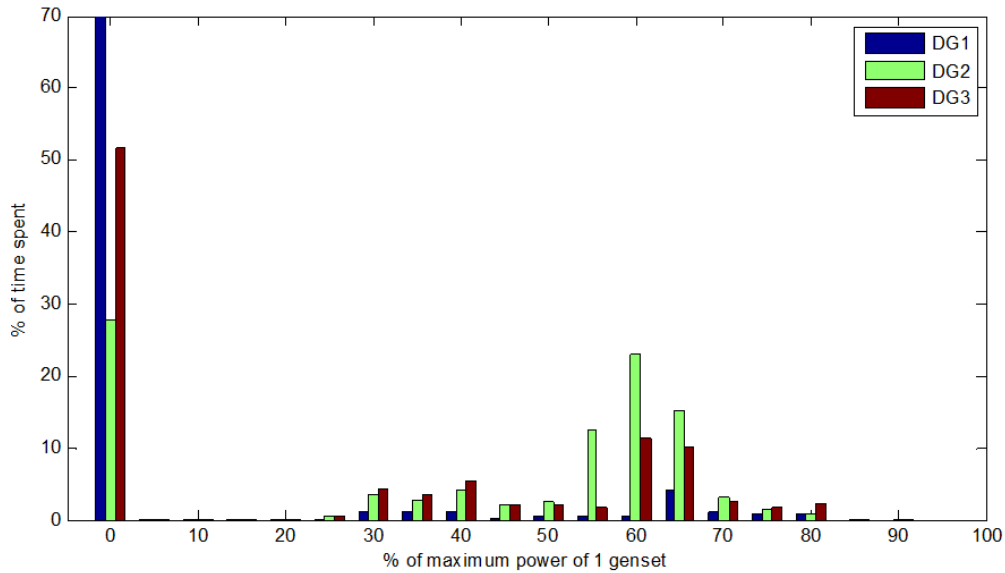
The relatively low generator loading (between 30% and 60%) during a total time of around 8 hours has a significant impact on the daily fuel consumption, as described in section 2.1.4.

Most of the time when the ship is sailing, one generator set can handle the entire electric load, as visible in Figure 21a. The total electric load is up to 60% of the rated load of one of the installed generators for around 70% of the time. As seen in Figure 21b, the individual generators are loaded mostly between 45% and 65% of their rated load. High generator loading, i.e. above 75%, is uncommon but not unused. As described in section 2.1.4, this generator load profile results in high specific fuel consumption and high specific emissions..





(a) The total generator load distribution of a ship, only considering the time that it is not in harbour. More than 100% load means that more than one genset is required.

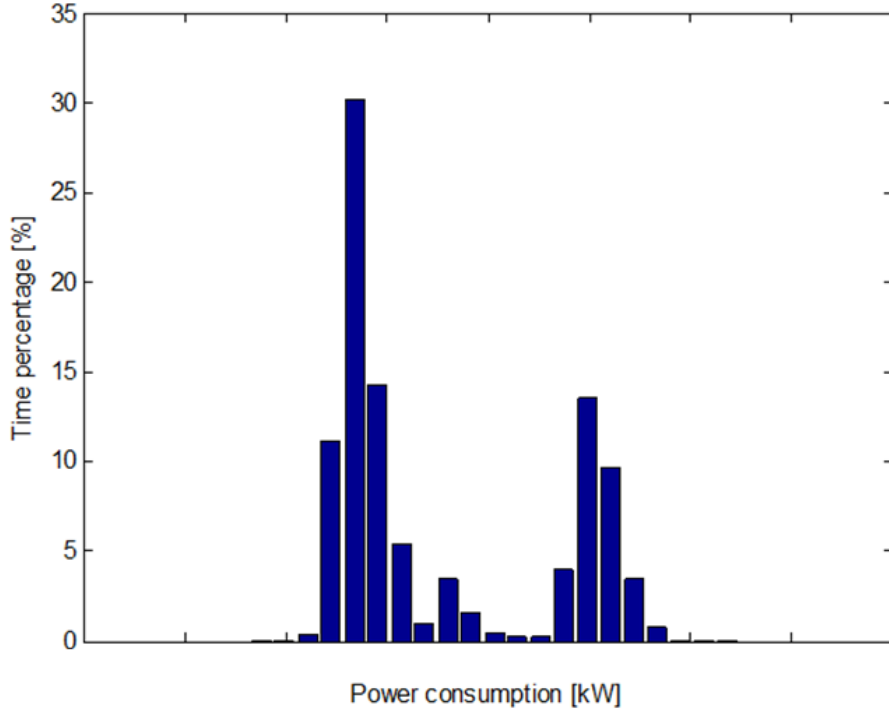


(b) The individual generator load distribution of a ship, only considering the time that it is not in harbour.

**Figure 21:** The total and individual load of the gensets on board of a Holland class OPV during August 2014.

### 4.1.2 Comparison to design

Figure 22 shows the electric power consumption time distribution in a typical month of sailing, while the ship is in Patrol mode. This distribution is used to determine mean and maximum electrical power, as well as fuel consumption. For all other operational modes, similar figures are shown in Appendix D.



**Figure 22:** The electrical power consumption distribution in the Patrol operational mode.

**Table 4:** The ratio of maximum consumed electric power to its design power in different modes of three Holland class OPVs.

Operational mode	Holland	Zeeland	Groningen
Shore connection	0.70	0.72	1.56
Harbour	1.07	0.99	0.83
Maneuvering	0.80	0.84	0.45
Patrol	0.90	0.80	0.87
Patrol (max)	0.86	0.75	0.77
Diesel propulsion	0.71	0.69	1.31

Table 4 shows the ratio of actual maximum power consumption to the expected maximum power consumption, according to Equation (5).

$$r_{max} = P_{max}/P_{ELB} \quad (5)$$

These maximum powers are taken from the distributions per operational mode as shown in Appendix D.1, such that less than this power is consumed at least 99% of the time. The closer the value in Table 4 is to 1, the better the estimate was. Most values are fairly close to 1, so the designers did well in estimating the maximum power consumption per mode. This results in an adequate sizing of the power generation machinery, resulting in no generator overload or loss of power during operation.

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**Table 5:** The ratio of average consumed electric power to its design power,  $r_{average}$ , in different modes of three Holland class OPVs.

Operational mode	Holland	Zeeland	Groningen
Shore connection	0.32	0.52	0.49
Harbour	0.78	0.64	0.55
Maneuvering	0.44	0.33	0.41
Patrol	0.64	0.52	0.72
Patrol (max)	0.77	0.68	0.73
Diesel propulsion	0.56	0.46	0.46

Table 5 shows the ratio of actual average power consumption to the expected average power consumption, see Equation (6).

$$r_{average} = P_{average}/P_{ELB} \quad (6)$$

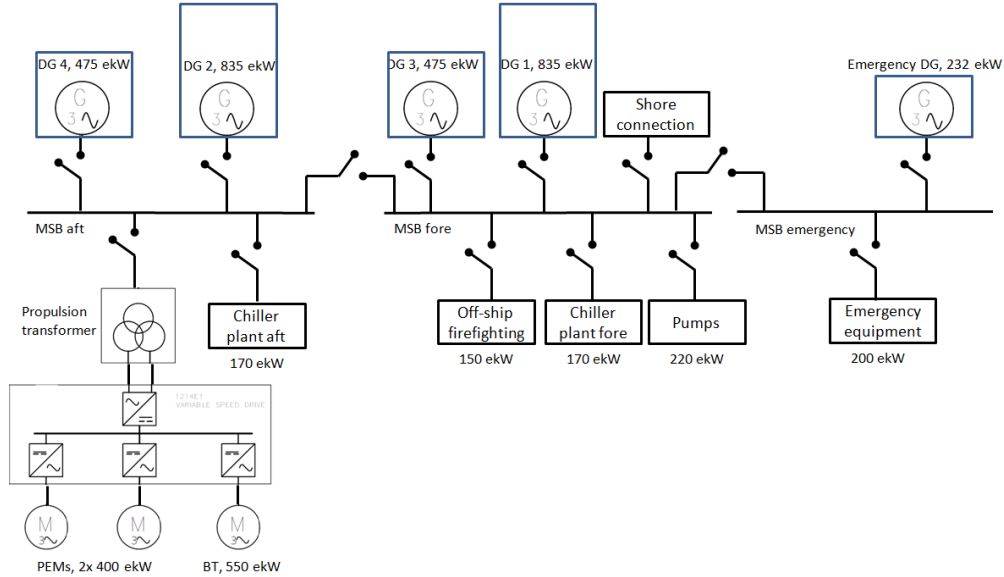
Results of only three of the four ships are listed, because there was not enough data available of the Friesland. This table gives an insight in the performance of the generator sets in terms of fuel consumption, and can be used for Life Cycle Cost calculations as well. The ratio of actual average power consumption to expected power consumption varies between 0.3 and 0.8. There are significant differences between ships, for example in Patrol mode the ratio varies between 0.521 and 0.723 for different ships.

### 4.1.3 Alternative generator setup

**Table 6:** Mean and maximum electric power consumption as observed on HNLMS Holland. Shore Connection mode is not relevant for generator setup selection, only for the dimensioning of shore connection equipment.

Operational mode	Shore	Harbor	Maneuv.	Patrol	Pat. (max)	Diesel
Mean power [kW]	327	547	655	1040	1413	594
Maximum power [kW]	420	745	1180	1420	1580	750
ELB Estimate [kW]	657	698	1375	1620	1839	1045

Based on the observed maximum and mean powers as listed in Table 6, an alternative generator plant setup is described. As described in Section 2.2.4, the Holland class OPVs are equipped with 3 DG sets of 920 kW. Two of these gensets are enough to provide all of the ships required electric power, one extra genset is installed for redundancy purposes.



**Figure 23:** A simplified Single Line Diagram of the father-son configuration. This configuration consumes less fuel and has better redundancy than the installed generator setup.

An alternative generator plant consists of two 835 kW “Father” DG sets (one is for redundancy) and two 475 kW “Son” DG sets, as Figure 23 shows. According to engineers involved in the design phase, these genset sizes are commercially available and were considered as possibilities in the design phase. Choosing this setup results in a total installed genset power of 2620 kW instead of 2760 kW. Assuming the installation cost of a DG set scales with the power rating, this 5% reduction in installed power results in 5% lower installation costs.

**Table 7:** DG loading of the actual generator configuration (3x 920 kW) and the proposed alternative configuration (835 kW + 2x 475 kW). The largest difference is seen in the Patrol operational mode, when the observed mean power is required.

	Mean DG load [%] (#DGs used [-])		Maximum DG load [%] (#DGs used [-])	
Operational mode	Actual setup	Father-son setup	Actual setup	Father-son setup
Harbor	59.46 (1)	65.51 (1)	80.98 (1)	89.22 (1)
Maneuvering	71.20 (1)	78.44 (1)	64.13 (2)	90.08 (2)
Patrol	56.52 (2)	79.39 (2)	79.35 (2)	81.79 (3)
Patrol (max)	76.79 (2)	79.16 (3)	85.87 (2)	88.52 (3)
Diesel	64.57 (1)	69.88 (1)	71.14 (1)	89.82 (1)

Table 7 shows the genset loading of the actual configuration and the proposed father-son configuration. Values in this table are based on load splitting between gensets proportional to their maximum power. A higher loading results in a lower specific fuel consumption, as described in Section 2.1.4. All operational modes show an improvement in performance, with the largest difference in the Patrol operational mode. One method of calculating the fuel consumption is using the average load and its associated specific fuel oil consumption:

$$Fuel\ consumption = P_{average} \times sfoc(P_{average}) \quad (7)$$

Assuming a specific fuel consumption as shown in Figure 8 and Equation (7), the 23% higher loading in Patrol mode results in 12.7 g/kWh of fuel consumption saved. Given the operational mode distribution in Figure 18a, this 6.1% fuel saving is a significant improvement.

$$Fuel\ consumption = \sum P_i \times sfoc(P_i) \quad (8)$$

**Table 8:** Fuel consumption of the gensets in the ships operational modes. If the load profile has a strongly varying load profile, the fuel consumption must be calculated according to Equation (8) to obtain accurate results.

	Fuel consumption, using Eq. (7) [kg/h]		Fuel consumption, using Eq. (8) [kg/h]	
Operational mode	Actual setup	Father-son setup	Actual setup	Father-son setup
Harbor	113.0	110.8	112.4	110.2
Maneuvering	130.7	128.7	126.2	123.6
Patrol	217.2	204.0	181.3	177.0
Patrol (max)	278.5	277.3	279.9	278.7
Diesel	120.7	118.5	115.1	113.0

However, this method of calculating fuel consumption is inaccurate for strongly varying load profiles, such as the one shown in Figure 22. Table 8 lists the

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fuel consumption of the gensets per mode, as calculated using the two different methods. Using Equation (8) yields roughly the same fuel consumption as Equation (7) for operational modes that have a narrow bandwidth of power consumption. Using Equation (7) is always accurate, but requires more information about the electrical load profile. The father-son configuration uses 0.4% to 2.4% less fuel to generate electricity than the currently installed configuration.

An added benefit of the father-son setup is an improvement to the ships power generation redundancy. In the current setup, the three gensets are positioned in two engine rooms. If, for whatever reason, one of the two engine rooms becomes unavailable, one or two gensets are unavailable (depending on which engine room is unavailable). In the worst case scenario,  $2/3$  of the electric power is not available. Using the father-son setup, the power generation capacity can be split evenly over two engine rooms. In this setup, only half of the power generation capacity is lost when an engine room is lost.

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## 4.2 Use of dominant electric consumers

This section describes the operational use of a number of large consumers on the Holland class OPV. The largest electric power consumers on the Holland class Oceangoing Patrol Vessel, with available data, include:

- Chilled water AC compressor plants
- Fresh water and sea water cooling water pumps
- Engine room ventilation fans
- Fuel Oil purifier
- Propulsion electric motors (PEMs)
- Bow thruster

The PEMs consume power exclusively in the Patrol and Patrol (max) operational modes, while the Bow Thruster only consumes power in the Maneuvering operational mode. The operational data is available in two types: either a power consumption signal, or an on-off signal. The type of available operational data defines the quality of the analysis, as described in section 3.1.1.

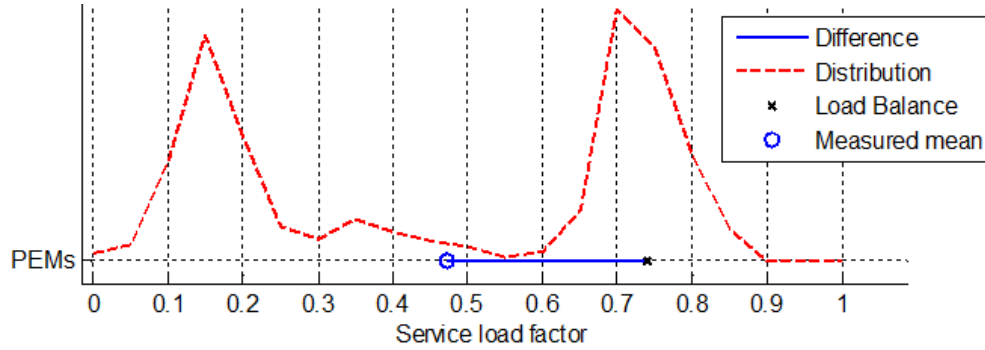
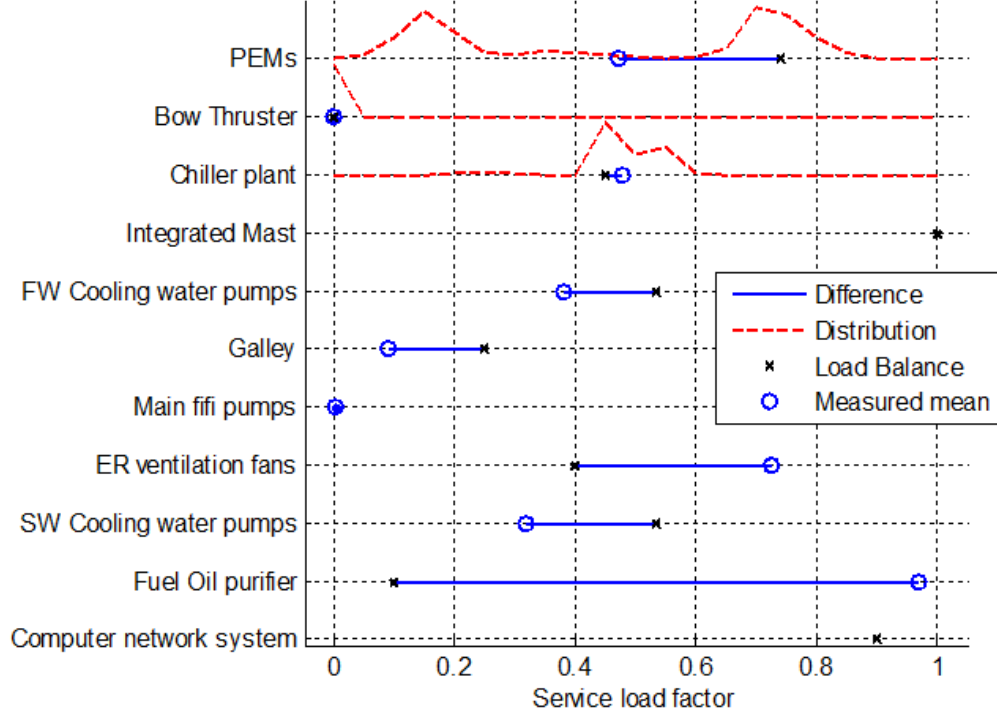


Figure 24

Figure 24 shows the comparison of the PEM observed and expected service load factor  $k_s$ , and its observed distribution. The black cross indicates the estimate as given in the Electric Load Balance, while the blue circle indicates the actual service load factors. The red dotted line shows the power consumption distribution, the blue circle is the average value of this distribution. This distribution is only available when a power-time signal is available for the consumer in question, as described in Section 3.2.

### 4.2.1 Observation

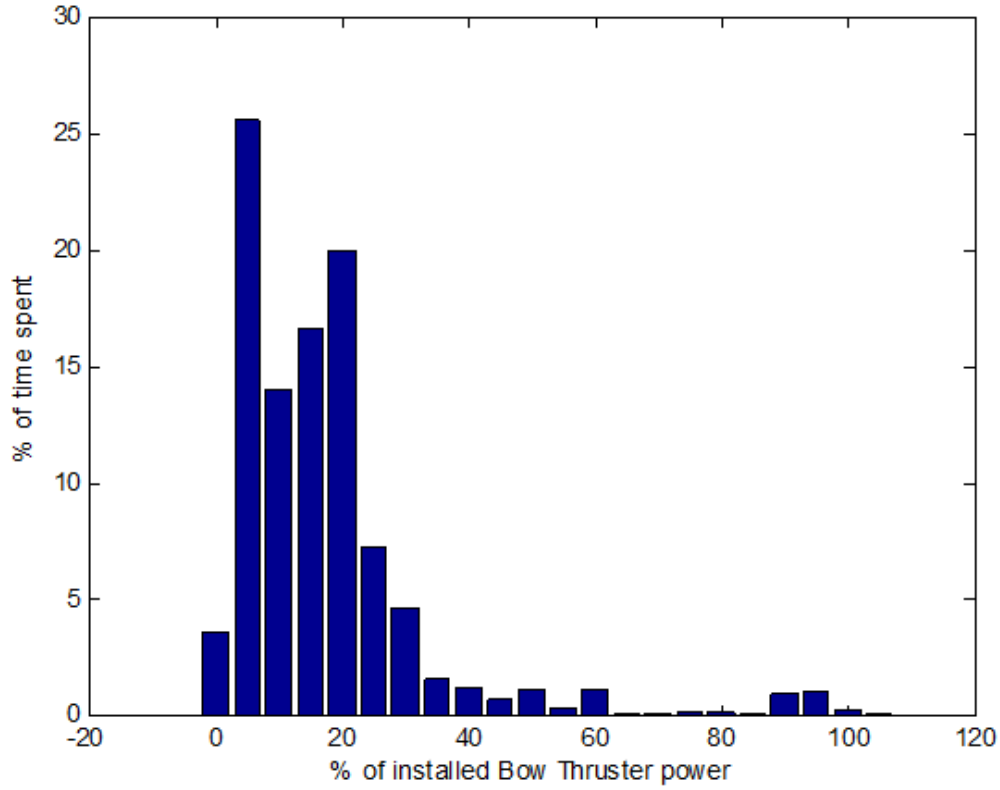


**Figure 25:** The observed service load factors in Patrol mode for some of the dominant consumers. The dashed lines show that a large portion of the time is spent at the estimated load factor by the PEMs and chillers.

Figure 25 shows the observed service load factors  $k_s$  in the Patrol mode, similar figures are shown for all other operational modes in Appendix D.2. The Engine Room ventilation fans have two settings: High and Low. The service load factor is a combination of the operational time in each setting and the corresponding load fraction (0.3 for Low, and 0.9 for High):  $k_{s, ER fans} = 0.3 \times k_{2, low} + 0.9 \times k_{2, high}$ . For the rest of the consumers, the shown value is the product of the (observed) time fraction of operation and (measured or observed) average power consumption when the consumer is switched on.

The PEMs are used primarily at two operational points, at  $k_s = 0.15$  and  $k_s = 0.7$ . This suggests that the definition of the Patrol operational mode is not specific enough, and could be split into two operational modes. Another possibility is to define the load of dominant consumers as a distribution, rather than exclusively as an average value. The use of the PEMs is described in more detail in Section 4.3.





**Figure 26:** The time distribution of the Bow Thruster power absorption, only considering the time it absorbs any power. Most of the time, the bow Thruster is loaded below 40% of its rated power.

Another dominant consumer is the Bow Thruster, which is used exclusively in the Maneuvering operational mode. Figure 26 shows the power-time distribution of the Bow Thruster, only considering the time it is used. The Bow Thruster rarely consumes more than 40% of its rated power, and very rarely consumes between 60% and 85% of its rated power. The Bow Thruster consumes close to its maximum power for approximately 2% of the time. No correlation was found between Bow Thruster power and propulsion power.

## 4.2.2 Comparison to design

	Shore connection			Harbor			Maneuvering			Patrol			Patrol(max)			Diesel propulsion		
	ELB	Analysis	Difference	ELB	Analysis	Difference	ELB	Analysis	Difference	ELB	Analysis	Difference	ELB	Analysis	Difference	ELB	Analysis	Difference
PEMs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74	0.47	-0.27	1.00	0.93	-0.07	0.00	0.00	0.00
Bow Thruster	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.17	-0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chiller plant	0.20	0.16	-0.04	0.30	0.46	0.16	0.45	0.44	-0.01	0.45	0.48	0.03	0.45	0.47	0.02	0.45	0.39	-0.06
FW pumps	0.27	0.38	0.11	0.53	0.38	-0.15	0.53	0.38	-0.15	0.53	0.38	-0.15	0.53	0.38	-0.15	0.53	0.38	-0.15
Galley	0.20	no data		0.25	0.09	-0.16	0.25	0.09	-0.16	0.25	0.09	-0.16	0.25	0.09	-0.16	0.25	0.09	-0.16
FIFI pumps	0.27	0.00	-0.27	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ER ventilation fans	0.40	0.23	-0.17	0.40	0.56	0.16	0.80	0.64	-0.16	0.40	0.72	0.32	0.40	0.74	0.34	0.80	0.63	-0.17
SW pumps	0.27	0.00	-0.27	0.80	0.15	-0.65	0.53	0.31	-0.22	0.53	0.32	-0.22	0.53	0.31	-0.22	0.53	0.32	-0.21
Fuel Oil Purifier	0.25	0.00	-0.25	0.00	0.92	0.92	0.40	1.00	0.60	0.10	0.97	0.87	0.10	0.98	0.88	0.60	1.00	0.40

**Figure 27:** The service load factors  $k_s$  of the dominant consumers in all operational modes, as expected in the Electric Load Balance versus their observed value.

Figure 25 shows that for some consumers, the estimated service load factor was too low, while for others it was estimated too high. In other words, there is no consistent sign of the direction of the difference between estimated and actual values. Comparing Figure 25 with the Figures in Appendix D.2, and using Figure 27, some observations are made:

- The Bow Thruster is used significantly less than expected in the Maneuvering operational mode, as it uses a small amount of power for a large portion of the time. Figure 26 shows the distribution of its power consumption.
- The chiller plant estimation is consistently close to its actual value, with the exception of the Harbor operational mode. In the Harbor operational mode, the chiller service load factor  $k_s$  was 0.48 instead of 0.3.
- The power consumption of the Fresh Water cooling water pumps is independent on the ships operational mode. This is similar to the ELB, but the power consumption is estimated too high in the ELB. The Sea Water pumps show a similar result, except they are used significantly less than expected in the Shore Connection and Harbor operational modes. Both these differences are most likely due to the lower than expected continuous power consumption of the pumps (in other words, the load fraction  $k_1$  is lower than anticipated, while the time fraction  $k_2$  is as expected). Testing equipment before implementing it on a vessel prevents this type of mistake for future ships.
- The Engine Room ventilation fans are estimated too high when the Diesel engines are used (in the Maneuvering and Diesel Propulsion operational modes). Both modes have a similar service load factor of 0.63. They are estimated too low in the Patrol and Patrol (max) modes. The largest difference is seen in the Patrol (max) operational mode, where the service load factor  $k_s$  is 0.7352 instead of 0.4. The PEMs reduce speed by dissipating heat in resistance brakes, which are located in the engine room. To compensate for this heat dissipation, the ventilation fans must be used more intensely.
- The Fuel Oil Purifier is used differently than expected. In almost all operational modes, the actual service load factor  $k_s$  is higher than expected,

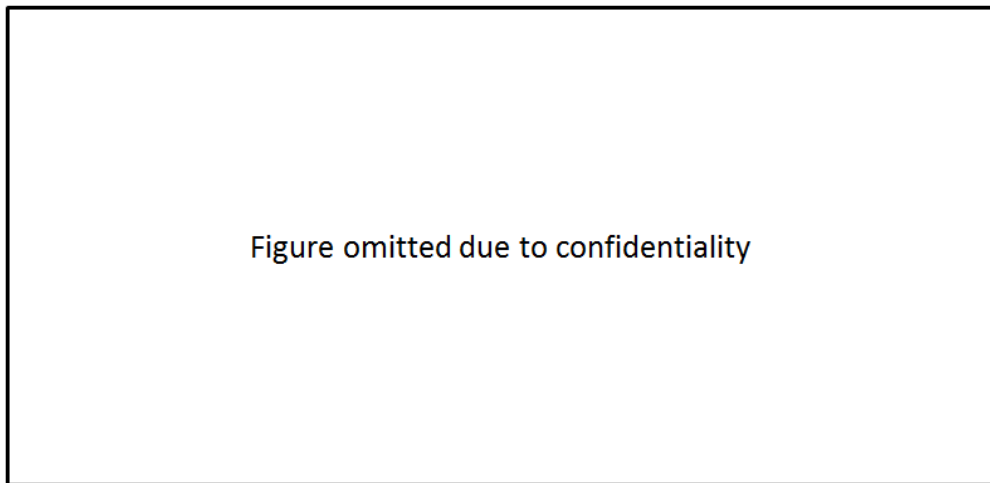
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and in the Shore Connection operational mode the actual value is lower than expected. In all sailing modes (Patrol, Patrol (max), Maneuvering and Diesel modes), the actual value is around the same value: 0.97 to 1.

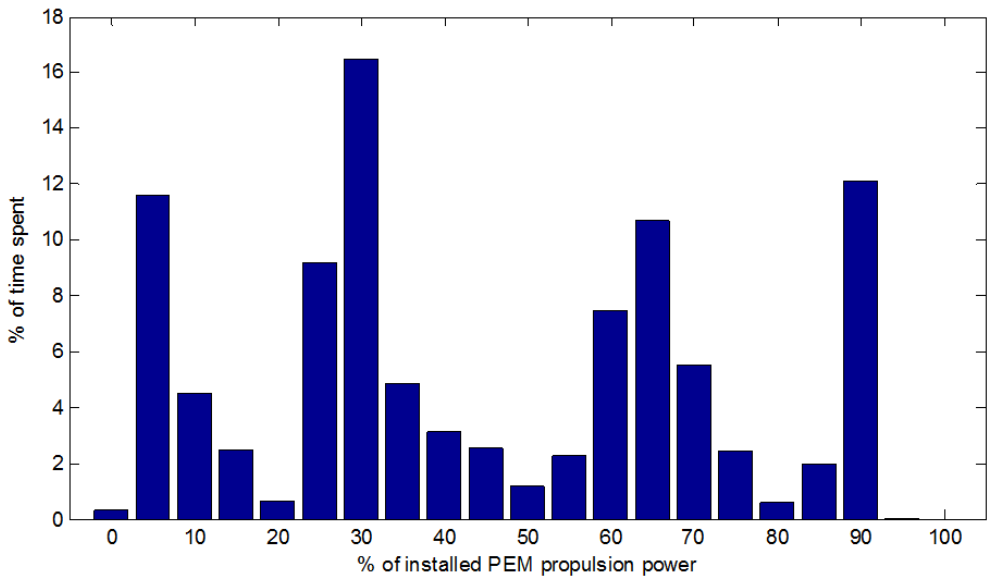
- Multiplying the observed service load factors of the dominating consumers (or, in the case of the PEMs, the maximum observed  $k_s$ ) with their respective installed power accounts for 65% to 85% of the observed maximum power per operational mode. The lower value of 65% suggests more large power consumers should have been taken into consideration, such as the IMM or Computer Network. Unfortunately, no operational data is available of these consumers, as described in Section 3.2.
- In general, most service load factors are estimated too high in the Electric Load Balance in most operational modes. This results in a lower total power consumption than expected, as described in Section 4.1. This results in a ship that (almost) never loses electrical power, but has too large generator sets.

## 4.3 Use of propulsion machinery

### 4.3.1 Observation



(a) The operational envelope of the starboard Propulsion Electric Motor of HNLMS the Holland.



(b) The load distribution of the Propulsion Electric Motors of HNLMS Holland, while they are engaged.

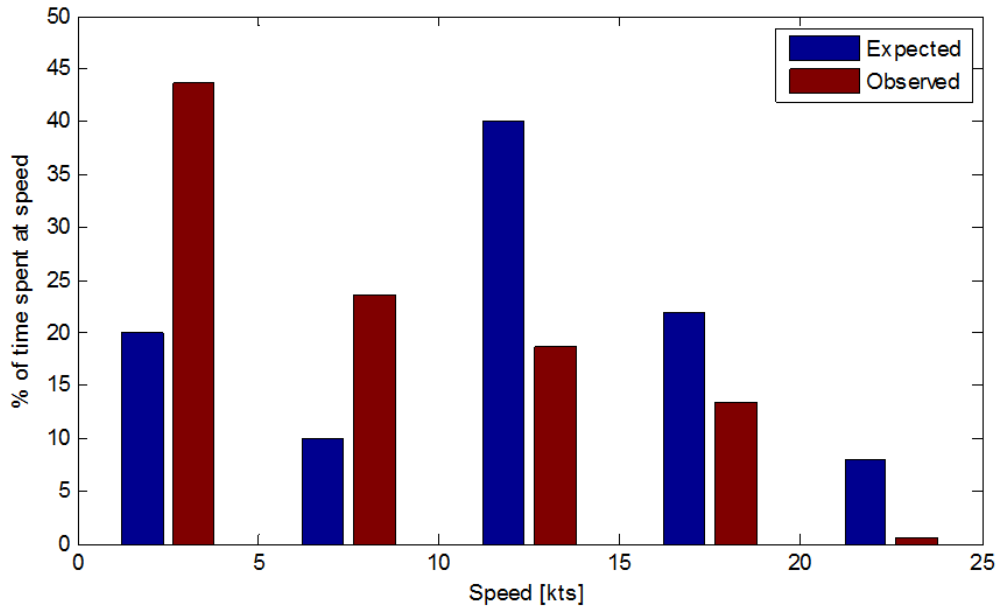
**Figure 28:** The operational envelope and load distribution of the Propulsion Electric Motors of HNLMS Holland in June 2014.

As this report focuses on the electric energy distribution system, only the use of the Propulsion Electric Motors, not the use of the Diesel engines, is described in this paragraph. Figure 28a shows the measured operational envelope of the starboard PEM. A number of data point clusters are visible, around 900 rpm, 1180 rpm, 1260 rpm and 1520 rpm. Limits of the motor, such as minimum ro-

tational speed, maximum torque and maximum power, are clearly visible. The minimum rotational speed is not so much a limit of the motor as it is a limit of the propeller shaft, as the shaft needs to have a certain minimal rotational speed to ensure proper lubrication in all of the bearings. The PEMs are limited in torque by the maximum armature current, to prevent overheating of the rotor windings [6].

Figure 28b shows the load distribution of the PEMs during a typical month of sailing, ignoring the time that the PEMs are not engaged. It shows four peaks in the use of the PEMs; low, medium, high and maximum load are the most common in the operational load distribution. The loads between these four peaks are used less frequently.

### 4.3.2 Comparison to design



**Figure 29:** The time distribution of sailing speed intervals. The OPVs sail slowly more often than expected.

Figure 29 shows the difference between the expected and observed speed distribution of the OPVs. The ships sail slowly more often than expected during the design phase. The maximum sailing speed was very rarely used in the research period. This results in a significantly lower fuel consumption than expected.

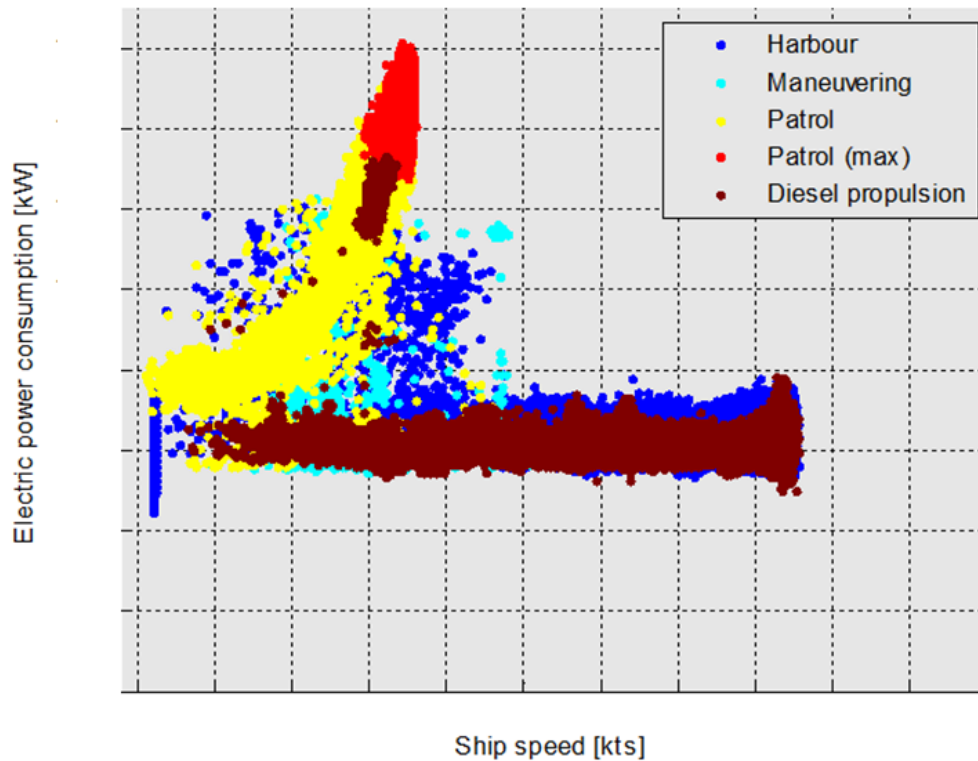
The deviation from the expected speed profile is due to the type of operations of the ships. The observed ships mostly sailed patrol missions, where presence in an area is required for extended periods of time. The ship sails around in the area, responding to intelligence from third parties or own observations. Rapid action is undertaken using small interception crafts or a helicopter. The ship therefore does not need to sail fast for a large portion of the time.

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## 4.4 Variables influencing the electric power consumption

During the design phase, designers often assume a relation between power consumption of a ship and certain operational or environmental variables. Two variables with an expected relation to the ship electrical power consumption are ship speed and outside air temperature.

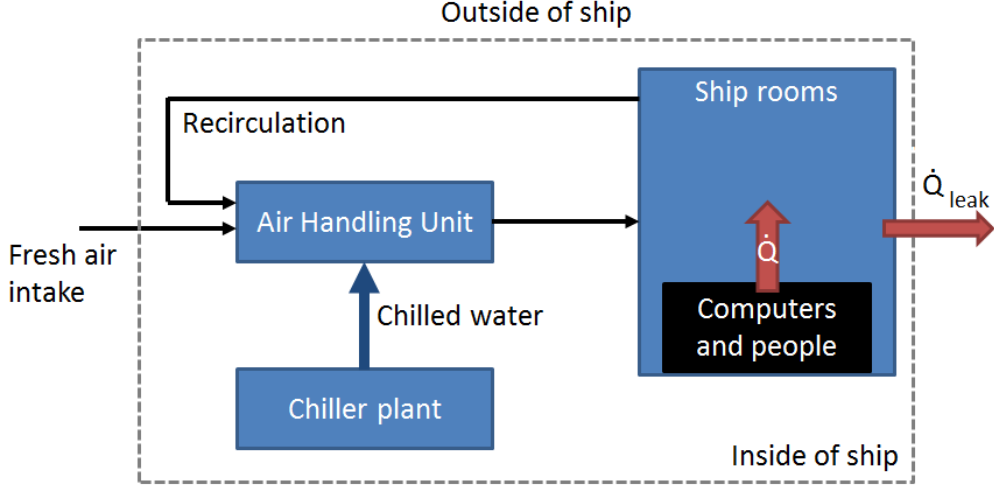
### 4.4.1 Ship speed



**Figure 30:** Ship speed only influences the electric power consumption in certain operational modes.

Figure 30 shows the relation between ship speed and the total power electrical power consumption of the Holland class OPV. Firstly, in the Patrol and Patrol (max) operational modes, there is a clear relation between ship speed and power consumption. In these modes, all propulsion power is provided by electric motors, so the speed-dependency is to be expected. While the ship uses Diesel propulsion, there appears to be no relation between ship speed and total electric power consumption. Secondly, there seem to be some mode misidentifications by the algorithm. The high power consumption in maneuvering mode is due to the use of an electrically-powered bow thruster.

#### 4.4.2 Outside air temperature



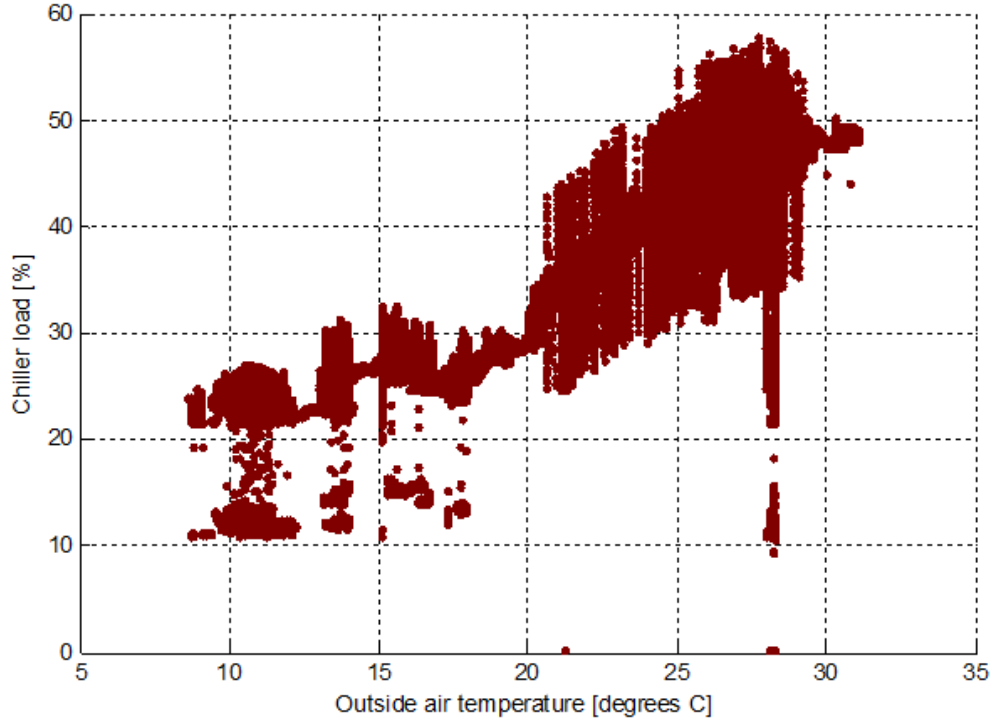
**Figure 31:** Schematic representation of the ships air conditioning system. People and computers are a heat source inside the ship, while there is also heat flow across the ship hull.

Figure 31 schematically shows the air conditioning system, with two types of heat fluxes that influence the load on the Air handling Units (AHUs). The first is the heat flux through the ship hull, which should be as close to zero as possible because of proper insulation. Any heat flux through the ships hull results in either a required cooling or heating of the recirculation air, both of which are negative effects. The second, and more significant, heat flux is the production of heat by equipment and personnel in the ship. This heat flux is dependent on the ambient (in-ship) temperature, which is approximately constant. This constant ambient temperature results in a constant heat production in the ship, and therefore a constant load on the chillers.

Figure 32 shows the chiller plant load as a function of the outside air temperature. To improve readability, only measurements from the Diesel operational mode are shown. The constant chiller load, resulting from in-ship heat production, is visible in the chiller load below approximately 16 °C. The chiller plant load increases from 25% to 48% approximately linearly (as is to be expected [11]) with increasing temperature from 16 °C to 30 °C. This translates to an increase in power consumption of around 80 kW.

$$P_{chiller} = \dot{m} \times (h_{incoming} - h_{outgoing}) \quad (9)$$

The power consumption of the chiller plant depends on two parameters: the mass flux and the specific enthalpy difference over the plant, see equation (9). The specific enthalpy of a gas depends on its composition and temperature. Assuming a constant temperature and humidity setpoint,  $h_{outgoing}$  is constant. The required mass flux through the chiller plant  $\dot{m}$  depends on the number of people on board, as the produced carbon dioxide and water vapour must be ventilated properly. For practical reasons, the mass flux through the chiller

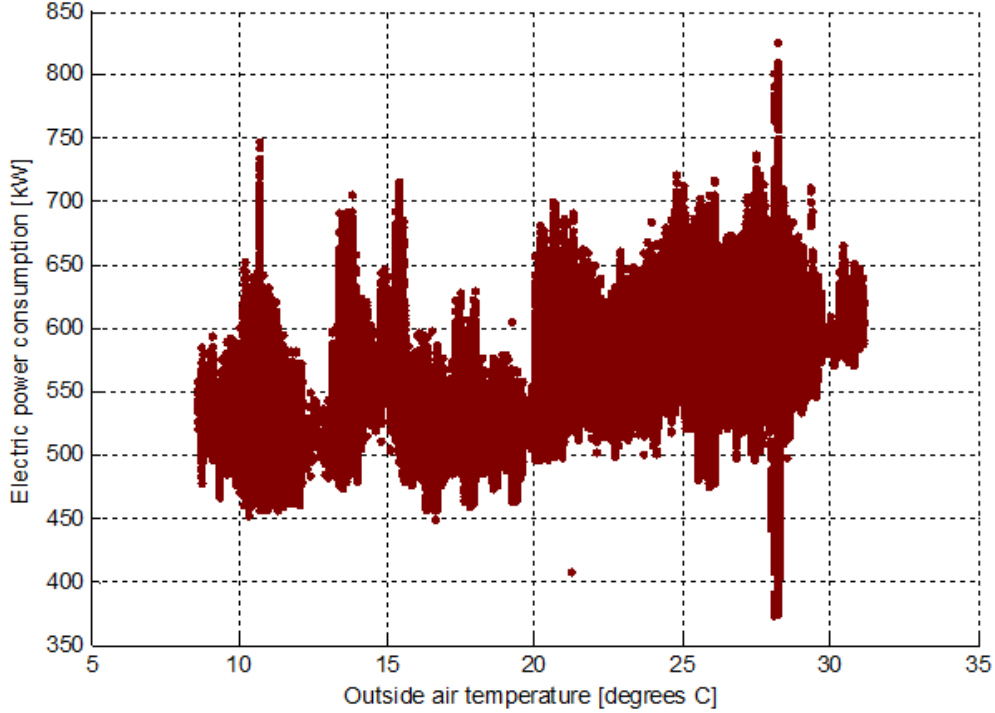


**Figure 32:** The outside air temperature influences the chiller load, as is to be expected. The chiller plant provides the cooling capacity for the HVAC system.

plant is often set to a constant value. Assuming a constant amount of people on board, the mass flux is constant. The only remaining parameter that influences the power consumption of the chiller plant is therefore the specific enthalpy of the outside air,  $h_{incoming}$ . This results in the visible linear temperature dependency of chiller load on outside air temperature.

Figure 33 shows the total electric power consumption of the ship as function of the outside air temperature, in Diesel operational mode. The power consumption increases approximately linearly with temperature, from around 520 kW at 16°C to around 600 kW at 30 °C. This power consumption increase and the general trend in the graph exactly follow the characteristic of the chiller load as shown in Figure 32. The temperature-related increase in power is therefore assumed to depend exclusively on the chiller plant. The Engine Room ventilation fans are not found to consume more electric power as the outside air temperature rises.





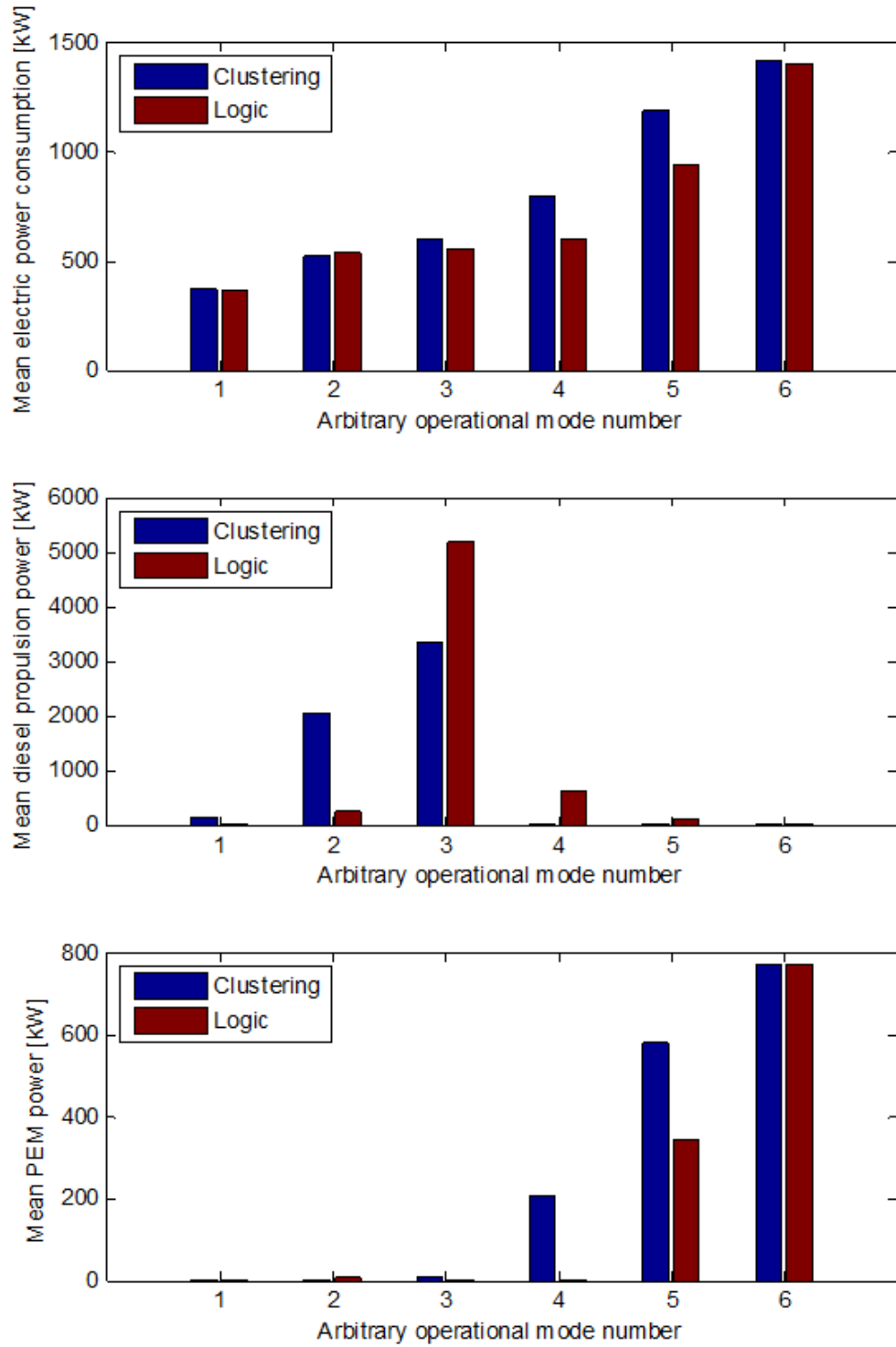
**Figure 33:** The power consumption increases with the outside air temperature, due to increased power consumption of the chiller plant.

## 4.5 Cluster analysis

In contrast to the “A priori” (logic) method of analysis, “A posteriori” (clustering) analysis is an alternative method. The data has been clustered based on one variable: the total electric power consumption. Manual selection of six clusters results in Figure 34 for an arbitrary month of data. The clustering algorithm yields three clusters that have similar average power consumption as the average power consumption of the “A priori” method: clusters 1, 2 and 6.

A difference between the results from the “A priori” and Clustering analysis is the number of PEM-propulsion modes. The clustering analysis yields three modes with different PEM power consumption means, while the logic method only has two modes. This result is to be expected from the results shown in the  $k_s$ -distribution in Figure 25, where two typical PEM power consumption modes are found within the Patrol operational mode.

The limited results obtained from this cluster analysis give a first insight into the differences in results when using different methods of analysis. However, as one of the main objectives of this research is to compare the operational use of a ship to its design considerations, cluster analysis will not be further used. The overlap between the clustering results and the modes as defined in the ELB is too small to make a proper comparison between the two.



**Figure 34:** The used clustering algorithm finds three modes where the diesel engines are used, and three modes where the PEMs are used. Operational mode 2, 3 and 4 have similar mean total electric power consumption.

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## 5 Sensitivity and uncertainty

Uncertainty analysis is defined as the study of how uncertainty in the output of a model can be apportioned to different sources of uncertainty of the model input [13]. This analysis consists of two parts: firstly a study of how the output  $z$  of a model changes with a change in its input  $x$  ( $\partial z/\partial x$ ), and secondly how the uncertainty of an input  $x$  influences the uncertainty of the output  $z$  ( $\sigma_x \rightarrow_z$ ). To improve clarity, the first portion of the analysis is referred to as “Sensitivity analysis”, while the second portion of the analysis is referred to as “Uncertainty analysis”.

The inputs in this analysis are the service load factors  $k_s$  per operational mode of the dominant electrical consumers. The output is the total electric power consumption per operational mode. These inputs and outputs are chosen, because they determine the choice of the power generation plant.

### 5.1 Sensitivity analysis

The goal of the sensitivity analysis is to determine how a change in an input affects the outputs of the system or model in question. There are various ways to perform sensitivity analysis, such as the Linearization method [14], using scatter plots or using Variance-based methods. In this report, the Linearization method is chosen because it best suits the output function.

$$P_{E, total} = \sum_{i=1}^n k_{s, i} \times P_{max, i} \quad (10)$$

$$P_{E, total} = k_{s, PEM} \times P_{max, PEM} + k_{s, chillers} \times P_{max, chillers} + k_{s, FW pump} \times P_{max, FW pump} + \dots \quad (11)$$

As described in Section 2.1.2, the average electric power consumption per operational mode is the sum of average powers of all individual electrical consumers, see equation (10). Equation (11) shows three terms for the Holland class Ocean-going Patrol Vessel. This makes the sensitivity analysis fairly straightforward: all  $\partial z/\partial x$  are equal to the rated power of the electrical consumer in question. So for the service load factor of the Propulsion Electric motors, input  $k_{s, PEM}$ ,  $\partial z/\partial x = P_{max, PEM}$ . Similarly, for the service load factor of the chillers, input  $k_{s, chillers}$ ,  $\partial z/\partial x = P_{max, chillers}$ . These sensitivities are the same for each operational mode, as the rated power of each consumer is independent of the operational mode of the ship.

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## 5.2 Uncertainty analysis

The goal of the uncertainty analysis is to determine the uncertainty of the output (total electric power consumption), based on a given uncertainty of input variables (service load factors  $k_s$  of dominant consumers). This uncertainty dependency is directly linked to the sensitivity analysis. The sum of  $N$  normally distributed independent variables is also normally distributed, with the mean of the sum  $\mu_{sum}$  being the sum of the means  $\mu_i$ . The variance of the sum  $\sigma_{sum}^2$  is then equal to the sum of the variances  $\sigma_i^2$  [15]. Suppose the service load factors  $k_s$  of the dominant electric consumers are normally distributed.

### 5.2.1 Quatization of specific uncertainties

Three types of specific uncertainties are identified: sensor uncertainty, measurement uncertainty, and dataset size-related uncertainty. Sensor uncertainty refers to noise and other disturbances in the values in the used dataset. Measurement uncertainty refers to the errors in measured load factors on board of the Zeeland as described in Appendix C. Dataset-size related uncertainty results from the limited amount of available operational data.

#### Sensor uncertainty

All sensors used on board of the Holland class Oceangoing Patrol Vessel are of commercial quality, resulting in a low uncertainty. No concrete values are readily available of the on-board sensors, but most commercially available sensors have a measurement error of less than 5%. The sensor error is therefore assumed to be normally distributed with a 95%-interval of  $(0.95\mu; 1.05\mu)$ , where  $\mu$  is the logged sensor value. As the inputs (service load factors  $k_s$ ) are mean values over a period of time, any zero-mean noise will filter out eventually.

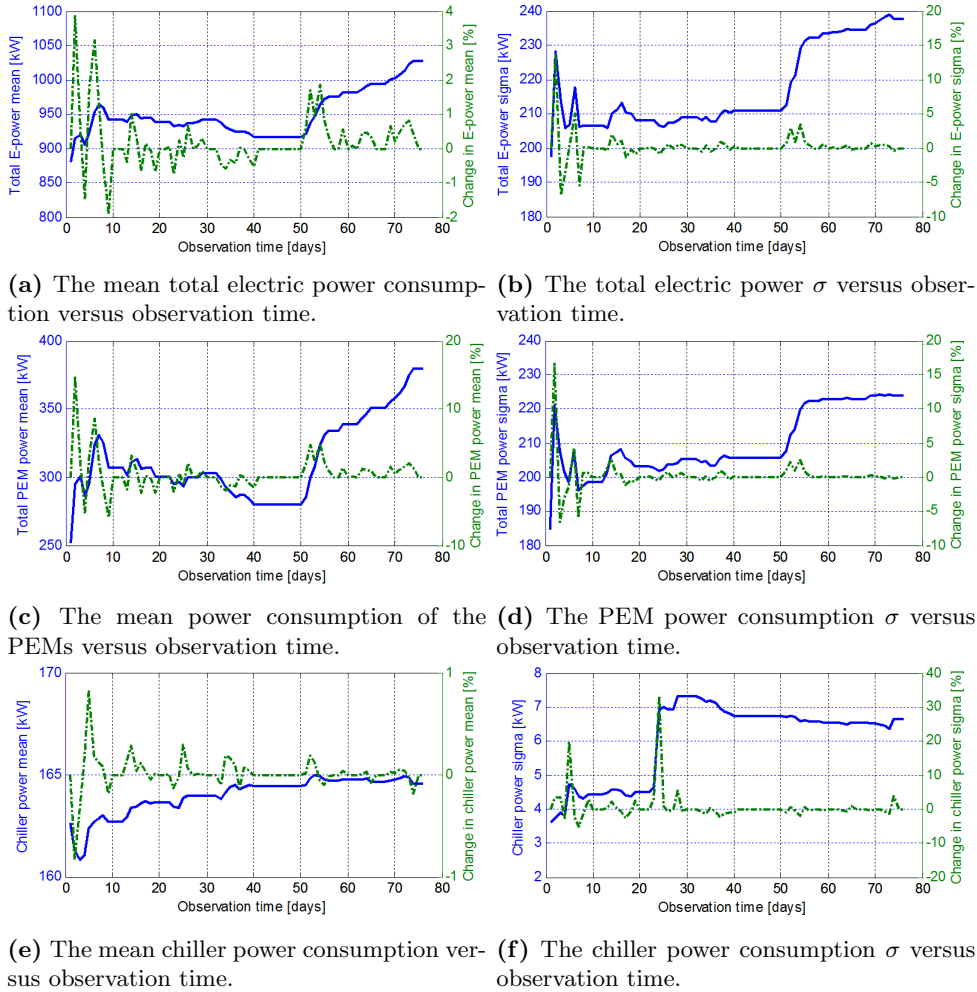
#### Measurement uncertainty

Some additional measurements have been performed on board of HNLMS Zeeland, as described in Appendix C. These measurements were performed over a varying timespan, ranging from several minutes to several hours, depending on the consumer. The measured pump components were measured for a shorter time than the galley, as the pumps were observed to consume approximately constant power while the galley consumes varying power. The measurements are assumed to be normally distributed, with a standard deviation of 5% of the measured value.

#### Dataset size uncertainty

Of the four OPVs, the Holland has operational data available for the longest period of time, approximately six months of data is available. In this time, all operational modes were observed for a significant portion, see Figure 18. This results in an adequate amount of data points for each operational mode. More data results in lower uncertainty, but no more workable data was available at the time of writing of this research. The uncertainty related to the observation time differs significantly between consumers. For example, a comparison is

made between results in the Patrol operational mode from individual months worth of data and the total dataset. The service load factor  $k_s$  for the PEMs varies between 0.33 and 0.75 in individual months, while the Fresh Water cooling pumps consistently have a service load factor  $k_s$  of 0.67 in each observed month.



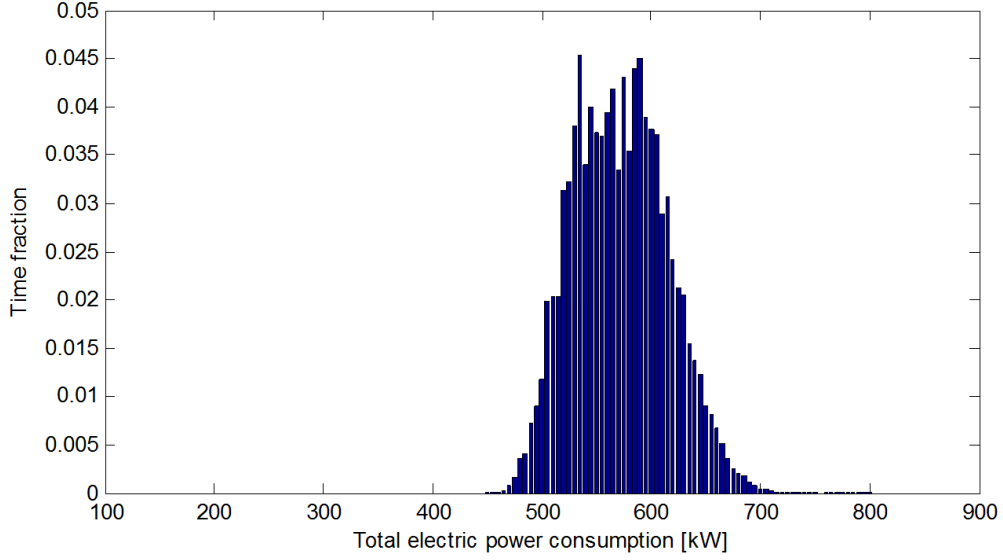
**Figure 35:** The change of  $\mu$  and  $\sigma$  of total electric power consumption, PEM power consumption and chiller power consumption flattens out with enough observation time

Figure 35 shows the influence of observation time on mean and standard deviation of three observed variables in the Patrol operational mode. The blue lines indicate the parameters in question, while the green dashed lines show the change in the parameter. Figures 35a and 35b show less than 1% change in total electric power  $\mu$  and  $\sigma$  after an observation time of 60 days. Figures 35c and 35d show a similar development of  $\mu$  and  $\sigma$  of the PEMs, albeit with a slightly larger change in  $\mu$ . Figure 35e shows a change of less than 1% of chiller power consumption over the entire observation period. Figure 35f shows that after 30 days of observation, the chiller power  $\sigma$  barely changes. An observation period of 60 days is therefore the minimum time required to obtain a reliable

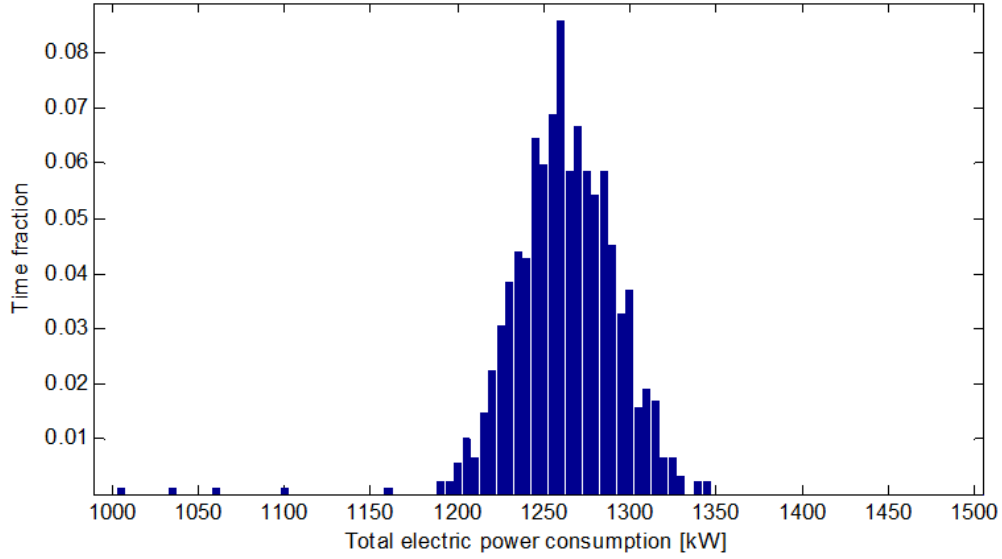
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assessment of these parameters.

Figure 36 shows the distribution of the output (the total electric power consumption per operational mode), as measured by the sensors on board. The distributions both span a relatively narrow bandwidth, with the maximum power consumption close to the average power consumption. For the dimensioning of future similar ships, it is recommended to take the maximum power consumption per operational mode as  $P_{max} = \mu + 3\sigma$ . This results in a smaller overall safety factor, and a less oversized generator set. Take, for example, the Patrol operational mode with a power consumption distribution as shown in Figure 36b. The maximum power would be 1420 kW, as opposed to the estimated power of 1620 kW during the design phase. As the typical price of a DG set is around \$300 per kW cite:DGprice, this 200 kW difference results in savings of up to \$60 000 in installation costs.



(a) A representative distribution of the total electric power consumption in the Diesel operational mode during a one-month period. It is approximately normally distributed, with  $\sigma = 42.88$  kW,  $\mu = 572$  kW.



(b) A distribution of the total electric power consumption in the Patrol operational mode during a one-month period. It is approximately normally distributed with  $\sigma = 53.14$  kW,  $\mu = 1260$  kW.

**Figure 36:** Total electric power consumption distributions in the Diesel and Patrol operational modes during a one-month period.

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## 6 Conclusions and recommendations

### 6.1 Conclusions

In all defined operational modes, the analyzed Holland class OPVs used significantly less electrical power than expected by the designers in all but one operational modes. HNLMS Holland used between 70.0% and 90.1% of the estimated power per operational mode, while HNLMS Zeeland used between 69.4% and 84.2% of the estimated power per operational mode. The exception is the Harbour operational mode, where HNLMS Holland and HNLMS Zeeland used 106.7% and 98.9% of the estimated power, respectively. Due to this fact, the generator sets were overdimensioned. This overdimensioning of the gensets leads to much part-load operation. In the analyzed period, the gensets are loaded mostly at loads between 50% and 70% of their maximum load, which results in a high specific fuel consumption.

An alternative genset setup is described, which uses a father-son configuration instead of the installed equally-sized gensets. The alternative configuration consists of two 835 kW "father" gensets and two 475 kW "son" gensets, as opposed to the three equally-sized 920 kW gensets currently installed. Based on the observed power consumption distribution, this alternative setup saves 0.4% to 2.4% fuel. The father-son configuration also has better redundancy than the three equal gensets.

The service load factor  $k_s$  of some dominant individual consumers was estimated very well by the designers, while others were estimated poorly. For example, the estimated  $k_s$  of the chiller plant is very close to its observed actual value, while the estimated  $k_s$  of the Fuel Oil Purifier was much too low (0.1 instead of 1 in some modes). The cooling water pumps are loaded significantly lower than expected in all operational modes.

The ships sail considerably slower than expected. This is due to the type of operations of the ships. In the analyzed period, patrol missions are most common, where only presence in an area is required instead of frequent fast sailing. Ship speed is found to affect the total electric energy consumption exclusively when the Patrol Electric Motors are used, i.e. only in the Patrol and Patrol (max) operational modes. In the Harbour and Diesel operational modes, the ships use between 500 and 700 kW of electric power. In the Maneuvering mode, the Bow Thruster power consumption is added. The Bow Thruster uses less than 60% of its installed power most of the time, while it is loaded between 90% to 100% of its installed power for 2% of the time.

The total electric power consumption increases with outside air temperature above 16°C. This increased power is consumed by the chiller plant, no other consumers show a temperature-dependent power consumption. It was expected that the Engine Room ventilation fans consume more power as the outside air

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temperature increases, but this is not the case.

## 6.2 Recommendations

Based on the observed generator load and PEM usage in the Patrol operational mode, define an extra operational mode with low PEM load. This results in a less strongly varying genset load profile in the Patrol modes. Cluster analysis also finds three PEM-propulsion modes with distinctly different PEM loads.

Use a load distribution to calculate the fuel consumption of the ship, instead of an average value per operational mode. Using a distribution instead of an average value gives a significantly better estimate of the actual fuel consumption of the ship, especially if the power consumption strongly varies. This distribution of genset loading might also be used to estimate maintenance requirements and costs in future studies, though this application is not pursued in this research.

As this report describes results from a single case study, it cannot be carried over to different ships. Operational data analysis methods similar to this research should be applied to different ship types to obtain better reference material for these ship types. A large database of reference ships could be a result of a number of operational data analyses, to improve the design of future ships of all types.

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## References

- [1] M. Andre, M. Rapone, R. Joumard. “Analysis of the cars pollutant emissions as regards driving cycles and kinematic parameters”. ARTEMIS project, 2006.
- [2] E. Fleuti, J. Polymeris. “Aircraft NOx-Emissions within the Operational LTO Cycle”. 2004.
- [3] B. Sievenpiper. “Electrical ship demand modeling for future generation warships”. Master Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, United States of America, 2013.
- [4] K. Azad. “Understanding the Pareto Principle (The 80/20 Rule)”. Internet: <http://betterexplained.com/articles/understanding-the-pareto-principle-the-8020-rule/>, [Oct. 30, 2014]
- [5] K. Valkeekarvi. (2006, May). “The ship’s electrical network, engine control and automation”. *Gallois magazine*. [Online]. 3(1). Available: [http://www.gallois.be/ggmagazine\\_2006/gg\\_03\\_05\\_2006\\_102.pdf](http://www.gallois.be/ggmagazine_2006/gg_03_05_2006_102.pdf), [Oct. 30, 2014].
- [6] H. Klein Woud, D. Stapersma. *Design of Propulsion and Electric Power Generation Systems*. London: Institute of Marine Engineering, Science & Technology, 2002.
- [7] United States Environmental Protection Agency. (1998, September). “Incremental Cost Estimates for Marine Diesel Engine Technology Improvements”. Engine Programs and Compliance Division, Office of Mobile Sources, U.S. Environmental Protection Agency.
- [8] Naval Sea Systems Command. (2012, September). “Design Data Sheet - Electric Power Load Analysis (EPLA) For Surface Ships”. United States Ministry of Defence Public Release.
- [9] G. Tsekouras, I. Hatzilau, J. Prousalidis. (2009). “A new pattern recognition methodology for classification of load profiles for ships electric consumers”. *Journal of Marine Engineering and Technology*. [Online] 2009 (A14), pp 45-58. Available: <http://202.114.89.60/resource/pdf/3859.pdf> [Oct. 1, 2014].
- [10] J. Vesanto. “Data Exploration Process Based on the Self-Organizing Map”. Doctor of Technology dissertation, Helsinki University of Technology, Finland, 2002.
- [11] “Equations describing the physical properties of moist air”. Internet: <http://www.conservationsphysics.org/atmcalc/atmocl1.php#enthalpy>, [April 23, 2015]

- 
- [12] H. Klein Woud, D. Stapersma. *Design of Auxiliary Systems, Shafting and Flexible Mounting Systems*. London: Institute of Marine Engineering, Science and Technology, NLDA version 2012. (Under development)
  - [13] A. Saltelli, M. Ratto. *Global Sensitivity Analysis. The Primer*. West Sussex: John Wiley & Sons Ltd, 2008.
  - [14] A. Vrijdag. "Estimation of uncertainty in ship performance predictions". *Journal of Marine Engineering and Technology*, Vol. 13, pp. 45-55, Dec. 2014
  - [15] E. Weisstein. "Mathworld: Normal Sum Distribution." Internet: <http://mathworld.wolfram.com/NormalSumDistribution.html>, [June 26, 2015].
  - [16] J. Barrett, "The Average Heat Output of a Computer". Internet: <http://smallbusiness.chron.com/average-heat-output-computer-69494.html>, [May 12, 2015]
  - [17] "Emergency Back-up Power Generation for Water & Wastewater Facilities". Internet: [http://www.aptnet.net/info\\_center\\_papers/Emergency\\_power\\_presentation3.pdf](http://www.aptnet.net/info_center_papers/Emergency_power_presentation3.pdf), Aug. 6, 2013 [June 6, 2015].
  - [18] FLUKE. "Fluke 434/435 Three Phase Power Quality Analyzer, Users Manual". Internet: [http://assets.fluke.com/manuals/434\\_435\\_umeng0300.pdf](http://assets.fluke.com/manuals/434_435_umeng0300.pdf), Jan. 8, 2009 [April 13, 2015]

Note that this bibliography uses the IEEE citation style as available online: <http://www.ijssst.info/info/IEEE-Citation-StyleGuide.pdf>

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## A Electric Load Balance

This appendix shows the Electric Load Balance as used by the designers of the Holland Class Oceangoing Patrol Vessels, to dimension the generator sets. Each consumer is listed with its respective installed power, and its service load factor in each specified operational mode.

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## B K-means cluster tests

This appendix briefly describes the time-dependency of different methods of clustering in Matlab. Two methods were tested, with different results. The *Sequential* method yields better results, but takes more calculation time than the *Batch* method.

**Table B.1:** The time in seconds it takes to calculate cluster centroids using different methods for various dataset sizes.

Dataset size	Batch	Sequential
150x3	0.0131	0.0844
1500x3	0.0074	0.7844
15000x3	0.0093	7.8704
150000x3	0.0266	80.3490
150x6	0.0065	0.0788
1500x6	0.0070	0.7948
15000x6	0.0109	7.9109
150000x6	0.0297	80.4414

Table B.1 shows the time it takes to calculate cluster centroids for different methods available in the free, online available clustering software Self-Organizing Maps. Different dataset sizes are used to determine the dependency of calculation time on dataset size. This is important because this research uses large datasets. The number of rows in a dataset indicate the number of samples per variable, while the number of columns indicate the number of variables in the dataset.

The table shows that the *Batch* method yields significantly faster results for all tested dataset sizes. Furthermore, it shows little to no significant dependency on the dataset size. Contrastingly, the *Sequential* method shows a seemingly linear dependency of the calculation time on the number of rows in the dataset. Both methods show no significant dependency on number of columns in the dataset.

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## C Measurements on board of HNLMS Zeeland

However useful a large set of operational digital data might be, some things are not available in a dataset. For instance, not every single system is equipped with power or even switch sensors, which is the case for the Galley and for the Integrated Mast Module, amongst others. However, these components have a significant maximum power consumption, so an a more in depth investigation was required for more insight. Another important missing piece of information is the human factor or the operational conditions. Therefore additional measurements were performed on board of the Zeeland OPV, in the context of this research. This appendix describes this measurement period, both the electrical measurements as well as insights gained from conversations with the ships crew.

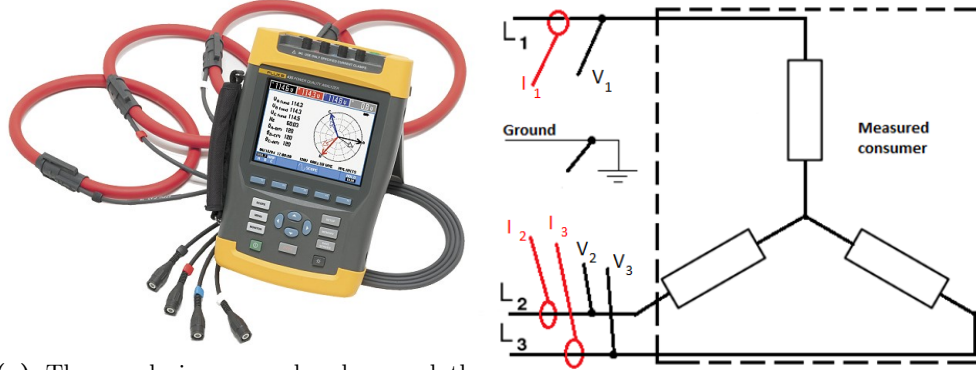
### C.1 Goal and timeframe of measurements

The main reason to perform measurements on board of one of the Holland class Oceangoing Patrol Vessels (OPVs) was to obtain additional information that is not present in the available dataset. Experiences of the ships crew and information from the logbooks are also very useful sources of insight and information. Actual use of the ship is influenced by the crew, captain and mission of a ship, not only by the implemented systems. Also, some information is not logged in the Integrated Platform Management System (IPMS), as described in Section 3.2. Some of this information was obtained by sailing with the Zeeland OPV from 20 to 30 March of 2015, while the ship was performing duties as Station Ship Caribbean.

The list of components (with installed power in brackets) to be measured, in decreasing order of importance, is as follows:

- Engine room ventilation fans
- Integrated mast module
- Chiller plant
- Main fire fighting (fifi) pump
- Galley
- Fresh water cooling water pump
- Sea water cooling water pump
- Fuel oil purifier
- Rotating crane hydraulic unit
- Water monitor

## C.2 Measurement device



(a) Three red rings are placed around the three phases and measure current, while (b) The clamps and rings are connected as shown here. I and V indicate current and voltage measurements, respectively.

**Figure C.1:** A Fluke 435 Power Quality Analyzer and its connection scheme.

To perform the electrical power measurements, a Fluke 435 Power Quality Analyzer was used, as shown in Figure C.1a. This device measures voltage, current and power factor of each cable. These measurements are used to calculate apparent, active, and reactive power. As the OPVs have a floating electrical grid, three current rings and four voltage clamps are used, as shown in Figure C.1b. The Fluke is rated up to 1000Vrms/20 kArms systems [18], which is well above the 440V voltage used by the measured components. Different options are available to assess various quantities, but for this research only the active power and the power factor were deemed important. The active power and power factor were recorded manually at set time intervals.

## C.3 Performed measurements

**Table C.1:** Four components were measured on board of the Zeeland. Low power factors are the result of partial loading. *Values omitted due to confidentiality.*

Component	$P_{peak}$ [kW]	$P_{avg}$ [kW]	$\cos(\phi)$	$t_{observed}$ [hr]
Chiller plant	8	*		
Main fifi pump				
SW cooling water pump				
Galley				

\*The average power was not the objective of this measurement; the objective was to establish the relation between the power as indicated by the IPMS and the actual power consumption by the component.

Table C.1 shows the four components that were measured. The chiller plant

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was found to have a linear relation between IPMS indicated power (as indicated by a percentage) and the actual power consumption. If  $x$  is the power fraction as indicated on the IPMS system, then the power consumed by the chiller plant was found to be:

$$P_{chiller} = ax + b \quad (12)$$

The offset of kW in Equation 12 is a result of the control signal that is supplied to the compressor controller.

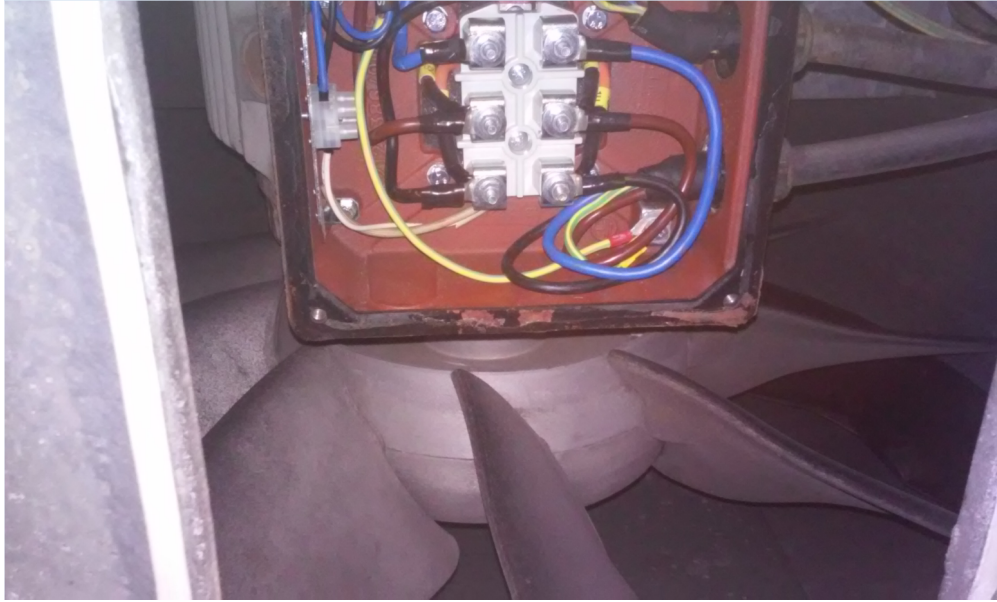
The two pump components were found to be constant-power components. The main fire fighting pump switches on automatically when fire fighting actually takes place, it is switched off the rest of the time. A pressure-water installation keeps the fire fighting system at a constant pressure when there is no take-off of fire extinguishing water. The measurements on this component were performed while bilge water was pumped off the ship. According to the system specification, the pump is rated at *confidential* kW. This means that the load factor  $k_1$  is *confidential* / *confidential* = 0.314.

The SW cooling water pump operates on near-constant power. Power spikes were observed during the measurement period, but these were too short to record. These power spikes are likely the result of the opening of a valve, which results in a pressure drop. The cooling water pump then shortly consumes more power than its average power, up to *confidential* kW. Observed power consumption spikes lasted for less than a second per spike. According to the system specification, this pump is rated at *confidential* kW. The load factor  $k_1$  is *confidential* / *confidential* = 0.480.

The galley was measured between 0800 hours and 1300 hours, during which the kitchen crew prepares the meal for the day. There is no information in the IPMS system at all about the galley, so this observation period provides some insight, even though the observed period is effectively only one day. Power consumption likely fluctuates, depending on the meal that is cooked. Therefore it is advisable to measure for a longer period of time - at least a week - if a deeper insight in this consumer group is desired. When the galley is used, its load factor  $k_1$  is *confidential* / *confidential* = 0.0946.

Initially, ten types of components were selected to measure on board. Unfortunately, during the available operational measurement period between *confidential* and *confidential*, only the previously described four components were measured, due to operational and physical limitations. The operational limitation refers to the fact that the ship is sailing in an operational theatre while measurements are to be performed. A component must be switched off and made tension-free to safely attach the power analyzer to the component. This is not always possible in an operational environment; for example the Integrated Mast Module and the Fuel Oil Purifier were not measured due to this limitation.

Another limitation is the physical attachment of the power analyzer to the mea-



**Figure C.2:** It is not always possible to physically connect the power analyzer to a component. Here, at one of the Engine Room Ventilation Fans, connecting the meter results in an unsafe situation.

sured component. This is not always possible due to the arrangement of the cables in the ship. For example, the power supply cables that deliver power to the Integrated Mast Module are shielded behind plates in the ship. Another example of a component with a physical connection limitation is the Engine Room Ventilation Fan, as shown in Figure C.2. With this component, connecting the cables causes an inability to operate the component safely. The fan would suck in the power analyzer or disconnect the cables, if it were switched on while the meter is connected.

## C.4 Crew insights

For the Zeeland in particular, the Diesel operational mode was used for a relatively large period of time. Conversations with the crew and reading the ships logbooks explain that this is due to the mission of the ship. During diesel-heavy operational periods, the ship was being used in various training exercises, from submarine training to NATO-confidential training. During some of these training programs, the ship is required to reduce and increase speed relatively often. As the Propulsion Electric Motors have a limitation in their allowed decreases of power per hour, the Diesel engines were used during most of these exercises. The PEM-limitation is a result of the way that the PEM-brakes works: the PEM uses a resistor brake, which dissipates electrical energy in the form of heat. Reducing PEM power often results in a tremendous heat release in these resistor brakes.

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Another new observation is the under-dimensioning of the installed Air Heating Units (AHU). These installations play an important role in the HVAC of the ship, cooling or heating fresh air intake and spreading this conditioned air through the ship. During the measurement period, the ship was in the Caribbean Sea, which is one of the most heavily taxing places for the HVAC installation. This is due to high outside air temperature and humidity. The AHU's heat exchange units work perfectly, as the air that exits the AHU is a comfortable 17 to 18 degrees Celcius. The problem was however, that the flow of fresh air to the ship was insufficient. This resulted in a sometimes warm and clammy atmosphere in manned parts of the ship. The AHU manufacturer has since performed a modification to handle this problem.

A final insight has to do with the ship operation, and thereby improved the mode identification algorithm as described in Section 3.1.2. There is a switch on the brigde that indicates and controls how many gensets are in operation. It is required for the use of Patrol and Maneuvering mode that at least two gensets are switched on. This requirement is the result of the large power consumption of the Bow Thruster and the Propulsion Electric Motors. The crew does not directly use the operational modes as specified in the ship design, but there are some restrictions and rules to ensure the gensets and diesel engines to avoid overloading.

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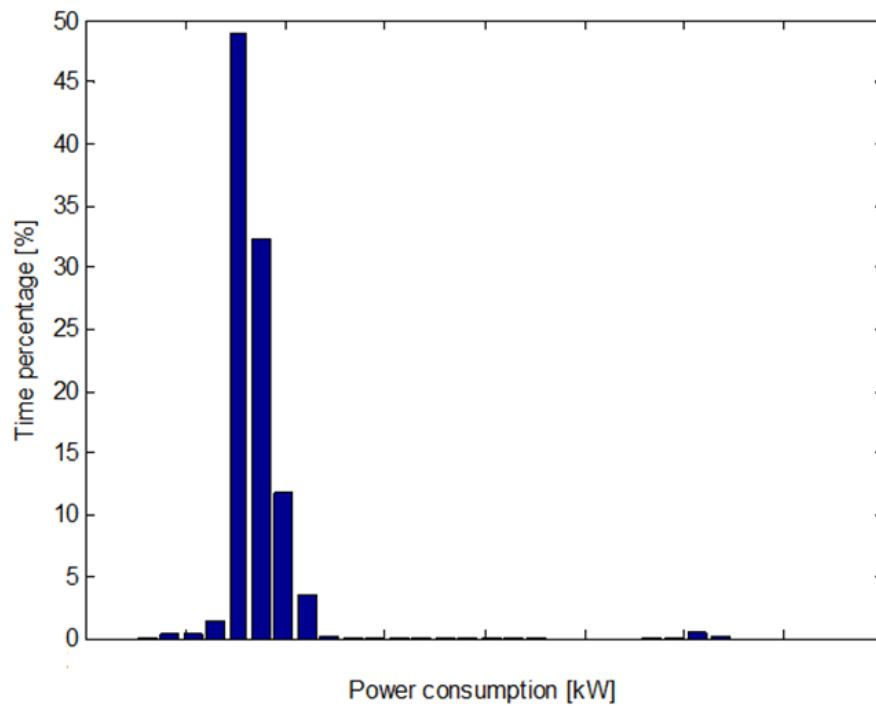
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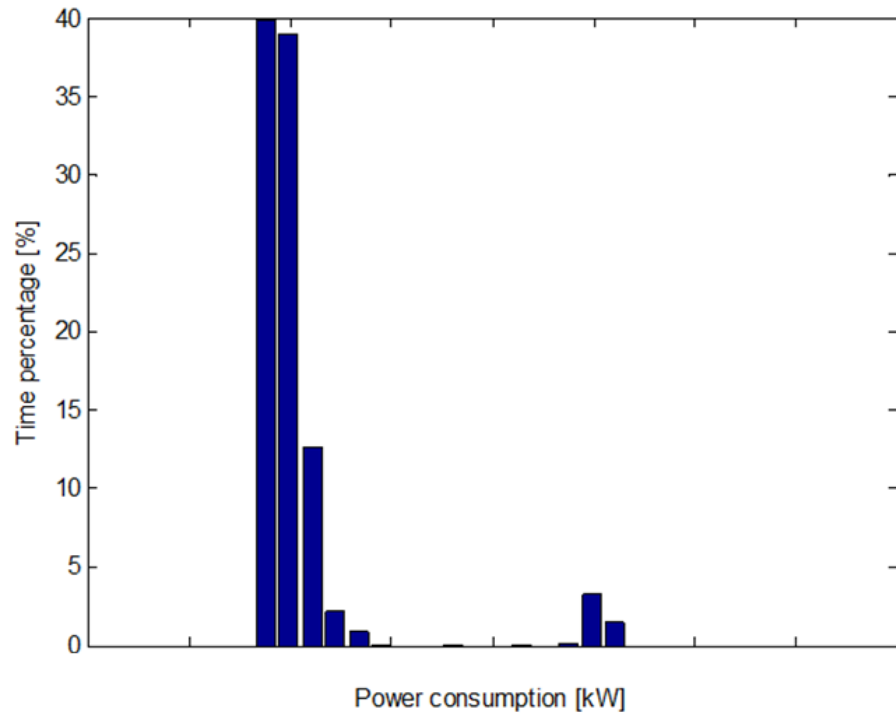
## D Additional pictures

This appendix contains figures that are omitted from the main report, to improve readability.

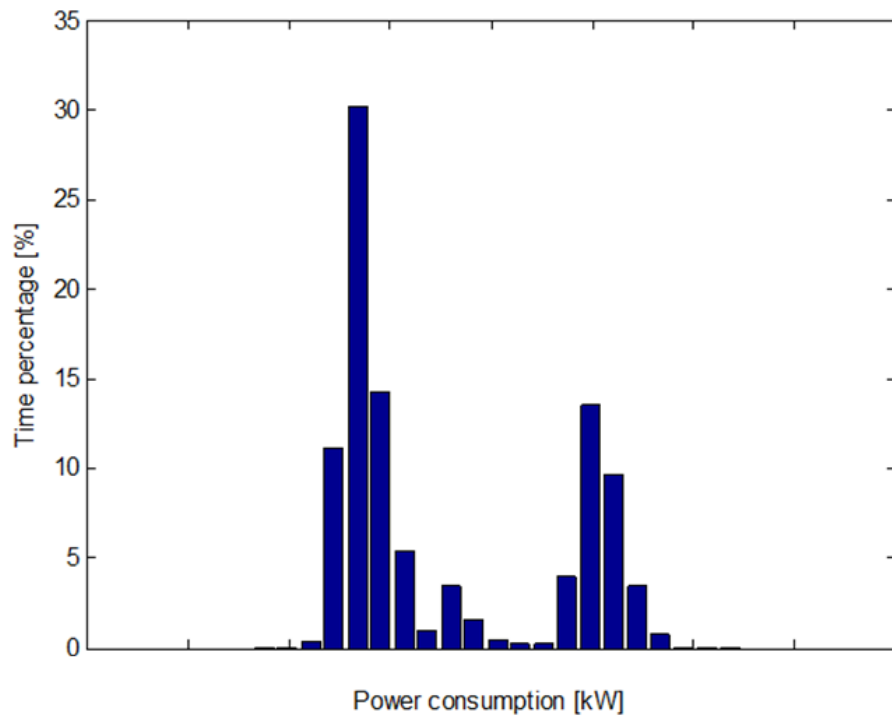
### D.1 Detailed generator load distribution per operational mode



**Figure D.1:** The power consumption in Harbor operational mode in a typical month. A large portion of the time, one DG set is loaded between 45 to 70 %.

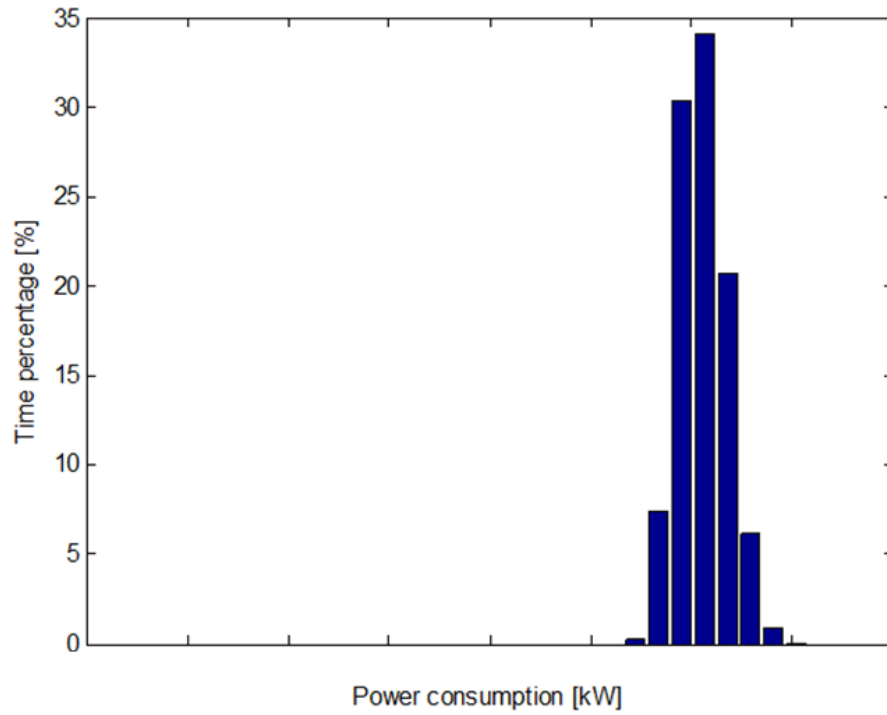


**Figure D.2:** The power consumption in Maneuvering operational mode in a typical month. Two typical power consumption centers are present.

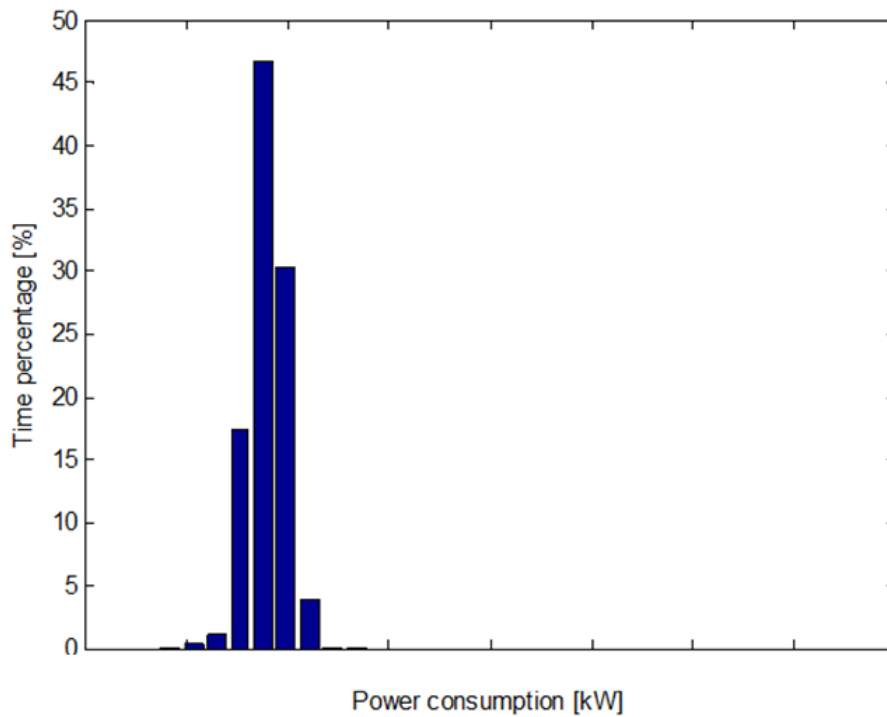


**Figure D.3:** The power consumption in Patrol operational mode in a typical month. Two power distributions are seen within one operational mode.



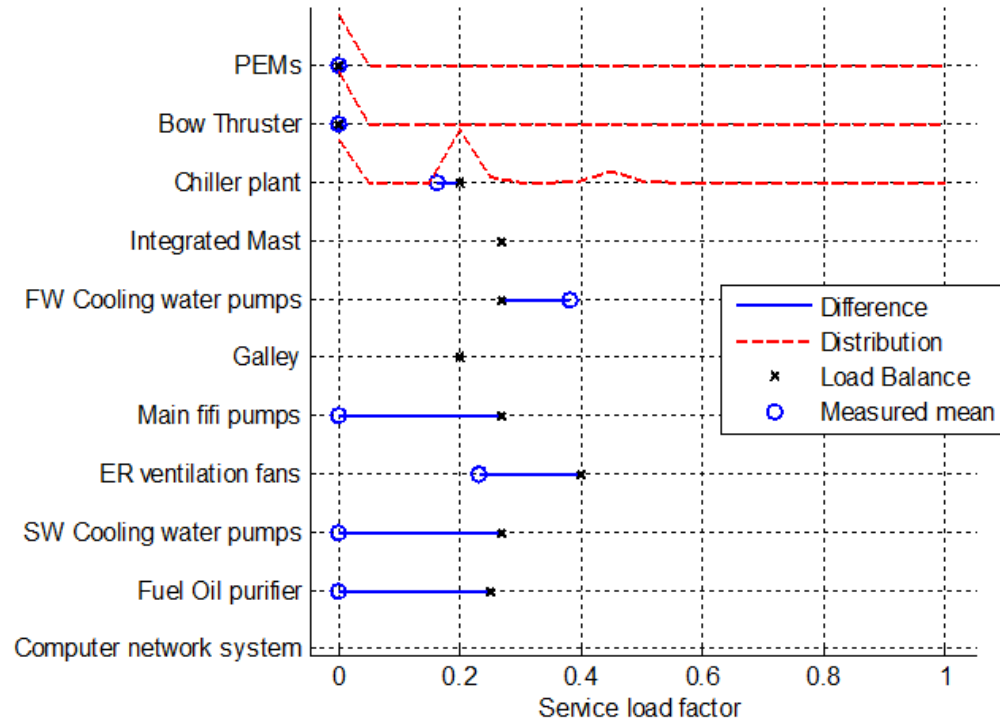


**Figure D.4:** The power consumption in Patrol (max) operational mode in a typical month. The power consumption is centered around a high power consumption.

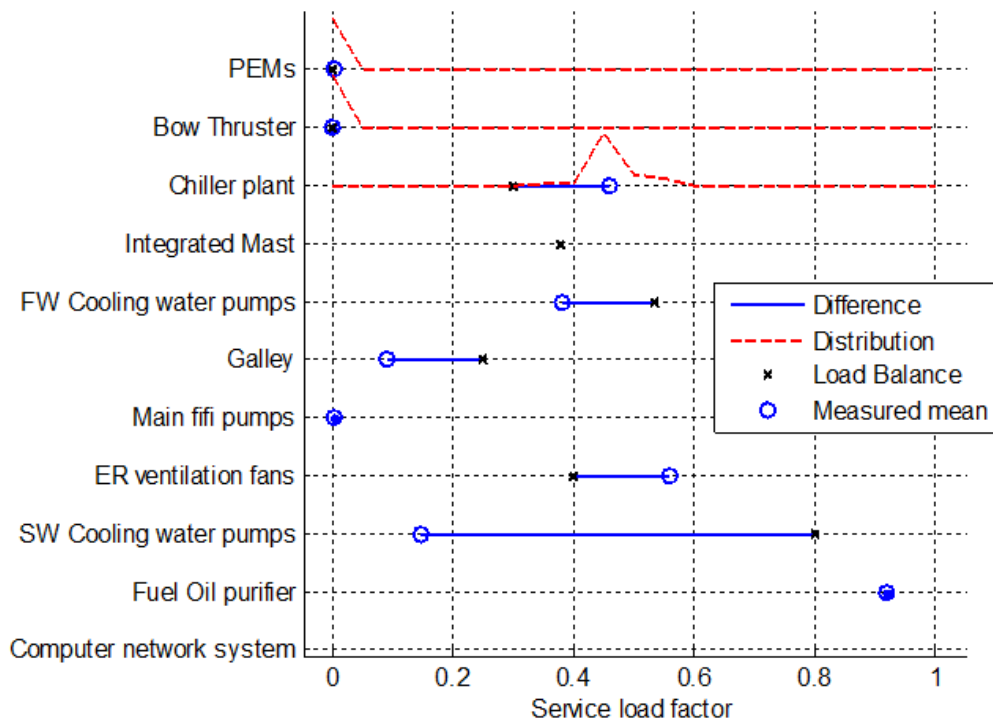


**Figure D.5:** The power consumption in Diesel operational mode in a typical month. The electric power consumption has a narrow distribution.

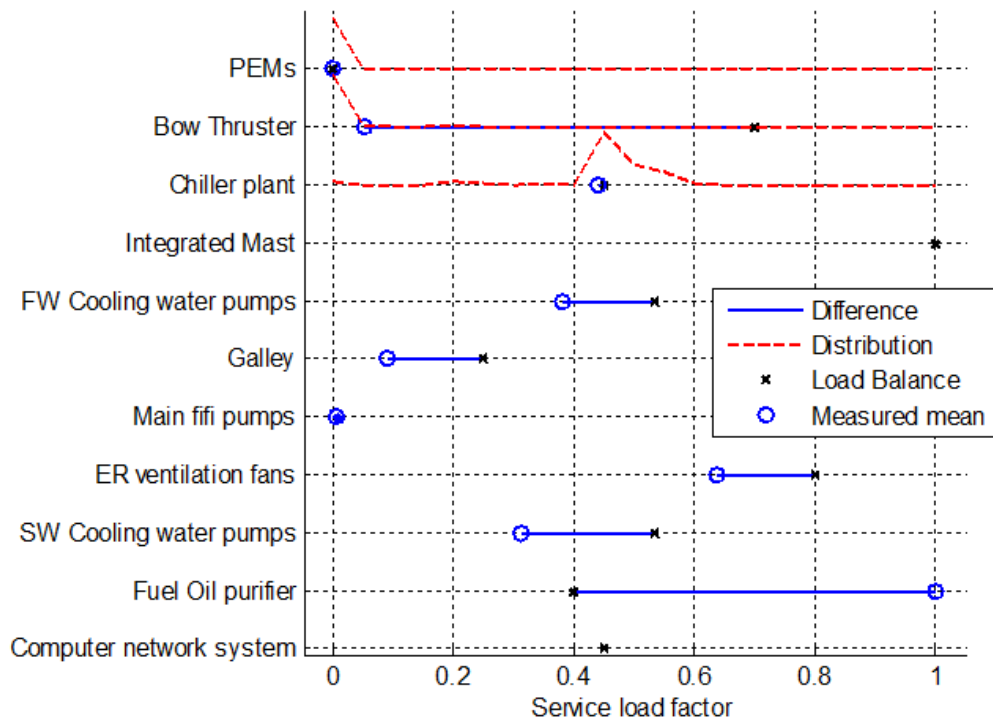
## D.2 Service load factors per operational mode



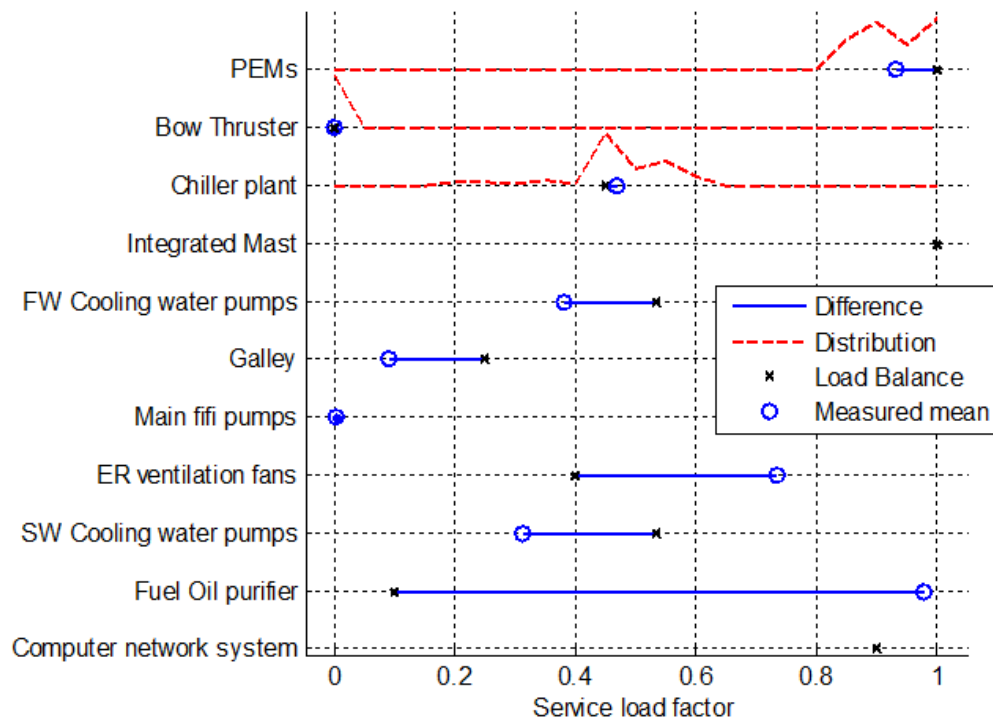
**Figure D.6:** The observed service load factors in Shore connection operational mode for some of the dominant consumers. The fresh water cooling water pumps are loaded more than expected, while other consumers are loaded less than expected.



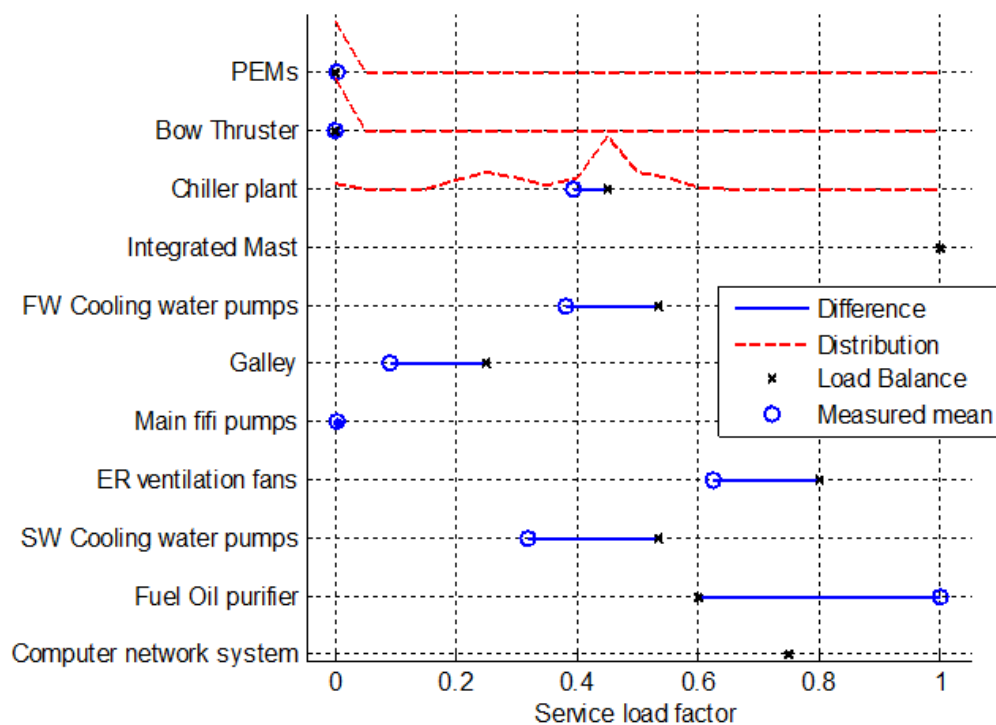
**Figure D.7:** The observed service load factors in Harbor mode for some of the dominant consumers. The cooling water pumps are used less than expected while the chiller plant and the engine room fans are used more than expected.



**Figure D.8:** The observed service load factors in Maneuvering mode for some of the dominant consumers. The cooling water pumps are used less than expected while the chiller plant, engine room fans and fuel oil purifiers are used more than expected.



**Figure D.9:** The observed service load factors in Patrol (max) mode for some of the dominant consumers. The dashed lines show that a large portion of the time is spent at the estimated load factor by the PEMs and chillers.



**Figure D.10:** The observed service load factors in Diesel propulsion operational mode for some of the dominant consumers.