Modeling the Electric Power Consumption of a Yacht

MSc Thesis Marine Engineering

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Delft University of Technology

November 2022

TU Delft

Thesis for the degree of MSc in Marine Technology in the specialization of Maritime Operations and Management & Ship Design

Modeling the Electric Power Consumption of a Yacht

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Project Duration:	Delft University of Technology Faculty of Mechanical, Maritime and Materials Engineering December, 2021 - November, 2022

Cover Image: Ngoni yacht by Oceanco

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Preface

Ever since I was a little kid, I was always inspired by the medals from the regattas my grandfather and great-grandfather participated in and by the photos and stories of their sailing boats, even though I never had the chance to meet these great men. This led me to start sailing and to the beginning of a never-ending journey of love for the ocean and everything about it.

Years later and here I am, graduating in the Marine Technology Master program at the Delft University of Technology. Moving to a different country at such a young age, to study a Bachelor in a language I could barely understand, felt immensely scary. However, looking back, it was the experience of a lifetime, which shaped the person I am today, and of which I couldn't have any less regrets. For this I am eternally thankful to my dearest pai, mãe, Joana e Mané, who have gone through all to be able to provide me with the very best that this beautiful world has to offer.

Delft has presented me with some of the best people I have ever met, from all around the world and from all kinds of different backgrounds. To you I am immensely grateful for all the incredible moments that I will forever cherish. I will never forget you.

To Robert van Tol, Jeltje Borneman, Hanna Dąbrowska and Jeroen Pruyn, my sincere thank you for introducing and guiding me throughout this exciting research opportunity which allowed me to work with some of the biggest players in the fascinating yachting industry. To Jeltje, a special thank you for your guidance not only in the graduation project but on the project which we call life too.

Despite all the difficulties I encountered during all these years, I was always at peace knowing that even though I had left my home, I had the best friends one could possibly ask for back in Lisbon who would never forget me and would continue to support me no matter what. This too would have not been possible without you all.

Finally, the most special acknowledgment is due to the beautiful Nerea Miró for all the support and patience during these hard months of research. You have been my main source of inspiration and motivation. Words cannot express how thankful I am to have you by my side to share the best laughs and the worst tears.

J.P. van Eesteren 1 and J.P. van Eesteren 2, I think you would have been proud.

I love you all.

J.P. van Eesteren 3
Porto, Portugal
September 2022

Abstract

As the emissions resulting from several different industries all over the world continue to increase, awareness towards the impact of these greenhouse gas emissions has risen equally. From all these industries, the maritime industry is no exception. With the vast majority worlds trade being transported by sea, the need for improvement in the sector is of paramount importance.

With the goal to curb the increasing emissions from the maritime industry, the International Maritime Organization (IMO) has set several measures in motion in order to tackle the problem strategically. The introduction of the Energy Efficient Design Index (EEDI) is currently enforced in vessels above 500GT engaged in international shipping. This index attributes a score to the vessel according to its emissions, expressed in grams per of CO_2 per capacity-mile. However, there is no consensus in regards to this method being correctly applicable to yachts.

This is where Water Revolution Foundation comes into action. Currently developing the Yacht Environmental Transparency Index (YETI), which aims at scoring a yacht according to its environmental impact by bench marking it to the current fleet. This will allow for an educated discussion between shipyards and prospective clients in order to ultimately reduce the environmental impact of the yachting industry.

A yacht's power consumption, which reflects emissions, can be divided into two main categories: propulsion power and auxiliary power. The latter is the focus of this research and also the most complex one due to the several variables which influence the dynamic behavior of auxiliary power consumption on board the highly complex system which is a yacht.

This research attempts to design a method which allows the calculation of an estimated yearly electric power consumption on board a yacht. For this, vast research was conducted regarding the current measures enforced by international entities and the theory behind them as well as over the existing methods which are used in different industries for predicting power consumption of complex projects.

As operational data could not be made available, load balances have been used as a proxy for this data. These load balances have been thoroughly analyzed and correlations have been found between different consumer groups and certain sizing characteristics. These served as a basis for the installed power estimation. To this installed power, a load factor is applied based on its utilization throughout a 24 hour period as well as it's output power. Coupling this with the previously defined average operational profile of a yacht, a yearly estimation is calculated. Due to the lack of available data, these results have only been compared to the real consumption of a small sample of yachts.

The results did not prove to yield an estimation within acceptable intervals. To this, several reasons can be attributed to the outcome. Nonetheless, this work provides a solid basis for the continuation of this complex research of which information is scarcely available in the scientific community.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AIS	Automatic Identification System
BBM	Black-Box Model
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
EPLA	Electric Power Load Analysis
GT	Gross Tonnes
HVAC	Heating, Ventilation and Air Conditioning
IMCO IMO	Inter-Governmental Maritime Consultative Organization International Maritime Organization
MAPE	Mean Absolute Percentage Error
MCR	maximum continuous rating
MEPC	Marine Environment Protection Committee
mmt	million metric tons
PDF	Probability Density Function
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SLS	Stochastic Load Simulations
SOLAS	International Convention for the Safety of Life at Sea
UN	United Nations
WBM	White-Box Model
YETI	Yacht Environmental Transparency Index

Symbols

Symbol	Definition	Unit
P	75% rated installed shaft power	[kW]
SFC	Specific fuel consumption	[g/kWh]

Symbol	Definition	Unit
C_f	75% rated installed shaft power	[kW]
DWT	Deadweight tonnage	[ton]
V_{ref}	vessel speed at design point	[kt]
$P_{eff(i)}$	Main engine power reduction due to individual technologies for mechanical energy efficiency	[kW]
$P_{AEeff(i)}$	Auxiliary engine power reduction due to individual technologies for electrical energy efficiency	[kW]
$P_{PTI(i)}$	75% of rated power consumption of shaft motor	[kW]
P_{AE}	Combined installed power of auxiliary engines	[kW]
$P_{ME(i)}$	Individual power of main engines	[kW]
$f_{eff(i)}$	Availability factor of individual energy efficiency technologies	[-]
f_i	Correction factor for ship-specific design elements	[-]
f_w	Coefficient indicating the decrease in ship speed due to weather and environmental conditions	[-]
f_i	Capacity adjustment factor for any technical /regulatory limitation on capacity	[-]
f_c	Cubic capacity correction factor	[-]
f_l	Correction factor to compensate deadweight losses through cargo-related equipment	[-]
C_{FME}	Main engine composite fuel factor	[-]
C_{FAE}	Auxiliary engine fuel factor	[-]
$C_{FME(i)}$	Main engine individual fuel factors	[-]
SFC_{ME}	Specific fuel consumption main engine (composite)	[g/kWh]
SFC_{AE}	Specific fuel consumption auxiliary engine	[g/kWh]
SFC_{AE^*}	Specific fuel consumption auxiliary engine (adjusted for shaft generators)	[g/kWh]
$SFC_{ME(i)}$	Specific fuel consumption main engine (individual)	[g/kWh]

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”Three passions, simple but overwhelmingly
strong have governed my life:
the longing for love, the search for knowledge
and the unbearable pity for the suffering of mankind.”

BERTRAND RUSSELL

1 Introduction

1.1. Yachting and its Environmental Impact

Undoubtedly, global shipping plays a significant role in the transportation of goods worldwide. According to the International Chamber of Shipping, in the case of the European Union, approximately 80% of the exported and imported goods, in volume, are transported via shipping. In terms of economic value, this represents around 50% of goods. A relevant characteristic of global shipping is that, on a per-ton basis, shipping is not only the cheapest but also the method of transportation with the lowest environmental footprint [10]. On a yearly basis, shipping is responsible for the transportation of, for example, 1 billion tonnes of iron ore, 350 million tonnes of grain, and 2 billion tonnes of crude oil. The transportation of such impressively large quantities of goods, which are essential to allow countries to further develop and drive prosperity, would not be possible by any other form of transportation, be it by air, road, or rail.

Nonetheless, in recent years, the environmental impact that humankind has on the planet is increasingly becoming a central topic of discussion. Shipping impacts the environment in several ways, such as air, water, acoustic, and oil pollution, therefore affecting both the aquatic and atmospheric environments at once. There is a growing concern over greenhouse gas emissions, and according to a study performed by the International Maritime Organization (IMO) [22], the total CO_2 emissions resulting from international shipping (international, domestic and fishing) in the year 2018 amounted to 1,056 million tonnes, a 9.3% increase from the 962 million tonnes of the year 2012. This means that global shipping was responsible for 2.89% of global anthropogenic emissions, having increased from 2.76% in 2012.

Within global shipping, for what concerns the yachting industry, the focus of this study, the sector was responsible for 4.9 million tonnes of CO_2 emissions in the year 2018. Despite the impact of COVID-19 in early 2020, the yachting industry showed a resilience not seen in many industries. According to the 2022 Global Order Book, the year 2022 accounted for a total of 1024 yachts in build or on order, which represents an increase of 24.7% compared to the year 2021, in which 821 projects were recorded [2]. The yacht market is expected to keep growing due to several reasons: among them, the growth of high-net-worth individuals, coupled with a rise in marine tourism. This is accounting not only for privately owned yachts but also for the growing number of charter operating companies. According to the Superyacht Times, in 2019 there were 5060 yachts over 30 meters in length in operation, and this number is expected to rise over the next years [27]. In a study conducted by TNO, a Dutch independent research organization, researching the greenhouse gas emissions reduction potential of maritime transport, a prediction of the growth of the world's yacht fleet is presented [17]. This can be seen below, in Figure 1.1.

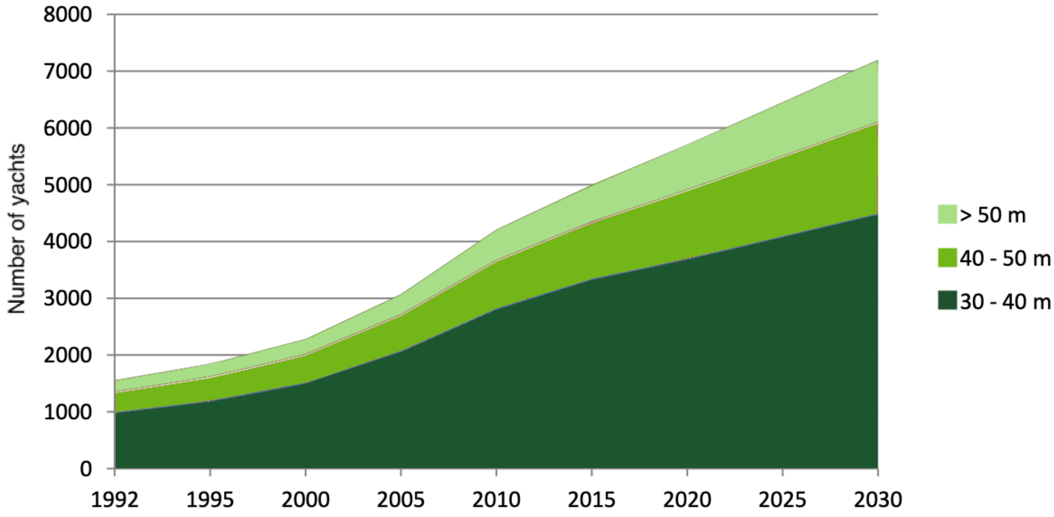

Figure 1.1: Growth prediction of yacht fleet [17]

With the recent events undertaking place in Ukraine, a lot of light has been shed on the assets of high-net-worth individuals, such as planes, real estate, and helicopters, but especially, yachts. As these assets continue to be seized by authorities all over the world, discussions arise over the greenhouse gas emissions of these individuals and the ethics around them. As an example, Chancel and Piketty have conducted a research at the Paris School of Economics in which it has been estimated that, globally, the richest 1% emit close to 100 times more than the poorest 10%. Despite the yachting industry being recognized as being at the front of technological development, it has been found from research that yachts are the most polluting asset of these individuals. In a study of potential emission reduction of a yacht, it was estimated that a 50-meter yacht emits approximately 1167 tonnes of CO_2 in a year, of which 630 tonnes result from propulsion and 557 tonnes from auxiliary power [18]. That is approximately 253 times more than the average car, emitting 4.6 tonnes of CO_2 on a yearly basis [28].

These values constitute cause for concern, and, thankfully, action is being called upon, by both international regulation agencies, such as the International Maritime Organization, as well as several non-profit organizations, such as Water Revolution Foundation. Both of these constitute an important part of this research.

1.1.1. International Maritime Organization

In the course of the 19th century, several countries agreed that the creation of a permanent international body was necessary to promote safety at sea. The establishment of the United Nations (UN) in 1945 facilitated this process and, in an international conference in Geneva in 1948, a convention was adopted to formally establish the Inter-Governmental Maritime Consultative Organization (IMCO). In 1982 the name was changed to International Maritime Organization (IMO).

As Article 1(a) of the Convention summarizes, the purposes of the Organization are: "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, the efficiency of navigation and prevention and control of marine pollution from ships" [11].

After its first task of adopting a new version of the International Convention for the Safety of Life at Sea (SOLAS) in 1960, IMO went on focusing on other topics such as facilitating international maritime traffic, the carriage of dangerous goods, and revising the measuring system of ships tonnage. Despite safety remaining the utmost priority of IMO, a new problem arose: pollution. Accidental oil spillages began to draw attention as well as the routine operations of cleaning oil cargo tanks and the disposal of engine room wastes. In order to tackle these issues, IMO went on to introduce several measures, the most important one being the International Convention for the Prevention of Pollution from Ships, in 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78).

In 2013, as the discussion around CO_2 emissions of all the industries became continuously inevitable, IMO introduced new measures. All vessels of 400 gross tonnes (GT) and above would now be required to have an International Energy Efficiency (IEE) Certificate. In order to obtain said certificate, the vessel must comply with the Energy Efficiency Design Index (EEDI). Ultimately, the goal is to promote the use of more energy efficient, and therefore less polluting, equipment or engines on board vessels. It is aimed at stimulating continuous improvements in innovation and technical development of all parameters of a vessel that influence the fuel efficiency starting at the design phase. This mechanism is performance-based and non-prescriptive, meaning the shipbuilding industry and ship designers have the freedom of choice of technologies to be used for the specific ship as long as the required level of energy efficiency is attained [23]. However, there is a general lack of consensus on whether this index could be correctly and fairly applied to yachts.

1.1.2. Yacht Environmental Transparency Index

Water Revolution Foundation, an Amsterdam-based non-profit, is developing the Yacht Environmental Transparency Index (YETI). YETI's objective is to calculate the environmental impact of the operational use of a yacht by defining a general profile, allowing both yachts and concepts to be benchmarked based on their environmental footprint. Similarly, as to what is done with energy labels for dishwashers or cars, this is aimed at allowing to further encouraging clients to opt for more sustainable decisions during the design phase of the order as well as to benchmark the existing fleet and to provide concrete solutions to further upgrade these yachts with better alternatives.

One could argue that the International Maritime Organization has already developed such a tool to assess the environmental impact of commercial vessels: the EEDI and the more recently introduced measures, the Efficiency Existing Ship Index (EEXI) as well as the Carbon Intensity Indicator (CII). This later one, despite being similar to the EEDI is a yearly assessment of all vessels above 5000 GT, as opposed to the one-time certification of EEDI. However, there is no general consensus within the yachting industry as regards to these being the most efficient methods to assess the overall impact of a yacht. The main reasoning behind this is the fact that both EEDI and EEXI are described per cargo and tonne-mile and take only one single point of the operational profile into account: sailing. As most yachts spend around 10% of their time sailing and the other 90% at anchor or in harbor, their operational profile differs considerably from that of a commercial vessel, hence the lack of consensus. This has also been the case for roll-on/roll-off (RORO) vessels due to the number of passengers on board and, for this case, special adjustments have been made for the EEDI regulations for RORO ships.

During the development of YETI 1.0, three working groups were created. Working Group 1 (WG1) was responsible for defining the general operational profile of a yacht, Working Group 2 (WG2) for defining the hotel load, and Working Group 3 (WG3) for translating the resulting consumption into an environmental impact through the use of ecopoints. WG1 and WG3 managed to complete the goals successfully. However, defining the hotel load turned out to be a more difficult task than expected. The team has developed the Quick and Dirty (QAD) method, which calculates hotel load based on installed generator power. In this way, in order to obtain a better YETI score, one would be required to install more efficient systems, reducing generator power. However, the major issue with this method is how it will affect the use of extra redundancy in installed generator power. Redundancy is a common practice among shipyards to ensure maximum comfort and safety on board yachts in the case of failure of one of the generators. This is the main reason why WG2 has decided to reject this approach. The team then decided to try another approach: the hybrid calculation. As this process was considered to be a critical part of the tool and quite time-consuming, it was agreed to attribute this project to a master's student from the Delft University of Technology.

Since the beginning, the YETI project has been in close cooperation with several experts in the yachting industry as well as several research institutes such as the Delft University of Technology and the Dutch independent research institute TNO. As data was crucial for this project, the following shipyards involved in the project were approached over the course of this research:

- Oceanco (Netherlands)
- Lurssen (Germany)
- Abeking & Rasmussen (Germany)
- Fincantieri (Italy)
- Sanlorenzo (Italian)
- Heesen Yachts (Netherlands)
- Royal Huisman (Netherlands)
- Azimut Benetti (Italy)
- Damen Yachting (Netherlands)
- Feadship (Netherlands)

YETI auxiliary power calculation

In order to assess how the calculation of yearly electric power consumption can be made and implemented into the YETI tool, it is of utmost importance to first analyze in which way it is currently calculated. In the most recent version of the YETI tool, auxiliary power is divided into five different input parameters. These are average hotel load electric, average hotel load heat, thrusters, and condition-dependent loads (stabilizing, DP, steering, navigation) split into anchor/low speed and high speed. All these values are independent input parameters and are to be decided by the shipyard analyzing any specific yacht.

In the image below, 1.2, the input table for auxiliary power is presented.

NOTE: the hotel load, normally calculated in a load balance, is split into 5 parts below. Make sure when filling in the input data that you do not double any input. Example: if a heat recovery system is used on board, the "average hotel load heat" should show the average power of those consumers fed by the heat recovery, and those should be subtracted from the "average hotel load electric". When no dedicated heat system is present, all heat is assumed to be supplied electrically and both loads can be combined under "average hotel load electric"

Average hotel load electric	75	
(guest mode, 30deg/80% outside, 21 degree 55% inside)		
Average hotel load heat	20	
(guest mode, 30deg/80% outside, 21 degree 55% inside)		
condition dependent loads [kW]	anchor/low speed	at higher speed
stabilising, DP, steering, navigation	15	9
(bow) thrusters [kW]	105	
	5%	running when loitering / manoeuvring / DP

Figure 1.2: YETI input parameters for auxiliary power

This is of course not ideal if a tool is to be designed with the goal of assessing the environmental impact of a yacht. By allowing the tool user to input a value of hotel load of its own choice, the transparency and comparability of the tool cannot be guaranteed, especially considering the large impact that hotel load has on the total consumption of a yacht. This is not ideal when several key superyacht builders in the industry are assessing their yachts with the same tool.

1.2. Problem Definition

In the design phase of a vessel, it is necessary to estimate the required power for both propulsion and auxiliary systems in order to select the correct operating range of the engines and generators to be installed. Propulsion power is estimated based on calculated hull resistance and the power-speed curve [14]. The estimation of auxiliary power, however, turns out to be more troublesome. Traditionally, the total operating load is estimated by performing an Electric Power Load Analysis (EPLA) [19]. This is done by constructing a load sheet containing all the electric consumers to be installed on board. For each of these consumers, a load factor is attributed according to its relative mean operational use. Depending on their purpose, consumers might operate continuously or intermittently. The product of each consumer's absorbed power with the load factor results in an average absorbed power which can then be used to obtain the complete required auxiliary power for each operating mode of the complete operational profile of the vessel. Based on this value, the maximum electric power demand, the generator configuration is chosen taking this value as its minimum power output. An example of a load balance can be found in the image below:

Electric load balance 440V, 60 Hz, 3 phase alternating current (primary electric power supply)

consumername	number installed	power at full load	installed power E-motor	absorbed electric power	in port				at sea		
		[kW]	[kW]	[kW]	number in service	load factor	sim. factor	average absorbed power	number in operation	etc.	
Propulsion system - - - Auxiliary systems - - - etc. 115 V, 60Hz,1phase 24V, DC											
Total											

Figure 1.3: Example of a balance sheet [14].

There is, however, one major drawback with this so-called deterministic approach to electric power load analysis. The selection of the load factors is purely subjective and depends solely on the prior experience of the naval architect or electrical engineer building this load sheet. When selecting a load factor for a certain pump of, for example, 0.2 (20%), instead of assuming that the pump is fully loaded several times a day totaling 20% of a 24-hour period, the calculations are in fact assuming that the pump is partially loaded at 20% for the entire 24 hour period. This will eventually lead to a wrong estimation of the total operating load at certain operational modes and, subsequently, the wrong sizing of generators.

A second issue with this method is the fact that redundancy plays a large role upon the selection of the generators. As yachts aim at providing the utmost luxury to their owners and guests, both safety and comfort cannot be overlooked and therefore the total operating load is generally overestimated by applying large safety margins. Subsequently, this results in the selection of larger generators than is actually required. Nonetheless, it ensures maximum safety since, in case of failure of one of the generators, operations can continue to run smoothly. This overestimation of electrical power demand and required generator power results in over-sized generators which ultimately lead to both higher investment and operational costs as well as higher emissions since the generators will operate at lower loads than they were designed for and, therefore, outside their efficient operating ranges.

The calculation of the electric power consumed on board proves to be quite the challenge despite playing a large role when assessing the CO_2 emissions of a yacht. This is mainly due to the large amount of electric consumers onboard and their complex and dynamic behavior throughout a 24-hour period [7]. It is important to notice that when a yacht is at anchor, all the power required to supply the hotel services is provided by the generators. This translates into a large part of the total emissions of the operation of the yacht. However, further research showed that there appears to be a gap in information when it comes to the assessment of the auxiliary power of yachts.

In a very detailed report, comprised of 524 pages, the International Maritime Organization addresses the greenhouse gas emissions from international shipping in its "Fourth IMO Greenhouse Gas Study 2020" [22]. In this report, there is a table labeled as "Detailed results for 2018 describing the fleet (international, domestic and fishing) analyzed using the bottom-up method". This table has a total of 70 entries to account for all size ranges (TEU for container ships, DWT for others) of 19 different vessel categories. Surprisingly enough, there is only one category that has the value zero for emissions resulting from auxiliary power demand. This category turns out to be yachts. This comes as a surprise since earlier in the report, it is assumed that the auxiliary power demand for yachts is 130 kW. This table can be verified below:

Ship type	Size category	Unit	Number of vessels			Avg. DWT (tonnes)	Avg. main engine power (kW)	Avg. design speed (kn)	Avg. days at sea*	Avg. days international*	Avg. days in SECA*	Avg. SOG at sea* (kn)	Avg. distance sailed* (nm)	Median AER	Avg. consumption (kt)*			Total GHG emissions (in million tonnes CO_2e)	Total CO_2 emissions (in million tonnes)
			Type 1 and 2	Type 3	Type 4										Main	Aux.	Boiler		
Ro-Ro	0-4999	dwt	615	1,175	384	1,406	1,618	11.2	129	56	24	8.1	26,155	226.2	0.7	0.9	0.5	6.8	6.7
	5000-9999	dwt	200	0	2	6,955	9,909	17.6	201	183	73	14.2	68,850	50.7	6.1	1.4	0.4	5.0	4.9
	10000-14999	dwt	135	0	0	12,101	15,939	19.6	218	264	137	15.5	81,605	39.3	10.0	1.9	0.5	5.3	5.2
	15000-+	dwt	89	0	0	27,488	19,505	19.1	199	299	171	15.2	72,760	22.4	11.1	1.8	0.5	3.8	3.7
Vehicle	0-29999	gt	168	7	0	5,151	7,264	17.3	213	167	63	13.6	69,764	53.9	4.6	0.9	0.4	3.2	3.1
	30000-49999	gt	189	0	0	13,571	11,831	19.4	254	297	36	14.7	90,133	21.8	7.1	1.0	0.3	5.0	4.9
	50000-+	gt	487	0	0	20,947	14,588	19.9	281	309	47	15.5	104,956	16.4	10.4	0.9	0.2	17.8	17.5
Yacht	0-+†	gt	1,665	7,914	542	1,077	1,116	16.7	78	36	64	10.7	20,358	405.8	0.4	0.0	0.0	4.9	4.9
Service - tug	0-+†	gt	8,805	58,478	8,983	1,218	1,086	11.9	80	14	82	6.6	14,451	422.7	0.3	0.2	0.0	41.0	40.3
Miscellaneous - fishing	0-+†	gt	9,140	17,583	9,807	468	983	11.7	164	42	89	7.5	32,028	304.3	0.3	0.3	0.0	40.7	40.0
Offshore	0-+†	gt	4,322	11,696	875	4,765	2,010	13.9	80	25	111	8.5	17,852	152.8	0.6	0.5	0.0	20.9	20.5
Service - other	0-+†	gt	3,157	8,104	1,158	2,496	1,620	13.6	96	25	90	8.1	19,960	205.3	0.6	0.4	0.0	14.3	14.1
Miscellaneous - other	0-+†	gt	138	55	56	11,496	15,301	18.2	102	70	154	10.7	27,189	31.6	2.1	0.4	0.2	1.3	1.3

Figure 1.4: 2018 emissions per vessel type. [22]

As a result, in this same study, a graph is presented outlining the proportion of GHG emissions per operational phase in 2018. This graph is given in 1.5. It can be observed that for yachts, emissions resulting from anchor mode or in port are nonexistent. As a result, it can be concluded that the calculations of emissions from the yachting industry performed in this study are most likely incorrect since they do not take into account the generator's emissions. Taking all this into account, the necessity of a way of calculating the yearly electric power consumption on a yacht becomes apparent, for both regulatory reasons of international authorities as well as for technological improvement within the yachting industry.

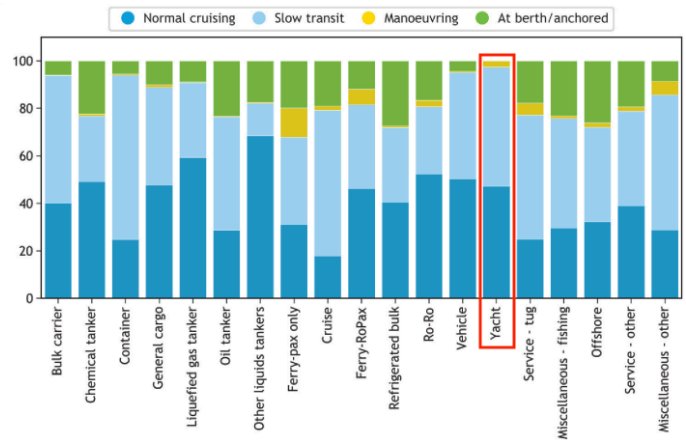

Figure 1.5: Proportion of international GHG emissions (in CO2e) by operational phase in 2018, according to the voyage-based allocation of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port, and main engine load [22]

In order to overcome the inaccuracy and subjectivity of the deterministic approach to electric power load analysis, several other methods have been researched. N. Doerry, in [19], besides the deterministic approach, presents other alternatives such as the simulative and zonal approach but focuses primarily on the probabilistic approach to EPLA. In his Ph.D. thesis [4], Boveri attempts to fill the gap between the sizing and management of power systems between land and marine applications by, too, introducing a probabilistic approach. In this method, all random variables that describe the operating load of each consumer are identified and a probability density function (PDF) that describes the behavior of those random variables is created. This method can then be tested using a Monte Carlo simulation. This method, however, requires information on how these consumers operate in reality, therefore requiring real operational data. This is information that only shipyards have access to. In line with methods that require operational data, some research has been done that utilizes White, Grey, and Black Box Models to simulate auxiliary power consumption, by combining physical laws of certain systems with high-quality data to build a mathematical model that analyzes relations between physical inputs and associated outputs [20].

Overall, considering the results of such a large study conducted by IMO, the very few research and publications on auxiliary power demand on marine vessels, and the difficulty in assessing the electric power consumption on a yacht due to its complexity, it is possible to conclude that this is an area that proves to have a gap of scientific research and information. This research will aim at closing this gap.

1.2.1. Research Questions

The end goal of this project lays therefore on the design of a method that allows determining the hotel load of a yacht, based on the previously defined operational profile, which ultimately allows for the calculation of the yearly consumption of electrical energy on-board the vessel. In the end, the shipyard should be able to enter the required input in an honest and transparent way to obtain the resulting ecopoints which then translate into a YETI score for the yacht or concept. The main focus of the research will be focused towards the design of the method and its requirements and finding a solution that validates all the previously defined requirements. The problem definition of this research, altogether with the necessary requirements for the design of the method, will be extensively clarified during the literature research as more knowledge of this field is acquired.

As the project evolves, research is done and the problem is examined and defined, the research questions are formulated as follows:

- *"In which way can a method be designed that defines the auxiliary power demand of a yacht, taking data sensitivity into account, providing a realistic calculation of yearly electric power consumption, for later implementation into the YETI tool, and what is the reliability of it?"*

Having this main research question in mind, the sub-questions were formulated in the following way:

1. *"EEDI and EEXI: what are they and how are they designed?"*
   (a) *"Are there any other regulations which calculate the electrical power consumption for commercial vessels?"*
   (b) *"Could the EEDI, EEXI or other available methods be applied to the yachting sector?"*
2. *"What are the requirements for such a method to be designed and how do these different methods score against the requirements?"*
3. *"How can the yearly power consumption of hotel load be calculated?"*
   (a) *"What is the most reliable approach in theory?"*
   (b) *"In which way do shipyards calculate the hotel load in different phases of the design, engineering, and building process?"*
   (c) *"What are the correct parameters for the newly designed method for hotel load calculation to be based on?"*
   (d) *"How can the designed method and the input data for said method be validated?"*
4. *"How can the method resulting from this research be implemented into the YETI tool as to find a correct hotel load power consumption?"*
   (a) *"How can other yachts be compared based on this method?"*

1.2.2. Requirements

Prior to the design of the calculation method, it is important to define what the requirements are for it to be designed. These requirements set some rules but these are, nonetheless, subject to change over the course of the investigation. The requirements can be defined as follows:

- Correctly estimate the yearly electric power consumption of the hotel systems.
- Take into consideration the different operating modes of the total operational profile previously defined by YETI.
- Any data used for the design of the method must be of trustworthy origin, namely YETI's partners and collaborating shipyards.
- The method must be green-washing proof. In order to avoid the possibility of manipulating values to obtain better scores inadvertently. This is ultimately a very important requirement for this project since, as seen, the current YETI tools allow for manual input of the auxiliary power consumption. This makes it impossible to ensure that real values are being used.
- Ability to accommodate a large range of vessel sizes according to the available fleet. As yachts range from anywhere between 30 to 180 meters, the tool must be able to calculate auxiliary power consumption for this entire range.
- Must be able to calculate hotel load at an early stage of the design phase, meaning little information is available. This means that the input parameters of the tool must be concise and clear. It is not suitable to include parameters that are not available at the point of using the tool as that makes the goal of YETI unfeasible.
- Ease of use as to ensure its future use by shipyards with potential clients. In order for the tool to be generally accepted within the yachting industry, and for it to be used regularly by shipyards with customers for educated discussions on potential emission-reducing technologies, it should be built in a transparent way, allowing for a straightforward understanding of its use as well as its input parameters and output results.

1.3. Report Outline

This report has been structured in a way as to guide the reader through the same path that was taken during the investigation itself, with the aim of making it a smooth journey from beginning to end.

In an attempt to perform this research in a well-structured way, the Logic Theory of John Dewey has been taken as guidance. John Dewey (1859 - 1952) was an American philosopher, psychologist, educator, and co-founder of the philosophical movement known as pragmatism and played an essential role in the progressive movement in education in the United States.

In his book *Logic: The Theory of Inquiry* (1938), Dewey states that "The existence of inquiries is not a matter of doubt. They enter into every area of life and into every aspect of every area." [6]. Dewey suggests that all inquiries, despite being simple or complicated, share one main commonality: a controlled transformation of an indeterminate situation into a determinate one. Therefore, moving from uncertainty and confusion towards something clear and coherent. In *How We Think* (1910) [5], equally written by Dewey, the 5 phases of inquiry are presented in a book whose purpose is to teach critical thinking. In this book, Dewey presents these phases in the form of a circle, in which the outcomes of a particular inquiry will serve as input/background from which subsequent inquiries will emerge.

These five phases of inquiry, applied to this research are structured as follows:

- Phase 1: **The Indeterminate Situation.**
  This is the initial phase in which there is a felt difficulty or a disturbance of a situation of some sort.

This disruption is the cause that brings the cognitive and conscious resources into action. This indeterminate situation began in the WG2 meetings and lead to the origin of this project.

- Phase 2: **The Problem Definition.**
  In this phase, the felt difficulty is intellectualized into an actual problem to be solved. All that is relevant is filtered from what is irrelevant and the inquirer locates and defines the problem. This is presented in this current Chapter 1, in which the problem is introduced and defined.
- Phase 3: **A Suggested Solution.** At this point, the inquirer has the problem well defined and moves on to provide a suggested solution to tackle it. This is done on the grounds of actual observations and facts by assembling possible hypothetical solutions to the problem. As this suggested solution is merely a hypothesis/conjecture, its validity cannot be fully assured prior to the next step. In this research, the suggested solution is presented in Chapter 2, in which background research is conducted to assess the different regulations enforced today as well as different methods to assess the hotel load of complex engineering projects.
- Phase 4: **Refining the Suggestion**
  The suggested solution is further developed and refined in phase 4 of the inquiry process of Dewey. In this phase, all the consequences of the proposed solution are traced in an attempt to assess its capability of solving the initially presented issue. This work is conducted in Chapter 3, Modeling Methodology, in which the suggested solution is refined and studied, with the goal of achieving the determinate situation, which is, in this case, the estimation of yearly electric power consumption onboard a yacht. In this Chapter, the method is explained and its possible implementation into the YETI tool is given.
- Phase 5: **Testing the Suggestion** In this final step of the inquiry, the verification and corroboration of the proposed hypothesis take place. Similarly, as to how the inquiry process began with the observation of the present difficulty, and the process ends with observation. This evaluation is made in Chapter 4, Method Evaluation. In this Chapter, the feedback provided by the shipyards in regard to the output result of the developed method is analyzed and conclusions can be drawn from it.

This research is concluded in Chapter 5, in which the conclusions are presented, together with the main obstacles that arose during the investigation and the future recommendations that can be followed to further continue this investigation into the hotel load of the yachting sector.

2

Background Research

In order to decide which path to take to arrive at an estimation of the electric power consumption on a yacht, background research was conducted. This was made in an attempt to better understand which emissions regulations exist and are currently enforced by international organizations, how they work and whether these are suitable to be applied to the yachting sector. This will be the starting point of this current Chapter. Furthermore, research was conducted in order to find which methods exist that allow for a calculation of hotel load in a vessel.

2.1. Energy Efficiency Design Index

As pollution increasingly became the central topic of discussion, the issue was eventually recognized by the Marine Environment Protection Committee (MEPC) which, at its 62^{nd} session, included new amendments to the MARPOL Annex IV. The new Chapter 4 was introduced, with the aim of preventing air pollution originating from ships. After 4 years of discussion and development, these measures came into force from January 1^{st} 2013, requiring all ships above 400 gross tonnes to have an International Energy Efficiency (IEE) Certificate. In order to obtain said certificate, the vessel must comply with the Energy Efficiency Design Index (EEDI).

2.1.1. EEDI implementation and future projections

After a two-year phase 0, EEDI was implemented in a three-step phase over 5-year increments, meaning the regulation would require vessels to be 10% more efficient by 2015, 20% more efficient by 2020 and the next goal is to have the fleet 30% more efficient by 2025. This is exemplified in Figure 2.1. The implementation of these measures came with some exceptions, namely that each individual flag country could be allowed to defer the mandatory requirements for up to 4 years beyond the implementation date. This exemption was added to ensure that developing countries could have time to improve their shipbuilding industry in such a way as to be able to deliver ships complying with the new EEDI requirements. This exemption was in line with IMO's policy of equal treatment for all (ETFA). This means that 2019 was the first year in which ships would ultimately have to be EEDI compliant.

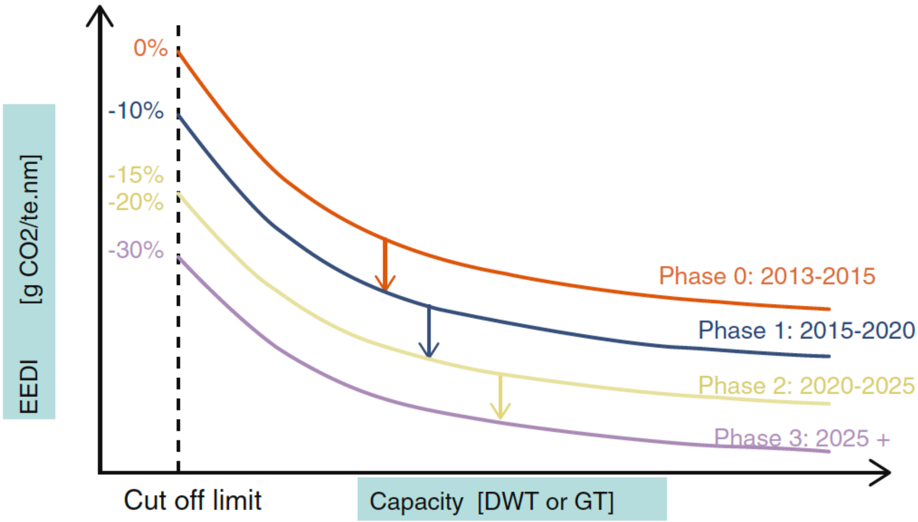

Figure 2.1: EEDI reduction factors and cut-off limits. [23]

Besides EEDI regulations, the new Chapter 4 of annex VI also presents the necessity for all vessels engaged in international shipping to have a Ship Energy Efficiency Management Plan (SEEMP). This is a voluntary operational measure that institutes a mechanism to improve the energy efficiency of a vessel. The SEEMP provides shipping companies with a form of managing ship and fleet efficiency performance by recurring to the Energy Efficiency Operational Indicator (EEOI) as guidance [25].

According to previous projections made by the International Committee for Clean Transportation, based on certain methodologies and using IMO ranges for projected fleet growth, by implementing the EEDI regulations without the 4-year delay, it would be possible to avoid the emission of between 141 to 263 million metric tonnes (mmt) of CO_2 per year by 2030. By allowing the 4-year delay to all ships, the reduction in emissions drops to about 80 to 143 mmt by 2030 [9]. These estimates for the on-time and delayed scenarios are presented in Figure 2.2 .

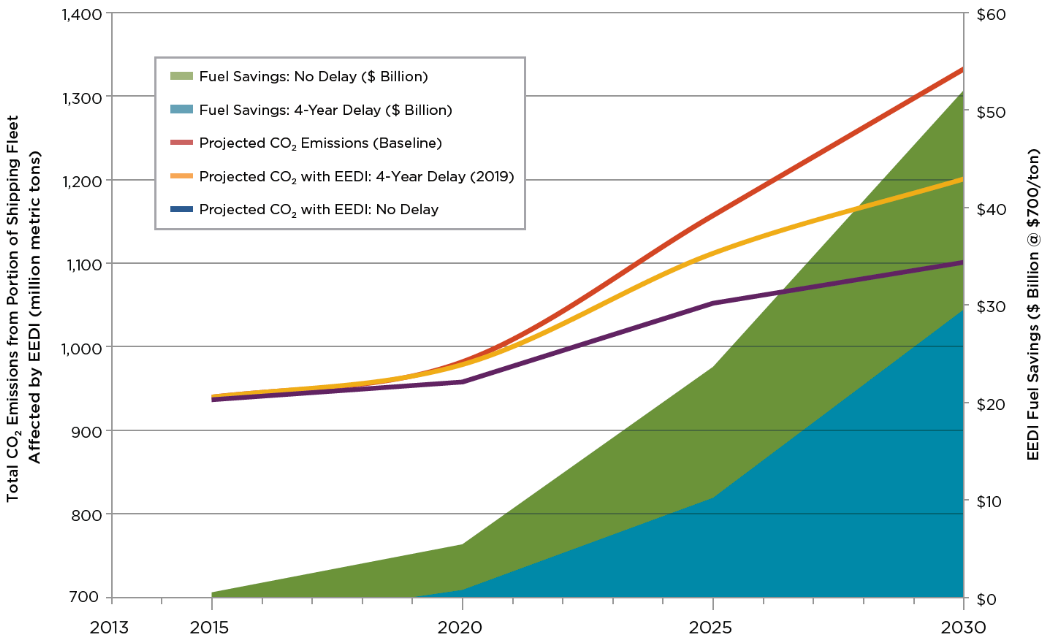

Figure 2.2: IMO projections of CO_2 emissions and fuel savings until 2030 by the fleet enclosed by EEDI's regulation. Scenario with and without 4-year delay. [9]

2.1.2. EEDI formula

The attained EEDI evaluates the CO_2 emissions of a ship per ton-mile of transported goods. It attributes a specific value for each individual ship based on several technical design parameters. In a way, it is a cost/benefit ratio to society, with CO_2 emissions as a basis.

$$\textit{EEDI} = \frac{\textit{Impact to environment}}{\textit{Benefit to society}} \tag{2.1}$$

In other words, this can be defined in a simplified way as:

$$\textit{EEDI} = \frac{\textit{CO}_2\textit{ emissions}}{\textit{Transport work}} = \frac{P * SFC * C_f}{DWT * V_{ref}} \tag{2.2}$$

From which P is defined as 75% of the rated installed shaft power, SFC is specific fuel consumption of the engines, C_f is CO_2 emission rate based on the vessel's fuel type, DWT is the ship's deadweight tonnage and V_{ref} is the speed of the vessel at design load.

The complete formula for the attained EEDI, extended in such a way as to be applicable to several ship types, diverse configurations of propulsion systems, different fuel systems, and several energy-efficient systems, is given as follows:

$$EEDI_{\text{att}}\left(\frac{g}{t \cdot nm}\right) = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} C_{FME(i)} SFC_{ME(i)}\right) + \left(P_{AE} C_{FAE} SFC_{AE}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

$$+ \frac{\left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{AE} SFC_{AE}\right) - \left(\sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{eff(i)} C_{FME} SFC_{ME}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}} \quad (2.3)$$

This formula can be split into 5 main parts as depicted below:

Table 2.1: Main components of complete EEDI formula

Main engines emissions	$\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)$
Auxiliary engines emissions	$P_{AE} \cdot C_{FAE} \cdot SFC_{AE}$
Shaft generator/motors emissions	$\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{AE} SFC_{AE}$
Efficiency technologies	$\left(\sum_{i=1}^{n_{eff}} \cdot f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)$
Transport work	$f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}$

As observed in table 2.1, the main EEDI formula can be decomposed into five main parts: main engine emissions, auxiliary engine emissions, shaft generators/motors emissions, efficiency technologies, and transport work. The components of each of these parts are further detailed below, in table 2.2.

Table 2.2: Complete EEDI formula components and definitions

Engine power (P)		**Correction and adjustment factors**	
Individual engine power depending on application (e. g. PME = 75 % maximum continuous rating for diesel-mechanic propulsion)		Non-dimensional factors that were added to the EEDI equation to account for specific existing or anticipated conditions that would otherwise skew the ratings of individual ships	
$P_{eff(i)}$	Main engine power reduction due to individual technologies for mechanical energy efficiency	$f_{eff(i)}$	Availability factor of individual energy efficiency technologies (=1.0 if readily available)
$P_{AEeff(i)}$	Auxiliary engine power reduction due to individual technologies for electrical energy efficiency	f_i	Correction factor for ship-specific design elements, e.g. ice-classed ships which require extra weight for thicker hulls
$P_{PTI(i)}$	75 % of rated power consumption of shaft motor	f_w	Coefficient indicating the decrease in ship speed due to weather and environmental conditions
P_{AE}	Combined installed power of auxiliary engines	f_i	Capacity adjustment factor for any technical /regulatory limitation on capacity (=1.0 if none)
$P_{ME(i)}$	Individual power of main engines	f_c	Cubic capacity correction factor (for chemical tankers, LNG carriers and RoPax)
		f_l	Correction factor to compensate deadweight losses through cargo-related equipment like cranes, RoRo ramps, etc.

CO2 emissions		**Specific fuel consumption (SFC)**	
CO2 emission factor based on type of fuel used by given engine		Fuel use per unit of engine power	
C_{FME}	Main engine composite fuel factor	SFC_{ME}	Main engine (composite)
C_{FAE}	Auxiliary engine fuel factor	SFC_{AE}	Auxiliary engine
$C_{FME(i)}$	Main engine individual fuel factors	SFC_{AE^*}	Auxiliary engine (adjusted for shaft generators)
		$SFC_{ME(i)}$	Main engine (individual)

Ship design parameters	
V_{ref}	Ship speed at reference conditions (see PME defintion, etc.)
Capacity	Deadweight tonnage (DWT) rating for bulk ships and tankers; a percentage of DWT for container ships; DWT indicates how much can be loaded onto a ship; gross tonnage for passenger ships (cruise)

2.1.3. EEDI calculation for Auxiliary Power

Within the EEDI formula, the one that concerns auxiliary power is the one of most interest for this research. It is the one that represents the hotel load of a ship and therefore it is of high interest to evaluate how the attained EEDI would calculate a yacht's CO_2 emissions. The formula for auxiliary engine power and the subsequent emissions is given as follows [21]:

$$\text{Auxiliary engine power emissions} = C_{FAE} \cdot SFC_{AE} \cdot P_{AE} \tag{2.4}$$

From which C_{FAE} is the conversion factor of fuel oil to CO_2 emissions. In the case of the installation of engines with different fuel types, this conversion factor is to be calculated as a weighted average of those conversion factors of the different engines. The units are given in $gCO2/gfuel$. The formula for this conversion factor is the following:

$$\mathrm{C_{FAE}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{nAE}} \mathrm{C_{FAE(i)}} \cdot \mathrm{MCR_{AE(i)}}\Big)}{\sum_{\mathrm{i}=1}^{\mathrm{nAE}} \mathrm{MCR_{AE(i)}}} \tag{2.5}$$

SFC_{AE} represents the specific fuel consumption of the auxiliary engines. This value must be documented at 50% of the maximum continuous power (MCR) power of the auxiliary engines. This unit of this is given in g/kWh. Similarly to equation 2.5, this too is calculated as a weighted average in the following way:

$$\mathrm{SFC_{AE}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{SFC_{AE(i)}} \cdot \mathrm{MCR_{AE(i)}}}{\sum_{\mathrm{i}=1}^{\mathrm{nAE}} \mathrm{MCR_{AE(i)}}} \tag{2.6}$$

P_{AE} is defined as the auxiliary engine power which is required to provide a normal maximum sea load. This includes the power which is necessary for propulsion machinery, propulsion systems, and accommodation, for example, main engine pumps, navigation systems, and all the living systems on board. This definition however, excludes power, not for propulsion, such as thrusters, ballast pumps, cargo gear, and cargo pumps, among others. The unit of auxiliary power is kW. The calculation of auxiliary engine power is divided into two segments:

- In the case where a vessels total propulsion power $\left(\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0.75}\right) \geq 10.000$ kW, P_{AE} is calculated as:

$$P_{AE} \;\; (_{ME}(i) \geq 10,000\text{kW}) = \left(0.025 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI}(i)}{0.75}\right) + 250 \tag{2.7}$$

- In the case where $\left(\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0.75}\right) < 10.000$ kW, P_{AE} is defined as:

$$P_{AE} \;\; (_{ME}(i) < 10,000\text{kW}) = \left(0.05 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0.75}\right)\right) \tag{2.8}$$

From the previous formulas 2.7 and 2.8, one can observe how the auxiliary engine power is calculated based on the installed main engine power. This is a method that could prove accurate for merchant ships, however, the ratio of propulsion power and generator power between these vessels and yachts is substantially different. Auxiliary power in a container vessel plays a different role than it does on board a yacht.

2.1.4. Electric Power Table

As defined in [21], there are some cases in which the calculation of auxiliary power with the method presented in section 2.1.3 is not suitable since the calculated value P_{AE} differs significantly from the actual total power used at normal sailing. This is the case for, for example, passenger ships. In these exceptions, according to [21], the value for P_{AE} should be estimated by analyzing the electric power, except for propulsion, that is consumed when the vessel is engaged in sailing, at reference speed V_{ref} as defined in the electric power table. This value should then be divided by the average efficiency of the installed generators weighted by power. When this is the used method for calculating auxiliary power, this electric power table must be examined and approved by the EEDI verifier. IMO also defines that if any ambient conditions have implications for the electrical load in the power table, as is the case for HVAC systems, the ambient conditions that result in a maximum design electrical load for said system should be applied in the overall calculation.

When applying this method to yachts in general, using the reference speed will push up the emissions calculation and harm the overall vessel's score as yachts spend around 10% of the time engaged in actual sailing while these calculation methods assume that the ships are sailing around the year.

In appendix 2 of [21], the guidelines for the actual development of this electric power table for the calculation of auxiliary power for EEDI regulations are presented. The auxiliary power P_{AE} is to be calculated as described in section 2.1.3 of this report and, additionally, taking into account the following three conditions:

- Non-emergency situations (meaning no fire, flood, blackout, or partial blackout conditions).
- In a 24-hour time frame evaluation in order to take into account consumers that are used intermittent manner.
- Condition in which the vessel is fully loaded with passengers and/or cargo plus crew members.

In order to facilitate the verification process as well as to allow the identification of possible energy-saving solutions for all the loads present on board a vessel, these loads have been categorized into several groups. This allows a proper breakdown of auxiliary consumers. These groups have been defined as follows:

1. A - Hull, deck, navigation, and safety services;
2. B - Propulsion service auxiliaries;
3. C - Auxiliary engine and main engine services;
4. D - Ship's general services;
5. E - Ventilation for engine rooms and auxiliaries room;
6. F - Air conditioning services;
7. G - Galleys, refrigeration, and laundries services;
8. H - Accommodation services;
9. I - Lighting and socket services;

10. L - Entertainment services;
11. N - Cargo loads;
12. M - Miscellaneous.

There are several data elements that must be included in the electric power table to be used in the calculation of the auxiliary power. These elements and a short description of them are the following:

1. Load's group - to which group the specific consumers belongs to;
2. Load's description - identifies the consumer;
3. Load's identification tag - identifies the consumer according to the specific shipyard's tag system;
4. Load's electric circuit identification - tag of the electric circuit which is supplying the load;
5. Load's mechanical rated power "Ppm" (kW) - rated power of an electric motor driven mechanical device;
6. Load's electric motor rated output power (kW) - output of electric motor as defined in its technical specification;
7. Load's electric motor efficiency "e" (/) - must be included in the table only in the case that the mechanical load is being driven by an electric motor;
8. Load's Rated electric power "P_r" (kW) - the maximum electric power that is absorbed by the consumer's electric terminals. This is indicated in the maker's technical specification. In the cases in which the mechanical load is driven by an electric motor, the rated electric power is given as: $P_r = P_m/e$ (kW) ;
9. Service factor of load "k_l" (/) - in the case when a load absorbs less power than its rated power, k_l gives the reduction of the rated electric power to the actual necessary electric power;
10. Service factor of duty "k_d" (/) this factor indicates how many loads perform a certain function. For example, when two pumps serve the same system, their k_d will be $1/2$ and $1/2$ respectively;
11. Service factor of time "k_t" (/) - this is a time factor based on the actual use of the consumer in a 24 hour time frame. This factor is subjective to the shipyard's evaluation of its use;
12. Service total factor of use "k_u" (/), where $k_u = k_l \cdot k_d \cdot k_t$ - this service factor takes into account all the previously presented factors into one;
13. Load's necessary power "P_load" (kW), where $P_load = P_r \cdot k_u$ - represents the individual consumer's contribution to the auxiliary load power;
14. Notes - to be used in case certain explanations are to be provided to the verifier;
15. Group's necessary power (kW) - the summation of all the loads necessary power P_load from groups A to N;
16. Auxiliaries load's power P_{AE} (kW) - the summation of all the loads necessary power, P_load, of all loads, and divided by the average power weighted generator efficiency. The formula is given as:

    Ultimately, the following formula is used for the estimation of average power demand. No information could be found regarding the decision of the "service factor of time", otherwise known as the load factor.

$$P_{AE} = \frac{\sum P_{load(i)}}{\text{average generator efficiency weighted by power}} \tag{2.9}$$

2.1.5. Required EEDI

In order for a vessel to comply with EEDI regulations, its attained EEDI must fall below the value of the required EEDI for that specific type of vessel. This required EEDI value depends on a reference line and a reduction factor. These reference lines have been developed for every type of ship and are a function of size (deadweight tonnage or gross tonnage).

By analyzing ships that were built between 1999 and 2009, data was gathered that represents their average energy efficiency. With this data, a mathematical distribution was built, meaning the reference line is a regression. These reference lines are built as follows:

$$\text{Reference EEDI} = a \cdot b^{-c} \tag{2.10}$$

It should be noted, however, that no values for a, b or c exist for yachts.

Since the goal of EEDI is to incentive the use of more efficient technologies on board a vessel, the reference line is based on the industry average and the goal of being a certain percentage more efficient is defined on 5-year increments. This is a good solution for an energy-efficient comparison method since it is extremely complicated to define one vessel as being the ultimate environmentally friendly design. This comparison method will be taken into account later in this research.

2.1.6. Limitations of EEDI

With this research on EEDI and its applications, it became apparent that EEDI's method of calculating auxiliary power contains some limitations when applied to a yacht. EEDI calculates auxiliary power consumption based on installed main engine power which does not provide a reliable calculation for a type of vessel that has so many factors that influence the actual auxiliary power demand.

It is yet unclear how EEDI bases its comparison of the attained value since yachts are not part of the different vessel categories included in the guidelines. Without this category, there are no a, b, and c parameters available for the calculation of the category-specific reference line upon which the comparison is to be made. In order for this calculation to be applicable to yachts, a complete analysis of the existing yacht fleet must be conducted in an attempt to evaluate what the best values for said parameters would be to allow for a proper comparison and a correct evaluation of the yacht's energy efficiency.

Yet another limitation is the fact that EEDI takes only one operational mode into consideration: sailing. Since EEDI has been created mostly aimed at commercial shipping, other operational modes have been neglected. However, in the case of a yacht, the anchor and in harbor modes represent a large percentage of a yacht's use. It is estimated that yachts spend only around 10% of their time in actual sailing mode and the rest of the time either in port or at anchor.

In a succinct way, the main limitations can be summarized as follows:

- Auxiliary power consumption calculation based on installed engine power does not provide a reliable result as a yacht's hotel demand differs considerably from that of a commercial vessel.
- Absence of category ”yacht” with parameters for calculation of reference line for comparison with attained EEDI value.
- Only one operational mode is taken into consideration, sailing, which does not match the operational profile of a yacht.

2.1.7. Conclusions

It is clear that the IMO is committed to overcoming the current environmental crisis by introducing and implementing legislation focused on surveying and scrutinizing the existing merchant fleet in order to pinpoint what can be improved and enhanced in terms of efficiency. These regulations stipulate strong deadlines for these improvements to be conducted as the EEDI does. The way the average fleet is established as a basis for comparison for new builds, as well as existing ones, has a great potential for reduction of future CO_2 emissions among other greenhouse gas emissions. However, it became apparent that this regulation is accompanied by some limitations when it comes to its application to the yachting sector. On one side, when the emissions from propulsion are calculated, the wrong operational profile is taken into account, penalizing the industry as a yacht's operational profile differs substantially from that of a merchant vessel. On the other side, when assessing the emissions resulting from the auxiliary power, a function of propulsion power is used. This too is a flawed way of assessing the consumption since the hotel load of a yacht is much higher than that of a merchant ship. The result is a lack of consensus among the yachting industry as to whether this regulation could be correctly applied to a yacht.

With the purpose of finding a more efficient and accurate way of assessing the auxiliary power consumption on board a yacht, the following section investigates which methods are currently in use within the maritime sector, however, not exclusively. From this initial research into EEDI regulations, the division of consumers into different A-M groups will be used forward as it will facilitate the overview of all consumers when working with the shipyards involved in this research who are already familiar with this categorization.

2.2. Hotel Load: Calculation Methods

In this Chapter, an extensive research will be conducted on the different existing methods that allow for the calculation of hotel load in the different phases of the design, engineering, and building process of a yacht. As a starting point, the division of electric power use is made between auxiliary power, hotel, and propulsion.

2.2.1. Electric Power

For the purpose of this research, it is important to have well-structured definitions of the different categories of electric consumers onboard a vessel. When analyzing a list of consumers of a vessel, it is possible to separate them into two main categories: propulsion/machinery systems and auxiliary systems. However, since this research is solely focused on a specific category of vessels, namely yachts, the distinction between auxiliary systems and hotel systems will be made. This is done similarly to cruise ships, where hotel systems represent a large percentage of electric power consumption due to all the consumers that are specifically targeting the well-being of guests and crew, as opposed to, for example, a container vessel [26].

Auxiliary Power

Auxiliary power can be defined as power consumed by systems that contribute to the overall correct functioning of a yacht.

For ease of interpretability, throughout this research, the previously presented EEDI consumer groups will be used. These groups are categorized in a range from A to N according to their main purpose. This allows for a proper breakdown of electric consumers onboard a vessel. From these groups, A to N, the ones that are attributed to auxiliary purposes are defined as follows:

- A - Hull, Deck, Navigation and Safety services
- C - Auxiliary engine and main engine services
- D - Ship's general service
- E - Ventilation for engine rooms and auxiliary rooms

Hotel Load

One can define hotel systems as all equipment installed with the purpose of providing comfort and entertainment for passengers on board the vessel. In a study of the energy demand of cruise ships [3], Boertz researched a bottom-up approach, a method that takes into consideration multiple independent model contributors and was able to predict the average 24-hour loading of several operating conditions. In this research, it was found that HVAC systems are by far the largest consumers of electric power, with a demand for power in the range of 30% up to 50%.

Coming back to EEDI groups, the ones that describe the systems dedicated to the hotel load of a yacht are the following:

- F - Air conditioning services
- G - Galleys, refrigeration, and laundries services
- H - Accommodation services
- I - Lighting and socket services
- L - Entertainment services
- N - Cargo loads
- M - Miscellaneous

Propulsion Power
The electric consumers for propulsion power on a yacht are generally based in two categories: the main engines, in case of a diesel-electric power configuration, and bow thrusters and supporting systems [14]. In the case of diesel engine propulsion systems, the largest consumers will be the bow thrusters but these are not considered in the main operational modes: sailing, harbor, and at anchor. They will, however, have a large contribution in maneuvering conditions.

In the case of propulsion power, there is only one EEDI group for systems that complement the propulsion system of a vessel and that is group B:

- B - Propulsion, service auxiliaries

This group, despite being directly associated with the propulsion of a yacht is still part of the auxiliary electric power consumption and it is not yet included in the main YETI tool. Therefore, group B will too be part of this research.

2.2.2. Electric Power Demand Calculation

One of the most important decisions to be made during the design phase of a vessel is the decision on how to provide the necessary auxiliary power to feed all the systems and equipment on board. In order to assess this required power, the different conditions in which the vessel operates must be taken into account. Usually, these operational conditions are: sailing, maneuvering, in port, and at anchor, [14]. In the case of YETI, the conditions are max speed, cruising fast, cruising, maneuvering, at anchor, and harbor. Depending on the vessel type, extra conditions may be required to be taken into account. In some cases, such as a cruise vessel equipped with large HVAC units, it may be necessary to make a distinction between ambient conditions, such as winter or summer, as the load will differ significantly. As a general rule, the maximum calculated electric power demand will be the minimum value of power to be installed on generators in the vessel for electric power supply [4]. For this, all scenarios are analyzed, considering extreme exterior ambient conditions, different operational modes, and the distinction between crew or guests plus crew on board.

The three main ways of determining the electric power demand of a vessel are through the use of empirical formulas, performing the traditional electric power load analysis, and via simulations.

Empirical formulas
When enough data is available of similarly sized ships performing similar operations, empirical formulas can be used to determine a first estimate of the demand for electric power in a pre-design phase. It must be noted, however, that in later phases of design and engineering, one of the other methods is required to actually obtain a reliable result of electric power demand for a correct design of the vessel and its electrical systems. These empirical formulas can be used to calculate electric power demand by using certain sizing characteristics, such as deadweight or, as used by EEDI, installed propulsion power.

Electric Power Load Analysis
The traditional way of estimating electric power demand is done by performing an Electric Power Load Analysis (EPLA). This is a balance sheet containing all electric power consumers along with their characteristics. The left part of this sheet contains the nominal characteristics of the consumers, namely their name, the number installed, their power at full load, the installed electric power load, and the nominal absorbed power. The right side of the sheet contains the power characteristics for every operational condition that the vessel operates in. This includes: the number of consumers in service, its

load factor, the simultaneity factor, and the average absorbed power [14].

Some consumers are only used in certain operational conditions and, therefore, the number in service indicates how many consumers of the same category are in service at a certain point in time. There is also the possibility that certain loads have been installed for the sole purpose of redundancy and, in this case, the number in service will be less than the number installed. The load factor is an indication of the relative load of the consumer and specifies how much electric power is actually absorbed in a certain condition. This factor varies between 0 and 1. The simultaneity factor, also varying between 0 and 1, indicates the relative mean operational time of a consumer that works intermittently instead of continuously.

The average absorbed power is then the product of the absorbed power of the consumer, the number of consumers in service, and their respective load and simultaneity factors. The total sum of the average absorbed power results in the total absorbed power for a certain operating condition.

As brought to the attention by Klein Woud and Stapersma [14], the main issue with the EPLA however, is the way the load factor is chosen. Traditionally, this load factor is relatively subjective as it results from experience gained while working in the sector. This will result in overall discrepancies across different shipyards in the superyacht industry. Methods for power system design should provide results that are not too high nor too low. A resulting rating that is too low will ultimately result in failing to provide the required power under normal operation of the vessel, higher maintenance costs, and require costly generator refits after delivery of the vessel [19]. In order to avoid this, the opposite path is taken, and usually, load factors are chosen in a more conservative approach, resulting in over-estimations of electric power demand. This too has its downsides as the generator sets will end up having higher investment costs and will be running at a low average load, thus, not at its optimum operating point, resulting in higher specific fuel consumption leading to higher CO_2 emissions [20].

Simulation

Increasing reliability even further than the two previously presented methods, a simulation of the ship's operations at different operational conditions will provide a more accurate prediction of electric power demand. In this method, Stochastic Load Simulations (SLS) are performed, modeling the load and simultaneity factors taking into account all the interactions between the equipment onboard the vessel. More specifically, Probability Density Functions (PDF) can make the estimates more reliable by considering uncertainty margins in the full operating range of the ship [14] [20].

In Klein Woud and Stapersma [14], an example is given which provides an understanding of the advantage of running a simulation for an EPLA. When considering the functioning of a steering gear pump in the load sheet, the load factor, as presented in section 2.2.2, assumes that the pump is partially loaded all the time, when in reality the pump is only fully loaded occasionally. When simulations are run for a long period, it becomes possible to obtain an insight into the possible maximum and minimum loads as well as the probability of exceeding a certain limit. This method will eventually lead to a more reliable result and thus, provide a solid ground for generator sizing as well as fuel consumption predictions.

2.2.3. Probabilistic Approach

Traditionally, the electric power demand was calculated using a deterministic approach, in which load factors were rather subjective and dependent on the previous work experience of the naval engineer working on a specific project. However, with the continuous development of power electronics and the continuous increase of installed electric systems onboard vessels, this method has become less effective at accurately predicting the total operating load of electric systems [4].

When performing a probabilistic approach to electric power load analysis, the probabilistic characterization of the loads is of paramount importance. For this, it is necessary to identify all random variables that describe the operating load of each consumer in the load list. In the PhD work by Alessandro Boveri [4], three modeling approaches are presented with the purpose of identifying said random variables, together with four methods to identify the corresponding probability distribution functions according to the available information of those consumers. Furthermore, a Monte Carlo Simulation process has been adopted with the purpose of combining all the loads and calculating the total operating load.

At a first glance, opposed as to what happens in the deterministic approach to electric power load analysis, in which the load power is considered to be only a single deterministic value (obtained from deterministic load factors), in the probabilistic approach the load power is obtained through statistical laws since it is considered to be a random variable.

Two notions of probability theory and statistics are used as a basis for the probabilistic approach of EPLA. The probability density function serves as an indication of the dispersion of the quantity and the cumulative distribution is an indication of the probability of a given value not being exceeded. These two concepts are depicted in Figures 2.3 and 2.4 [4].

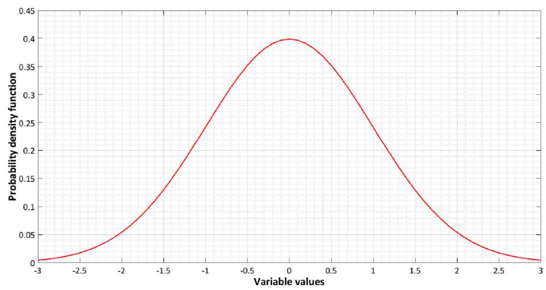

Figure 2.3: Normal probability density function. [4]

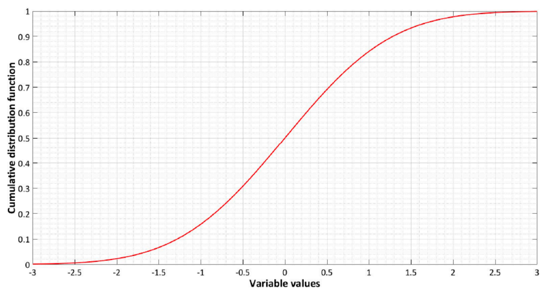

Figure 2.4: Normal cumulative distribution function. [4]

The main goal of a probabilistic approach to EPLA is therefore to calculate a probability density function p_{load}, instead of one single value that identifies load power. In the probabilistic approach, it is assumed that some loads are dependent on certain system configurations. As a matter of fact, some loads have certain behavior dependency on environmental conditions, the ship's operating conditions, other loads in operation, and even the level of power absorbed. This will require that correlations be made between random variables and the calculation of conditional probabilities. In Figure 2.5, the necessary steps to build a probabilistic approach to the electric power load analysis are depicted:

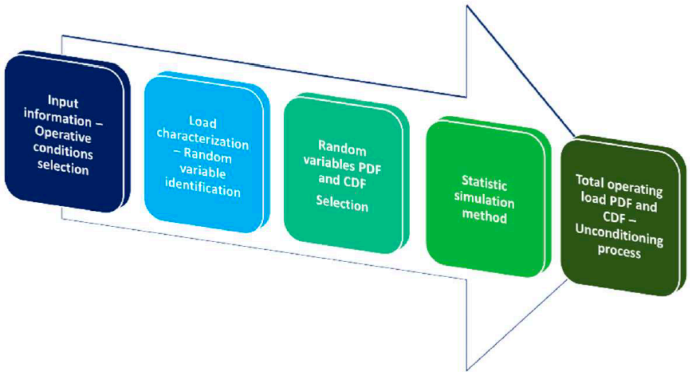

Figure 2.5: Steps towards a probabilistic approach to EPLA. [4]

Most of the loads can be characterized by three different scenarios. With a single random variable, it is possible to represent a load that is constantly on. This variable corresponds to the uncertainty that is present when estimating that load. For loads that alternate between on and off with no dependency on other loads, a function with two random variables is required. These two random variables describe the amount of time that the load is in operation and how much electric power is absorbed by the load, respectively. In a third case, in which a load is dependent on configuration, a discrete random variable is attributed for each of the possible configurations that describe the probability for each of those unique configurations. In order to determine the probability density function of the total load, all the values of the individual loads are added together. For this, the method which is most widely used is the Monte Carlo Simulation [4]. This research allowed for a better estimation of auxiliary power demand which would ultimately allow for the installation of smaller generators and still provides for the real power demand on board of two vessels that were used for the case studies, namely a bulk carrier and a large cruise vessel.

2.2.4. Modelling Approach

There are two main mathematical approaches that can be implemented in order to allow the modeling of physical systems. These are the White-Box Models (WBM) and Black-Box Models (BBM). Despite having the same purpose of modeling physical systems, these two approaches have different methods of achieving the end result [20]. The White-Box approach is based on prior knowledge and it relies solely on physical laws and deterministic first-principle relations, while the Black-model approach, on the other hand, requires no prior knowledge of the system and is solely based on observed data, for example, input-output measurements. Per definition, these methods are based on several statistical approaches, for example, machine learning models and auto-regressive models. Comparing both methods, it is clear that each has its strengths but its weaknesses too. While well trained Black-Box Models are known to be considerably more accurate than White-Box Models, the first ones will require much larger amounts of quality data in order to train the model and, on the other hand, as opposed to White-Box Models, Black-Box Models are at a disadvantage when it comes to interpretability and extrapolating ability [1]. In an attempt to combine the advantageous sides of both models and overcome their weaknesses, Grey-Box models have been developed in a way that both White-box and Black-box approaches are integrated into one model only [30]. All these three models are widely used within the maritime industry in several applications [20].

White-Box Modelling

White-Box models are generally used in the maritime industry to obtain early-stage estimations of energy consumption and predict ship performance. As presented in section 2.2.2, the electric power demand is usually calculated with the use of an electric power load analysis or via simulations which usually are formed by multiple aggregated White-Box Models. Based on Klein Woud and Stapersma [14] guidance for designing air conditioning and ventilation systems in ships, Odendaal developed a WBM approach to determine the energy consumption of HVAC systems [20]. Taking into consideration several dynamic factors such as solar radiation, people on board, heat transmission, and lighting, the WBM has the power necessary to maintain the required state of equilibrium. In Figure 2.6, Odendaal presents an overview of the different existing methods to predict electric power demand for auxiliary systems together with a scale of fidelity and practicality for a better analysis.

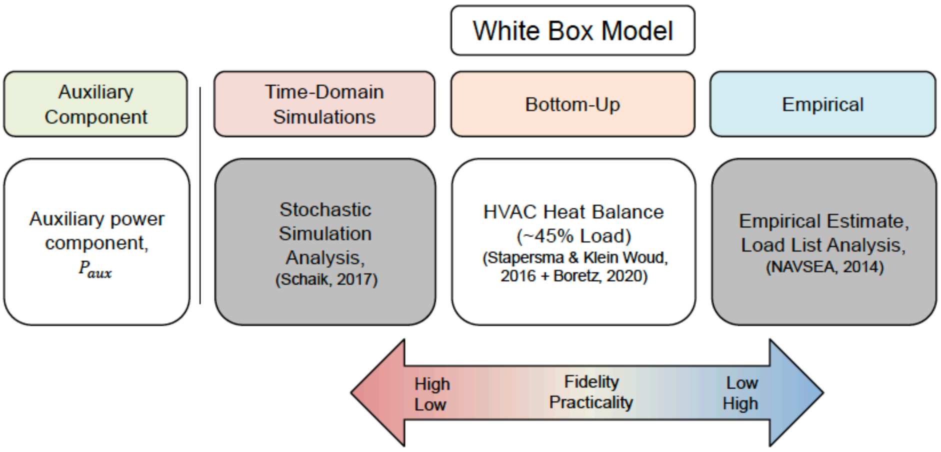

Figure 2.6: Different approaches to estimation of auxiliary power demand [20].

Black-Box Modelling

As seen before, as opposed to White-Box models, Black-Box models require a large amount of high-quality data in a mathematical method that analyzes the relations between the physical system's inputs and associated outputs. In the case that this data is not reliable, the result will be higher uncertainty within the model. However, due to this model's high dependency on data, the extrapolation characteristics of the model are rather limited to the data sets from which the model has been derived from [15]. This uncertainty can also be traced to the parameter selection that has been made for the model. These models have been vastly applied within the maritime industry in attempts to predict different aspects of a vessel's performance. These include, among others, speed, fuel consumption, propulsion power, wave effects, and fouling influences [20] [31]. Several machine learning algorithms have been applied in the field, from which the Artificial Neural Network (ANN) and the Gaussian Process Regression (GPR) have proven to yield great results. The schematics of these two machine learning algorithms are depicted in Figure 2.7 below.

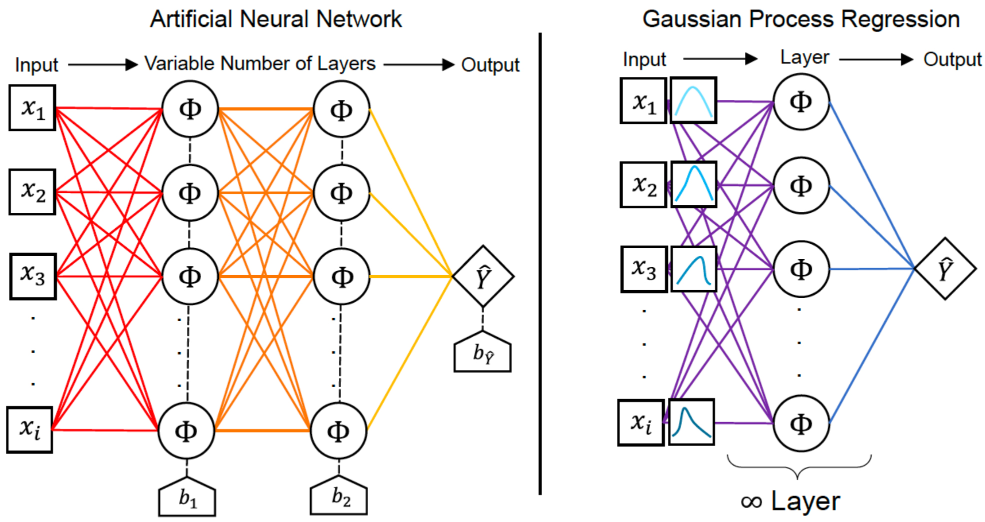

Figure 2.7: Schematics of an Artificial Neural Network and of a Gaussian Process Regression [20].

In research with the purpose of training an ANN to predict the propulsion power of container vessels, propulsion power measurements were implemented as prediction data targets [24]. Additionally, several other variables from four different loading conditions such as wind speed and direction, sea and air temperature, and ship speed were used as input features for the model. The result was a neural network capable of predicting propulsion power with a mean relative error of only 2.7%. From this literature research, however, it became apparent that most applications of Black-Box Models are directed toward propulsion power and there is no evidence of this method being applied to auxiliary power prediction. Several studies have been performed in which Black-Box Models were created to predict electric power demand for commercial buildings with rather remarkable results [12]. This could too be applied within the maritime sector with the use of real operational data as primary input parameters for such a neural network.

A Gaussian Process can be defined as a collection of random variables in such a way that every one of those finite collections of random variables has a normal distribution. Some papers have been written regarding the use of a Gaussian Process to predict fuel consumption on ships [31]. Using training data from real-life operational use, the model can study the effects of input factors such as speed, wind, trim, and waves on fuel consumption. Similarly, this could be done for the prediction of electric power demand using real operational data from yacht voyages, such as the load on generators linked back to the consumers in use at a specific moment. This would eliminate the constraints associated with the inaccuracy of the load factors and allow for a correct prediction per operational mode.

Grey-Box Modelling

A Grey-Box Model is the result of the combination of conventional analysis of the physical principles of a White-Box model with the complex dynamic behaviors that can be obtained from the operational data by a Black-Box Model. The main purpose is, therefore, to combine the advantages of both models into one new method, increasing its accuracy, reliability, and, ultimately, its extrapolation capability [20]. Another advantage of this type of model is its reduced need for real data. Grey-Box models have been vastly studied within the maritime industry in recent years [16] [13]. This type of models can be split into serial modeling and parallel modeling, depending on its application purpose, as depicted in Figure 2.8.

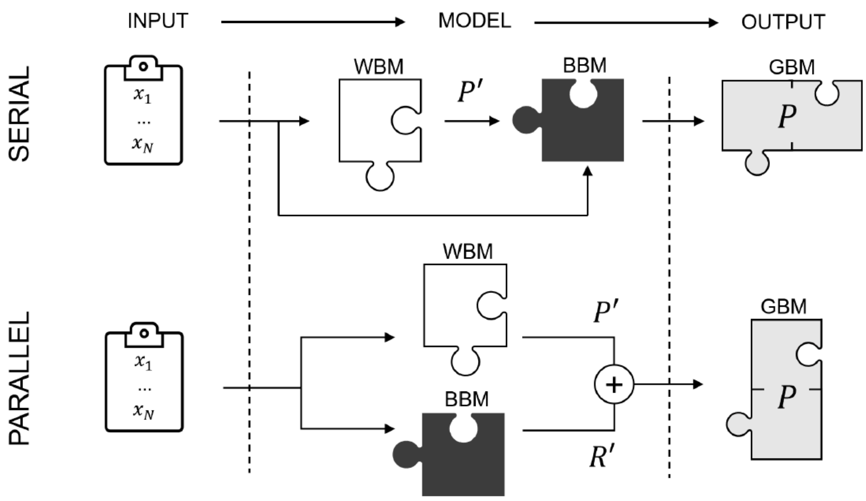

Figure 2.8: Schematics of serial and parallel Grey-Box modelling [20].

In the serial model, the White-Box and Black-Box models are set in series, in which the initial input is fed to both models from the initial prediction. From here, the initial prediction of the White-Box is used as input for the Black-Box model, allowing for physics models and available data to be mapped internally. In the parallel configuration, while the White-Box model makes its first prediction, the Black-Box model is minimizing the residual between prediction and target data.

Only one publication has been found that investigates the potential of Grey box modeling for the prediction of auxiliary power demand and that is the master thesis of K. Odendaal [20]. In his work, the power demand from HVAC systems is modeled using its physical properties as defined in Klein Woud and Stapersma [14], in the form of a WBM. The rest of the electric power consumers are modeled using real operational data in the form of a purely BBM. The two are then modeled together in the form of a GBM, bringing together the advantages of both types of models. It must be noted, however, that GBM are applied in other industries for electric power demand prediction such as the forecasting of electricity demand in one city in the western region of China [32].

2.2.5. Other industries

In the early years of IMO regulations, not all vessel types were included within its scope. Yachts, the central topic of this research, is one of those types. From all those categories included, the one that shares the highest resemblance is passenger cruise ships. Both these vessel types are focused on passenger comfort, safety, and entertainment and are equipped with several systems designed specifically for this purpose. HVAC systems, responsible for a large share of electric power demand, play a large role in both yachts and cruise ships.

In a 2018 study, [26], Simonsen et al., created a model for predicting the fuel consumption of cruise ships sailing Norwegian waters. As input to the model, Automatic Identification System (AIS) data and several cruise-specific characteristics were used, such as service speed, the number of engines installed, and total power. AIS data was retrieved using real-time speed in order to calculate the distance traveled. In order to distinguish sailing from port mode, a speed cut-off value of 4 knots was used meaning if the vessel is sailing at speeds slower than 4 knots it is considered to be in port or maneuvering in port.

From the available data, and since the speed is known at every instant, the power required to attain that speed is calculated by finding the load on the power rating necessary to attain that given speed. This load is the proportion of installed power currently in use which is then used to find the applied power rating in kW. The model then assumes that part of the total power is used for hotel load such as HVAC systems, lighting, and hot water provision and that the remainder of the total power is used for this purpose. Meaning 1 minus the propulsion factor is used for auxiliary systems. This method, however, cannot be considered accurate enough to be applied to the yachting sector as it is assumed that all installed power is constantly in use and that is not the case in the operational profile of a yacht. As seen before, redundancy plays a large role upon the installation of generators, and using installed power will not translate into an accurate prediction of auxiliary power consumption.

2.3. Conclusions

Rounding up the background research, all the options were studied however, only one approach can be fully researched in this investigation. As operational data is not available, the box models have been rejected. For the probabilistic approach, more data is required from shipyards which cannot be obtained realistically, and, therefore, it has been opted to follow the electric power load analysis method. It became apparent that the only data which would be possible to obtain was in the form of load balances. Therefore, these will be gathered and thoroughly studied.

The possibility of a bottom-up approach was considered, by analyzing pieces of equipment separately and coupling them together, ending up in the complex system which is a yacht. Taking HVAC power as an example: this system could be calculated by analyzing all the variables which play a role in the functioning of an HVAC system, namely the prediction of heat gain in a cabin, calculating the required number of air changes, calculating a fresh air ratio to the volume of the cabin, and further calculating the intermediate conditions for the fan coil unit obtaining heating, cooling and humidification demands together with required air volume for the fan power. Two main issues were found as a result of this approach. First, this approach requires information that is not readily available at an early stage of design, namely the general layout with the number of cabins (further discussions on this topic can be found in Chapter 5). Secondly, this is an approach that is based on a best-case scenario or, in other words, the best possible design. Since the goal of YETI is to assess the environmental impact of yachts, this ought to be done based on the reality, not based on some ideal scenario. In a study on the energy demand of a fuel cell-driven cruise ship, such a breakdown of systems was made and a bottom-up approach was taken to calculate power demand individually. The result for the maximum power demand of the HVAC systems turned out to be 5.8% above the value that had been predicted in the vessel's load balance [3]. In Figure 2.9 below, it is possible to observe how the prediction model compares to the results in the load balance. Is it visible that the variation is not too significant.

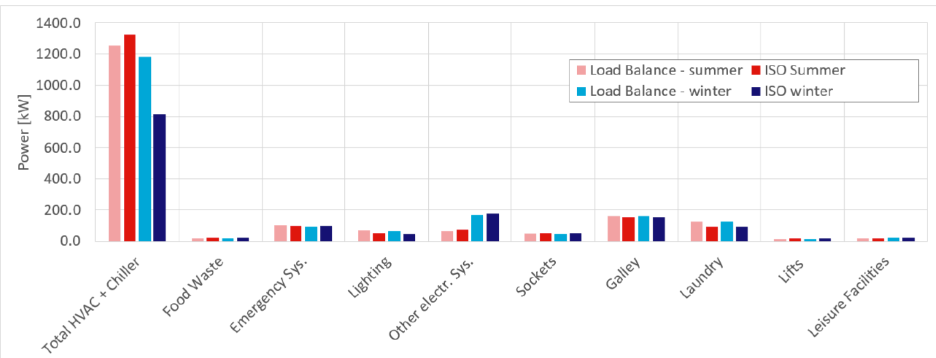

Figure 2.9: Comparison of maximum power demand of systems obtained in prediction model and load balance [3].

3

Method Development

Having set all the goals for this project, and with the background research conducted, it was decided that the approach to be taken would be that one of the load balances, since this is the only kind of yacht data that could be agreed upon for sharing with WRF.

The underlying principle of the following methodology is that the calculation result should represent the reality of yachts are currently designed and how they are actually operated. As seen in the conclusions of the previous chapter, a bottom up approach was studied but it was decided that this would be creating a best case scenario, calculating the minimum required for the essential operation, safety and comfort of the yacht. This is the approach that ought to be used within shipyards to assess how much power should be installed and to size the required generators for such a power demand. However, since this tool is to be implemented into YETI, and the goal is to incentive the use of more power efficient technologies and to reduce the carbon footprint of yachts, it was decided to base the calculations on the existing fleet, to showcase how yachts are designed and used today. In this way, it is possible to compare a future yacht to the existing fleet and set the goal to design it in a way to make it x% less impactful than the average by making it more efficient and consuming less, reducing emissions.

3.1. Data Inquiries

3.1.1. Shipyards

For every of the shipyards presented in Chapter 1, an initial meeting was conducted with a representative of each yard and in the presence of the supervisor from Water Revolution Foundation. In these meetings, the scope of this project was introduced and explained and the data requests proceeded. In these meetings, several questions were asked about the way the shipyards perform the electric power load analysis for their yachts, in case it was via load balance, in which way the load factors are decided upon, which systems were considered to be the largest electric power consumers and any other remarks they could have to share for the purpose of this research.

It was clear from the start of this research that HVAC systems were considered to be the largest consumers of all. Besides this, stabilizers also have a large impact on power consumption. It was therefore decided that these consumers would be calculated separately. And since the amenities of a yacht, that is, pool, jacuzzi, and sauna are considered to be customer specific, these would too be calculated on the side. As such, the distinction further on is made between a baseline of general consumers which are common to all yachts, the HVAC systems, stabilizers, and the yacht's amenities.

3.1.2. Load Balances

For this research, data was considered to be crucial since its beginning. It would provide an insight into the operation of a yacht, as well as the type of consumers installed and their power. Ideally, for an accurate estimation of electric power consumption, real operational data would be required. With such data from yachts of various size ranges and statistical analysis, extrapolations could be made that would result in a statistically correct estimation. However, some issues arose around this topic.

Privacy Issues

Over the course of the initial stage of this project, one circumstance became apparent as being the main obstacle in the way of achieving a correct prediction of the yearly electric power consumption of a yacht: the data sensitivity. As a yacht's operational data constitutes private information of the vessel's owner, even in the cases in which shipyards are allowed to obtain this information for their own research and development purposes, they are, understandably, not allowed to share it with WRF for the purpose of this research project. As this data is not available, the possibility of building a grey-box model has been discarded. This grey-box model would be an inter-relation of a white-box model describing the electric power consumption of HVAC systems by using empirical formulas describing the physical systems, together with a black-box model using the operational data as input for an artificial neural network.

Taking this into account, a solution must be found that circumvents these constraints. As such, the only data that can be made available by the shipyards involved in this joint industry project is in the form of load balances and average loading of generators. These load balances contain all the electric consumers installed in existing yachts and their respective power and load factors for all the different operational modes that form the operational profile of a yacht.

Load balance example

As load balances were the only data that the shipyards were willing to share, these became a proxy for this research, acting as a substitute for the ideal real operational data. A total of 33 load balances were received from the shipyards partnering with YETI. These load balances are generally quite identical among shipyards, however with some discrepancies. In Table 3.1 below, an example of a general load balance is presented. In it, all the consumers are presented in the first column, their total load, the phase in which they operate, and four different columns for four different operational modes. For each operational mode, one power factor (load factor) is attributed according to the relative use of that consumer in that specific operational mode, which is then multiplied by the total load to obtain the power consumption in that same mode. Adding up the loads of all different consumers results in the electric power consumption per operational mode.

Table 3.1: Example of a general load balance

Consumer list	Total load kW	Phase	Normal sailing		Shore		Harbor		Maneuvering	
Category xxxx			power factor	kW	power factor	kW	power factor	kW	power factor	kW
Consumer 1	58	3	0,3	17,4	0,2	11,6	0,45	26,1	1	58
Consumer 2	40	3	0,7	28	0,1	4	0,15	6	0,3	12
Consumer 3	38	3	0,12	4,56	1	38	0,11	4,18	0,05	1,9
Consumer 4	43	3	0,26	11,18	1	43	0,1	4,3	0,06	2,58
Consumer 5	5	3	0,4	2	0,4	2	0,04	0,2	0,05	0,25
Consumer 6	23	3	0,4	9,2	0,8	18,4	0,04	0,92	0,5	11,5
Consumer 7	10	3	0,25	2,5	0,75	7,5	0,26	2,6	0,23	2,3
Consumer 8	12	3	0,8	9,6	0,12	1,44	0,1	1,2	0,2	2,4
Consumer 9	49	3	0,05	2,45	1	49	1,1	53,9	0,1	4,9
....	......	....	....	.....	......	......	.....	.....	.....	.....

3.1.3. Data Overview

During the initial phase of the YETI project, the shipyards were approached and several data characteristics were requested. All this data comprised a Microsoft Excel Sheet with the following variables:

- Year of build
- Type of motor yacht (displacement, fast-displacement, semi-displacement or planning)
- Type of sailing yacht (Schooner, ketch or sloop)
- Size: gross tonnage, length over all, length water line and beam
- Construction material of hull and superstructure
- Weight: deadweight and lightship weight
- Speed: at max power, at 75% power, at 50% power and idle
- Interior: total space, luxury space, and average headroom
- Engine: brand, type, and power configuration
- Sail area (when applicable)
- Total generator power
- Stabilizer power consumption: at anchor and while sailing

In total, the Excel is comprised of 132 yachts

Unfortunately, not all shipyards were able to share data for the purpose of the project and, in the end, a total of 33 load balances were received. This is, therefore, the starting point for the continuity of this research. A general overview of the size ranges of the load balances is depicted below, together with the size ranges of all the yachts in the initial data set.

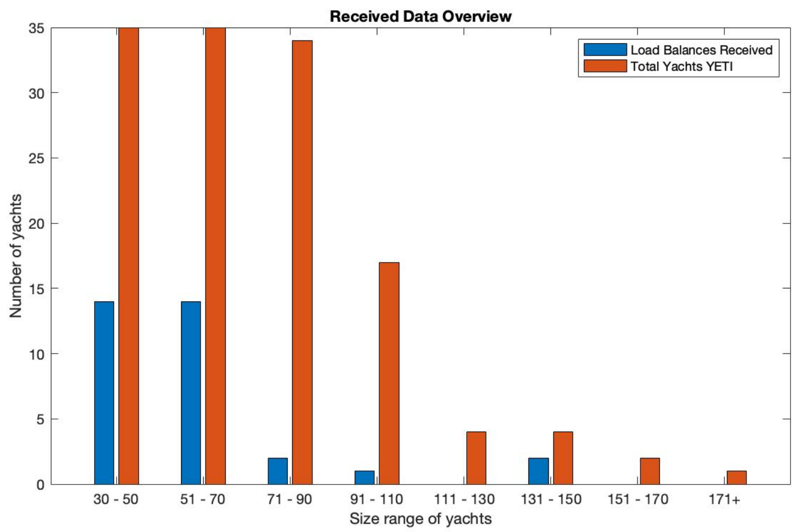

Figure 3.1: Overview of the total data received during the project.

3.1.4. Operational Profile

The operational profile of a yacht is a quantitative characterization of how the vessel is used throughout the year. It defines division over different operational modes, its speed, the percentage of the year that it spends in each mode and, therefore, the number of hours, its relative percentage of guest occupation and the miles traveled.

In the beginning of the YETI project, its fleet consisted of 130 yachts submitted by the project's participants. From these yachts, a total of 297 years of AIS (Automatic Identification System) was acquired to analyze their behavior on a yearly basis. All this data was combined resulting in the following average operational profile:

Table 3.2: YETI average operational profile of a yacht [8].

YETI Operational Profile				
	% of year	**Relative % guests**	**Hours**	**Miles**
Harbor (shore power if available)	56,0%	3%	4906	0
At anchor (stabilized)	34,0%	20%	2978	0
Loitering / maneuvering / DP	1,5%	45%	131	876
Cruising slow = range speed	7,6%	45%	666	4136
Cruising fast	0,8%	45%	70	1578
Maximum speed	0,1%	100%	9	297
Total	**100%**	**11%**	**8760**	**6886**

This operational profile establishes a general overview of how the yacht is used and provides useful insight into how the calculations must be conducted. Different operational modes require different consumers and different load factors. This will serve as a basis for the distribution of hours in use over the course of a year. In this general operational profile, there are three different modes for sailing: cruising slow, cruising fast, and maximum speed. Since the two latter represent less than 1% of the yearly activity, it was assumed that there is only one sailing mode for this research. This is a result of the different load balances that were received from the shipyards partnering in this joint industry project. Since load balances are built differently between different shipyards and sometimes between different yachts of the same shipyard, there is no uniformity regarding the different modes available. This research assumes, therefore, 4 different operational modes: harbor, at anchor, maneuvering, and sailing.

3.1.5. Consumers

Within the load balances, all the electric power consumers are described in a long list. Most of these load balances contain hundreds of consumers. In order to facilitate the grouping of said consumers, the EEDI groups previously presented in chapter 2 will be used. In previous research conducted by WG2 at an earlier stage of the YETI project, it had been discussed the idea of separating part of the consumers which are customer specific from the consumers that are common to all yachts. With this in mind, some large consumers will too be analyzed separately in order to better understand how the consumed power is distributed throughout the yacht.

With this in mind, we start by analyzing the EEDI consumer groups from A to M and, for each group, some examples are provided for a better visualization of these groups:

- A - Hull, Deck, Navigation, and Safety services
  - Deckwash
  - Anchor & mooring
  - Bilge system
  - FiFi system
  - HPU rescue crane and life-raft
  - Fire doors
  - Watertight doors
  - Navigation equipment
  - Alarm system
- B - Propulsion, service auxiliaries
  - Stabilizer system
  - Steering gear
  - Bow/Stern thruster
  - Grease system
- C - Auxiliary engine and main engine services
  - Fuel oil system
  - Lube oil system
  - Exhaust system
  - Cooling system
  - Battery chargers
  - Pre-heaters
- D - Ship's general service
  - Air compressor
  - HPU's doors, hatches and platforms
  - Person elevators
- E - Ventilation for engine rooms and auxiliary rooms
  - Engine room ventilation
  - Generator room ventilation
  - Em. Engine room ventilation
- F - Air conditioning services
  - Air conditioning system

  - Floor heating
- G - Galleys, refrigeration, and laundries services
  - Household equipment
  - Galley equipment
  - Laundry equipment
  - Cool & Freeze
  - Food lifts
- H - Accommodation services
  - Black and grey water system
  - Fresh water system
  - Hot-water system
  - Fitness equipment
  - Spa and pool equipment
  - Electrical doors
- I - Lighting and socket services
  - 110v converters
  - Lighting
  - AV systems
  - Wi-fi system
  - CCTV
- L - Entertainment services
  - Diving gear
  - Entertainment AV
- M - Miscellaneous
  - Tender and Heli filling
  - Sliding cranes

Groups A, B, C, D and E are considered to be common to all yachts. Despite being possible to install more efficient subsystems, these will have little impact on the final YETI score. Nevertheless, it is possible to account for these more efficient subsystems in the entire YETI tool. For this research, we focus on assessing the average consumption. These baseline consumers ensure the correct functioning of the ship's propulsion, ventilation for propulsion machinery, and safety on board. From group B, one consumer stands out: stabilizer systems. This is known to be a large consumer and, for this reason, will be treated separately. Group F, will throughout the rest of this report be named as HVAC. This is known from previous research to be one of the largest consumers and its consumption is strongly dependent not only on exterior ambient conditions but on the owners and crew's way of use too. This group is responsible for maintaining the desired temperature inside the living areas, cabins, and galleys, as well as providing the correct number or air circulations as required by regulatory agencies. Group G contains all the electric components one finds in a galley, that are used to provide all the meals on board as well as to perform the required laundry and drying of all clothes and uniforms of both guests and crew. Despite this being a group strongly correlated to guests and crew, it is not considered to be customer specific as this is something that is found in every yacht. The same happens with group I, lighting. This includes all the lighting systems on board, converters, and sockets. Similarly to HVAC systems, the consumption of lighting on board the yacht is very much dependent on the guests and crew. Some people enjoy having all the lights on at all times. Some cannot handle it. However, similarly to the galley consumers, these are equal to all yachts and will not be treated as customer-specific. Within group H, one finds water treatment systems as well as fitness, spa, and pool equipment. While water systems are common to all yachts, the luxury equipment is not necessary. Therefore, the power destined to supply spa, pool, and sauna equipment will be analyzed separately as it is considered to be customer specific. Groups L and M, are treated as being common to all yachts. These will generally include Audio and Video systems which translate into sound systems and televisions as well as diving gear such as oxygen pumps. Sliding cranes are an example of the miscellaneous group, which are also present in the vast majority of yachts to allow for the launch and retrieval of tenders and other equipment to and from the yacht.

With this division in mind, the structure of the method will focus on 4 main groups of consumers:

1. Groups A, B (without stabilizers), C, D, E, G, H (without amenities), I, L and M. These are considered to be the general consumers.
2. HVAC power.
3. Stabilizer power (fins or gyroscopes).
4. Amenities (spa, pool and jacuzzi) power.

3.2. Methodology

As a starting point, it is important to have a clear overview of how to achieve the final goal of this research: an estimation of yearly electric power consumption onboard of a yacht. In order to calculate the power consumption of any appliance, the wattage of said appliance must be multiplied by the number of hours that it is in use. Since this research deals with the power consumption of superyachts, which have thousands of watts of power installed, the unit kilowatt (kW) is used. Hence, the formula can be written as:

$$\text{Power consumption (kWh)} = \text{Installed power (kW)} \times \text{Hours in use (h)} \tag{3.1}$$

Therefore, this research focuses on two major parts: the installed power of a certain electric consumer and its hours in use. For the first half of this equation, using the provided load balances, an estimation is made for the installed power of all the consumers on board. This value can then be multiplied by the number of hours in use. This second part of the equation is a combination of the average operational profile of a yacht with an average load factor, defining the actual number of hours or the amount of power actually being used throughout a 24-hour period of time.

As guidance for the structure of the research, a mind map was created at an early stage of the method development which would set the way for the used methodology. This mind-map can be found in Figure 3.2, on the following page.

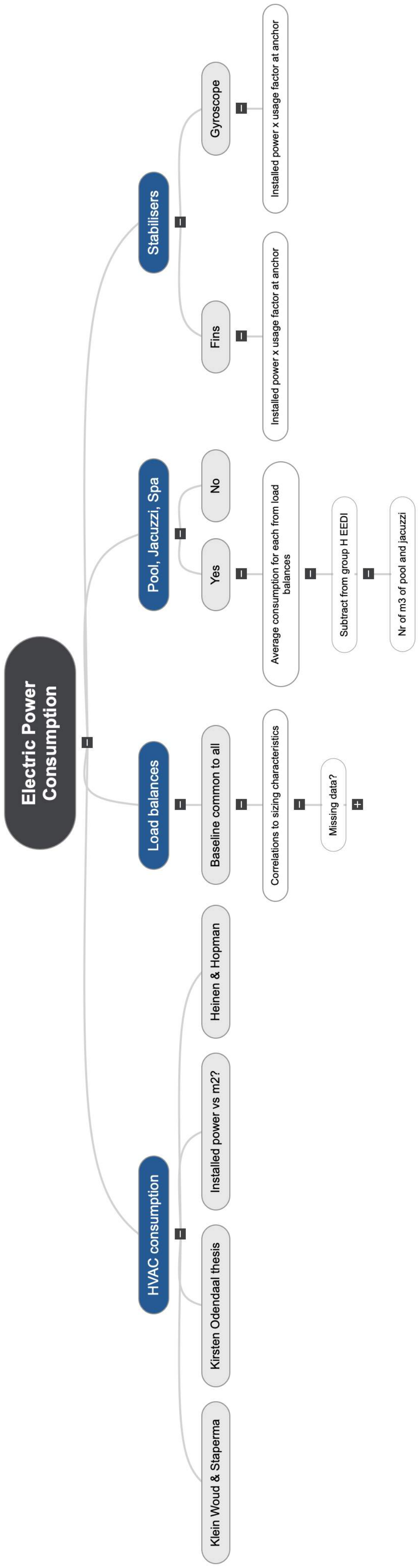

Figure 3.2: Mind map of the research plan

3.2.1. Installed power

In order to be able to predict this installed power, the data received has been thoroughly analyzed in order to find statistically correct correlations between the multiple sets of data that were filtered from the received load balances.

All the load balances were filtered using Excel and sorted into a new one in order to separate the required values for analysis and calculations. This consists of:

1. All standard sizing characteristics previously gathered by WRF.
2. Power consumption at anchor, in harbor, sailing and maneuvering.
3. Installed power per EEDI group (A-M)
4. Contribution of each EEDI group to power consumption at anchor, in harbor and sailing.
5. Installed power dedicated to amenities (pool, jacuzzi and spa).
6. Stabilizer power.

It must be noted however, that YETI has divided sailing into three different modes: maximum speed, cruising fast, and cruising slow (range speed). Taking into consideration that these three modes amount to 8,5%, as seen in table 3.2, and the fact that the majority of the load balances make no distinction of these different operational modes, for the purpose of this research, no distinction was made neither. Therefore, only one sailing mode is taken into account.

The EEDI groups are further detailed in subsection 3.1.5. It should be noted that there are 12 groups as defined by the IMO in the EEDI guidelines (A, B, C, D, E, F, G, H, I, L, N, M), however, group N, cargo loads, was neglected throughout the rest of this investigation as no load balance contained consumers that belonged to this category. In order to achieve this categorization, all load balances were manually checked, and, for every consumer in the list, a letter was attributed according to its purpose. Once all consumers were categorized, the Excel filter command allowed for a correct sum of each group's total installed power.

As a first insight, it was noted that there is quite a strong correlation between the total installed power and the vessel's gross tonnage. This correlation can be seen in Figure 3.3 below. It can be observed that the total installed power follows a rather linear trend.

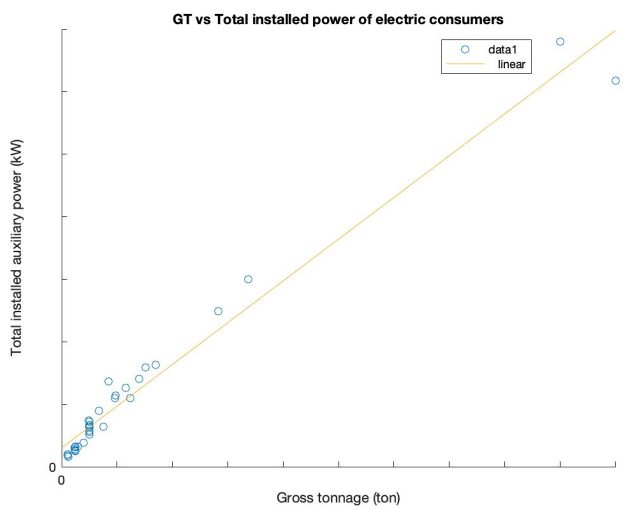

Figure 3.3: Gross tonnage versus the total power of electric consumers installed on-board

It must be noted, however, that the two furthest data points at the right end side of Figure 3.3 will always deviate from the trendline in order to make it a better fit. Below, in Figure 3.4, a comparison is given on how this trendline would look without taking those two data points into consideration. As seen, the line indeed shifts slightly above, however, the value of R^2 has no significant change. This effect will be taken into consideration throughout the rest of this study when analyzing the complete set of data. Ideally, as the tool should serve for a wide range of the yacht's size, taking the largest data points into account is important. However, this might have an effect on the smaller yachts. If we were to estimate the total installed power based on gross tonnage alone, and take the two furthest data points into account, as the trendline shifts down, the power of the smaller yachts will be slightly underestimated. This effect is too taken into account in the future recommendations presented in chapter 5, in which the collection of more data to close the gap between the 4000 and 9000 GT is highly recommended.

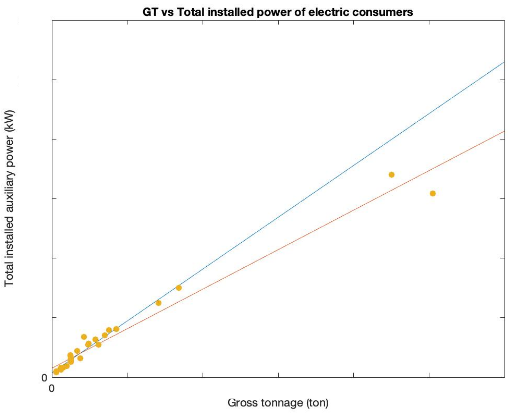

Figure 3.4: Gross tonnage versus the total power of electric consumers installed onboard.

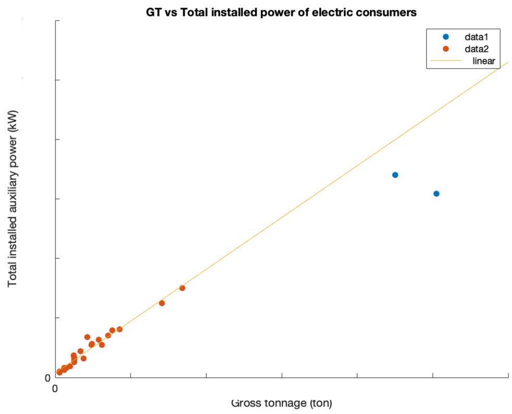

Figure 3.5: Gross tonnage versus the total power of electric consumers installed onboard without the two largest data points.

Pearson's Correlation

After the correct distribution of electric consumers over the different EEDI groups as presented in 3.2.1, the correlation analysis can begin. This correlation analysis is made with the goal in mind of predicting future installed power in a vessel, as the first half of calculating electric power consumption. For the strongest correlation between a certain group of consumers and a certain sizing characteristic, a function is created which allows for the prediction of the installed power of that group by using the sizing characteristic as an input parameter in the tool.

A correlation is a widely used statistical test as a means to calculate how strong the relationship between two variables is. There are several different correlation tests (such as Pearson, Spearman, Kendall), however, the most widely used, and the one that will too be used for the purpose of this research, is the Pearson correlation [29].

The Pearson coefficient (r) is a value that lies between -1 and +1, from which 1 indicates the strongest possible positive correlation and -1 corresponds to the strongest possible negative correlation. When the correlation is positive, it means that as one variable increases, the other variable increases too. The absolute value of r indicates the strength of the relationship, meaning a r value closer to -1 or +1 indicates a stronger/more regular relationship. On the other hand, as the r value approaches 0, the relationship is weaker. It is also important to note that the coefficient r is independent of measurement units.

The Pearson coefficient can also be more easily interpreted as visualizing the r value as a measurement of how accurately a straight line, which represents a linear relationship, described the data cluster in a scatter plot. Looking back at Figure 3.3, one can observe how the linear trend-line is very close to the scatter of the data dots. This correlation translates into an r coefficient of 0.99, indicating a very strong positive relationship between the variables *gross tonnage* and total *installed power of electric consumers*.

The formula to compute the Pearson correlation coefficient is given below, in equation 3.2. In the equation, 'SP' corresponds to the sum of the products and 'SS' to the sum of squares.

$$r = \frac{SP_{xy}}{\sqrt{SS_x SS_y}} \tag{3.2}$$

The equations for the two sum of squares are given as follows:

$$SS_x = \sum (X - \bar{X})^2 = \sum X^2 - \frac{\left(\sum X\right)^2}{n} \tag{3.3}$$

$$SS_y = \sum (Y - \bar{Y})^2 = \sum Y^2 - \frac{\left(\sum Y\right)^2}{n} \tag{3.4}$$

Lastly, the formula for the sum of products is given below:

$$SP_{xy} = \sum (X - \bar{X})(Y - \bar{Y}) = \sum XY - \frac{\left(\sum X\right)\left(\sum Y\right)}{n} \tag{3.5}$$

In order to find statistically correct correlations, a Persons analysis was conducted. In this analysis, the different EEDI groups were correlated to several different sizing characteristics that were deemed relevant for comparison. These are gross tonnage, length of waterline, length overall, and total interior space (both guests and crew areas). In table 3.3 below, the coefficients are presented. In order to perform this analysis, the Excel's function **=PEARSON(array1, array2)** was used. In the place of array1 and array2, the pair of variables is substituted.

Every consumer group has been compared to the 4 different sizing characteristics and the results are color graded with green corresponding to a stronger correlation. It can be observed that the strongest correlations are, therefore:

- Power group A with gross tonnage: 0.98
- Power group B (excluding stabilizers) with gross tonnage: 0.91
- Power group C with interior space: 0.86
- Power group D with interior space: 0.94
- Power group E with interior space: 0.94
- Power group F with interior space: 0.98
- Power group G with length waterline: 0.86
- Power group H (excluding amenities) with interior space: 0.94
- Power group I with interior space: 0.80
- Power group L with length waterline: 0.92
- Power group M with length waterline: 0.86
- Stabilizer power with gross tonnage: 0.98

Table 3.3: Pearson's correlation coefficient between EEDI groups and sizing characteristics

Pearson's Correlation Coefficient				
	GT	**LOA**	**LWL**	**Interior Space**
Power group A	0,98	0,94	0,95	0,97
Power group B (- stabi)	0,91	0,89	0,85	0,88
Power group C	0,78	0,83	0,85	0,86
Power group D	0,92	0,88	0,88	0,94
Power group E	0,93	0,89	0,89	0,94
Power group F	0,98	0,89	0,91	0,98
Power group G	0,83	0,85	0,86	0,84
Power group H (-amenities)	0,93	0,93	0,92	0,94
Power group I	0,70	0,71	0,70	0,80
Power group L	0,88	0,92	0,92	0,89
Power group M	0,79	0,86	0,86	0,80
Stabilizer power	0,98	0,92	0,94	0,97

At a first glance, most of these correlations can be logically explained and are somewhat expected. As for example group A (Hull, Deck, Navigation, and Safety services) and B (Propulsion, service auxiliaries) are strongly correlated to gross tonnage. The larger the yacht, the more power it will require for propulsion and service auxiliaries as well as for hull, deck and safety services. Also, group F, HVAC power, is strongly correlated to interior space. This correlation is also logically explained as the larger the interior area of the yacht, the more power it will require to supply heating, ventilation, and air conditioning to all the enclosed spaces. Some groups, such as H (Accommodation services) and I (Lighting and socket services) are strongly correlated to interior space. This can be explained due as the larger the interior space, the more lighting is required as well as more black, grey, freshwater and hot water systems will be required to supply all the guest and crew cabins. Also, the larger the interior space, the more electric doors will be present throughout the yacht. Not depicted in the table below is the correlation between stabilizer power and light weight of the yacht. This correlation proved to be even stronger than the correlation with gross tonnage, as expected, since the heavier the yacht, the more power will be required to counter its roll motion. However, since the main YETI tool does not include lightweight as an input parameter, this correlation was neglected and gross tonnage remains as the strongest relationship.

P-value

The confidence in a relationship is not solely based on the correlation coefficient but also on the pairs of data present in the data. In order to measure the actual significance of such an empirical analysis, it is common, in statistics, to use the so-called p-value. The p-value represents the probability, for a certain statistical model, that in the case when the null hypothesis happens to be true, the test results would be at least equal to, or more extreme than, the results that were actually observed previously. Supposing the goal is to find out whether the relationship between gross tonnage and the interior area is significant, the analysis starts with the null hypothesis which states that, for this particular case, *gross tonnage and interior area are unrelated*. That means that the obtained results are due to mere chance and do not provide any relevance to the idea being investigated. The alternative hypothesis, however, states that one variable does indeed affect the other one and that it is not due to chance, thus, supporting the idea that is being investigated.

This p-value, between 0 and 1, translates into a level of statistical significance. Typically, a value of $p < 0.05$ is considered to be statistically significant. It indicates that there is a probability of less than 5% that the null hypothesis is true, therefore indicating strong evidence against it, allowing to reject it and maintain the alternative hypothesis. On the other hand, a value of $p > 0.05$ indicates that the chance that the results were obtained by chance is higher than 5%. That means it is not statistically significant and provides strong evidence in favor of the null hypothesis. It should be noted, however, that a statistically significant result does not automatically mean that the research hypothesis is correct, as that would imply 100% of certainty. Instead, it can be stated that the results indeed 'show evidence of' or 'provide support for' the research hypothesis, as there is a small probability that the results have occurred by chance.

In order to obtain the p-value for a Pearson correlation for every combination of relationships, the number of pairs must first be counted. These pairs are depicted below, in table 3.4. It should be noted that the number of pairs is not the same for every combination since not all data parameters were equally available for every yacht or load balance.

Table 3.4: Number of pairs of all combinations of variables.

Number of pairs				
	GT	**LOA**	**LWL**	**Interior Space**
Power group A	33	33	33	32
Power group B (- stabi)	31	31	31	29
Power group C	33	33	33	32
Power group D	32	32	32	30
Power group E	24	24	24	22
Power group F	33	33	33	32
Power group G	33	33	33	32
Power group H (-amenities)	33	33	33	32
Power group I	31	31	31	29
Power group L	30	30	30	28
Power group M	20	20	20	20
stabilizer power	20	20	20	18

Once all the pairs have been accounted for, the t-test for every combination can be calculated. This value t is calculated based on the obtained correlation coefficient r and the number of pairs n using the following formula:

$$t = \frac{r \times \sqrt{n-2}}{\sqrt{1-r^2}} \tag{3.6}$$

Having all the values for the t-test t and the number of pairs n, the p-values can be calculated using Excel's function **=TDIST(x, degfreedom, tails)**. In this function, x is substituted by the t-test t, the degrees of freedom is equal to $n-2$ and tails is, in this case, 2 for a two-tailed analysis.

By performing the calculation for all the different combinations, it became clear that for all of them the resulting p-value was very close to zero. Therefore it is possible to conclude how all the p-values are below the threshold of $p < 0.05$. This means that for all correlations studied, the probability that the results were obtained by chance is less than 5%. It is therefore possible to conclude that these correlations are statistically significant and that evidence suggests the existence of a relationship between the variables.

Installed power estimations

Once the strongest correlations have been investigated, it is possible to move on to the actual estimation of installed power for every consumer group on the EEDI list. All the strongest correlations, which were previously presented, were plotted in a scatter plot using MATLAB software. For every plot, the trend line is plotted too, along with its defining equation and coefficient of determination R^2.

These graphs are plotting a trendline of the average of what is currently being installed on board a yacht. This forms a solid basis for predicting what will actually be installed in a future build, always keeping in consideration what the average fleet looks like.

In Figures 3.7 to 3.18, all the plots of the correlations are shown. For all these plots, with the aid of MATLAB, three different types of trend lines were plotted and each was individually analyzed. These types are linear, quadratic, and cubic. The general rule was to identify which trendline fitted the data points the best, by comparing the values of R^2. However, this is not always the best method. In the following Figure 3.6, an example of this is given. By comparing the R^2 of all three trend lines, one would assume that the cubic one gives the best fit for the data points. However, by looking at the green line in the plot, we can see how the line grows exponentially after the 2500GT. This would ultimately influence negatively the installed power of lighting systems on larger yachts. For this case, the linear trend line is chosen as the most optimal fit for the correlation.

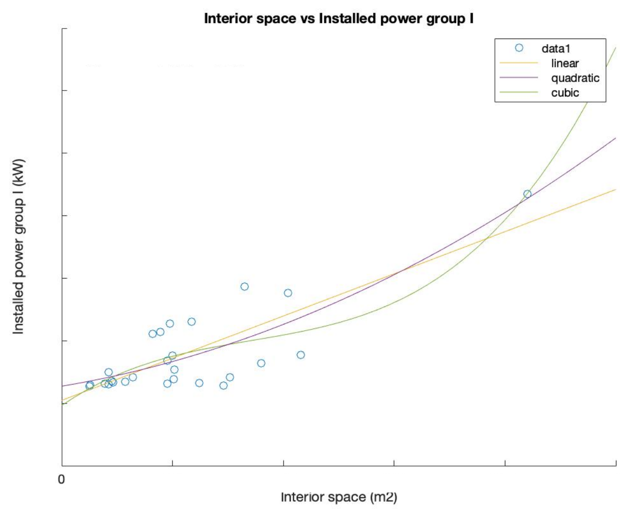

Figure 3.6: Trendlines of the correlation between interior space and the installed power for group I (lighting)

This analysis has been made for all the different correlations and these plots can be found in appendix A.

For the majority of these graphs, it is possible to identify the correlation between the data points.

This is initially somewhat expected since the larger the vessel, whether in GT, length, or interior area, the larger will be the installed systems. For some, however, the correlation is not fully consistent, such as in the case of Figures 3.15 for example the correlation between interior space and installed power for lighting. This could be explained by the fact that some yachts are equipped with LED lamps and others with halogen. Nevertheless, the chosen trendlines and their respective values of R^2 have the best fit for the available data set.

In a previous phase of the YETI development, WG2 studied the possibility of a hybrid method, extracting large consumers for a separate calculation. The rest would be considered to be the general baseline of consumers common to all yachts. This baseline was compared to several sizing characteristics by some shipyards involved. However, for this study, it was decided to further break down these baseline consumers into different groups to maximize the accuracy of the prediction. Despite some graphs having some data points away from the trendline, the idea is that by breaking down the baseline consumers into different categories and taking a specific function for these, there is a higher probability that any over or under-estimation will be balanced out in other correlations, ensuring a better overall prediction of installed power. This will be later analyzed in chapter 4.

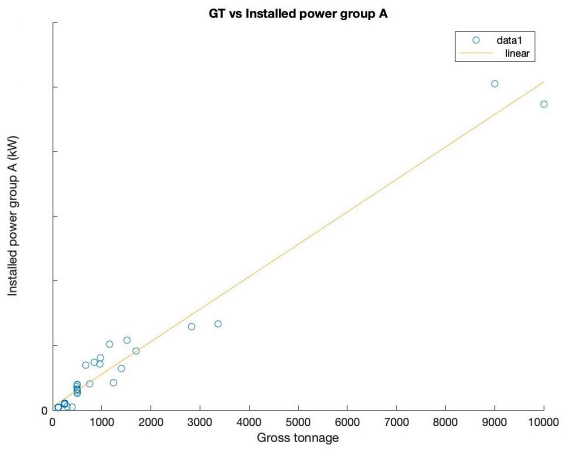

Figure 3.7: Plot of gross tonnage versus total installed power of EEDI group A.

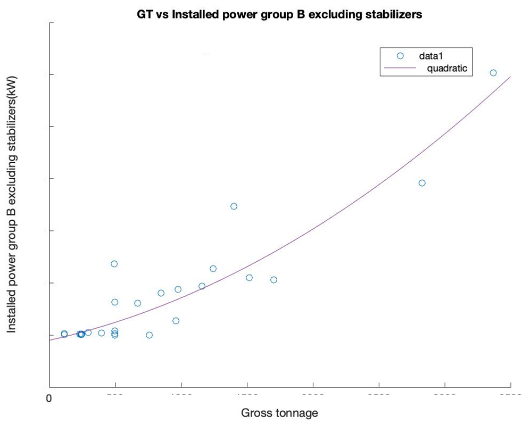

Figure 3.8: Plot of gross tonnage versus total installed power of EEDI group B excluding amenities.

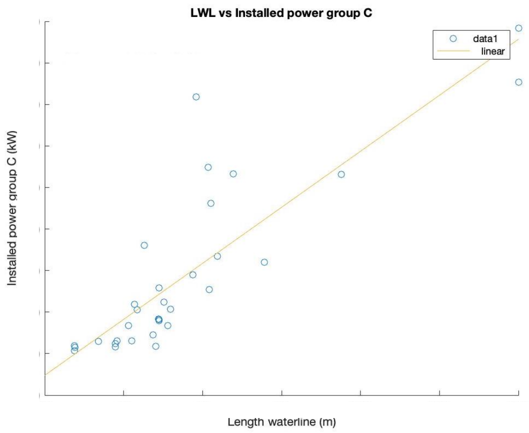

Figure 3.9: Plot of length of waterline versus total installed power of EEDI group C.

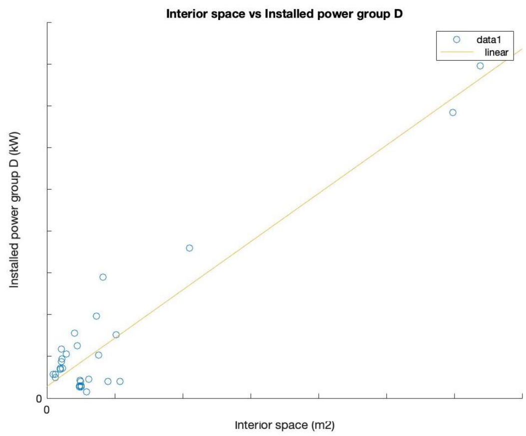

Figure 3.10: Plot of interior space versus total installed power of EEDI group D.

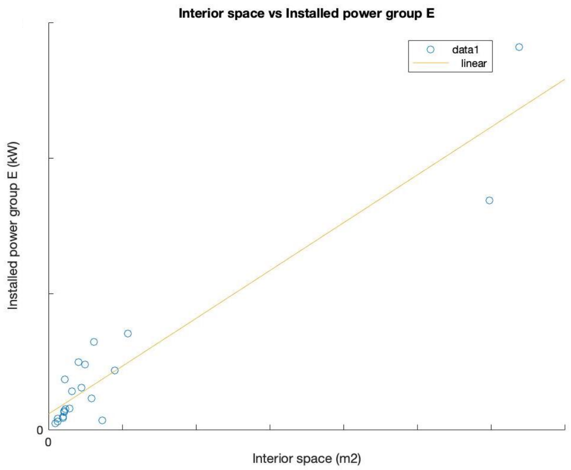

Figure 3.11: Plot of interior space versus total installed power of EEDI group E.

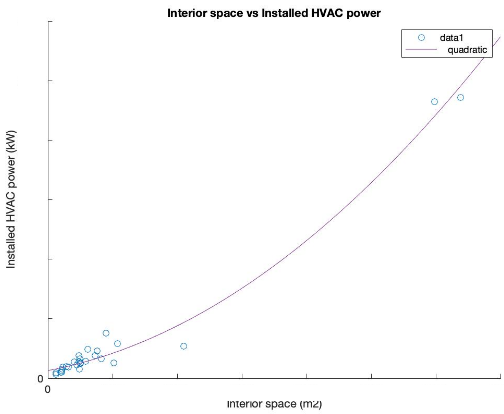

Figure 3.12: Plot of interior space versus total installed power of HVAC systems (group F).

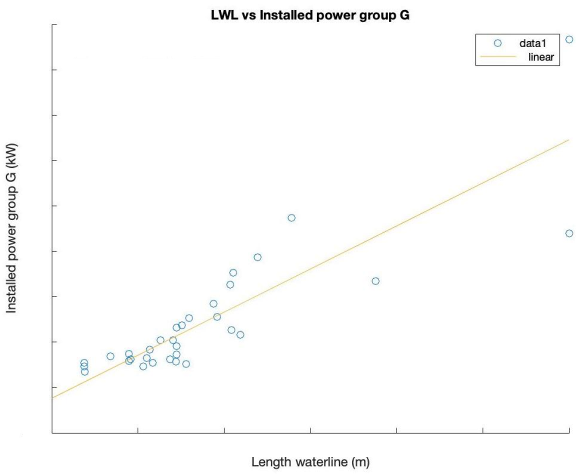

Figure 3.13: Plot of length of waterline versus total installed power of EEDI group G.

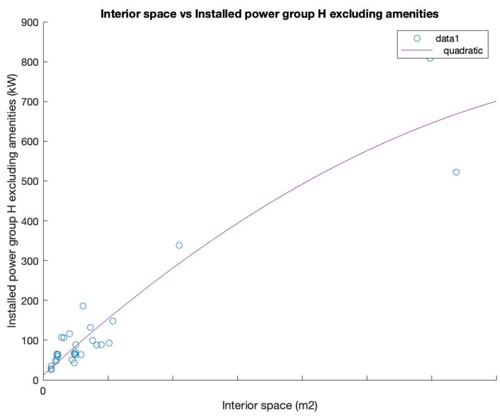

Figure 3.14: Plot of interior space versus total installed power of EEDI group H excluding amenities.

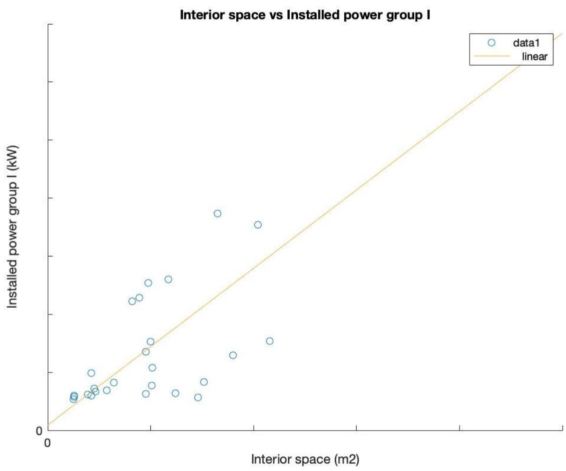

Figure 3.15: Plot of interior space versus total installed power of EEDI group I.

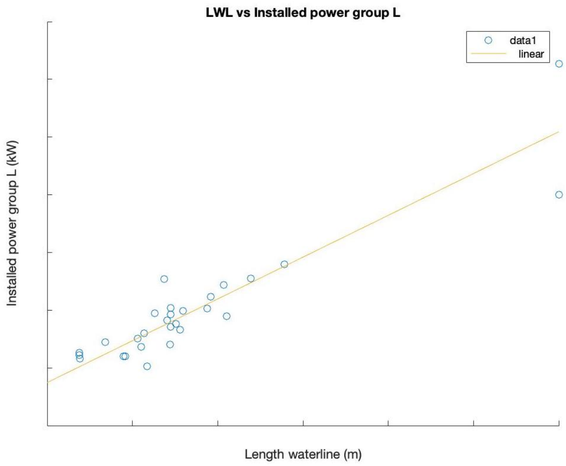

Figure 3.16: Plot of length of waterline versus total installed power of EEDI group L.

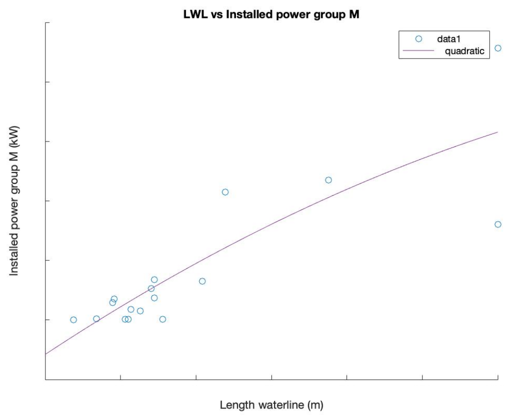

Figure 3.17: Plot of length of waterline versus total installed power of EEDI group M.

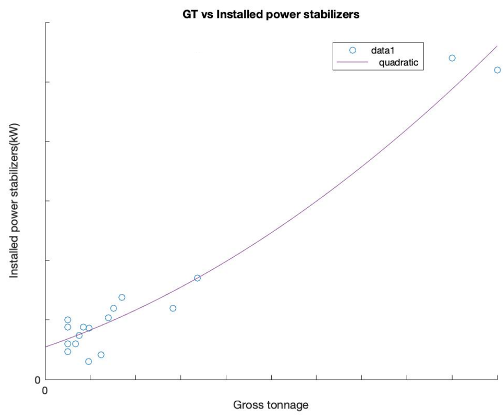

Figure 3.18: Plot of gross tonnage versus total installed power of stabilizers.

It should be noted that for two of these plots, the data points for the two largest yachts were not accounted for. In the case of group I (lighting and socket services), these data points were removed as they were considered to be strong outliers that would have too large of an effect on the data set. In the case of group B (propulsion, service auxiliaries) the two largest yachts were also removed as there were no bow thrusters within the load balances and this too would affect the general data set.

These trend lines will serve as guidance for the estimation of the installed power. The correlations and their corresponding equations are given below. In these equations, y represents the value for the installed power and x is to be substituted by the variable for which the group was correlated (GT, interior area, LWL).

- Power group A - GT
$$y = 0.1004 \cdot x + 11.04 \tag{3.7}$$
- Power group B (excluding stabilizers) - GT
$$y = 5.063 \cdot 10^{-5} \cdot x^2 + 0.1123 \cdot x - 20.53 \tag{3.8}$$
- Power group C - interior space
$$y = 3.372 \cdot x - 93.65 \tag{3.9}$$
- Power group D - interior space
$$y = 0.02308 \cdot x + 5.653 \tag{3.10}$$
- Power group E - interior space
$$y = 0.01762 \cdot x + 5.701 \tag{3.11}$$
- Power group F - interior space
$$y = 4.26 \cdot 10^{-5} \cdot x^2 + 0.1024 \cdot x + 64.84 \tag{3.12}$$
- Power group G - LWL
$$y = 4.744 \cdot x - 118.5 \tag{3.13}$$
- Power group H (excluding amenities) - interior space
$$y = -7.208 \cdot 10^{-6} \cdot x^2 + 0.1488 \cdot x + 12.01 \tag{3.14}$$

- Power group I - interior space

$$y = 0.135 \cdot x + 4.591 \tag{3.15}$$

- Power group L -LWL

$$y = 0.7244 \cdot x - 19.57 \tag{3.16}$$

- Power group M - LWL

$$y = -0.001776 \cdot x^2 + 0.9067 \cdot x - 29.01 \tag{3.17}$$

- Stabilizer power - GT

$$y = 1.221 \cdot 10^{-6} \cdot x^2 + 0.01308 \cdot x + 27.26 \tag{3.18}$$

3.2.2. Usage ratios

Once the power estimations are complete, it is possible to focus on the second part of the calculation of power consumption: the hours in use. In this second part of the method, the usage ratios are calculated for the different groups. As previously mentioned, not only does every mode have a different set of electric consumers in operation, every consumer has its own load factor, translating into its hours in operation.

In order to apply this reduction factor to the installed power, a usage ratio was calculated for every EEDI group of three operational modes: at anchor, harbor, and sailing. This usage ratio is found by dividing the actual used power of a certain EEDI group by the total installed power of that same group. The second part, the total installed power, has been previously calculated, in section 3.2.1. The actual used power was filtered from all load balances using the sort filter option. As the consumers had been categorized by their purpose, by filtering the sheet for group A, for example, the total used power at anchor, for example, can be found. Dividing this value by the total installed power of group A gives the usage ratio of group A at anchor. After repeating this process for every load balance available, an average value was taken for this ratio. This is represented by the first blue bar on the left part of the graph in Figure 3.19. The Figure below depicts the usage of all EEDI groups for the three different operational profiles.

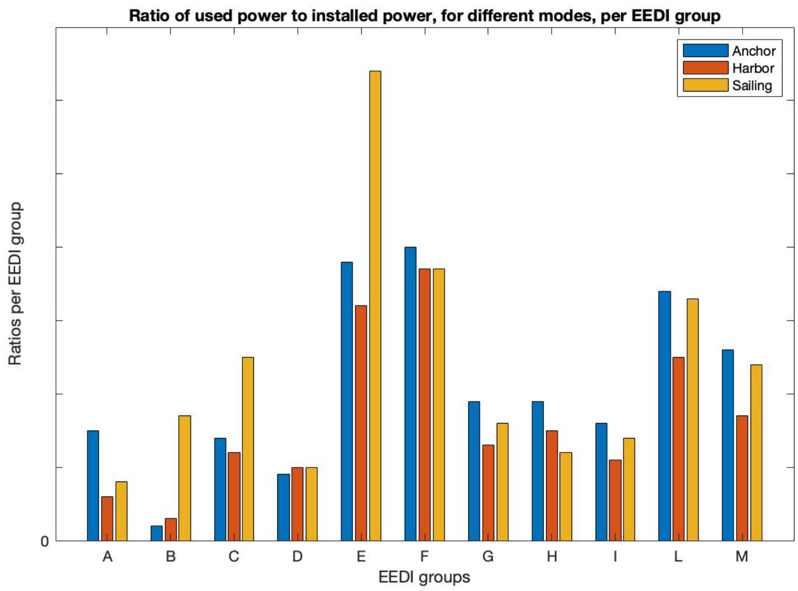

Figure 3.19: Ratios of used power over total installed power, in different operational modes, per EEDI group

As one can observe in the previous Figure, each group has a rather different average usage ratio, most of them as expected. Take for example group B (propulsion and service auxiliaries) or group C (auxiliary engine and main engine services) consume more power during sailing when the main engines are in operation. The same happens for group E (ventilation for engine rooms and auxiliary rooms); while the auxiliary engine rooms require ventilation while in harbor and at anchor, during sailing almost 65% of this available power comes into operation. As for the rest of the groups, there is not much variation between operational modes, with a deviation of less than 10%. In this figure, it also becomes apparent the influence that group F (HVAC systems) has on the power consumption of a vessel. This group already represents a large share of the total installed power and, on top of that, has a high average usage ratio of around 40%.

The precise values of these load factors are given in Table 3.6 below, per consumer group and per operational mode:

Table 3.5: Ratios for anchor, harbor and sailing

Groups/Ratios	Anchor	Harbor	Sailing
A			
B			
C			
D			
E			
F			
G			
H			
I			
L			
M			

3.3. Power consumption estimation

By combining all previous research together, one can begin with the actual calculations of power consumption of EEDI groups A to M and stabilizers at anchor, harbor, and sailing. In this section, the rest of the consumers as well as the consumption during dynamic positioning will be analyzed and calculated.

3.3.1. EEDI groups A to M

In section 3.2.1, the installed power was estimated using a statistical analysis based on the provided load balances, and in section 3.2.2, the usage ratios were calculated providing the necessary data to perform an estimation of the electrical power consumption of groups A to M in three operational modes.

Recalling the power estimation equations:

$$\text{Estimated power A} = 0.1004 \cdot GT + 11.04 \tag{3.19}$$

$$\text{Estimated power B} = 5.063 \cdot 10^{-5} \cdot GT^2 + 0.1123 \cdot GT - 20.53 \tag{3.20}$$

$$\text{Estimated power C} = 3.372 \cdot \textit{interior space} - 93.65 \tag{3.21}$$

$$\text{Estimated power D} = 0.02308 \cdot \textit{interior space} + 5.653 \tag{3.22}$$

$$\text{Estimated power E} = 0.01762 \cdot \textit{interior space} + 5.701 \tag{3.23}$$

$$\text{Estimated power F} = 4.26 \cdot 10^{-5} \cdot \textit{interior space}^2 + 0.1024 \cdot \textit{interior space} + 64.84 \tag{3.24}$$

$$\text{Estimated power G} = 4.744 \cdot LWL - 118.5 \tag{3.25}$$

$$\text{Estimated power H} = 0.103 \cdot \textit{interior space} + 32.12 \tag{3.26}$$

$$\text{Estimated power I} = 0.135 \cdot \textit{interior space} + 4.591 \tag{3.27}$$

$$\text{Estimated power L} = 0.7244 \cdot LWL - 19.57 \tag{3.28}$$

$$\text{Estimated power M} = -0.001776 \cdot LWL^2 + 0.9067 \cdot LWL - 29.01 \tag{3.29}$$

And recalling the usage ratios from table 3.6:

Table 3.6: Ratios for anchor, harbor and sailing

Groups/Ratios	Anchor	Harbor	Sailing
A			
B			
C			
D			
E			
F			
G			
H			
I			
L			
M			

To take as an example, the following parameters were used as input:

- Gross tonnage = 1000
- Length water line = $60m$
- Interior space = $400m^2$

The resulting estimated installed power and electric power consumption for a yacht with these characteristics are given below, in table 4.1. In this table, the installed power is calculated using the formulas above and the consumption value is calculated by multiplying the installed power with the different ratios of the different operational modes.

Table 3.7: Estimated installed power and electric power consumption for anchor, harbor, and sailing.

EEDI Group	Installed power	Anchor ratio	Anchor consumption	Harbor ratio	Harbor consumption	Sailing ratio	Sailing consumption
A	111,44	0,15	17,04	0,06	6,77	0,08	8,84
B minus stabilizers	183,70	0,09	16,90	0,03	6,12	0,17	31,32
C	108,68	0,14	15,11	0,12	12,85	0,25	27,45
D	14,73	0,09	1,27	0,10	1,50	0,10	1,42
E	13,00	0,38	4,94	0,32	4,15	0,64	8,35
F	209,72	0,41	85,12	0,38	79,31	0,37	78,29
G	166,08	0,19	31,84	0,13	22,41	0,16	26,68
H minus amenities	73,76	0,20	14,53	0,16	11,59	0,12	8,56
I	58,22	0,16	9,28	0,11	6,55	0,14	8,05
L	23,89	0,34	8,21	0,25	6,04	0,33	7,87
M	16,88	0,26	4,43	0,17	2,95	0,24	4,03
Total Power	980,09		208,67		160,24		210,84

3.3.2. Stabilizers

During the research, contact was made with a USA-based company, Quantum Stabilizers, that engineers and manufactures marine stabilizer systems for not only yachts but also for the military and commercial industries. This contact was made in the hope of gaining a better understanding on how the sizing of the stabilizers is conducted and finding a suitable way to predict the behavior of these systems in a yacht, in order to estimate its power consumption. The contact person immediately showed interest and willingness to aid in this challenge however, unfortunately, but understandably, due to constraints, it was not possible for Quantum Stabilizers to allocate the necessary time and resources to this task within the required time frame.

As an alternative, previously, in section 3.2.1, the estimation for stabilizer power was conducted. This was based on the values of installed power of all load balances that included stabilizers. A strong and statistically significant correlation was found between the installed power of the stabilizing systems and the yacht's gross tonnage. Recalling the formula for this calculation:

$$\text{Estimated power stabilizers} = 1.221 \cdot 10^{-6} \cdot GT^2 + 0.01308 \cdot GT + 27.26 \qquad (3.30)$$

Applying the same parameters used in the previous section 3.3.1, the resulting installed power for the stabilizers is $41.8kW$. In order to find the utilization rate of the stabilizing systems, the load balances were filtered and the average of the load factors was calculated for anchor, harbor, and sailing. It should be noted that while in harbor, only the systems in the form of gyroscopes can operate as fins are not suitable in close contact with other yachts. The resulting usage ratios and the corresponding power consumption for the three operating modes are the following:

Table 3.8: Estimated installed power and electric power consumption of stabilizers for anchor, harbor, and sailing.

Stabilizer power	Anchor Ratio	Anchor power	Harbor Ratio	Harbor power	Sailing Ratio	Sailing power
41,8	0,5	20,9	0,25	10,45	0,51	21,3

These ratios are the result of the fact that the stabilizers are not always operating at 100% of their power combined with the fact that they are not operating the whole time.

3.3.3. Amenities

As the amenities of a yacht, such as swimming pools, jacuzzis, and spas, are considered to be customer-dependent, it was decided that these should not be incorporated into the baseline which is common to all yachts. As a result, the electrical consumers dedicated to these amenities were subtracted from group H (Accommodation services) and calculated separately.

Pool

During the data collection phase, the volume of the swimming pools installed onboard in cubic meters was requested from the shipyards. As the load balances were sorted and filtered, the installed power for the maintenance of the swimming pool (such as filtration, pumps, and heating) was grouped. Two categories were created, with heater and without heater. This total power destined for the swimming pool was divided by the volume of the pool, resulting in a certain amount of kW per m^3. As a general result, if the pool is installed with a heater, the power per cubic meter is higher than for a non-heated pool. Based on a total of 7 yachts equipped with swimming pools (5 heated, 2 non-heated). The average power per cubic meter of a heated pool is $15.6kW$ and for a non-heated pool, it corresponds to $6.1kW$. It should be noted here, however, that the sample is rather small and there are quite some discrepancies between kW/m^3 values.

Within the tool, this kW/m^3 is multiplied by the size of the pool to obtain the total installed power destined for the swimming pool facilities. These consumers are, in most cases, filling pumps, circulation pumps for filtration, jet stream pumps, lighting, heaters, and UV lighting for sanitizing. The assumption is taken that the swimming pool is used in a total of 2.5% of the year. The installed power is then multiplied by this percentage and the number of hours of each operational mode to form the total yearly consumption.

Jacuzzi

Similarly, as to what has been done with the swimming pools, the size of the jacuzzis in cubic meters was also requested in order to find the power per cubic meter. The consumers for the jacuzzis are the circulation pumps, heaters, lighting, and air blower. As the size of the jacuzzi is also an input parameter of the tool, this is multiplied by the kW/m^3 value to obtain the installed power. For the jacuzzi, it is also assumed that it is used a total of 2.5% of the year. The installed power is multiplied by this percentage and the total number of hours, resulting in the yearly consumption.

Spa and hammam

A spa in a yacht can generally consist of several consumers such as a steam room with a steam generator, a duftdose, a sauna, or a hammam with a treatment unit. At first, by filtering and sorting all consumers in the load balances, it was found that, on average, a yacht has a total of $14.4kW$ of installed power dedicated to the spa, based on 15 yachts equipped with spa units. However, by analyzing the box and whiskers plot in Figure 3.20, it can be observed that there are two major outliers in terms of spa installed power. This corresponds to the larger yachts. In Figure 3.21, one can observe how it is possible to assume a trend line between the installed power for the spa and the size of the vessel in gross tonnage.

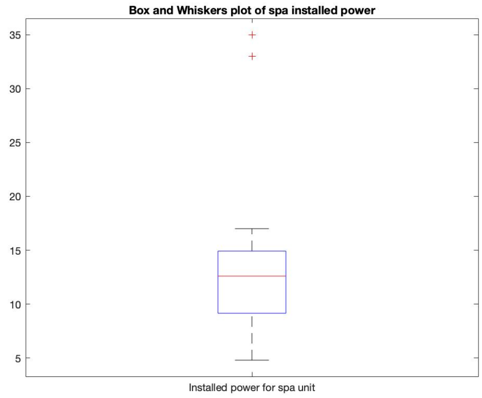

Figure 3.20: Box and whiskers plot of spa installed power.

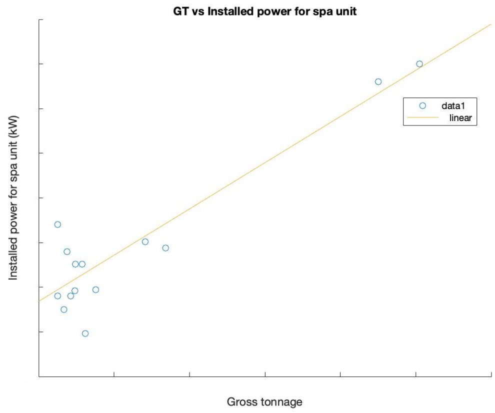

Figure 3.21: Plot gross tonnage versus total installed power dedicated to spa unit.

As a yacht increases in size, so do its spa facilities, as there is more available space. By assuming a fixed average for spa, $14.4kW$, the tool would be penalizing smaller yachts and benefiting the larger yachts, and, since the goal of the YETI is to benefit yachts with a lower environmental footprint, it was decided to take the second approach. Therefore, it has been considered that the fairest way to calculate spa power is by using the following equation:

$$\text{Estimated spa power} = 0.0026 \cdot \textit{gross tonnage} + 8.414 \tag{3.31}$$

In this case, it was assumed that the spa facilities are used for a total of 1.5% of the year. Multiplying the installed power with the usage percentage and the number of hours in a year yields the yearly consumption of the spa.

3.3.4. Maneuvering/Dynamic Positioning/Loitering

Maneuvering is the fourth operating mode of the operational profile taken into consideration in this research. This mode consists of the positioning of the yacht in its docking position in a harbor, positioning for anchor, or just maintaining a position while awaiting to berth, using dynamic positioning. From all operating modes, this is the one that consumes the most auxiliary power since in this mode the bow thrusters come into action and these are large consumers with high installed power. Maneuvering, however, takes place only during 1.5% of the time in a year, according to the previous YETI research in which the operational profile was set up. Seeing it is such a small part of power consumption, a different approach was taken to calculate auxiliary power consumption.

When analyzing all the data available from the load balances, due to irregularities in the way these are built between shipyards, it was decided to shift the focus to the total consumption given for the maneuvering mode. It was found that, on average, maneuvering consumes 30% more when compared to sailing. The spread of these values can be seen in Figure 3.22. Seeing that some load balances did not include bows and/or stern thrusters, these data points were excluded from the calculations.

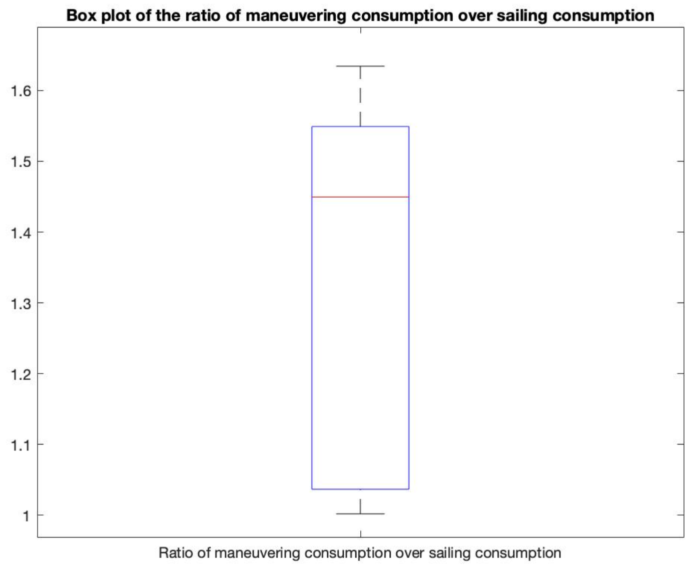

Figure 3.22: Box plot of the maneuvering power ratio.

3.4. Tool Format

Seeing that the existing YETI tool is built in Microsoft Excel, the model for the calculation of auxiliary power consumption has been built with the same software. In this way, the integration into the existing tool is simplified and can be easily done.

3.4.1. Input and Output Parameters

As seen throughout this chapter, the required data to perform the calculations presented in this method, which serve as input parameters for the tool, are the following:

- Gross tonnage: used to calculate installed power of EEDI groups A, B and F.
- Length water line (m): used to calculate installed power of EEDI groups G, L and M.
- Interior area (m^2): used to calculate installed power of EEDI groups C, D, E, H and I.
- Jacuzzi: size (m^3).
- Pool: size (m^3) and existence of pool heater.
- Spa: number of units.
- Stabilizers: gyroscope or fins.

These parameters, using the same example yacht as before, have been implemented into the tool in the following way:

Data input required in yellow cells

Yacht Input Data

Sizing characteristics	Value	Unit
Gross tonnage (GT)	1000	gt
Length Waterline (LWL)	60	m
Interior area	400	m^2

Amenities:	Installed	Quantity	
Jacuzzi	Yes	Cubic meters:	2
Pool	Yes	Cubic meters:	10
		Heater	No
Sauna/hamman	Yes	Number of saunas	1

Stabilizers	Yes	Gyroscope

Figure 3.23: Input parameters of auxiliary consumption calculator tool

Once the input parameters have been inserted, the calculations are made and the output is given. This is in the form of installed power estimation per category, total auxiliary power consumption in a year in kWh as well as a distribution of this power consumption per type of consumer and per operational mode. For a better overview of how this power is consumed, the average power demand per operational mode is also given in a separate table. These output results can be better visualized in the example of Figure 3.24 below:

Yacht Output Data

Yearly electric power consumption (kWh)
1418416

Consumer	Consumption (kWh)	%
EEDI groups ABCDEGHILM	891056	63%
HVAC	369023	26%
AMENITIES	28951	2%
Stabilizers	129385	9%

HARBOR	668075	47%
ANCHOR	572758	40%
MANOEUVRING	27381	2%
CRUISING SLOW	134297	9%
CRUISING FAST	14137	1%
MAX SPEED	1767	0%

Average consumption per operating mode (kW)			
Anchor	Harbor	Sailing	Manoeuvring
168	122	173	197

Estimated total installed power	1060	kW
Estimated installed power EEDI groups ABCDEGHILM	770	kW
Estimated installed HVAC power	110	kW
Estimated installed power for amenities	139	kW
Estimated installed power for stabilizers	42	kW

Figure 3.24: Output parameters of auxiliary consumption calculator tool

For a general idea of how the consumption is distributed between the different groups of consumers as well as per each operational mode, two pie charts are added as follows:

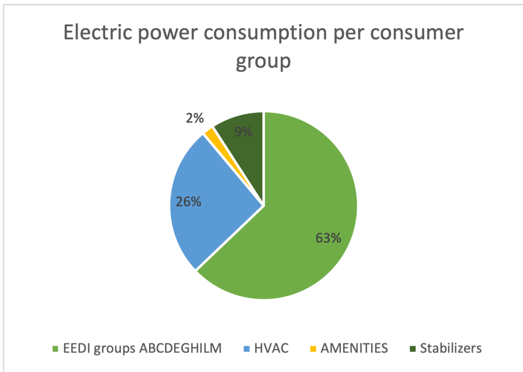

Figure 3.25: Example of yearly auxiliary power consumption distribution per consumer group.

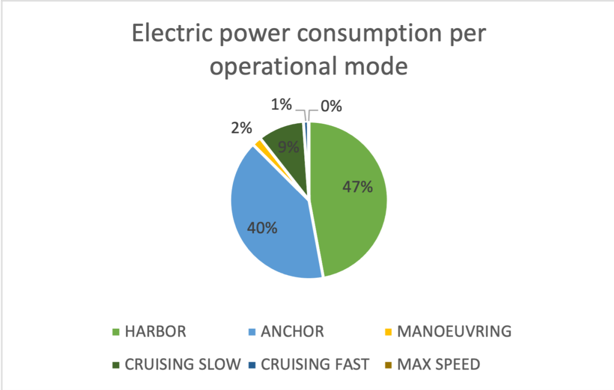

Figure 3.26: Example of yearly auxiliary power consumption distribution per operational mode.

3.4.2. Implementation into YETI Tool

As the method for the estimation of auxiliary power consumption has been equally designed in EXCEL, its future implementation into the YETI tool has been facilitated.

The score of YETI is calculated according to attributed ecopoints. These ecopoints depend on some factors, among which, the CO_2 emissions. Since the electric power consumed on board the yacht has different origins, it is important to assess how that energy is produced.

When implementing this method in the YETI main tool, and since the output parameters indicate the distribution of the consumed power per operational mode, the assessment of the power origin can be made.

In the case of **sailing**, the required power for hotel load can be drawn from a power take-off system in case this is available. This is an input parameter that is already present in the main tool. In case there is no option for power take-off, this power demand will have to be provided for by the installed generators on board.

In the case of **anchor** mode, since the yacht has to be fully autonomous, this power demand must be provided by the generators.

When the yacht is in **harbor**, it will be generally connected to shore power. However, this is sometimes not enough to support all the equipment on board. When this is the case, the generators need to compensate for this lack of power. In this case, the power provided by the generators will result in certain CO_2 emissions, while the power provided by the shore connection will have a different environmental impact.

When the yacht is **maneuvering**, the generators need to support the high power demand of the bow and stern thrusters, so in this way, it is also possible to assess the corresponding CO_2 emissions for this operational mode.

In this way, when analyzing the different contributions for the auxiliary power consumption, one can distinguish the origin of this power and attribute its environmental impact. However, one important aspect which was outside the scope of this research is the implementation of power-saving technologies. These can have two influences on the consumption of auxiliary power: reduce the consumption or provide clean energy. As an example, solar panels are a source of clean electric energy. In case these are installed onboard, they will produce a certain amount of kWh. This power can then be subtracted from the output of the total electric power consumed in a year, as this power will not be produced by the generators of obtained from shore power and will, therefore, have a lower impact than if no solar panels were installed. The same happens with battery packs used for peak shaving. These can be used to provide the extra power demand required during maneuvering, resulting in less CO_2 emissions from the generators. In terms of reducing energy consumption, take heat recovery systems as an example. In case these are installed in the yacht (an existing input parameter in the YETI tool), the power demand for the amenities, used for heating up the pool or the jacuzzi, can be provided by this system, therefore reducing the equivalent power required by the electric heaters which would be powered by the polluting generators.

3.5. Conclusions and Remarks

For an overview of the methodology described in this chapter, a diagram is shown on the next page which summarizes what has been done, allowing for an easier interpretation.

In the end, this methodology focuses on estimating the power demand of a yacht by investigating two major components: the estimation of the amount of power of the electric consumers installed on board and the hours in use which is a combination of the average operational profile of the yacht with the load factors, describing the hours in use and the output rated power in operation. This means there are two methods to reduce the environmental impact of the yacht: either to reduce the installed power or reduce the hours/power in use by installing a more efficient system, for example. This is to be done upon the coupling of this method to the complete YETI tool. Let's take the example of a newly launched stabilizer system that is able to operate at a much lower rated power, providing the same effect of stability and comfort on a yacht. The current method does not account for a change of installed power. It calculates what the average yacht would have installed and how much it would consume based on that. Therefore, within the complete tool, an input will be made that overrides this final consumption value and, to this value, subtracts the difference in consumption between the regular stabilizer system and the innovative one. This is the case for a system that is already included in the auxiliary power consumption calculations. For other innovative power-saving technologies the same must be done, for example, the heat recovery system. This is somewhat comparable to the current methodology applied by IMO for the calculation of the auxiliary power consumption within the EEDI in which a load balance can be constructed specifically for this purpose, which is later on analyzed by class regulators.

Had real operational data been made available for this research, the real power demand functions of different consumer categories could have been analyzed, and, based on that, the systems in which the possibility of reducing power demand was deemed possible could have been studied. However, this ended up not being possible and the power calculations had to be based on the available data. As such, this methodology mostly focuses on what the average power demand is and allows for improvements in the power supply once the combination is made with the complete YETI tool.

Over the final course of this research, there was a discussion with the entire YETI group, involving all the shipyards contributing to this research, in which the possibility of including an extra input parameter for the installed power of HVAC systems as well as a certain load factor for these systems. This is not yet decided and currently under discussion. This of course a reasonable method for the shipyard to demonstrate the installation of a better system, but could however represent a conflict between shipyards if each one is deciding upon its own load factor. This method does not ensure clear transparency among the industry.

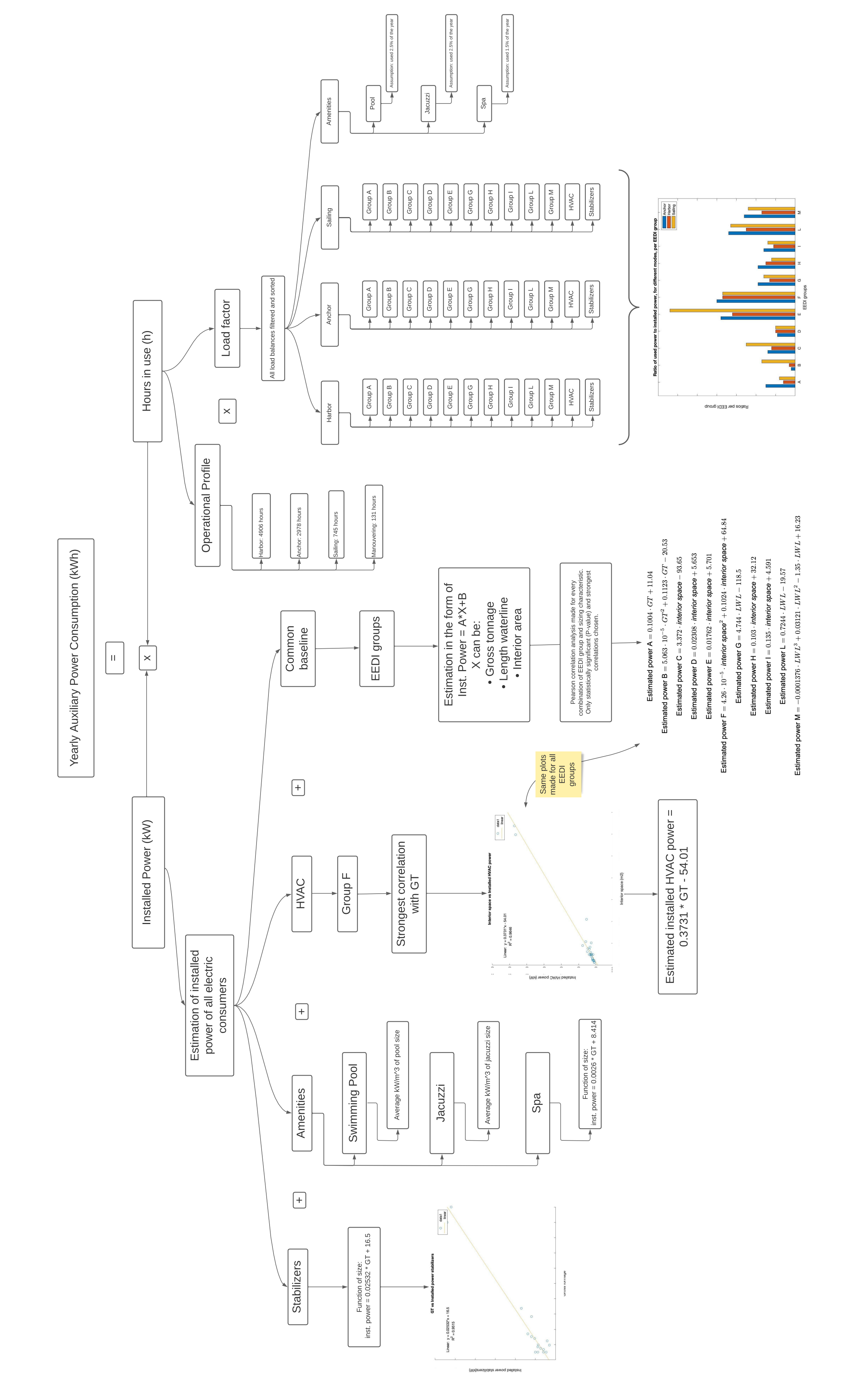

Figure 3.27: Diagram of the methodology taken for the auxiliary power consumption prediction.

4 Method Evaluation

In this chapter, the method that has been designed in chapter 3 is further discussed and evaluated with the existing data as well as with feedback provided by the shipyards after reviewing the tool and comparing it with real operational data that has been collected.

Before proceeding to this evaluation, it is important to keep in mind that one cannot expect the estimations resulting from these calculations to perfectly represent reality. There are so many factors that can influence the consumption of auxiliary power. Similarly as with a car, even if there is an energy label emitted according to European regulations and an expected fuel consumption of $l/100km$, it all comes down to the actual usage of the car. This depends on the person behind the wheel. Will that person drive in very low gears? Or even very high gears? Will that person use the air conditioning constantly at maximum power or with all the windows rolled down and increasing air drag? All these behaviors will affect fuel consumption. The same happens with a yacht. Despite having been found that the operational profile of a yacht is fairly similar in terms of usage throughout the year, how it is operated during those different operational modes will have a large impact on the consumption of auxiliary power. Not only will the auxiliary power consumption depend on several factors, but the CO_2 emissions resulting from that power demand will also vary drastically depending on the generators installed on board as well as it will depend on the engineer responsible for the power management onboard. As it became apparent during the interviews conducted with several key industry players, it was found that, on average, the generators installed onboard are loaded somewhere between 20% to 60%. This results in lower efficiency and higher and unnecessary emissions. This is sometimes the result of an engineer choosing to have two generators operating at a low distributed load instead of operating on one generator and suddenly requiring more power, only for the yacht to need to wait for the second generator to start before the required power is made available.

Unfortunately, it became apparent that the majority of the shipyards involved in this JIP do not collect any sort of operational data. As such, load balances were used as a proxy for said operational data.

4.1. Installed power

As a starting point for this evaluation, the estimation of installed power is assessed. This will give an overview of the systems that are installed on board which provide a basis for understanding how the vessel will operate. Figure 4.1 below provides an overview of the estimation of installed power for different categories. The Figure contains four box plots of the ratios of the estimated installed power divided by the actual installed power. The ratios are presented for total installed power, HVAC power, amenities power, and stabilizer power. A box plot provides a 5-number summary of a certain set of data. These correspond to the minimum, first quartile, median, third quartile, and maximum. In some cases, the box plot will also display outliers. The median is illustrated by the red line.

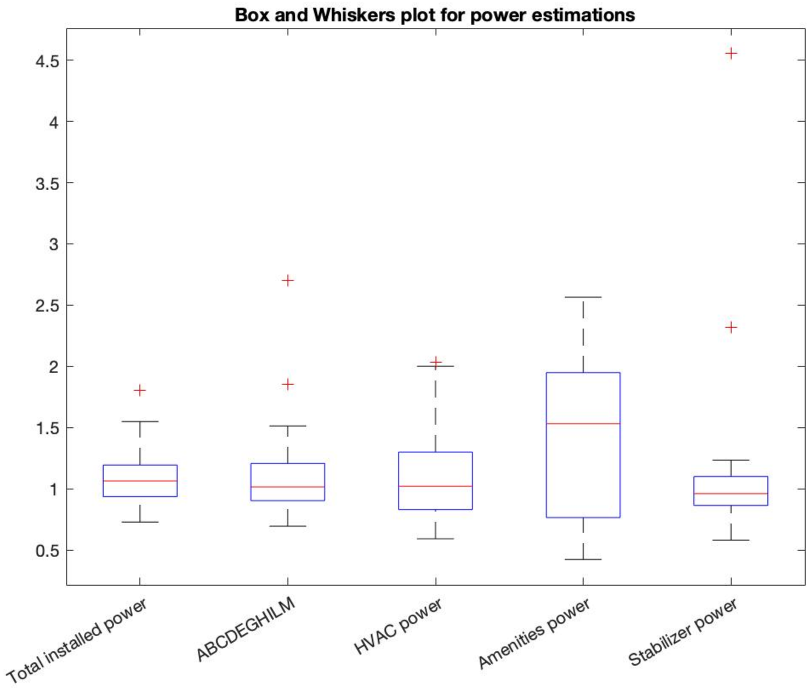

Figure 4.1: Box plot of power estimations

The following table summarizes the 5-number summary of each of the five presented box plots.

Table 4.1: Estimated installed power and electric power consumption for anchor, harbor, and sailing.

	Minimum	25th Percentile	Median	75th Percentile	Maximum	Outliers
Total installed power	0.72789	0.93543	1.0632	1.1937	1.5482	1.8039
ABCDEGHILM power	0.69434	0.90251	1.0145	1.2066	1.5127	1.8522 and 2.7022
HVAC power	0.59107	0.82949	1.0201	1.2993	2	2.0336
Amenities power	0.42188	0.76443	1.5309	1.9481	2.5641	-
Stabilizer power	0.58	0.86364	0.96008	1.1	1.234	2.3188 and 4.556

At a first glance, it is clear that the estimation for the power dedicated to spa, pool and jacuzzi is the least accurate one. While all other samples of ratios have a median close to 1, which indicates an accurate estimation of installed power, the power for amenities has a median of 1.51. However, this does not seem to affect the median of the total installed power. This can be explained by the fact that the power for amenities only represents, on average, 6% of the total installed power of electric consumers on board, as can be seen below in Figure 4.2. The median is 4.2%.

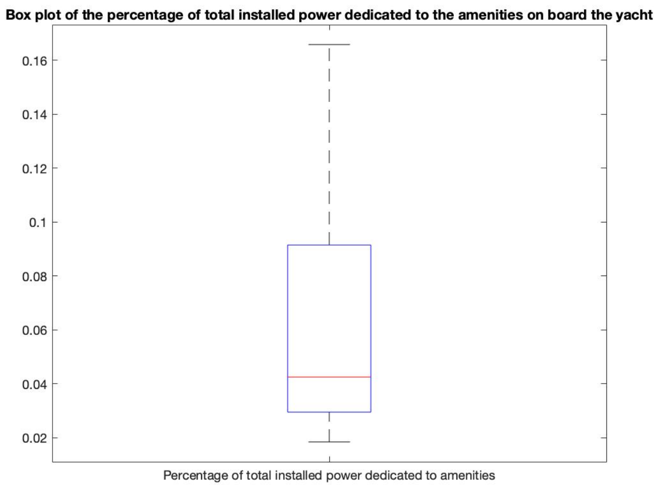

Figure 4.2: Percentage of total installed power dedicated to spa, pool, and jacuzzi.

Below, in Figure 4.3, a scatter plot is presented which illustrates a comparison of the actual total installed power with the installed power that was estimated by the tool. There are two clear outliers in this sample data which could be partially explained by the fact that these two vessels did not include bow and stern thrusters in their corresponding load balances and also by the fact that their large pool size pushed up the value of total power of amenities. In appendix A, the same scatter plots are presented for the individual groups of consumers (HVAC, A-M, stabilizers, and amenities).

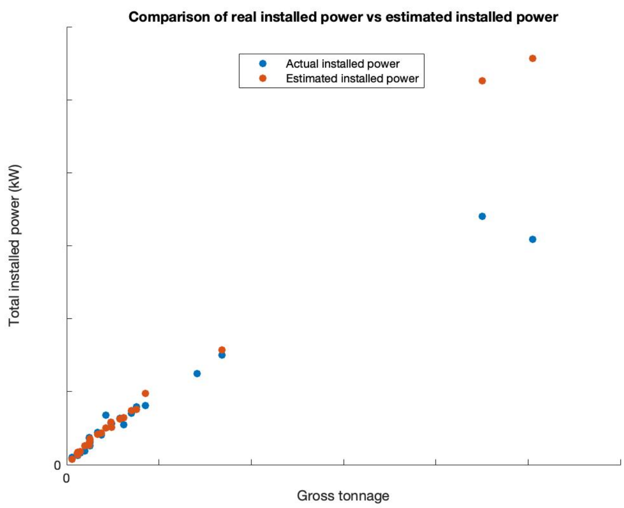

Figure 4.3: Comparison of real total installed power vs estimated value.

The table 4.2 below provides a detailed overview of Figure 4.1. With gross tonnage as a basis for comparison, the table is divided into the 5 main consumer groups: total installed power, power dedicated to groups A-M, HVAC power, amenities power, and stabilizer power. For each one of these groups, the absolute value of the error of the estimation is given, along with its corresponding percentage of deviation from the actual power of that same group. This translates into the absolute difference divided by the actual power, multiplied by 100. The last row provided the Mean Absolute Percentage Error (MAPE).

Table 4.2: Deviation percentage of estimated installed power per category for entire data set.

GT	Abs. diff. total installed power	Deviation %	Abs. diff. A-M power	Deviation %	Abs. diff. HVAC power	Deviation %	Abs. diff. amenities power	Deviation %	Abs. diff. stabilizer power	Deviation %
Mean Absolute Percentage Error		14%		17%		26%		56%		16%

As to what concerns the total installed power, the HVAC power, stabilizer power, and the power dedicated to groups A-M, it can be concluded that the estimation provides acceptable results for a prediction of installed power on yachts. This analysis is only possible since it is known, from the existing load balances, what the actual installed power is. The analysis of the final output of power consumption, however, is more troublesome. The tool has been distributed to all the shipyards with the request of feedback provision, with the aim of further improving the calculation method by comparing the output result with actual consumption data that might be available.

4.2. Total consumption

After analyzing the behavior of the estimation of installed power, it is possible to go further into the evaluation of the actual power consumption. This is where things become more troublesome.

Unfortunately, feedback was provided for only 7 yachts. This, however, did not come as a surprise but rather somewhat expected since most shipyards claimed to not have in place any sort of procedure that allows for the collection of operational data on board their builds. In the science world, this does not form a solid scientific basis for evaluation but it does provide a sense of the phenomena taking place behind the calculations as well as the actual power consumption of yachts.

First, an observation of the characteristics of the yachts for which feedback was provided is given in comparison to the characteristics of the yachts of the initial data set of this study is illustrated in Figure 4.4. It is clear that the feedback has been provided for much larger yachts than the average on which the estimation was based on.

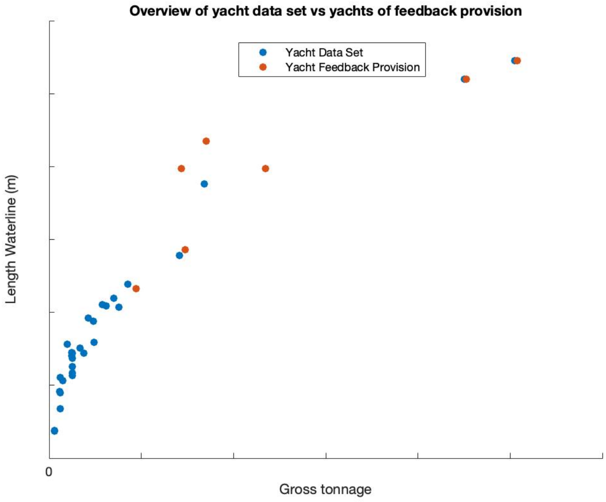

Figure 4.4: Overview of the complete yacht data set vs yachts received for feedback.

In table 4.3 below, the sizing characteristics of the yachts for which feedback has been provided are depicted together with the installed amenities information. The rightmost column of this table indicates the ratio of predicted yearly consumption divided by the actual yearly consumption. This means that, for the first row, the tool has given an output value for yearly electric power consumption estimation which is 2.13 times higher than what is actually consumed onboard. **It should be noted that there is no way to check the validity of the feedback received.**

Table 4.3: Sizing characteristics of the yachts for which feedback has been provided and consumption ratios.

Gross tonnage	Length waterline (m)	Interior area (m2)	Jacuzzi size m3	Pool size m3	Number of spa	Consumption ratio

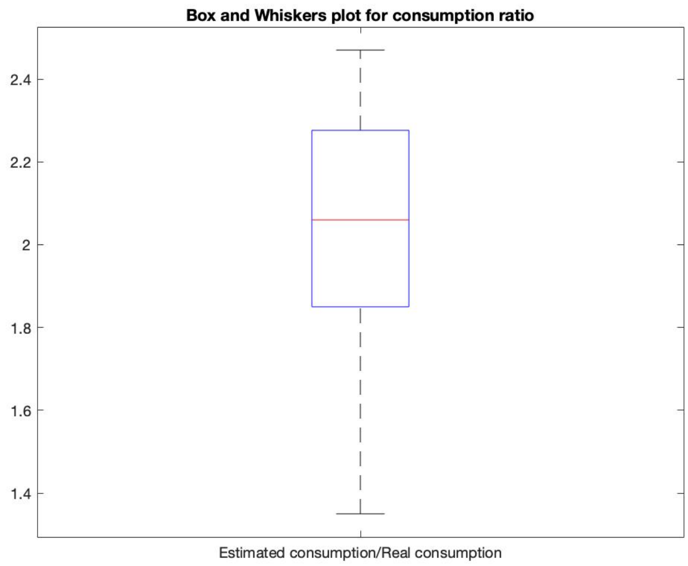

Figure 4.5: Box plot of feedback received

It is rather obvious that these ratios indicate a large overestimation of the electric power consumption. These discrepancies were somewhat expected when the possibility of obtaining real operational data was taken off the table. Coming back to the initial formula presented at the beginning of chapter 3:

$$\text{Power consumption (kWh)} = \text{Installed power (kW)} \times \text{Hours in use (h)} \tag{4.1}$$

There are two main components required for calculating power consumption: the installed power and hours in use. For what concerns the first part, the estimations carried out by the tool have turned out to have acceptable results predicting the installed power of systems on board. However, when analyzing the hours in use, the results lead to an overestimation of consumed power, according to the feedback received. In this calculation method, the hours in use are a combination of the previously defined operational profile, which contains the division of the yearly amount of hours by the different operating modes, with the problematic load factors. The use of the operational profile alone is not enough to calculate the hours in use as this would assume that the systems are operating at 100% of their installed power on a 24/7 basis. This is of course not a correct representation of reality since most systems have a dynamic behavior and work intermittently during a 24-hour period. On top of this, some of these systems don't always operate at their full power, such as the stabilizers that operate according to sea conditions.

4.3. Reduction Factor

Seeing as the output result overestimates the auxiliary power consumption, the possibility of implementing a reduction factor has been studied. This however would require a large set of feedback in order to allow for a scientifically correct estimation of what this reduction factor ought to be. This could be dependent on a certain sizing characteristic such as gross tonnage. Figure 4.6 plots the actual consumption ratios against gross tonnage for the 7 yachts for which feedback was provided. In this graph, a linear trendline is plotted too. Understandably, 7 data points are not enough to create a statistically significant correlation. The idea, however, is that with several more feedback inputs from more yachts and more shipyards, it could be possible to identify a certain pattern that provides an indication towards the magnitude of the overestimation resulting from the subjective load factors. It should be reminded again, that a fully accurate estimation is nearly impossible since there many variables that influence the dynamic behavior of auxiliary power consumption on board. The principle behind these calculations is that an average of what is currently consumed provides a scientifically accurate enough estimation to allow for an educated discussion with a prospective client, which, in the end, is the main goal of YETI.

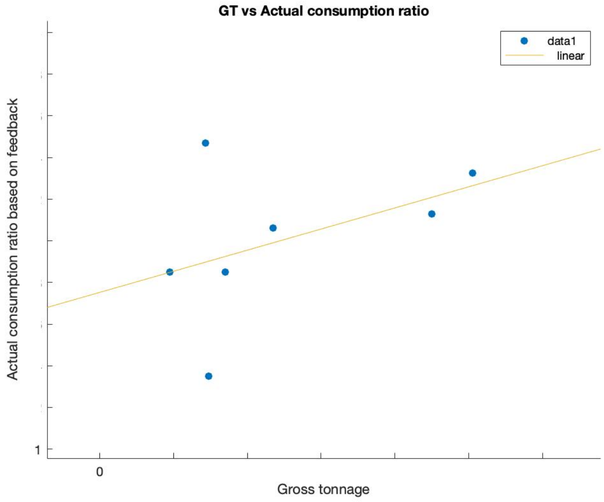

Figure 4.6: Plot of actual consumption ratios based on gross tonnage.

In Figure 4.7, an overview of the required reduction factors for each of the vessels for which feedback was provided. With sufficient data, this reduction factor could be a function of gross tonnage or other sizing characteristics of the yacht.

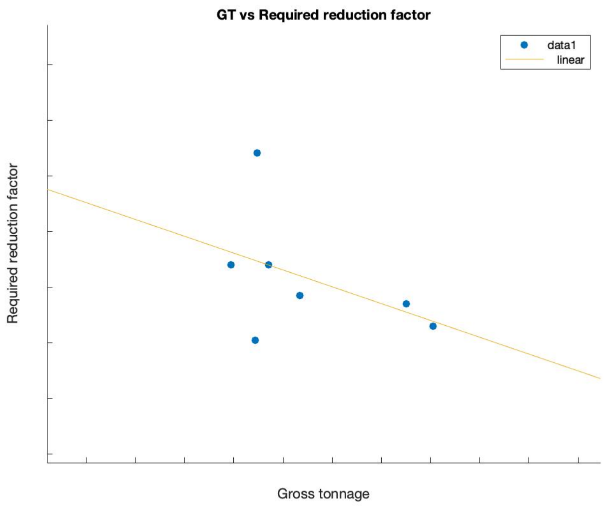

Figure 4.7: Plot of required reduction factor based on gross tonnage.

This possibility of including a reduction factor has not been well accepted by the shipyards as it was not considered to be scientifically sound enough. Therefore, the reduction factor remains a possibility for future implementation in the tool in case it proves possible to obtain a larger feedback data set for a wider spectrum of size, and a statistically significant trend is found among these.

4.4. Conclusions and remarks

When assessing the behavior of the designed method in obtaining an estimation of the yearly electric power consumption, the outcome is, according to the received feedback, largely overestimated. The first half of the calculations, which estimate the installed power, yields acceptable results when considering that no yacht is equal and that a very accurate estimation of the installed power of existing yachts is difficult to obtain. Instead, the tool allows for an estimation of what a future yacht will have installed, based on the average of the current yachting industry.

The second part of the calculations, however, represents the difficulty of the project. The conservatively chosen load factors used when building a load balance reflects in the overestimation of the output result of the tool. It should be taken into consideration that the only feedback received was for a size range considerably larger than the data set that has been used for the construction of the tool and there is no current way of validating the received feedback, relying therefore on honesty and transparency.

The current tool, however, forms a basis for the continuation of future work to be further executed in this field. In the following chapter, the conclusions to be drawn from this research as well as future recommendations for the continuation of this work are presented.

5

Conclusions and Recommendations

This research turned out to be a bigger challenge than initially expected. This project started out with the goal of modeling the auxiliary power consumption on board a yacht ranging from 30 to 180+ meters with the goal of estimating its yearly electric power consumption for a later implementation in the YETI tool. This chapter will analyze its main conclusions and present future recommendations for the continuation of this work.

5.1. Conclusions

Over the course of the study, some issues arose that imposed some bottlenecks on its fluent progress. The main obstacle turned out to be the hesitation regarding the sharing of data with the Water Revolution Foundation. This is the result of privacy policies over what concerns the operation of a privately owned yacht as well as sharing sensitive technical data of a shipyard which constitutes a possible threat due to market competitiveness. This resulted in data being made available solely in the form of load balances, instead of real operational data as initially hoped for. The lack of standardization in the structure of these load factors between shipyards even within the same company made it a complex task to analyze and filter the different groups of consumers as well as the different operating modes. Another constraint that slowed down the investigation was the understandably low priority given by shipyards to this study. Over the course of this year, the superyacht industry was put under the spotlight of world media due to the arrests being made of yachts owned by Russian clients in face of the current conflict between Ukraine and Russia. This complex situation in addition to the rising superyacht market size resulted in a long time of response to emails and communication in general, consequently resulting in difficulty in obtaining data and, ultimately, in unexpected delays. Towards the end, the very little feedback received regarding the designed method for auxiliary power consumption ended up being a significant limitation for end results.

The maritime industry has always been rather conservative when compared to the data and technology industry. This results in very few studies conducted in this field of study: the electric power consumption. In the specific case of yachts, even less. The traditional method in which a load balance is built using rather subjective load factors based on previous experience does not prove the be the most reliable method of predicting auxiliary power demand. The end result is overestimated as a consequence of the equally overestimated load factors which are defined as taking redundancy into consideration to ensure there is never a lack of power supply, offering maximum safety and comfort on board. Ideally, with the right amount of feedback data, a reduction factor could be applied if a clear trend were found in regard to the overestimation of these load factors. Unfortunately, not enough feedback has been received on time that allowed for this to be implemented.

Having this in mind, the previously presented research sub-questions are answered below, leading up to the conclusion on the main research question:

1. **"EEDI and EEXI: what are they and how are they designed?"**

   The EEDI and EEXI are indices that have been adopted by IMO with the aim to incentive the use of less polluting technologies in the shipping industry. These mechanisms have been imposed as regulations targeting the reduction of CO_2 emissions in 2013, marking the start of a two-year phase zero. Phase one meant a 10% reduction in emissions and this target is to be tightened every 5 years. These rates have been imposed until the year 2025 when a 30% reduction is expected. EEDI attributes a certain score to each vessel and uses a reference line, built out of similar vessels built between the years 1999 and 2009, to base its comparison for the targeted reductions.

   (a) **"Are there any other regulations which calculate the electrical power consumption for commercial vessels?"**

   Besides EEDI and EEXI, no other official methods or regulations were found that specifically analyze the electric power consumption of commercial vessels.

   (b) **"Could the EEDI, EEXI or other available methods be applied to the yachting sector?"**

   As seen in chapter 2, the way the EEDI formula calculates auxiliary power demand is by looking at total installed engine power. This is not the most accurate way of predicting energy demand on a yacht since its operational profile differs considerably from that of a commercial vessel. Taking into consideration the large role that auxiliary power plays in order to provide for all the amenities on-board a yacht, this power is provided by engines which are installed for this purpose only. Therefore, looking only at installed engine power will not provide a reliable method for calculating auxiliary power consumption.

2. **"What are the requirements for such a method to be designed and how do these different methods score against the requirements?"**

   There are some requirements that must be accounted for in order to have the method reach a correct prediction of consumed electric power. When analyzing the reasons why EEDI is not a viable method to account for electric power consumption, it became clear that these weaknesses were a starting point to define the requirements for a correct method. As such, referring back to section 2.1.6, it can be concluded that sailing alone is not a correct operational profile to take into account and, therefore, the total operational profile as defined by YETI must be used for the calculations. Another of the requirements is the existence of a correct reference line for comparison of the obtained ecopoints.

   The method must ensure ease of use in order for shipyards to be willing to use it and it must ensure that no manipulation is possible as to avoid any sort of greenwashing. Since the goal of YETI is to facilitate an educated discussion about sustainability with potential clients and to promote the use of energy efficient technologies, the applied method must ensure better scores are attributed to yachts equipped with such technologies. Ideally, the scores will be made dimensionless as to allow for different scores to be added together.

3. **"How can the yearly power consumption of hotel load be calculated?"**

   Ideally, in case real operational data were available, namely the average load on generators throughout different operational modes together with hours in use, it would be possible to perform a more accurate and realistic estimation of the yearly electric power consumption in a yacht.

However, as reported early in this research, due to privacy reasons, this operational data is strictly confidential and could not be shared for the purpose of this project. As an alternative, load balances have been used as a proxy of said operational data. These load balances contain all the electric consumers installed on board together with their operating power and the load factors. By thoroughly analyzing a large set of load balances, covering a certain size range, it is possible to find statistically significant correlations between sets of data and certain sizing characteristics. Using these correlations, the installed power of different EEDI groups can be estimated and, together with an average utilization ratio, it is possible to obtain an average load per operational mode. Since YETI has previously acquired AIS data and performed a study with the goal of defining the average operational profile of a yacht, the number of hours that a yacht spends in each of its operating modes is known. Since power consumption is calculated by multiplying power by the number of hours in use, this number of hours of each operating mode can be multiplied by the average load, resulting in the total power consumption per operational mode. By adding the result of all modes together, it is possible to obtain an estimation of the yearly power consumption of a yacht, based on a few input parameters such as gross tonnage, length of waterline, and interior space. In the end, it is expected that the final result is overestimated since the load factors used in the load balances are known to be taking redundancy into consideration, for both safety and comfort reasons. Therefore, when feedback is returned from these calculations from a substantial amount of yachts, a reduction factor can be applied to the final output result in order to approximate it as much as possible to a real yearly estimation of electric power consumption.

(a) **”What is the most reliable approach in theory?”**

The most reliable approach would be that of a Grey Box Model in which a mix of Black Box Modelling is built with real operational data coupled with a White Box Model which would model physical systems in an empirical form. However, this data was not made available and, therefore, an alternative solution had to be found.

(b) **”In which way do shipyards calculate the hotel load in different phases of the design, engineering and building process?”**

As presented in section 2.2, there are several methods to approach the electric power load analysis. Each one of these methods has its advantages but its disadvantages too. Among these methods is the traditional approach to EPLA. This is the method that has been widely used for several years but has proven to yield unrealistic values for a total load since it relies on subjective load factors, decided by the naval architect/electrical engineer based on prior experience with similar previous builds. From all interviews conducted during the course of this research, it has been found that the vast majority of shipyards recur to load balances as the general way to calculate the hotel load of their yachts.

(c) **”What are the correct parameters for the new designed method for hotel load calculation to be based on?”**

As this tool is to be used at an early stage of the design of a yacht, in order to better inform future clients of more environmentally friendly options to be installed in a yacht, there are not a lot of details available. As such, this method must be based on as few input parameters as possible in order to be viable and to ensure ease of use by both shipyards and potential clients. Over the course of this research, it was found that the total installed power, meaning the sum of the power of all the electric consumers on board, is very closely related to the gross tonnage of the vessel. By categorizing this total power into the different EEDI groups, other correlations were found. Eventually, the tool was designed with three sizing parameters as the main input: gross tonnage, length of waterline, and interior space. Another input parameter that was considered to be of paramount importance was related to the stabilizers. Since sailing yachts are not equipped with stabilizers and YETI is to be used for both sailing and motor yachts, not only the possibility to specify whether these are installed or not has been added but also its type (gyroscope or fins). This has been done since research and interviews pointed to stabilizers being one of the major consumers on board. In order to further differentiate the baseline consumers (common to all yachts), from the customer-specific consumers, a separate category for amenities has been created. The input parameters for this category include the existence of pools, jacuzzis, and spas onboard. In the case where a jacuzzi is installed, its size, in cubic meters, is another input parameter. Finally, the input parameters for a swimming pool onboard are similar to that of the jacuzzi with the addition of the possibility to indicate the existence of a heater.

(d) **"How can the designed method and the input data for said method be validated?"**

The input data for this method, the load balances, have no way of being validated. These have been shared by free will with the Water Revolution Foundation for the purpose of this research, showing a willingness to cooperate in such a project. The final method is validated by the shipyards themselves, experimenting with the tool that has been created, by inputting the required parameters of their yachts and comparing them to the real operational data that is available. These results are entered in a feedback sheet which allows for the calculation of a possible reduction factor to be applied to the final output value, the yearly consumption. It must be noted, however, that in this case, the validation of the model is based on the honesty and transparency of all parties involved.

4. **"How can the method resulting from this research be implemented into the YETI tool to find a correct hotel load power consumption?"**

The current YETI calculator requires manual input of the average hotel load. Since the current version of YETI has been created in Excel, the resulting method of this research, created in Excel as well, can be implemented within the main tool in order to complement each other. This new method will allow for a calculated value of the estimated electric consumption, as opposed to the manual input which does not warrant the avoidance of green-washing. This newly implemented calculation of hotel load will also allow for the differentiation of the origin of the electric power that is consumed. In this way, the corresponding environmental impact can be calculated whether the power originated from generators, shore power, power take-off, or even solar panels, for example.

(a) **"How can other yachts be compared based on this method?"**

This method allows for the estimation of the yearly electric power consumption. Since the goal of YETI is to calculate the environmental footprint of a yacht and to attribute a score to it, this yearly consumption can be converted into fuel consumption by using the specific fuel consumption (SFC) of the generators, which is already an input parameter of the YETI calculator. The consumed fuel translates into CO_2 emissions to which, in turn, ecopoints can be attributed. As the YETI database is composed of several yachts from shipyards involved in the project, a baseline can be used as a comparison method for the yacht being evaluated, similarly to what is done with the EEDI.

Answering these sub-questions leads to the main research question that was presented in chapter 1:

- ***"In which way can a method be designed that defines the hotel load of a yacht, taking data sensitivity and reliability into account, providing a realistic calculation of yearly power consumption, for later implementation into the YETI tool, and what is the reliability of it?"***

In the end, the outcome of this research is not what had initially been hoped for. Taking all the previously described constraints into account, the method which has been developed over the last months did not prove to yield an estimation of electric power consumption within acceptable intervals. This result is attributed to the subjectivity of load factors which are chosen upon a rather conservative method, altogether with the failed attempt of gathering real operational data. A correct prediction of power consumption in such a complex system which is a yacht is a very difficult task. However, a rough estimate can be calculated which allows to benchmark of how the existing fleet operates, allowing for a comparison of a new build. In order for this to be successful, reliable operational data will always be required to assess how the industry currently performs. Whichever estimations are made, only real data will be able to verify their accuracy. As per the last meeting conducted within the YETI project, no consensus was found with regard to the implementation of the current work into YETI.

It can be agreed upon the fact that the construction of a load balance is not the most scientifically innovative method of predicting the electric power demand on board a yacht. Ultimately, using these load balances built with subjective load factors does not prove to be the most reliable way of estimating consumption. Yet, this was considered the best method given all the constraints present in the scope of the project.

Nonetheless, I personally believe that this provides a great starting point for the further investigation of such a topic of which insufficient knowledge is readily available within the scientific community.

5.2. Future recommendations

This research is in need of future improvements and continuous investigation. For this reason, several future recommendations can be made in this respect.

The main recommendation that can be made for this entire study is regarding operational data. This is ultimately crucial to fully understand the dynamic behavior of auxiliary power consumption on board and to be able to correctly validate any results. A solid plan should be created among shipyards that allows for a viable way of obtaining this operational data, always taking privacy and confidentiality concerns to mind. This would ultimately allow for an improved estimation of the load factors which are applied in the power consumption calculations, if not for an improved reduction factor based on a larger data set.

Gathering more load balances is also of high importance for the estimation of installed power. As seen in chapters 3 and 4, the data set used for the power estimations is mainly within the range of 30 to 70-meter yachts, with two vessels in the range of 130 to 150 meters. It is recommended to close the gap between these ranges with more data.

At some point in this study, a company specialized in stabilizer systems, Quantum Stabilizers, was approached in order to inquire for help regarding the power consumption of these systems in a yacht. Despite their direct interest and willingness to contribute to the cause, it ended up not being possible to dedicate the required resources and time to helping in the subject within the duration of this graduation project. This is a starting point for future improvements regarding the consumption of stabilizing systems.

A better distinction can be made between the consumption of fins and gyroscopes. As most load balances did not specify which kind of systems was installed on board, an average of these systems was calculated. The result is a larger consumption for gyroscopes since these are assumed to operate in harbor conditions, as opposed to fins that cannot operate in close proximity to other vessels. This arose some questions during the feedback stage as gyroscopes should consume less power than fin stabilizers.

What regards the operational profile, the tool should be improved in order to accommodate a distinct category of yachts: explorer yachts. These are sometimes sailed in areas where the weather conditions are extreme, such as in the Arctic. The current tool estimates power consumption using the average load factors of the load balances provided for this research which, in general, were built for exterior temperatures between 20 to 30 degrees Celsius.

As the goal of this project was the estimation of auxiliary power consumption, the origin of this consumed power is not specified. This is to be further implemented into the YETI tool in order to attribute the environmental impact of the power which is originated from different sources, as explained in section 3.4.2. The power consumed while at anchor is provided by generators which, subsequently, has a larger environmental impact due to the generator's CO_2 emissions when compared to the power consumed while in harbor which is provided by the electrical grid of shower power, which can have its origin in renewable energies.

Power-saving technologies were not within the scope of this research. However, this is something that can and should be further implemented once the calculations of auxiliary power are incorporated into the YETI tool. Some of these technologies are already implemented within the current YETI, such as the heat recovery system or solar panels. The existence of a heat recovery system will reduce the power required to heat up a swimming pool or jacuzzi. This power which would otherwise be provided by a generator can then be subtracted from the yearly power consumption. In the case of solar panels, the power which these can produce in a year can too be subtracted from the yearly estimated power consumption since this power is considered to be clean.

The possibility of performing a bottom-up calculation approach to large systems such as HVAC can also be studied. This could be done with, for example, general layouts of yachts in case these can be obtained. An investigation into correlations between the number of cabins, their size, number of walls, enclosed volume, and number of guests could yield a more accurate prediction of HVAC consumption.

Another section of the current method which requires attention is the power calculations for amenities. Large discrepancies were found between the power installed per cubic meter of water in both pools and jacuzzis which, in the end, led to a dispersion of results of estimated power for these consumers.

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