DEVELOPMENT OF A SUSTAINABILITY IMPACT METHOD FOR PACIFIC INTER-ISLAND MARITIME TRANSPORT

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USP THE UNIVERSITY OF THE SOUTH PACIFIC

DEVELOPMENT OF A SUSTAINABILITY IMPACT METHOD FOR PACIFIC INTER-ISLAND MARITIME TRANSPORT

Master Thesis

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ABBREVIATIONS

CAPEX	Capital expenses
CATCH	Cost of Averting a Tonne of CO_2 Heating
CII	Carbon Intensity Indicator
DWT	Deadweight
EEDI	Energy Efficiency Design Index
JAMDA	Japan Machinery Development Association
KPI	Key Performance Indicators
LCA	Life Cycle Approach
LCIA	Life Cycle Impact Analysis
MACC	Marginal Abatement Cost Curve
MCST	Micronesian Center for Sustainable Transport
OPEX	Operational expenses
PICT	Pacific Island Countries and Territories
SV Kwai	Sailing Vessel Kwai
TRL	Technology Readiness Level
USP	University of South Pacific
VOYEX	Voyage expenses
WASP	Wind Assisted Ship Propulsion

Preface

The present work has been conducted to fulfill the graduation requirements of the Master of Science Marine technology within Delft University of Technology. During my three years time as a master's student, I focused primarily on Ship Design and Maritime Operation and Management courses from which I derived the invaluable knowledge that I further applied in the present research.

This accomplishment would have not been possible without the support from my family, friends and supervisors. I would like to express my gratitude to my thesis mentor, Dr. Austin Kana for his academic guidance and moral support during difficult times especially in the COVID-19 context. His guidance, recommendations and feedback have greatly improved my work and helped me achieve the goal of my thesis. I would also like to thank Dr. Peter Nuttall and Andrew Irvin, our collaborators from the University of South Pacific and Micronesian Center for Sustainable Transport for their informational support and availability to tackle the complex issue of the Pacific maritime transport. Our joint collaboration has also led to the introduction of captain Brad Ives to which I am grateful to for sharing the vital documents needed for developing the case study for my thesis.

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Summary

Maritime transport represents one of the main means of product delivery and passenger transportation across the world but its impact on climate change has positioned it among the world's biggest CO_2 pollutants[1]. One of the most impacted regions in the world by maritime transport emissions is the South Pacific Region. Studies show that if climate change is not mitigated, then the increase in temperatures could lead to droughts, changes in intensity, frequency and duration of cyclone seasons, sea rise and effects on ecosystems, food security and economy. Thus, the goal within this century is to keep the global mean temperature to 1.5°C[2] [3].

With this idea in mind, the regional goal of the Pacific Island Countries and Territories (PICT) was set for a decrease in carbon dioxide emissions from shipping by 40% until 2030 and complete decarbonization until 2050. A possible solution proposed by the the local organizations such as University of South Pacific (USP) and Micronesian Center for Sustainable Transport (MCST) is the implementation of Wind Assisted Ship Propulsion (WASP) on existing and new built vessels. In that regard, a collaboration was initiated between TU Delft and USP to assist by developing a methodology and a practical tool which can assess the technical performance and environmental, economic and societal impact of WASPs. Thus, the current report aims to answer the question:

"To what extent is it possible to assess the social, economic, and environmental impact of a WASP vessel in the Pacific island region in order to justify investment in large-scale production?"

The literature and studies provided by the USP counterparts have shown the applications of past and present vessels which were fitted with soft sails and which achieved considerable fuel saving of up to 40% [4]. As a result, the choice of of this study was on the soft sails technology and how well it performs in the South Pacific sailing environment. Concurrently, a case study was conducted on using a proven vessel which sailed in the region for the past 15 years: Sailing Vessel Kwai (SV Kwai). This vessel achieved considerable fuel reduction and in turn, emissions decrease.

The method employed for the overall research was an adaptation from the Life Cycle Impact Analysis (LCIA). The LCIA encompasses the environmental impact from cradle to scrap of a certain product. The present study considered only the operational cycle of the vessel's hybrid propulsion and its impact on the aforementioned categories. Aspects such as the impact of manufacturing, scraping, painting or machinery waste have not been included and need further research to conclude the LCIA. The following steps were taken during the Operational Cycle Impact Assessment:

- Driver: Needs analysis for the local region from a technical, environmental, economic and social perspective.
- Activity: Analysis of Sailing Vessel Kwai voyage data and operational profile

- System category: Assessment of the WASP and Diesel engine for performance and engine load balance.
- Calculation of pressure categories
- Analysis and reflection on midpoint impact categories
- Case study, benchmark and definition of endpoint level impact categories
- Operational Cycle Impact Assessment for the scalability and replicability characteristics

The conceptualized methodology represented the theoretical foundation for the development of a practical Excel tool. This has the purpose to assess the current case study vessel and can be also adapted to assess future WASP vessels. The novelty of the research stands in the assessment of SV Kwai from an academic perspective. This was done through the the verification of fuel consumption, emissions and international standards compliance. Empirical methods and frameworks were used for the impact on society, ship finances and environment. The results of the case study are promising for the future of shipping in the South Pacific region. Even though SV Kwai has the hull of a 71 years old fishing vessel and is retrofitted with sails and an oversized engine, it still accomplishes tremendous fuel reduction of around 37% per voyage. The calculations have shown that a similar trend line is encountered for the CO_2 and SO_x emissions. Provided that an adequate sailing hull and proper power plant would be installed on-board, than more fuel reduction could be achieved.

From an environmental and policy making perspective, SV Kwai fits within the international emissions standards by scoring 28.26 gr/tone-nautical mile on the EEDI chart, 36.10 gr/tone-nautical on the CII chart mile and 34.9 $/Tonne CO_2 in the CATCH index. EEDI and CII parameters were calculated with regards to reference line formulas provided by the IMO for general cargo vessels.

The economic analysis has shown that fuel and retrofits costs were not the main financial issues and that further studies are needed to analyze a possible decrease in operational and voyage expenses. The societal perspective has only been briefly touched upon from a critical reflection standpoint. As to that, the local communities can greatly benefit from improved passenger transport and lower cargo price rates but no other performance indicators have been quantified in this research. Lastly, the Operational Life Cycle Assessment over a 20 years operational cycle has shown positive and promising results with great fuel reduction, emissions decrease, fuel economy and low cargo rates which could make WASPs in the region competitive with the regional diesel-driven container vessel companies. Consequently, these results can represent an argument for the scalability and replicability characteristics of this type of vessel.

Overall, the present research is an indication of an early stage WASP design performance and impact on the local South Pacific region. Further studies are needed for a better insight into the impact of such a technology. Thus, future studies are suggested for the following fields: prospects of alternative WASP technologies, market analysis and regional competition, social impact analysis, complete LCIA study.

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1

INTRODUCTION

The subject of this MSc thesis is the development of a method and tool which aim to assess the long-term impact of newly introduced WASP vessels in a specific region of the South Pacific islands. Chapter 1 aims to present the problem context, research objective, and the research approach to attain the defined goal.

1.1. PROBLEM BACKGROUND

Effects of pollution in the South Pacific Islands region

The world nowadays finds itself at a crossroads regarding transitions to sustainable technologies and a decrease in emissions. The shipping industry is no exception since it is one of the significant transportation sector pollutants, accounting for approximately 940 million tons of CO_2, which is roughly 2.5% of the annual global emissions [5]. Even more, a side by side comparison with the most polluting countries in the world shows that worldwide shipping altogether places 6^{th}, being even more damaging to the environment than countries such as Germany or Canada [1], see Figure 1.1 .

There are few places where the effects of pollution are more evident than in the South Pacific Islands (Micronesia, Polynesia, and Melanesia). Annually, these countries face devastating consequences of climate change, including droughts, flooding, and changes in intensity, frequency, and duration of cyclone seasons, which impact ecosystems, food production, economy, and the general well-being of the population. Therefore, in IMO and the Paris Climate Agreement, these countries have been the most vocal advocates for the limitation of the global warming mean temperature to 1.5°C[2] [3].

However, their voices are not always heard, and the international regulatory bodies have not been able to assist efficiently. Thus, the PICT have taken matters into their own hands by initiating multi-country collaborations and partnerships with the private sector, such as the Pacific Blue Shipping Partnership, Cerulean project and MCST. These co-operations aim to revitalize old fleets, invest in port infrastructure, and bring novel sustainable technologies to the Pacific region while reducing Operational expenses (OPEX) [6]. This stems from the fact that these countries are dependent on petroleum imports,

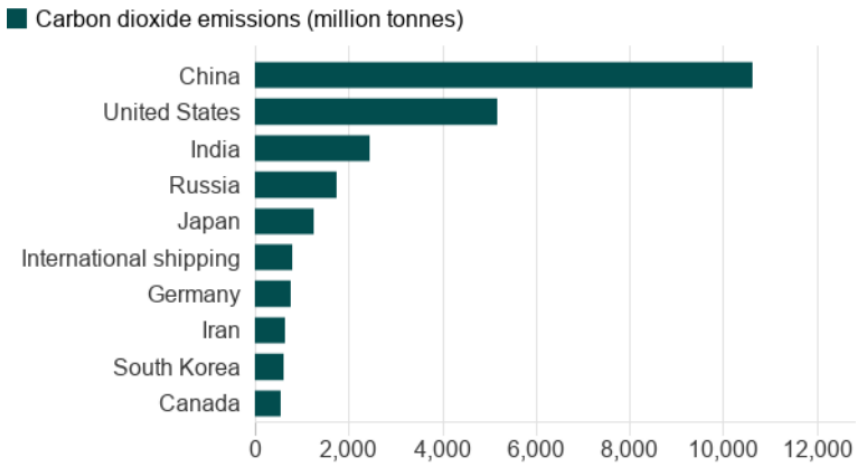

Figure 1.1: Countries to shipping emissions comparison[1]

making shipping increasingly more expensive in inter islands routes. An example is the Republic of Marshall Islands, where roughly 90% of its fossil fuel is imported at exorbitant prices and 70% of it goes to transport[7][8].

For the foreseeable future, the following goals are to be achieved:

- initial emission reduction target for Pacific shipping of 40% by 2030
- full decarbonisation for Pacific shipping by 2050

MCST-USP initiatives background

To better understand the problem context, a discussion was initiated with Peter Nuttall, Scientific and Technical advisor for MCST-USP, and Andrew Irvin, Project Officer in the Cerulean Project-MCST-USP. Both MCST and USP are key investigators in decarbonization and climate change mitigation in the South Pacific region and they undertake various projects with the countries of the South Pacific to implement the most optimal abatement measures. After several meetings and discussions, it was concluded that the following two directions would be beneficial to aid in the current problem:

1. Provide naval architecture expertise and consultancy for the development or retrofit of sustainable WASPs (e.g., Sails, Flettner Rotors) vessels.
2. Develop a method and a tool to assess the social, economic, and environmental impact of a prototype vessel in a particular island region/route to analyze its scalability and replicability characteristics.

Thus, the purpose of this master thesis will be to assist the MCST initiative with providing technical and theoretical knowledge on fulfilling the aforementioned goals.

1.2. RESEARCH OBJECTIVE

Despite the widespread research on the effectiveness of alternative propulsion solutions on commercial shipping, there is not much literature on its influence in specific cases such as the South Pacific Islands region. In addition, this case study poses unique challenges, such as economically poor regions, lack of infrastructure, and absence of naval architecture specialists for consultancy. Considering these issues, it would be beneficial to investigate the potential and impact of a low-cost and effective propulsion alternative such as WASPs for fleet renewal. As a result, the following main research question was formulated for the present work:

"To what extent is it possible to assess the social, economic and environmental impact of a WASP vessel in the Pacific island region in order to justify investment in large-scale production?"

Following a top-down approach (further explained in Section 1.3), the main research goal can be broken down into several segments. In each chapter of this thesis, the following sub questions will be answered:

Chapter 2

- *How will an improved shipping service influence the region from a technical, environmental, economic and societal points of view, and what are the needs for future improvements?*
- *What are the most suitable WASP options for a medium-sized Pacific cargo vessel?*

Chapter 3

- *What are the applicable impact assessment methods currently in use in the maritime world?*
- *What are the requirements for creating a suitable method for impact assessment specific to the pacific islands / maritime region?*

Chapter 4

- *Are there past and current proven applications of WASPs in the South Pacific region, and how relevant are they for developing future WASP vessels?*
- *How can a case study vessel be used to develop an assessment tool?*

Chapter 5

- *Which are the technical and environmental considerations of the hybrid propulsion calculation?*

Chapter 6

- *Which are the social and economic parameters and how are they calculated?*

Chapter 7

- *What is the impact of operational cycle for hybrid propulsion and what effect will it have on the vessel's scalability and replicability characteristics?*

1.3. RESEARCH METHOD

For this project to be achieved, the research method has to be established. A top-down approach will be adopted for the current topic. The top-down approach starts with one main requirement, of which the solution is created for the issue at hand.

Top-down approach

A top-down approach works by establishing an initial high-level goal. This is then broken down into several segments, which are detailed and resolved independently and then joined back in the last phase of the approach. As specified in Section 1.2, the purpose is to find a method to assess the impact of a WASP vessel in a specific region. This idea is broken into several research segments, which are solved one by one. A graphical representation of the research approach and work structure can be seen in Figure 1.2.

The first step in the process is to discover the method's requirements. To find this, in Chapter 2, a needs analysis is performed for the South Pacific region to understand how shipping currently impacts the society, economy, and environment. Also, an analysis is performed on how a better shipping service will improve all of these categories. This is followed by an overview of applicable WASP technologies which could be used to improve the local shipping situation. Then, in Chapter 3, various methodologies are reviewed based on requirements derived from the previous two chapters. In this sense, many tools and methods are collected to create a unique framework that will serve the purpose of this thesis. Finally, with all this information, a methodology is created and further elaborated in Chapter 4.

The second stage of the top-down approach is represented by creating a practical tool that has the created method as its theoretical framework. Before creating the tool, all the method parameters (vessel, propulsion, voyage, and Key Performance Indicators (KPI)) are established. This means translating the requirements to formulas, indicators, and indexes and tying the formulas together. This is performed in Chapters 5 and 6. These are integrated into a user-friendly interface for usage in Chapter 7. For testing, one model will be used: a proven vessel currently in operation. After running the vessels through the tool, the impact data will be analyzed and verified against international standards, indexes and norms.

The main advantage here is that available information on emissions, the current fuel consumption of fleets, and navigation routes can be derived from proven vessels and records provided by the project partners. However, the disadvantages are the lack of data on remote Pacific islands' specific needs (broad social studies on shipping impact, extensive economic analysis of regional shipping market, society opinion on investment in shipping instead of other sectors) and the risk of focusing on one specific group of islands instead of creating a broad methodology, applicable for other island regions as well. This risk comes from the available literature social and environmental studies which more often than not are conducted for specific cases (country or island) instead of a broader region.

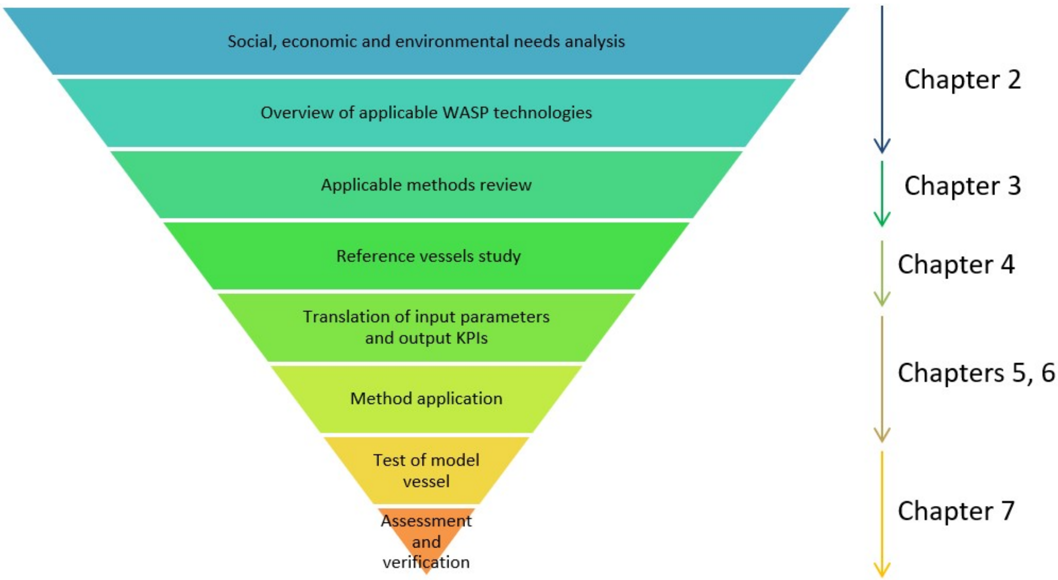

Figure 1.2: Top-down approach

2

LITERATURE REVIEW

The purpose of this chapter is to provide an overview of the South Pacific region and to analyze the impact that shipping has on local communities. First of all, the regional maritime sector is presented to understand its unique characteristics and challenges. Consequently, a needs analysis is performed for each impacted category, namely, social, economic, and environmental. The outcome of this chapter is the identification of specific needs of the region, which will be consequently translated into requirements for the development of the method (further elaborated in Chapter 3). Finally, a rundown of the existing WASP technologies is performed to assess which apply to the needs of the South Pacific countries.

2.1. PACIFIC FLEET

The South Pacific Region is divided into three main geographical groupings - Melanesia, Micronesia, and Polynesia, which are spread over an ocean area of around 36 million km^2. Across these waters, there are 22 PICTs spread which amounts to a population of approximately 10 million people. In addition, 7.3 million live in Papua New Guinea and 856,000 in Fiji, accounting for about 80% of the total population. For the other 20 PICT, the population density varies. Whereas the Marshall Islands and Tuvalu have high population densities due to their limited landmass, there are other countries on the other end of the spectrum, such as the Solomon Islands or Vanuatu, which are spread over multiple islands[9]. These geographical characteristics of the PICTs are unique and make these countries heavily dependent on maritime trade and commerce. This represents a challenges for their economic growth and social well-being. Nevertheless, in this environment, the shipping sector faces significant issues, and constraints which often lead to poor servicing [9][10].

Thus, both public and private shipping establishments are facing the following challenges in providing adequate services[11]:

- long distance voyages

- small populations and remote communities
- export-import imbalance and low trade volumes
- inappropriate port facilities

Besides these issues, another primary concern is the state of the vessels currently in service in the region. For a safe, secure, and efficient transportation service, the PICT have to invest in appropriate vessels, increase transit frequency and improve local port infrastructure. For a better idea of the in-service vessels, an overview from 2015 of some PICT fleets is presented in Table 2.1. Unfortunately, no updated situation on the Pacific fleet situation exists in more recent literature.

Table 2.1: Fleet overview [9]

	Kiribati	Tonga	Tuvalu	Vanuatu
Fleet	40 vessels with total GRT=5000t	5 Ro-Ro/Pax 3 cargo	3 Pax/ cargo	200 crafts (55 cargo/Pax) range: 20-500 GRT
Year built	unknown mostly second-hand	1963-2008	1988-2015	second-hand 2000-2010

Second-hand ships for domestic services are usually the norm for some Pacific Countries. However, in many cases, these vessels are at the end of their lifespan and no longer comply with the operational requirements and norms of classification societies. The old age of the vessel leads, in turn to high maintenance costs and requirements. More often than not, ship operators are unable to meet these demands regularly and are therefore compromising the ship safety, and transport security[6][12][4]. In this context, a poor and inefficient shipping service leads to a negative impact on all aspects of an island community. The relationship between shipping and the community issues is further elaborated in the following sections with a needs analysis.

2.2. PACIFIC ISLANDS SOCIETAL ASSESSMENT

According to an economic report conducted for the 64th United Nations General Assembly, most of the Pacific island nations have the status of developing countries due to their low GDP and quality of life indicators [13]. Critical situations on the lower end of the list include Kiribati, Samoa, and Solomon island of Tuvalu, where economies depend entirely on single or few commodities for export, such as copra, coconut oil, or cocoa. Thus, large segments of the population are relying on subsistence agriculture, and jobs in the public sector (see Figure 2.1) since private establishments are scarce on remote islands [14]. With this, it was estimated that almost 13% of the Pacific Island population is unemployed or underemployed, with most people immigrating to countries like Australia, New Zealand, or the U.S., leaving behind a gap in the available workforce [15].

With these facts in mind, it is almost imperative that every policy implemented in the region raise the quality of life and income and create more jobs. First, however, a social

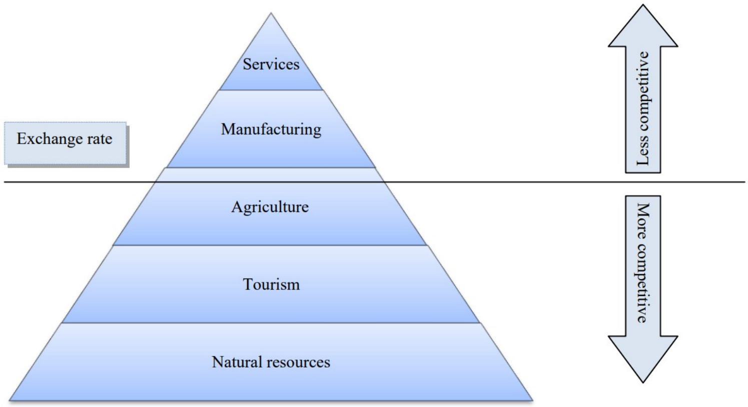

Figure 2.1: Comparative advantage of Pacific island countries[16]

analysis has to be performed to see how new vessels' introduction and fleets' expansion will impact the local communities.

This social analysis can identify a local community's needs, priorities, and patterns heavily dependent on imports. This is an essential component when devising technical solutions for the new/retrofit vessels to achieve social development outcomes. Unfortunately, there is limited information regarding the fundamental necessities of the communities, besides some humanitarian disaster relief studies that are not entirely applicable to the current case, and an onsite survey is nearly impossible. However, there are other studies conducted by the UN, the Asian Development Bank [17][11][15] and other reports on other similar island communities across the globe which might provide some insight into the societal needs. For this, research was performed to pinpoint the specific problems. Considering the challenges of the shipping sector presented in section 2.1, the societal analysis will be divided into four main areas: inter-island transportation, local infrastructure, population financial well-being, and job prospects.

Inter-island transportation

According to a study performed by the Asian Development Bank on Developing Member Countries of the Pacific, it was discovered that one of the top priorities is transport connectivity both within and across countries. Therefore, the organization emphasizes transforming the current shipping and transportation services into a climate-resilient, safe, well-maintained transport network. However, this proves to be a challenge since most of the vessels are operated by either the government or small shipping firms. Furthermore, it was observed that poor maintenance, old age, and inappropriate use of the vessels are frequently leading to delays or even suspension of charters to remote islands[11]. In short, the immediate need of the region consists of the development of an intermodal link that can better connect people to essential goods and services, markets, jobs, health facilities, and schools [17].

Local infrastructure

Improper port facilities represent one major setback for the shipping sector in the Pacific because they affect the operational performance of cargo handling. This, in turn, affects schedule times and decreases profit by delayed stays in ports. Generally speaking, the port infrastructure in the region ranges from modern container and bulk facilities to very basic wharves, and hardstands [11]. Unfortunately, the latter is the most predominant across the South Pacific. These offer essential utilities to tie up a vessel and load/unload cargo. In addition, most of the time, the ships themselves are expected to be fitted with cargo handling equipment [11]. In other more extreme conditions, the ships must moor away from the shore and transport cargo by dinghies.

The Asian Development Bank has initiated various projects to expand port facilities. So far, they have been able to build or rehabilitate nine domestic ports and 50 wharves and hardstands in countries like Fiji, Kiribati, Solomon Islands, or Vanuatu [17]. Thus, the region's critical need is to bring as many ports as possible to modern standards, which facilitate the cargo handling operations in an efficient, clean, and cost-effective manner. Further socio-economical studies are needed in the region to demonstrate the cargo demand in order to justify this large scale investment.

Population financial well-being

Generally speaking, the Pacific Island nations' average income per capita is meager, with amounts ranging from as small as $1000 per year in the Solomon Islands to $10000 in the Cook Islands. These figures place most of the Pacific nations on the lower end of the list for income levels in Asia and Pacific[11]. The consequence of this is the low average household expenditure. People are heavily reliant on imports which consist of products ranging from essential to luxurious goods, which, more often than not, arrive by sea and are highly-priced. Compared to the Asian market, the Pacific Nations pay approximately 315% more per TEU and 560% more per nautical mile [18].

From a maritime transport standpoint, these income gaps are essential. The demand for imports will increase proportionately with the rising income, but this is a matter of local policy and job sector investment. The issue which needs to be addressed is the shipping costs. The demand for diverse and qualitative goods will increase if the average price of goods decreases. Nevertheless, this can only happen due to lowering shipping costs.

Job prospects

Last but not least, another issue is the rate of increasing permanent emigration, which stems from the lack of job prospects and low income. Shipping and fishing can constitute a significant employer in the region, provided the necessary training can be done. Currently, there is a wide range of institutions giving maritime training, but the level of education is elementary or outdated [11]. With the introduction of new vessels in the region, trained personnel is required. Therefore, it would be more logical for the domestic companies to employ locals and help the economies rather than bring foreign seafarers. From this perspective, society requires institutions to update their curriculum or build more training facilities. As a result, future Pacific Island seafarers can navigate WASPs, alternative fuel vessels, or novel technologies. On the other hand, estimating how many jobs could be created requires additional data on unemployment, number of available professionals and number of expected WASP vessels in the regional fleets. The lack of this data makes this particular analysis a strenuous task and goes beyond the scope of this work.

2.3. ECONOMIC ASSESSMENT

In this subsection, the economic implications of decreasing shipping costs will be analyzed. Shipping has become increasingly expensive over the last decades in the Pacific region. In comparison to the the Asian market, freight rates are considerably higher as it can be seen in Figure 2.2

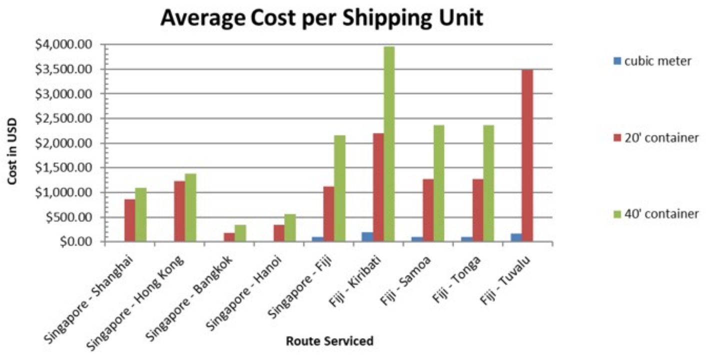

Figure 2.2: TEU average prices comparison[18]

This, paired with the geographical position and lack of infrastructure for transportation, puts a strain on the local economies because of the dependency on imports. Four major categories are identified: food, manufactured goods, fossil fuels, and machinery and equipment transport, amounting to approximately 70% of the Pacific region's total imports [19]. Most supplies are brought in from Australia, followed by France, the United States, Japan, China, and New Zealand.

However, even if Pacific nations do not possess large-scale manufacturing sectors, they can still rely on copra, coconut oil, cocoa, fruits, vegetables, fish, timber, and gold exports. This amounts to 20-30% of the nation's gross domestic product (GDP)[20]. By looking at the regional fossil fuel market, the PICT are almost entirely dependent on the import of fossil fuels by a staggering 95%. Out of this, almost 75% is used in the transportation sector[21]. This, in turn, could lead to harmful consequences on the stability of the import or long-term budget of the countries by creating a barrier in shipping development [22].

Based on the the sub-question posed in Section 1.2, another concern is how to make a vessel financially viable. To answer this question, the needs will be derived from 2 standpoints:

Investment costs and capital expenses

Even though there is a plethora of research on the various types of alternative fuels and propulsive technologies, no consensus is reached on the most financially optimal option for a vessel[23]. It is considered that in order to convince ship operators to make these transitions, more economic arguments should be brought upfront [24]. The first thing that a shipowner is interested in when considering a novel green technology on its vessel is the actual investment cost, net present value (NPV), and the rate of return (RoR)[24]. Thus, the ship owner's aim for the long term is to spend less than he would typically spend on traditional diesel engine-driven vessels while complying with the IMO norms[24]. Most of the alternative propulsion options, specifically WASPs, can be implemented by retrofitting vessels in existing fleets. With such an investment, the shipowner can increase the propulsion effectiveness, fuel efficiency and emission reduction of a vessel while maintaining low operational and voyage costs. Studies have shown that WASPs are a sound investment. However, it has yet to be implemented on a large scale in the South Pacific context [4]. This represents a knowledge gap in the economic context and, therefore, a need to find out which is more worth investing in, a retrofit or a newly built WASP (further elaborated in Chapter 2.6).

Operational and voyage costs

From the shipowner's perspective, the OPEX, Voyage expenses (VOYEX) and Capital expenses (CAPEX) are another set of economic indicators which need to be considered when assessing a new vessel option. The operational expenses consist of the daily costs associated with the vessel's running. These are dependent on the activity of the vessel when the vessel is sailing, loading/unloading, waiting, or in the dock, [24]. The only variable that applies to the WASP case is the crew associated with operating the added technology onboard [23]. On the other hand, bunker expenses are more felt by the shipowner. Thus it would be preferred to decrease that as much as possible.

2.4. ENVIRONMENTAL ASSESSMENT

As stated in Section 1.1, the struggle to combat climate change has turned into a fight for survival in the South Pacific region, considering the alarming rate at which the water level is increasing. According to observations made by NASA satellites since the beginning of the 90s, it can be seen that the water increased by 2-3 times the global average. As a result, it is predicted that by the year 2100, the water could rise as high as two meters, making many Pacific islands completely uninhabitable. In order to avoid this catastrophic scenario, the global average temperature needs to be kept below 1.5 degrees Celsius. Furthermore, since the shipping sector is one of the most significant pollutants in the Pacific regions, the emissions need to be reduced by 40% by 2030 and 100% by 2050. For this, several abatement measures have been considered, out of which the hybrid propulsion configurations with WASPs have the best chances of being implemented.

However, many WASP technologies are either in the design stage or in full deployment. Therefore, some assessment parameters are needed to decide the most suitable option for the Pacific context. Chapter 2.6 presents an extensive overview of all the available and applicable WASP options. Thus, several questions and needs arise regarding the WASP efficacy in operation: what are the most fuel-efficient options, what is the minor emissions emitting configuration, which is the overall best low-carbon freighter design, and which option has the lowest rate of land/port pollution. These needs are thus addressed in this thesis, and the answers will come to light after running the test case scenarios through the method.

Moreover, Nuttal et al. suggested that there is a dire need for the assessment of sustainable technologies [12]. However, no international standards or methods have been applied to compare various abatement measures.

Technology assessment

The current research on international shipping decarbonization measures suggests that many technologies are becoming available for operation. On the one hand, most of these alternatives are only realistically available to large-scale shipping services and well-developed economies. On the other hand, some studies imply that there are technologies that could be applied to small vessels without considering the economy of scale factor [25][26]. An overview of the readily available technologies can be seen in Figure 2.3

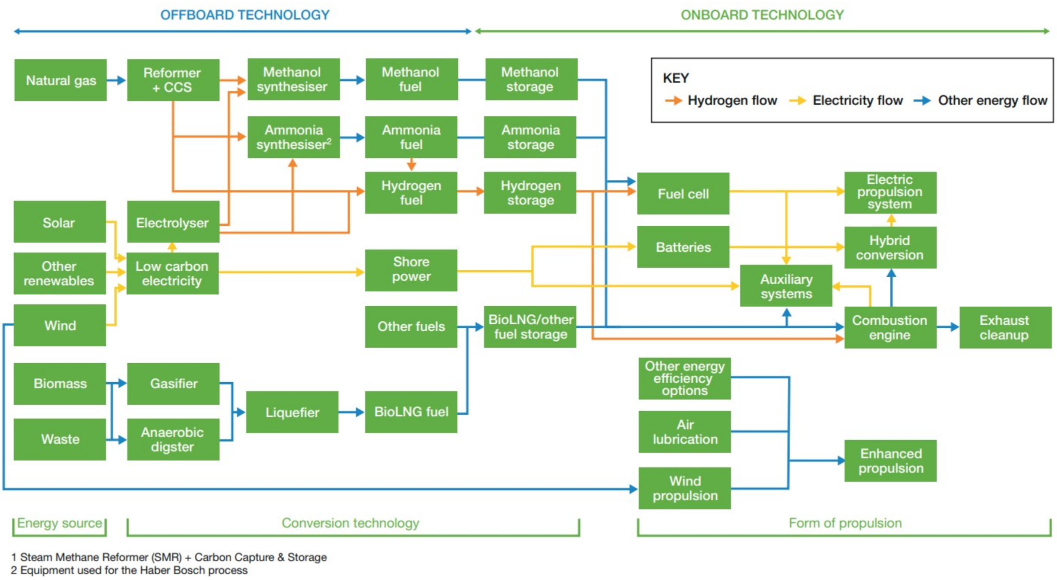

Figure 2.3: Technologies on pathway to zero emissions transition [27]

Most of the "on board" technologies could hardly be applied to most Pacific Islands nations. These countries already have struggles regarding the bunkering facilities of fossil fuels. The implementation of an alternative fuel source or batteries would pose significant problems such as new bunkering infrastructure, trained labor, new norms and regulations of operations, and technology investment[28]. Considering these factors, WASP technologies are an alternative that can be furthermore studied since many of the costs mentioned earlier can be avoided.

2.5. NEEDS ANALYSIS RESULTS FOR METHOD

So far, the social, economic, and environmental needs analysis for the South Pacific region has been performed to assess the issues which need to be addressed with the development of the methodology. An overview of the most critical identified needs can be seen in Figure 2.4.

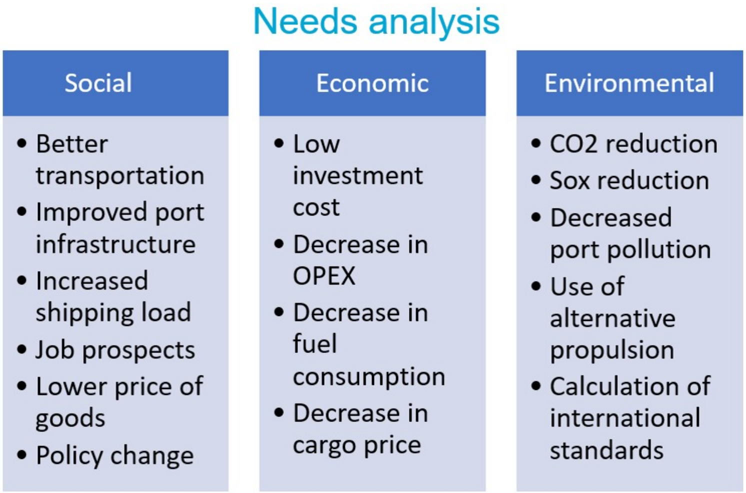

Figure 2.4: Needs analysis overview

Several outcomes are expected when assessing a WASP vessel with the designated framework. From the societal perspective, the newly introduced vessel on a given route will have to improve the cargo and people transportation in the region, giving people more freedom of travel, access to services, and an increased supply of goods. Depending on the type of WASP technology used and onboard equipment, the local port administrations will have to improve their cargo handling and bunkering facilities.

It can be assumed that an additional number of vessels in the regional fleet should create more job opportunities for the navigation and fishing sector. However this is hard to prove and quantify considering the lack of research on the job prospects for seafarers and the difficulty to quantify this into a parameter. As a result, this job and education aspects will be kept out of the scope of this work.

The exact number of vessel addition for a fleet can hardly be predicted at this research stage. However, after running some case studies for a specific region, the methodology will be able to give an insight into the scalability and replicability characteristics of a designated vessel. From an economic standpoint, the vessels have to prove themselves as a better investment opportunity and alternative to traditional diesel engine ships. First, the newly built or retrofit options need to have a feasible payback time to keep the local companies in the business. However, this requires an in-depth market analysis of the competitors, which is out of the scope of this work. Instead, the focus will shift to ship finances: CAPEX, VOYEX, OPEX, and the calculation of yearly costs to estimate the cargo price. Particular targets are OPEX and VOYEX. The OPEX can be decreased by analyzing the sailing profile and time spent in ports. VOYEX will be analyzed though fuel expenditures, which should be kept as low as possible. On a similar note, if fuel consumption is decreased through a WASP, then the emissions parameters should also be decreased to fit the norms. This means that the vessel design needs to be climate-proof and, if implemented on a large scale, will contribute to the 40% emissions target goal.

2.6. WIND PROPULSION

Following the requirement of WASPs research from the needs analysis, this section will provide an overview of the current WASP technologies. This will be made to understand how far the research in this alternative propulsion has gone and extract the necessary input parameters for the methodology. This subject will be based on the existing applications of these technologies in the market.

2.6.1. OVERVIEW OF WASPS

Ever since the 1970s, with the oil crisis significantly affecting global shipping, energy efficiency improvement onboard ships has started taking off as an essential research topic to aid against climate change. Various solutions have been studied across the years, such as alternative fuels (methanol, ethanol, ammonia, hydrogen) or renewable energy like wind and solar power[29]. However, the current findings have not yet shown a sustainable option in which these alternatives can work independently. Thus overall energy efficiency on a ship can only be achieved through a hybrid propulsion configuration(renewable and traditional fuel) [30]. Out of all the enumerated options, wind-assisted propulsion has a considerable advantage, given that it is a resource readily available on the open seas. Though it has been used for hundreds of years, it has started gaining popularity again since it displays impressive fuel savings [31], does not require particular infrastructure investment, and is highly efficient on high seas. Generally speaking, studies have found that the WASPs bring the following advantages as presented in Table 2.2.

Table 2.2: Advantages of WASPs

Studies	Statistics of WASPs
[32]	10-40% improvement in Energy Efficieny Operational Indicator
[33]	1-50% emission reduction
[34]	2-60%fuel saving in high sea shipping
[35]	no infrastructure required and proven technology across the years
[36]	High cost-effectiveness (negative marginal abatement cost)

When speaking about harnessing wind energy as a renewable source for ship propulsion, one might think just of the traditional sails, which have been used for thousands of years. However, ever since the beginning of the 20th century, several other technologies have emerged. These promise improved fuel efficiency and thrust power but might still be in an experimental stage, be more expensive to implement, or not proven for the target vessels of this study. To find out if that is the case, a run-through of all the available concepts will be made in this sub-section. According to the current state of research and implementation, the most notable technologies are [37]: soft sails, rigid sails, wing sails, towing kites, suction wings, hull sails, and Flettner rotors.

These will be analyzed through the following criteria:

- Working principles
- Applications
- Performance

2

- Technology Readiness Level (TRL). For this criterion, scores from 1 (basic principles and concept) to 9 (actual system proven in operational environment at large scale) will be given using the NASA TRL scale as presented in Figure 2.5.[1]
- application to target vessels (25-45m)

The choice for this particular vessel range is because of the the proven WASP vessels which sailed in the area during the past decades (see Section 4.1) and are within this length range. At the same time, another model developed in the Greenheart project fit within this range as well[38]. This shows that these ships with these dimensions might accomplish the mission of servicing smaller communities. Thus, the emphasis of this study will be to search for applications of WASPs which have been previously proven for cargo vessels of these dimensions.

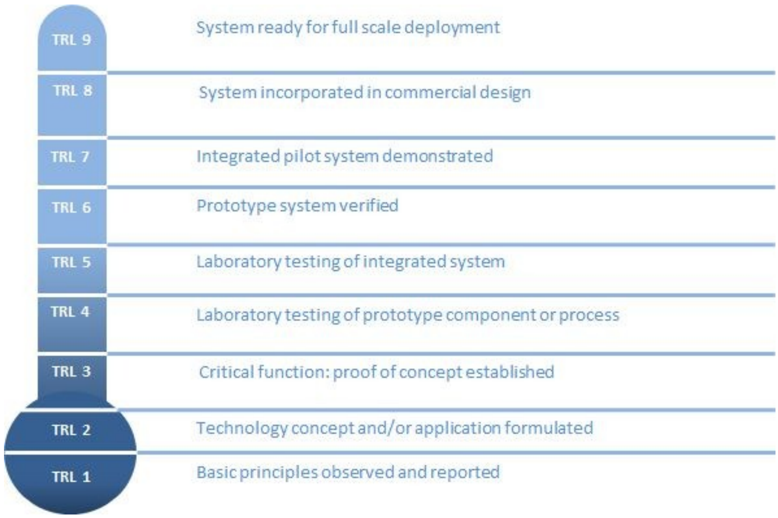

Figure 2.5: Technology Readiness Level[39]

2.6.2. SOFT SAILS

Working principles

Sails were the primary form of propulsion of galleons and schooners for centuries, with which top speeds of up to 9 knots were achieved without using any fossil fuels [40]. The architecture of the rig system was square with the veil area and masts number depending on the vessel dimensions. In a sense, the same system can hardly be applied on modern vessels as it does not display good propulsive behavior, is less aerodynamic efficient, hard to control in rough weather environments, and requires a larger sail area in comparison to other WASP options[41]. On the other hand, if the rig system is adequately designed, it can be very efficient when sailing downwind.

[1]Note* The grades will be granted according to the conclusion drawn from researching each technology from multiple sources

Applications

For this reason, the existing literature does not cover the application of soft sails on smaller commercial vessels (25-45m long) because a potential primary market for this technology was not yet identified, until now, when the initiatives in the Pacific Region displayed an increasing demand on cost-effective cargo sail vessels. Still, there are projects such as SV Kwai, Na Mataisau, Cagidonou, and the Indosail project, which can be used as reference vessels for the current study [4]. However, some of these trials and studies were conducted in the 1980s, the data is inconclusive, and the ships were short-lived. However, it shows that soft sails are still a good alternative in a hybrid propulsion configuration. On the other hand, SV Kwai is a sail vessel retrofit that has successfully undertaken charters across the Pacific Oceans for the past 15 years. However, no academic analysis has yet been performed on it. Thus, a more comprehensive part will be dedicated to the analysis of this ship in Section 4.

Still, it is worth mentioning that soft sails are more prevalent in the yacht market, with widespread application on both small crafts and superyachts. Therefore, the concept that might apply to this study's target range of vessels is the Dynarig veil system(see Figure 2.6), which has been successfully implemented on two superyachts, Maltese Falcon by Dykstra Naval Architects and Black Pearl Oceanco of 88.1 and 106.7m, respectively. The Dynamic is estimated to be twice as efficient as a traditional square veil system. Furthermore, it is designed in such a way as to automatically rotate the masts according to the wind direction in order to take advantage of the full wind potential while sailing [42].

Figure 2.6: Dynarig technology[43]

Performance

For vessels in the target range (25-45m) from the South Pacific region, it was found that up to 37% fuel savings can be achieved[4]. This was discovered through some experiments conducted in the South Pacific. More extensive information on performance for more traditional sailing rigs can be found in Section 4.1. Another interesting case is the Maltese Falcon, a full-rigged vessel that uses DynaRig technology. This vessel was completed in 2006, and during its 15 years of the voyage, it was estimated that 300 tonnes of fuel were saved every year. Moreover, this fuel decrease was recorded during eco-cruise speed and regular cruise speed, which makes up the primary navigation time of the yacht's operational profile, as can be seen in Figure 2.7.

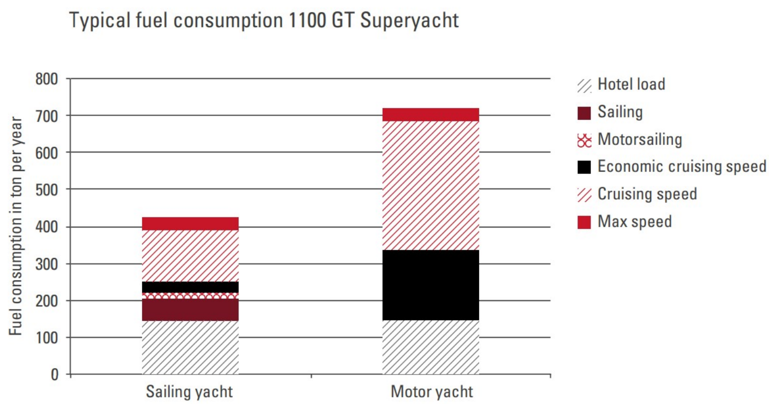

Figure 2.7: Typical fuel consumption for a 1100GT Superyacht[44]

The values were recorded based on a yearly average of 6000 hours of use and 31,000 nautical miles traveled. Even if the vessel displays some impressive output parameters, the cost of building is staggering, reaching as much as US$150 million to build in 2006[44].

Technology readiness level

Though not the most efficient option, soft sails are the most studied and proven concept available for deployment in hybrid propulsion configurations; their widespread application in the yachting sector in the desired vessel length range (25-45m) proves them to be a reliable and cost effective option. On the TRL scale, this technology scores 9.

2.6.3. RIGID SAILS AND WING SAILS

Working principles

By definition, rigid sails or wing sails are foil-like structures installed onboard the ship that use the aerodynamic forces to produce thrust for the vessel. In comparison to soft sails, rigid sails are equipped with a variable camber with an aerodynamic shape which provides more lift and a higher lift to drag ratio, which reduces wind-induced resistance. The physical principle behind it is that the shape of the aerofoil in contact with the wind flow creates a pressure difference between the sides of the foil, which in turn generates the lift force and provides the thrust to overcome the drag [45].

Applications

For this technology, some tests were conducted in the 1970s and 1980s by the Japan Machinery Development Association (JAMDA) with Shin-Aitoku Maru (see Picture 2.8), an oil tanker fitted with rigid sails. Nowadays, no vessel with this technology has been identified. However, RD companies such as COMSAIL Wing, Wing systems, Windship Technology, and Propel Wind are developing designs that are either in the concept phase, patent application, or on-land trials[23]. Rigid sails are applicable for both newbuilds and retrofits. However, it is noted that rigid sails are more suitable for smaller vessels since larger vessels would require sail areas of proportions that are not feasible for the overall architecture of the vessel [45][23].

Performance

In terms of fuel consumption, these have shown that implementation of rigid sails has a reduction of 10% to 30% during the vessel's lifespan. From a financial perspective, Gregory Atkinson et al.[46] have estimated the payback time using the JAMDA vessel as reference. Their assumptions for the calculation are 10% yearly fuel savings, 1,400 m^2 sails, the implementation cost of $2.5million, and fuel price for IFO380 of $200 per tonne. The results are that the payback time would be around 12 years.

Figure 2.8: Shin Aitoku Maru[47]

Technology readiness level

Technology-wise, rigid sails have only been applied on a limited number of ships during a set of experiments in the 1980s but have been unable to gain widespread acceptance despite the fuel and cost performance due to the fall in prices of oil[48]. However, more companies are starting to develop this technology and provide designs. As a result, deployments are expected in the following decade [23]. For this, this technology scores eight on the TRL scale.

2

2.6.4. TOWING KITES

Working principles

Towing kites provide thrust to ships with the lift generated by high-altitude winds. From 2008 to 2012, some commercial applications of towing kites were developed by Skysails; Airseas, a spin-off of the Airbus Group which developed these technology but has not seen much success on the market and went bankrupt as a result [49]. Towing kites represent another form of propulsive technology (see Figure 2.9, which besides its land applications, has started to take off as a marine option as well, ever since the beginning of the 1980s [50]. It stands out as both practical and straightforward technology, given the few components needed for the installation. Thus, the mechanism comprises a towing kite, towing rope, automatic launch/recovery system, and a central control switchboard. In comparison to other WASP options, kites have some advantages: they can be operated at high altitudes (100-500m) where wind speeds are better, and they are positioned in the forepart of the ship without interfering with the work deck or ship's maximum dimensions, and the dynamic nature of the kite enhances the apparent wind speeds, leading to increased thrust [51].

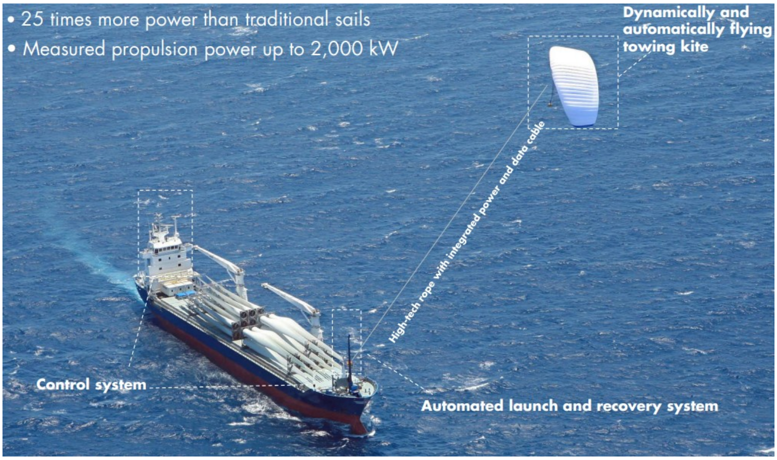

Figure 2.9: Towing kite application on a cargo vessel[49]

As previously stated, the ship is pulled by the kite through a rope attached to the ship's bow, which follows a circular motion. This has to satisfy an equilibrium condition where the lift and drag forces equal and counteract the opposite rope force. Therefore, the main performance parameters of the kite system are the lift coefficient Cl, the lift-to-drag ratio l/d=C_L/C_D, the kite sail area, and the upper limit for the force on the rope $F_{rope,max}$.

Performance

From a performance standpoint, vessels fitted with this technology have recorded yearly fuel savings of up to 10-15%, according to SkySails systems. For a 3,000-t cargo ship, this equals savings of 2-3tons/day and 10tons in good wind conditions. This stems from the fact that towing kites generate around 25 times more energy per square meter than traditional sails. This, in turn, translates to roughly 2,000 kW of power, which can be harnessed in favorable wind conditions [23].

Applications

So far, companies like SkySails have implemented kites on cargo ships, fish trawlers, and multi-purpose vessels of at least 100m long and with a maximum speed of 18knots. Nevertheless, applications on a smaller scale exist in the yachting sector, where companies like ArmorKite, installed kites for leisure boats. The technology is readily available for purchase, and it is predicted that more vessels will apply in the following decade. Towing kites were installed on both newbuilt and retrofit vessels [23].

Technology readiness level

So far, this technology has proven itself, but only a few implementation records exist until this option is proven on a larger scale; the technology scores eight on the TRL scale.

2.6.5. SUCTION WINGS

Working principles

The idea of suction wings (see Figure 2.10) started taking shape around 2009 when eConowind proposed a model which would inherit characteristics from both Flettner rotors and soft/rigid sails. The technology works on the boundary layer suction principle by preventing flow separation on the thick wing profile. Even if there is no external rotating mechanism, the suction wing can generate lift at the same level as a rotor and on a magnitude higher than a soft or rigid sail. Similar to a rotor, the wings require energy to run, but the amount is negligible [23].

Application

In terms of vessel applications, just one model was released for deployment so far, the eConowind unit[52]. However, CRAIN has more trials and full-scale testings planned for the following decade . It is reported that the preferred market for this type of technology is small vessels up to 50,000 Deadweight (DWT) with service speeds of a maximum of 12 knots. Moreover, suction wings are suitable for both new builds and retrofits [23].

Performance

After sea trials and operations, it was reported that the fuel savings could range between 10-30% fuel[52][23].

Technology readiness level

The RD of this concept began in 2009, and until now, it has been installed on only one ship. Thus further studies are needed for full validation. However, with this, the technology scores seven on the TRL scale.

Figure 2.10: Suction wings application[52]

2.6.6. HULL SAILS

Working principles

Hull sails: Hull sails are hulls that use relative wind with their symmetrical hull foils to generate aerodynamic lifts, which pull the ship's direction. According to the producer, this configuration is paired with an LNG propulsion system to reach the desired speed, save fuel and reduce emissions[53].

Applications

Currently, the application of this technology on commercial ships is non-existent. So far, just one noticeable concept design has been released, the commercial ship Vindskip by Lade AS, see Figure 2.11. The producer notes that this design could be applicable in the future for dry cargo vessels such as RoRos, RoPax, passenger vessels, and container ships. For the time being, the producers have registered a patent and are conducting on-land trials[53][23].

Performance

The product owners claim that as much as 60% fuel can be saved and a decrease in 80% fuel emissions [53] can be achieved; however, this has not been proven yet on a large scale vessel.

Technology readiness level

This technology is currently in its concept stage with no real-world applications, but tests are performed to apply it. For this reason, this option scores two on the TRL scale.

2.6.7. FLETTNER ROTORS

Working principles

Anthony Flettner developed the Flettner rotors in the early 1920s. They saw its first marine application on the Baden-Baden vessel in 1925 when it achieved the fantastic feat

Figure 2.11: Hull Sail concept by Lade AS[53]

of crossing the Atlantic Ocean between Europe and the United States, thus proving the potential of this alternative form of propulsion. This technology has the Magnus effect as its core principle, meaning that when the rotor sail meets the wind flow, a change in airflow speed creates a pressure difference on the sides of the rotor. Thus, this, in turn, generates a perpendicular lift force to the wind flow direction, which creates the thrust. As seen in Figure 2.12, the Flettner rotor can be described as a rotating cylinder that generates more aerodynamic lift and drags on a smaller area than other WASP options.

Applications

Norsepower rotor sails are the leading producer of this technology in this field. Their rotors are suitable for various vessels, from tankers and bulk carriers to ferries and cruise vessels. A current proven vessel is the M/V Estrada (9,700 DWT RoRo) which has been deployed as of 2015[54]. The company reports that the demand is increasing considerably, meaning that as many as 200 retrofits and newbuilds could have rotors installed onboard [23]. Until now, rotors have been applied on vessels bigger than 5,000 DWT, but research is promising for smaller vessels.

Estimations have been performed by Maritim in 2015 [23] for a 3,800 DWT ship that could reach a maximum speed of 12kn, but the ship has yet to be deployed.

Performance

In terms of delivered thrust, this technology can be ten times more efficient than soft and rigid sails [54]. However, fuel savings are relative and depend on favorable wind conditions. It is reported that between 5% and 30% savings can be achieved [23]. Due to its easy installation, rotors can be fitted on both new builds or retrofits. From a cost perspective, installation of these can amount to approximately $500,000.

Technology readiness level

The technology has been studied ever since the beginning of the 20th century and has seen applications both large and small scale. Thus, it is readily available for deployment. On the TRL scale, a score of eight can be given.

Figure 2.12: Flettner rotor[55]

2.6.8. FINAL OVERVIEW AND APPLICABILITY TO SMALL SCALE VESSELS

As seen in the previous sections, the current WASP technologies are in various states of deployment of the design concept. Even if most promise fuel savings and emissions reduction, the applicability to a wide variety of vessels is not yet proven since applications are limited to specific vessels (mostly large bulk carriers or oil tankers). A SWOT analysis summarizing the traits and market challenges of each WASPS is presented in Figure 2.13.

These technologies have various working principles and complexities and can be automated only to a certain degree. Thus, the operation would require a specialized crew that harnesses the full potential in favorable wind conditions. The current applications are limited, but it is reported that many designs are in trial stages. In the following decade, the market will see the deployment of more WASP vessels, and thus more conclusions will be drawn on how well these technologies behave in actual operation. In terms of fuel efficiencies, estimations and trials have shown each technology's enormous potential, provided good wind routes are chosen. All technologies apply to both newbuilds and retrofits. From a TRL perspective, most technologies have been researched and tested besides the Hull sails. However, only a few have seen actual deployment to validate the application. Lastly, besides the soft sails applications of past WASP vessels in the South Pacific and current yachting sector, no relevant information has been found regarding WASP for the target vessel range of 25-45m. After reviewing all these WASP options, the following characteristics analysis results can be seen in Table **??**.

In conclusion, for this thesis, the technology which will be further explored and incorporated into the methodology will be the soft sails. First, this option is the TRL level of 9, which this WASP has. Second, it is reported that research for this option is currently being performed for vessels in the range of 3,000 to 5000 DWT, which is the closest to the type of vessels currently planned for the South Pacific region (150-300 DWT-SV Kwai, Na Mataisau, Cagidonou, etc.). Thus the assumption is made that the trials and experiments in the following decade will display optimal fuel-saving and propulsive parameters for implementation on target vessels. Lastly, empirical formulas for performance

Table 2.3: Overview WASPs

Technology / Criterion	Working principle & Complexity	Current applications	Fuel efficiency and savings	Retrofit and newbuilt	Technology Readiness Level	Current application to target vessels (25-45m)
Soft sails	Traditional square rigs which capture wind. The simplest form of wind propulsion.	Widespread in both commercial and yachting sector. It propels small hybrid vessels and assists larger ships.	11-50%	applicable to both	9	some in the yacht industry
Rigid sails	Technology which uses wingsails to capture effective directional thrust from wind power with its camber aerodynamic shape. Improved lift and lift to drag ratio to soft sails.	Limited prototypes and sea trials. 80s experiment with 1475 dwt Shin Aiotku Maru	10-30%	applicable to both	8	none
Towing kites	The system tows the ship using large, dynamically flying towing kites.	cargo, fishing and multi-purpose vessels	10-15%	applicable to both	8	none
Suction wings	The technology works on the boundary layer suction principle by pre-venting flow separation on the thick wing profile .	1 bulk carrier	10-30%	applicable to both	7	none
Hull sails	This will generate an aerodynamic lift giving a pull in the ships direction, within an angular sector of the course.	none	approx .60%	newbuilts	2	none
Flettner rotors	A spinning cylinder that uses the Magnus effect, which harnesses wind power to propel a ship.	small vessels up to VLCCs	5-35%	applicable to both	8	none

Strengths	Weaknesses
• Reduction in fuel consumption • Reduction in emissions • Reduction in operating costs • Source of emergency propulsion • Improved vessel stability • Less space needed for fuel	• Impact on ship and crew safety • Initial cost • Additional operating costs • Variable performance • Interference with cargo operations • Space and storage requirements • Additional weight • Additional work load for crew • Additional training needed for crew
Opportunities • Implementation of environmental regulations • Trend towards lower emission shipping • Higher fuel prices • Desire to enhance brand image • Corporate and consumer pressure • Slow steaming	**Threats** • Competing technologies • Competing measures • Industry resistance • Lower fuel prices • Alternative lower cost fuels • Over-stated fuel savings not realised • Ships moved to unsuitable route • Sails deemed too complex

Figure 2.13: SWOT analysis for WASPS [46]

parameters have been found for all of the technology mentioned earlier, such as thrust, lift, drag, etc. These can be used to incorporate into the methodology and create the impact assessment tool.

3

METHODS

3.1. METHODS AND WORK

This chapter aims to provide an overview of applicable methodologies to the current situation of fleet renewal in the South Pacific. The methodology will have to assess the social, economic, and environmental impact of a WASP vessel in a designated region. In order to build a suitable methodology, a series of helpful impact assessment tools and methods will be evaluated considering the needs of the South Pacific region specified in Section 2.4.

3.2. OVERVIEW OF APPLICABLE METHODS

In this section, methodologies of interest will be presented to derive solutions for the final methodology of this work. The first criterion of selection for the methodologies was the applicability to the maritime sector and assessment of vessel characteristics based on the social, economic, and environmental spectrum. The second criterion was complexity. Considering that other researchers might utilize the tool, the method should be simple and easy to understand.

Method 1- Framework for economic impact on environmental and human welfare through ship subsystems analysis [56]

Description

In principle, the authors aimed to create a framework to assess how different ship systems that generate waste impact the marine ecosystems, air quality, and human welfare. Secondly, they quantified their environmental, societal, and economic impact on damage costs that result from marine eutrophication, marine ecotoxicity, reduced air quality, and climate change [56]. The first methodology comes from a study conducted in the Baltic Sea, which concerns the effects of shipping emissions over the coastal areas in the region. The study focuses on the overall shipping emissions in the region, including a case study on a ROPax vessel in their paper using the proposed method.

Method of work

In order to do this kind of impact study, the authors have used the DPSIR(Drivers, Pressures, State, Impact, and Response) framework. This enables the user to analyze the environmental issues and identify solutions by connecting the polluting factor to the impacted sector.

Overall, the emissions and waste of a ship are widely known to impact the environment, but scientists need to research more in-depth to find more specific correlations. With this framework, it is easier to trace and monetize what substance and waste affect what sector in particular [56]. An example of this framework applied to the Baltic area can be seen in Figure 3.1.

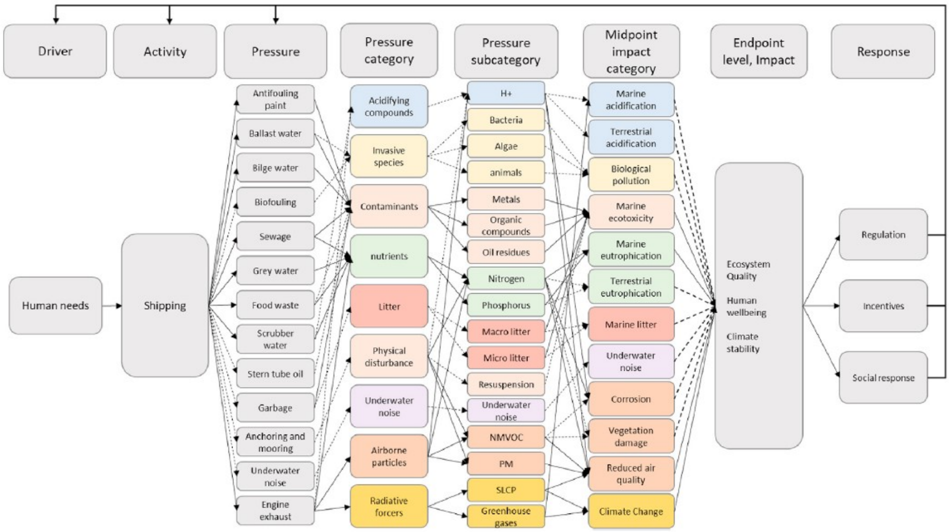

Figure 3.1: Method 1 framework[56]

The driver for this method is the societal needs of humans which translate to shelter, security, goods, and services [56]. In order to obtain these, people have to undertake specific activities, which in this case is maritime trading. However, shipping comes at a cost with pressures that impact the environment, such as antifouling paint, ballast water, scrubber water, bilge water, or food waste. The pressures are further categorized and subcategorized based on the pollutants emitted and spilled in the environment and are calculated with the help of empirical formulas provided by DNV-GL, EU Commission and IMO statistics, and other similar studies. The midpoint impact category is a list of detailed factors used for the cost evaluation. Each is connected with the designated chemical pollutant, and costs are calculated using empirical formulas. The numbers are then joined in the high-level impact groups, representing the whole region's cost and environmental impact. Based on these results, measures and solutions can be derived to decrease costs and emissions in the area[56].

Results were validated using classification societies norms (DNV-GL in this case), climate metric Global Temperature Potential (GTP), and peer studies.

Limitations

As described by the authors, this methodology can be implemented on a larger scale in other regions of the world, but it has some practical limitations. This assessment requires specific damage cost predictions (on-site and impact studies), which are unique for each region analyzed. Thus, the results used in the Baltic case study can hardly be used as a validation method.

In order to estimate the effects of the pressure categories, information from a range of 40-70 vessel subsystems was collected. Without this complex data, the volumes and amounts of contaminants in a whole region cannot be predicted accurately.

Method 2-Environmental and economic impact from vessel life-cycle perspective [57]

Description

Similarly, the second methodology was developed to assess the environmental and human health impact of a vessel by looking at the subsystem components individually. The difference consists in the long-term perspective and predictions since the methodology is built to analyze components for the whole life cycle of a vessel. In other words, this Method is designed for the analysis of more specific routes with more navigation data, focusing solely on the ship rather than the impact of a whole shipping market[57]. Thus, this study focuses on the air emissions emitted by an oil tanker in the Mediterranean over its life span, ranging from manufacturing pollution to the waste resulting from scraping.

Method of work

The framework for this study was built with a Life Cycle Approach (LCA) developed by ISO, which has the following stages: goal definition/system identification, inventory analysis, impact assessment, and interpretation. After defining the goal and the system boundaries and conditions, an inventory analysis is performed to collect information about the energy quantities, used materials, and emissions across the system's life cycle. After these initial steps, the LCIA can be used in order to quantify the actual human, and ecological effects of the designated system [57].

It was determined that the hull and machinery components are essential for the air emissions assessment for a vessel. The input is the energy and raw materials, and the output is the emissions (carbon dioxides, carbon monoxides, sulfur dioxides, etc.). Each subsystem can be independently calculated for its impact. A breakdown of the subsystems that the framework is made for can be seen in Figure 3.2

The framework can calculate various operational scenarios through algorithms and empirical formulas. Thus, in the beginning, information such as ship dimensions, cargo, trip duration, distance, and port waiting times are introduced. The characterization of the chosen system follows this. If, for instance, the main engine is chosen, then information and parameters about it are inserted into the framework to calculate the subsystem's performance. This is paired with the operational data of the vessel to calculate the total usage of the engines during a trip [57]. Once all the available subsystem data is collected, the LCIA can be performed.

Finally, the authors used the Eco-Indicator 99 method, which calculates one final KPI as a result of weighing three different damages: damage to human health(number of years lost), damage to ecosystem quality(loss of species during a time frame), and

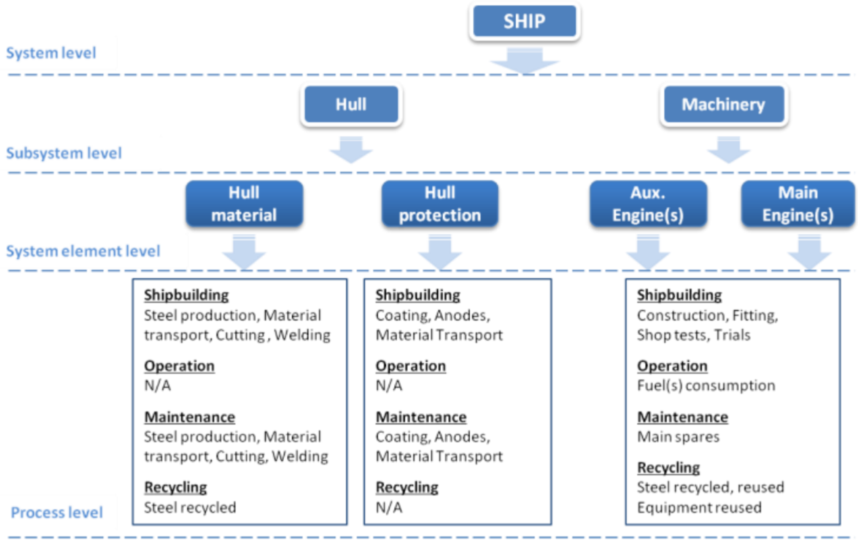

Figure 3.2: Ship systems and subsystems division[57]

damage to resources (amount of energy needed for future extractions of minerals and fossil fuels). After assessing all the systems individually, the results are combined for a final result of the total emissions impact on the environment of the whole vessel during its life-cycle[57].

Limitations

The framework is centered around assessing the impact on human health and the environment. However, it does not explicitly aim to quantify the economic damages or ship finances as output data. This study is instead considered as already known input information for the LCIA. Thus, these indicators need to be calculated and evaluated separately and integrated into the LCIA. On top of that, both LCIA and Eco Indicator 99 require special softwares for calculations which could not be obtained for the present work.

Method 3 -Eco indicator method paired with design tool[58]

Description

A methodology that can help the designer make more rational decisions about the model can be created from a design perspective. For example, one of the Eco-indicators, such as LCA, can be used alongside a design tool in order to optimize ship systems for a better social and environmental impact[58]. Given that many of the projected vessels for the South Pacific fleet are currently in their initial design stage in the current project, a framework that can aid the decision-making process can be created. Thus, the social, economic, and environmental factors can impact this early if the proper assessment and predictions can be made. Similarly, this tool can provide a sound option for the analysis between new build and retrofit designs and aid in the decision process.

Method of work

This framework can analyze various subsystems of the vessel independently and assess their efficiencies. In the matrix of data, the ship's characteristics are introduced, and the impact categories are selected based on the type of environment the vessel sails in [58]. A quantitative and qualitative evaluation of these results will allow the user to return to the design and make more rational decisions in the subsystem since identifying the impact sources is possible (emissions/processes). After modifications are made, the subsystem can be rerun through the framework for assessing and comparing the best design option. As it can be seen in Figure 3.3, the design tool can be paired with the Eco indicator 99 to quantify and weight the damages.

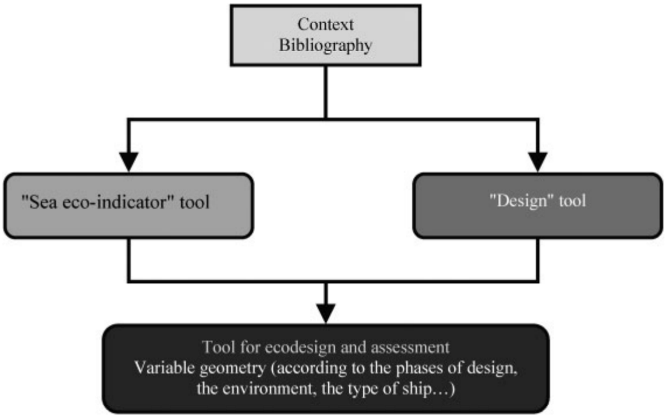

Figure 3.3: Design tool scheme[58]

Limitations

This method discusses the pairing of eco-indicators with design tools. The Eco indicator 99 and LCA frameworks are used, but this method does not account for practical limitations that a design tool might have when making these assessments; thus, whether a design tool can display the necessary parameters to quantify the economic and environmental impact and how these can be translated in the design context.

Method 4- Internationals standards, norms and frameworks for vessel design, economic and emissions assessment[59]

Description and norms

For the ship operators to comply with the emission norms, the IMO has set the Energy Efficiency Design Index (EEDI) regulations, which consist of a formula to calculate the vessel environmental impact at design point. This indicator analyzes the power plant design of a vessel for sustainability compliance. In other words, this standard can be described as "a method that estimates grams of CO_2 per transport work (g of CO_2 per tonne-mile), which can be expressed as the ratio of "environmental cost" divided by "Benefit for Society" [59]. The main formula used to assess the CO_2 is as follows:

$$EEDI = \frac{Impact\ to\ environment}{Benefit\ to\ society} = \frac{Power * Fuel\ consumption * CO_2\ factor}{Capacity * Ship\ speed} \tag{3.1}$$

Another indicator relevant for the sustainability calculation is the Carbon Intensity Indicator (CII) which assesses the vessel from an operational point of view and is applicable to the current situation. The calculation of the CII can be seen in Formula 3.2[60].

$$CII = \frac{Annual\ fuel\ consumption * CO_2\ factor}{Annual\ distance\ travelled * Capacity} \tag{3.2}$$

As of 2023, the CII will be implemented on all vessels above 5,000 GT. This measures the transportation efficiency of goods and passengers in grams of CO_2 emitted per cargo-carrying capacity and nautical mile. Consequently, the vessel is given a rating which ranges from A to E. CII is calculated yearly since it addresses the operational emissions whilst EEDI is a one-time certification for its design specifications[60].

The main goal of the operator is to reduce the EEDI and CCI values as much as possible, and this can be done through several methods:

- Reducing individual emissions of central systems such as main engine, auxiliary engine, shaft generator, switching to low carbon fuels such as LNG, or implementing solar and wind-powered technologies.
- Use efficient technologies for subsystems such as waste heat recovery, improved hull design, hydrodynamic modifications, hull coating, lightweight materials, etc.
- Increase the transport work by incrementally increasing deadweight or reducing design speed since the power required by the engine will drop considerably as well.

Method of work

There are many measures that a ship operator can take to comply with the EEDI and CCI. However, the question is how economically viable these are to keep the operator in the business. Thus, the cost-effectiveness of the EEDI reduction measures can be calculated using the Cost of Averting a Tonne of CO_2 Heating (CATCH) and Marginal Abatement Cost Curve (MACC) models[59]. CATCH is an indicator that estimates the cost of preventing 1 tonne of CO_2 emissions by using a particular abatement solution. This Method can be used individually for systems and subsystems[61]. With Formula 3.3 it can be calculated:

$$CATCH = \frac{\Delta C - \Delta B}{\Delta E} \tag{3.3}$$

ΔC is the cost of implementing a measure on a ship in $. This includes various expenditures such as installation, design, and OPEX. ΔB is the benefit (other than emission reduction) during the operational lifetime of a ship due to the implementation of a measure in $. This includes fuel cost savings and increased revenue. Both ΔC and ΔB can be estimated per year of operational lifetime. ΔE is the expected reduction of CO_2 -eq emissions during the expected operational lifetime of a ship due to the implementation of a measure in tonnes.

For the present study, all of these coefficients can be derived from the documents from the South Pacific partners. As previously mentioned, the CATCH tool can be utilized for the individual assessment of systems and subsystems on a vessel. However, as in the case of the designated Pacific fleet, several abatement measures can be implemented. Thus a tool to assess the overall cost-effectiveness of a fleet is needed, such as MACC. It is worth mentioning that the MACC curve is based on the results derived from CATCH.

As explained by Faber et al. [62], "A MACC depicts the maximum abatement potential of measures that do not exclude each other, sorted by their marginal costs." The MACC curve is an iteration process where an analysis is performed on a fleet by removing and adding ships with different or similar abatement measures until an overall CATCH indicator is achieved. Thus, the curve will display the potential for exhaust reduction for a year and the marginal costs for achieving the desired reduction. [63]. An example of the curve can be seen in Figure 3.4. This tool is useful to attain the scalability and replicability characteristics of a model vessel required by the collaborators.

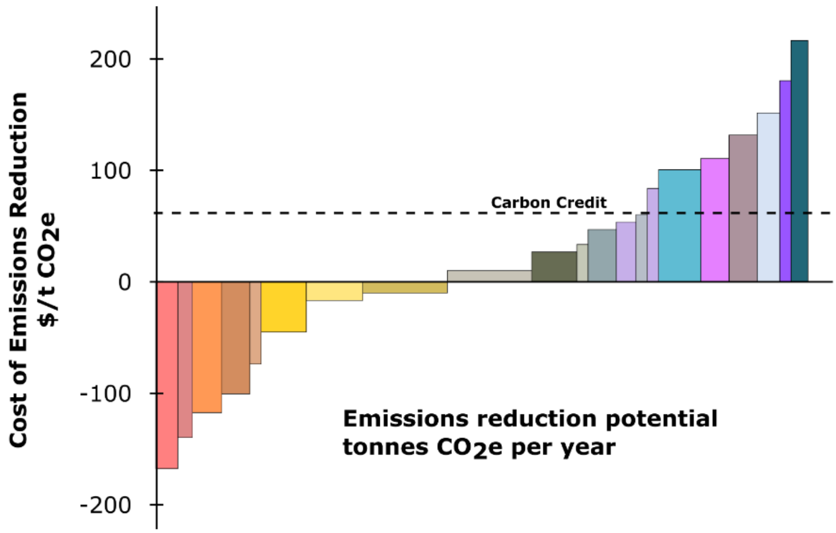

Figure 3.4: MACC curve representation [64]

Limitations

This Method consists of empirical formulas devised for impact assessment, including societal, economic, and environmental aspects. The EEDI and CII parameters have been developed only for ships above 400 and 5000 GT respectively.

Method 5- Labour and port infrastructure development assessment framework

Description

It is no secret that investment in better port infrastructure can facilitate a healthy business environment. Its competitiveness can be stimulated if key parameters are improved, such as logistics, administration costs, or transport efficiency [65]. Even more, a port should have characteristics like efficient services, accessibility, regional connectivity, import/export balance, and hinterland positioning[66]. Lastly, the port needs to be a regional economic aid by providing jobs and security to the population.

Method of work

In order to assess all of these operational and economic requirements of a port, a structural equation modeling (SEM) framework is used. The framework works by assessing the quality of the port infrastructure (QPI) employing analyzing a range of ports. A port's actual quality in a local region can be assessed only by comparing it to neighboring ports since they are trading similar cargo, using similar technologies, and applying similar policies and administration. For the Pacific case, that is indeed an advantage as it has been described in Section 2, that only a few ports are at modern standards, and others lack the necessary infrastructure.

For assessing the QPI parameter, the Likert scale is used from 1 to 7. A value of 1 represents significantly underdeveloped port infrastructure, whereas 7 represents the modern international standards.

However, only indicators related to port infrastructure improvement and employment prospects are of interest for the current study. Thus the QPI, LPICQ, and PGDP will be present.

Limitations

This study's main limitation consists of the type of complex data extracted to calculate all the efficiency parameters of a port site. In addition, to assess the ports of an entire region, data is needed to calculate the average port work indicators. Ports and harbors indicators cannot be validated without this comparative data.

3.3. METHODS TO REQUIREMENTS

From the methodologies overview, it was confirmed that frameworks for the impact assessment of a vessel on economies, human welfare, and ecosystem exist and are relevant for the current topic. Each reviewed methodology uses different analysis models and focuses on either low-level subsystem components' effects on climate or high levels like overall yearly emissions in a region. However, a methodology specifically applicable for assessing a WASP vessel from a social, economic, and environmental standpoint in the South Pacific region has yet to be created. With this new methodology, this thesis will try and fill a knowledge gap in the South Pacific shipping research. The current thesis focuses primarily on the local effects of a single WASP vessel navigating on a designated route. However, in the end, it should justify scalability and replicability in the long run for an entire fleet.

First and foremost, the methodology will primarily focus on low-level outcomes. For the local communities, this means: delivery supply of goods, improved inter-islands transportation, job prospects, decreased pollution, and increased local economy. For a single vessel, the aim is to decrease investment costs, VOYEX, OPEX and fossil fuel dependency, and emissions. However, after running the test cases, the results will be interpreted for high-level predictions on a yearly basis in deploying a fleet of the same type of vessel. The scalability and replicability characteristics should show an improved situation at a regional scale for the low-level outcomes.

The methodology will borrow application principles from each of the reviewed options. In order to see to what extent each methodology applies to the needs derived in Section 2, a relationship matrix was created in Figure 3.1. In this matrix, the needs are translated to requirements.

Table 3.1: Needs to Methods relationship

Needs analysis		Method 1	Method 2	Method 3	Method 4	Method 5
Social needs	Need for better transport		✓			✓
	Need for improved port infrastructure					✓
	Need for increased shipping load		✓	✓		
	Need for more job prospects					✓
Economic needs	Need for low investment/retrofit costs		✓	✓		
	Need for decreased fuel consumption		✓	✓		
	Need for decrease in cargo price		✓			
	Need for OPEX decrease		✓			
Environmental needs	Need for lower emissions	✓	✓	✓	✓	
	Need for alternative propulsion	✓		✓	✓	
	Need for international standards	✓			✓	

Thus, out of each methodology, the following principles can be extracted:

- Social

  For social impact assessment, three tools were found to contain formulas and tools to quantify life quality improvement parameters. Among these, the most relevant is Method 2 and Method 5. For example, to assess better transportation and increased shipping load, Method 2 is used. This is because, in the vessel assessment, information such as trip duration, voyage distance, and port waiting times are needed; thus, at the end of the analysis, a conclusion can be drawn about the cargo transport efficiency of the ship. On the other hand, method 5 focuses solely on analyzing port infrastructure and economy by benchmarking several ports in a region. The result of this method can help understand how much the ports of a region can be improved.

- Economic

  In the economic scenario analysis, two methods were chosen. On the one hand, with the help of Method 2, all the economic parameters can be calculated and assessed. Thus, Method 2 is a complex means of analyzing operational and investment costs. On the other hand, however, Method 3 provides the framework and thinking to compare various subsystems of the vessel through the economic criteria to make the most financially viable choices. Method 3 can be used for the benchmarking section to interpret the results.

- Environmental

  Given the broad interest in environmental issues on shipping, more research methodologies were found on fuel consumption and emissions analysis. These methods can be used to attain the sustainability requirement of the tool model and to check the policy making influence specified in the Needs Analysis. From 4 relevant methods, specific tools and formulas can be derived. Method 1 is a valuable tool for connecting subsystems pressure factors to impact categories, thus identifying where changes can be made to decrease fuel consumption and emissions. Method 4 integrates environmental and economic aspects using the EEDI and CII indexes for validation of results. The CATCH indicator estimates the cost of preventing emissions through various abatement measures. A MACC curve could be then applied for fleet extrapolation. Finally, for comparison of the best low-carbon design between systems and vessels, Method 3 can be utilized.

In Table 3.1, a total of twelve requirements and five applicable methods are presented. Each method represents a viable solution for the identified items, but only a limited number will be approached. The main reasoning for this decision is the time, complexity, and lack of information on some of the identified requirements. For instance, items which involve infrastructure and economic and environmental assessment of ports are hard to predict without complex data on all the ports and wharves of a specific vessel route. Also, the methodology for this kind of assessment is long and complex and is beyond the scope of the paper, given that the emphasis is on vessel analysis.

A similar situation applies to the job prospects requirement, which is hard to predict with the introduction of several vessels. In itself, this issue requires a more comprehensive socio-economic analysis and a deeper understanding of the local economies and policies, which is also beyond the scope of this thesis. Therefore, in the remaining part of this chapter, the items which can be translated to actual KPIs for the methodology will be presented:

Social:

- Inter island transit
- Cargo price

Economic

- Investment costs- the amount of money invested per newbuilt purchase or retrofit
- CAPEX, VOYEX, OPEX

Environmental

- Decrease fuel consumption- calculate parameteres: Spfc (specific fuel consumption) and emissions (SO_x and CO_2).
- Decrease emissions EEDI, CII, CATCH indexes specific pollutant index/magnitude of CO_2 and SO_2 emissions

Designated empirical formulas will support all presented KPIs for the most appropriate estimation. These parameters will represent the primary output data of the methodology by which a conclusion can be drawn about the impact of a new vessel introduced in a region. In the later stages of the thesis, the connections between the ship parameters and the impact on the specified KPIs will be made and integrated into the methodology.

3.4. DEVELOPED METHODOLOGY

The developed methodology will employ a LCIA approach but will only perform a specific segment of the analysis. The LCIA assess the ecological consequences of a product from manufacturing to scraping. The purpose of this work is not by any means to include the building stage of the vessel, the scrapping process or fuel production. Instead, this thesis aims to analyze the impact of the fuel burning during sailing, i.e. during the operational lifetime of the vessel. Furthermore, final KPIs calculated through the LCIA such as: marine eutrophication, damage to human health, marine ecotoxicity and others. Instead, the operational cycle will yield results for parameters such as fuel consumption, CO_2emissions and SO_x emissions. These substances are known to be main contributors to climate change. A quantification and a study on how precisely these substances impact, was considered out of the scope of this paper.

3

Considering the aforementioned boundaries, an adapted version of the LCIA was developed, see Figure3.5

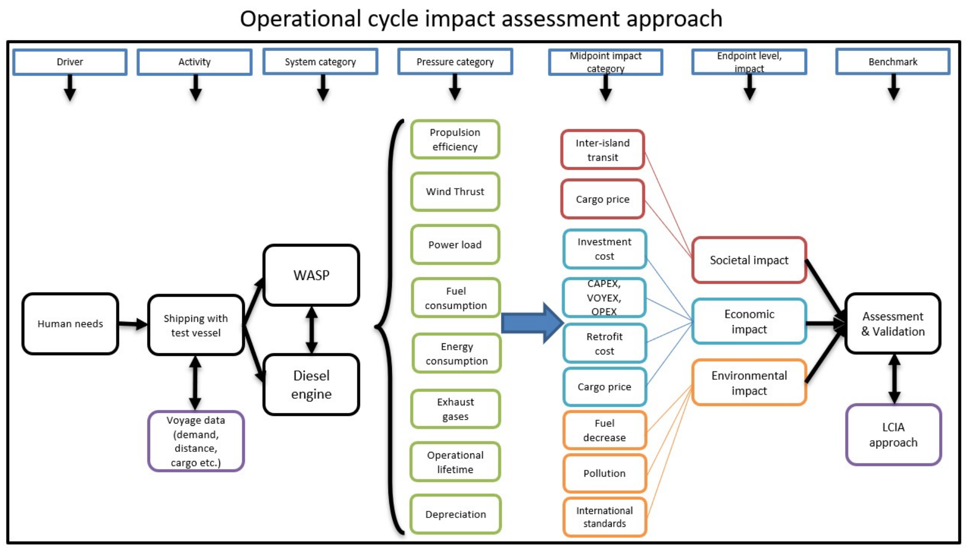

Figure 3.5: LCIA project adaptation

The method follows the same procedure of an LCIA but applied to the operational lifetime of a vessel. The method begins by analyzing the operational profile of the vessel as well as the voyage details. The analyzed system categories are independently analyzed and calculated for one voyage. Their input parameters are broken down in the pressure categories for a detailed overview. Sails and engine work in a hybrid propulsion, therefore the pressure categories are then joined again together to form unitary parameters. After a few iteration processes with the developed Excel tool, the midpoint impact categories will yield results. These are discussed, analyzed and then categorized in their designated endpoint level. Lastly, an assessment is performed over a 20-years cycle and results are compared between the impact of no sails, sails in 10%-20% margin limit and the baseline model. Conclusions are then drawn of what overall impact does the vessel have with its current hybrid propulsion configuration during its entire operational vessel.

4

Reference vessels

In this chapter, the relevant documentation regarding the case study vessel will be explored to highlight the key parameters, routes, and vessel information used to develop the present method.

4.1. Brief history of previous Pacific WASPs

One of the first recorded experiments with a modern sailing rig in the Pacific region was the 274 gross ton passenger/cargo retrofit vessel Na Mataisau(see Figure 4.1). The experiment was performed in collaboration with Southampton University, and test findings have shown positive results despite concerns regarding stability and leeward sailing.

Thus, some notable benefits have been discovered: 23% fuel savings, and a significant decrease in engine usage[67]. From a cost perspective, the retrofit investment amounted to roughly US$ 40,000. Consequently, the Investment Rate of Return(IRR) calculations have proved that the vessel can be economically viable in the short run. With that, the vessel could achieve an IRR of 30% on average inter-island routes and 123% in the more favorable ones, provided the ship is fully loaded, and the wind conditions are optimal [68]. However, the experiment lasted for only half a year since the vessel was damaged due to an accident in a developing cyclone. Nonetheless, the rig was installed on a larger vessel, Cagidonu, for a subsequent experiment. Similarly, the vessel displayed good numbers with average fuel savings ranging from 20% to 37% [68][69][67]. In the end, the economic context of the last 1980s saw the project's abandonment, given that the low fuel rates stimulated ship owners to opt for fossil fuels instead.

Several other projects are worth mentioning here. However, not all are adequately recorded, or results have not been sufficiently validated. Between 1984 and 1987, the local islanders of Kabara built a 50-ton sailing vessel with aid from the European Union. Scuttled in 2006, the longevity of this inter-island vessel proves that it met the needs of the local region[12]. Around the same time, organizations such as Save the Children Fund and FAO/UNDP have distributed various types of wind-assisted boats and vessels, which were reported to have up to 60% fuel savings. Lastly, Pacific Region governments

Figure 4.1: Na Mataisau [4]

initiated joint projects with either UN help or the private sector to develop sail-assisted trading rigs. Unfortunately, some never got beyond the design stage (e.g., Ha'Apai trader) due to the end of the oil crisis and the lack of research and applications of the WASPs elaborated in Section 2.6 [4].

A proven vessel that represents a strong catalyst for this green shipping transition in the Pacific Region is the SV Kwai (see Figure 4.2), a 179GT converted fishing vessel which undertook charters between Hawaii and remote locations such as Kiribati, Cook, or Christmas Islands. Given the available data provided by the USP counterparts and SV Kwai senior captain Brad Ives, it was decided to pursue this vessel as a reference for the methodology. Thus, in the following section, an analysis of the available ship's logs, routes, and fuel savings will be conducted.

4.2. VESSEL INFORMATION AND DETAILS

Supplying remote islands in the Pacific regularly is challenging for many companies. Most opt for profitable charters with container vessels in big ports rather than miscellaneous cargo for smaller communities. Nevertheless, where other companies struggle to deliver, SV Kwai(Figure 4.2) comes in, filling the supply gap while keeping with low emissions and fuel consumption and while operating efficiently, despite the old age of the vessel.

SV Kwai was built in the 1950s and then acquired from the Norwegian fishing fleet by Island Ventures Ltd and used for 14 years [71]. The dimensions of the vessel are presented in Table 4.1 and the general arrangement can be seen in Figure 4.3. As of 8th of January 2021, the vessel was sold to the Republic of Marshall Islands, where she will continue her shipping mission across the local region.

Figure 4.2: Sailing Vessel Kwai[70]

Table 4.1: SV Kwai parameters

Dimensions	Value	unit
LOA	43	m
B	7.12	m
T	3.2 m	m
Dwt	280	t
Gross tonnage	179	t

To better understand the SV Kwai operational profile and overall performance, a discussion was initiated with Brad Ives, former captain, and owner of the SV Kwai, on 31.03.2021, and Dr. Austin Kana and Andrew Irvin. This meeting provided valuable information about the fuel measurements, charters, vessel retrofits, and opportunities for future WASPs in the region.

The vessel was initially purchased for a price of around US$700,000. However, in order to adapt to make it profitable, the owners decided to retrofit the vessel with sails, thus installing a full mainmast, a bowsprit, and a mizzen[12]. Asked about the possibilities of further retrofits, captain Brad Ives acknowledged that the vessel's age would be the most significant impediment, followed by the lack of space. Besides minor adjustments to the rig system, conversion of the engine to an alternative fuel would be close to impossible. The vessel has enough space in the cargo holds to transport various products and materials, ranging from bulk loads such as copra and seaweed to store goods or even cars. According to their website, these charters were profitable enough to sustain the OPEX of the vessel, especially since she would mostly run on sails, thus saving up to 60% fuel in good weather.

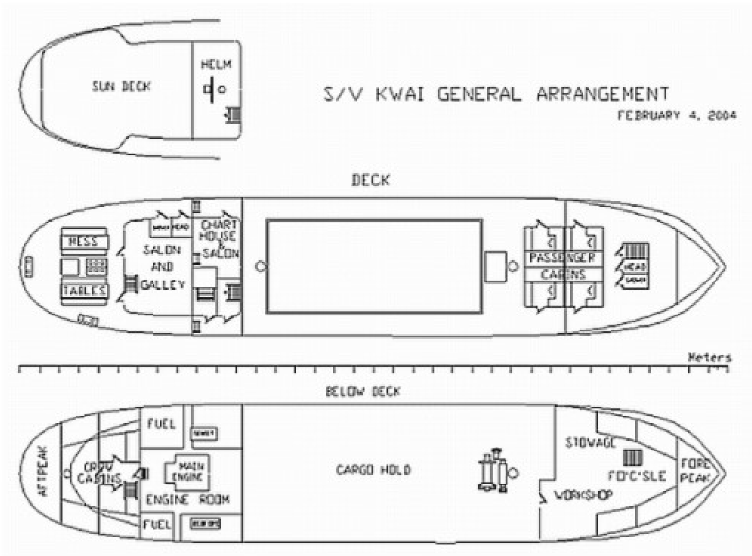

Figure 4.3: SV Kwai general arrangement[70]

4.3. RELEVANT DOCUMENTATION

For a more comprehensive analysis of SV Kwai, several documents were obtained from captain Brad Ives: ship logs from 2010 to 2020, fuel data and trip reports for 2020 and 2017 voyages, and cargo load overview for 2020 and 2017 trips. These documents represented the primary documentation source for understanding the operational vessel profile, frequency of routes between islands, fuel estimates, engine-sailing balance load, and validation of the workability of the designated tool. A detailed description is provided for each document to highlight the type of relevant information extracted.

Ship logs

The ship logs from 2010 to 2020 are a collection of annual ends of the year documents compiled by captain Braid Ives. These contain summaries of the number and type of charters, unforeseen circumstances, refitting history, cargo operations, trading rates, and financial figures. Each document concludes with a table of Profit and Loss statements. An average of the number of contracts and charters that the vessel takes yearly has been estimated from these logs. Also, the detailed profit and loss statements and their figures have proved to be the most useful in determining ship finances to calculate the economic parameters for the tool.

Fuel data and trip reports

These reports contain more detailed and specific information related to each trip of an entire voyage. This includes ports, times of arrival and departure, stand-by time, miles run, fuel burned underway and while stationed, and cargo loaded. On top of that, these reports also account for unforeseen circumstances that influence the delay or shortening of a journey. Moreover, the authors have also noted the number of hours and fuel consumption. At the same time, sailing, motor sailing, or motoring in various weather conditions provided a deeper insight into the vessel's operational profile.

Cargo Load overview

The cargo load overview is a detailed rundown of each trip which displays the weight and volume of each transported cargo. Thus, for all the ports, the document provides what type of cargo was loaded and which was unloaded. This data has been used for the economic parameters where profit was calculated based on the amount of cargo transported. Also, for the social parameters, it aided in approximating the number of essential resources that the vessel transported to cover an x percentage of the needs of the local inhabitants.

4.3.1. VOYAGE 55 AND VOYAGE 39 DETAILS

For a more comprehensive analysis of SV Kwai, an evaluation document was obtained from captain Brad Ives for four months during 2017 and another four months voyage in 2020. This contains information regarding the voyage routes, schedule, and fuel consumption. Both voyages are then compared for similarities to understand the vessel's operational profile.

4

VOYAGE 39

A detailed overview of the charters for the given period can be seen in Table 4.2

Phases of the voyage[1]

Table 4.2: SV KWAi voyage data

	Route	distance[Nm]	fuel c.[ltrs]	duration[hrs-d]	ASC[ltrs/Nm]
1	HNL-CXI	1148	1254	181-7.5	1.1
2	CXI-WA-CXI	768	3582	115.5-4.8	4.67
3	CXI-PEN	610	2320	109-4.5	3.8
4	PEN-PUK	478	3758	78.5-3.3	7.8
5	PUK-FA	957	3980	167-6.96	4.16
6	FA-WA-CXI-FA	596	2770	95-3.96	4.65
7	FA-HNL	1034	3925	156-6.5	3.8
Total		5591	21569	902-37.6	4.28

Fuel savings

One drawback in this analysis is the accuracy of the extracted data for fuel consumption. Because no advanced fuel sensors were installed on the fuel pumps, precise data gathering could hardly be performed. As a result, the calculation is influenced by different errors of measurements (sounding by dipstick, the impossibility of evaluation of fuel consumption per engine, list during measuring, different sea modes). In this work, a sensitivity analysis on sailing time based on various weather conditions can account for the fuel fluctuations present in the fuel report. Such a sensitivity study is further conducted in Chapter 7

[1] Abbreviations: HNL-Honolulu; CXI-Christmas Island; WA-Washington Island; PEN-Penrhyn; PUK-Puka Puka; FA-Fanning Island; fuel c.-fuel consumption; ASC-average specific consumption

Nevertheless, the established data gives an understanding and perspective on what alternative propulsion methods can benefit the ship's owners and environment. The given fuel report contains a comparison between a scenario in which no sails are used at all and one in which the sails are used in their typical operational profile. In Table 4.3 and Table 4.4, the fuel consumption for these two case scenarios is calculated for inter-island and sea passage routes.

Table 4.3: SV Kwai fuel savings on inter-island routes

	Route	distance[Nm]	fuel c.[ltrs] Original	fuel c.[ltrs] Calculated	duration [hrs-d]
1	HNL-CXI	1148	1254	5430	181-7.5
3	CXI-PEN	610	2320	3270	109-4.5
5	PUK-FA	957	3980	5010	167-6.96
7	FA-HNL	1034	3925	4680	156-6.5
	Total	5591	11479	18390	969-40.38

Table 4.4: SV Kwai fuel savings on sea passage routes

	Route	distance [Nm]	fuel c. [ltrs] Original	fuel c.[ltrs] Calculated	duration [hrs-d]
2	CXI-WA-CX	768	3582	4958.42	115.5-4.8
4	PEN-PUK	478	3738	3370	78.5-3.3
6	FA-WA-CXI-FA	596	2770	4078	95-3.96
Total		5591	10090	12406	289-12.04

The following data is then used to approximate the operational profile and fuel consumption between inter-island and sea passage sailing scenarios.

VOYAGE 55

Voyage 55 was the last voyage of SV Kwai before it was sold to the Republic of Marshall Islands and lasted roughly three months between 2020 and 2021. Captain Ives provided an Excel sheet which contains various information regarding the operational profile and trading. From the 86 days spent at sea, the following details were extracted:

- Operational profile

  -Sailing: 92 hours

  -Motor sailing: 320 hours

  -Motoring: 115 hours

  -Motoring in Lagoons/drifting: 135 hours

- Fuel consumption

  -Sailing: 0

  -Motor sailing: 6,400 liters

-Motoring: 3,450 liters

-Motoring in Lagoons/drifting: 4,050 liters

-Electrical generation: 800 liters

-Cargo gear: 1,500 liters

- Cargo estimates:

  -Outbound cargo: 1,265 m^3

  -Inbound copra: 1,296 m^3

  -Inbound Cargo: 25 m^3

  -Total cargo moved: 2,586 m^3

- Miles run: 3,630 nautical miles

4.4. OPERATIONAL PROFILE

The sailing conditions in the South Pacific ocean are challenging for the local maritime sector. Thus, vessels servicing remote islands have to adjust their speeds based on heavy winds, harsh weather conditions, and big waves. It is even harder for sailing boats operating on a schedule dependent on gusts of wind to make it to their destinations. This makes the operational profile of such vessels unique from the traditional operational profiles devised for more traditional fossil fuel running cargo vessels. SV Kwai is thus no exception in this case, and the trip logs altogether with the fuel reports display some relatively new challenges that a cargo vessel is facing.

From the relevant documentation, it is understood that the main modes of operation for SV Kwai are: port loading/unloading, mooring, sailing, motor sailing, and motoring. However, as noted in the fuel report, the fuel consumption for these modes varies greatly between sea passages, inter-island transportation, and lagoon navigation. The following conditions are thus explained. Sea passages refer to the navigation in open sea routes, which favors the use of sails and in which the weather conditions allow to reach a cruise speed of 6 knots and sometimes up to 10 knots without the use of main engines. Inter-island passages are routes between islands. The wind conditions are less favorable for wind sailing and are used instead as auxiliary means of propulsion to take some load off the main engine. Lastly, navigation in lagoons is the profile in which the primary propulsion is through motoring or motor sailing due to the drifting of the vessel, which increases the usage of auxiliary engines on board. In that regard, the inter-island and lagoon navigation are similar, except for a slight increase in fuel consumption. For ease of calculation, only sea-passage and inter-island profiles will be considered since motoring in lagoon only happens in exceptional circumstances. In contrast, the first two are almost the case for every trip. As a result, the tool will include a special section for motoring in the lagoon to be added.

With these details in mind, it can be seen that the complexity of the operational profile increases. As a result, it complicates the chain of calculation for the propulsion. On top of that, the trip documentation provides navigation hours for the sailing, motor sailing, and motoring times; however, these are not precisely specified for the sea passage or inter-island conditions in all trip documentation. Only one trip from 2017 provides such details. Nevertheless, an estimation can be derived from these numbers, and a pattern can be created.

According to the estimation of the report author, the following item ratios have resulted between sea passage and inter-island travel.

Ratio. The sea passage to inter-island ratios are calculated. These are an indication of how much transit time, fuel and distance covered difference difference there is between the two sailing profiles.

- transit time is 2,12:1
- fuel consumption is 1,38:1
- distance is 2,04:1

By comparing the ratios, it can be observed that although double time was spent during long sea passages, the amount of fuel in total in the inter-island trades is slightly less than in the sea passages. Captain Brad Ives notes that the main reason is the three running diesel engines (electricity, propulsion during drifting, hydraulic for cargo crane). A second reason for this is the busy charter schedules that needed to be done to make profits.

Based on the information provided by captain Brad Ives, it was found that in order for the vessel to follow its tight schedules, the operating cruise speed should be in the range of 5 to 6 knots in any operation mode. In almost ideal conditions, top speeds using sails of almost 10.5 knots have been reached. However, for motor sailing and motoring, the cap has been set to only 6 knots due to the limitation of the engine (see details in Chapter 7).

5

TECHNICAL CALCULATION

As previously described in the Methodology in Figure 3.5, two system categories will be analyzed: the sails and the diesel engine. These systems are broken down and the impact pressure categories are calculated: propulsive efficiency, thrust, fuel consumption, energy consumption, exhaust gases, contaminants and power load.

5.1. SAILS

In this section, the first system category of the Operational Cycle Impact Assessment(Figure 3.5) will be analyzed and calculated following the calculation flow presented in Figure 5.1. First, an aerodynamic study for sails is performed to calculate the maximum potential of wind power in sailing and motor sailing conditions for a given sail area. Next, this preliminary performance study is conducted using a prediction model applied to the sail configuration of the SV Kwai. The resulting aerodynamic parameters are then paired with the diesel propulsion data to find the optimal balance for fuel consumption, prioritizing the use of sails. Finally, the results are verified from an operational profile standpoint with information from the voyages detailed in Section 4.3.

5.1.1. SAILS TYPE

As previously mentioned in Chapter 2, SV Kwai possesses a hybrid propulsion capability. This means that the main engine is aided in propulsion by using a sails configuration by taking some of the engine load and sometimes relying solely on plain sailing. However, the weather is not always favorable for sailing. Even if it is, factors like wind speed and wind direction will influence the capability to use sails for a specific route. Thus, the use of sails is a complex problem, and the total efficiency and additional thrust gained from it is challenging to predict because of two factors: primarily because of the unpredictable nature of the weather and secondarily from an engineering perspective, because of the rig-wind interaction on various apparent wind angles.

In this thesis, the Hazen model for the rig and soft sails aerodynamics will be used. This is a model developed by G Hazen in 1980 in "A model for of sail aerodynamics for di-

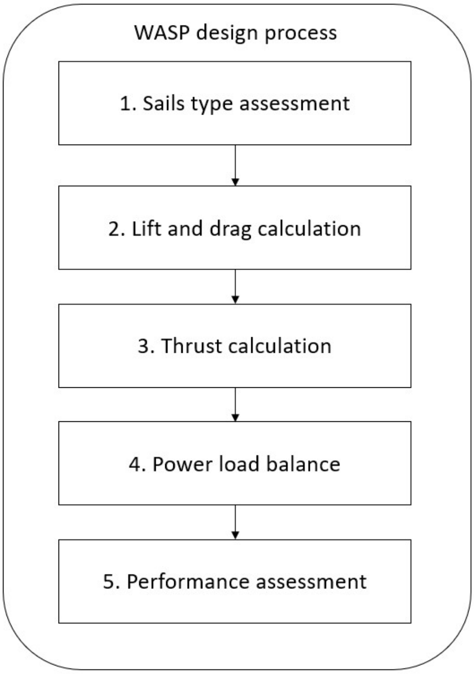

Figure 5.1: Sails flow calculation [72]

verse rig types". The paper however is under embargo, but a practical calculation model was found in the "Principles of Yacht Design" by Larsson and Eliasson [72]. This includes the original model calculations and parameters estimations. On top of that, the authors bring additional improvements and updates to the calculation to fit with 21^{st} century sail boats. The model is crude but application proof considering that it has been used the framework for various Velocity Prediction Programs such as the IMS handicap system. It provides a good insight into the aerodynamic performance of soft sails and thus, can be used an early stage design tool for assessment which is what is needed for the scope of this work [72].

The first step of the analysis consists of identifying types of sails. This calculation model predicts sails' performance, typically having the following components: mizzen, mizzen-staysail, mainsail, foretriangle jib, and spinnaker. These results in a multitude of configurations depicted in Figure 5.2 which can be analyzed.

Looking at the sails plan of SV Kwai presented in Figure 5.3 it can be seen that arrangement 1B fits the SV Kwai configuration and therefore the Hazen model can be applied.

In its current state, SV Kwai has the following sail types: main, mizzen, main topsail, staysail, jib, flying jib, mizzen staysail one, and mizzen staysail 2. However, Hazen's model does not account for all types of adjacent sails to the main ones, and only the primary classic sails components are considered. As a result, some slight modifications

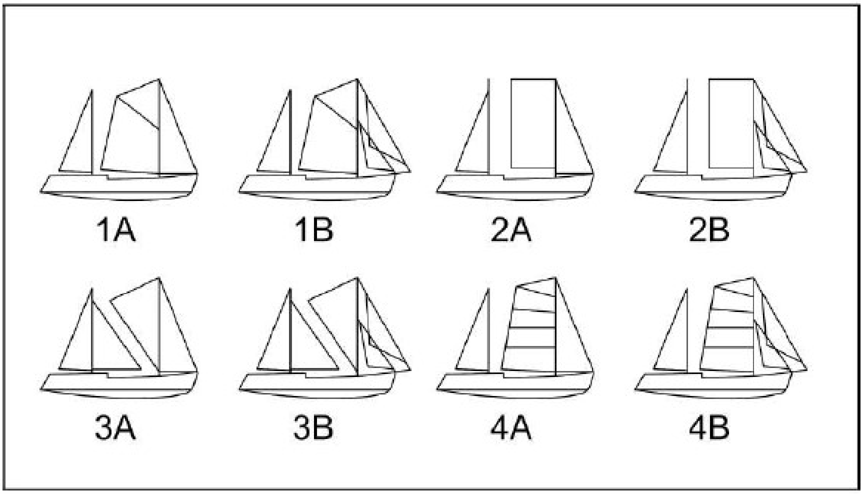

Figure 5.2: Sails configuration [73]

to the calculation are made to fit this model described in the previous paragraphs.The mainsail and main topsail are integrated under the same mainsail area coefficient due to similarity and positioning. On a similar note, the jib and flying jib are also joined and calculated together. Lastly, the two mizzen staysails are summed up and calculated under the same coefficient. With all due considerations, the sail areas per rig component are presented in Table 5.1.

Table 5.1: Sail components dimensions

Sails type	Nominal sail area[m^2]	Type of coefficient used
Main sail area	165	A_m
Mizzen sail area	77	A_y
Jib sail area	112	A_j
Mizzen staysail area	80	A_{ys}
Total sail area	434	A_{total}

Besides the sail surface areas, there are several other rig components which play an important role in the calculation and are presented in Table 5.2

The Assumed parameters in Hazen's model
CE = Centre of effort from ordinate 0[m]
EHM = Mast height above sheer [m]
BMAX = Maximum beam [m]
FA = Average freeboard [m]
EMDC = Average mast diameter [mm]

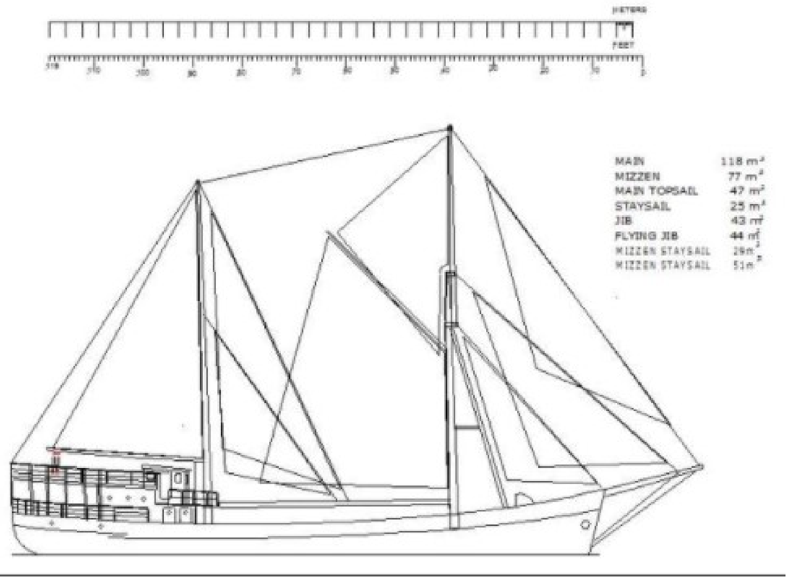

Figure 5.3: SV Kwai sails plan[70]

With this sail configuration and sail areas, the following calculation is performed for the calculation of lift and drag coefficients.

5.1.2. LIFT AND DRAG CALCULATION

In sailing, lift and drag are the principal components that form the total aerodynamics of a sail. Lift usually occurs on sails that act as airfoils and are perpendicular to the air stream (apparent wind velocity). In this sense, the lift results from the pressure difference between leeward and windward surfaces and are heavily influenced by the angle of attack, sail shape, and apparent wind speed. Generally, the lift effect can only be used in angles of attack of up to 40 degrees for regular sails and 30 degrees for advanced wing sails [74]. Drag, on the other hand, occurs when the angle of attack increases by sail trimming. Sails that operate with the apparent wind angle behind them (downwind sailing) make use of the drag force [75].

The calculation of lift and drag coefficients has two purposes for the present work. First and foremost, these coefficients will enable the calculation of the thrust force generated by the use of sails for various wind speeds and give an insight into how much power load it can take off the engine in motor sailing conditions. Second of all, the coefficients can be further interpolated and expanded into the Side force and Driving force factors which are dimensionless parameters used for the performance prediction of the sails. In the following paragraphs, the lift and drag calculations are further explained.

Hazen's model calculates the coefficients for five apparent wind angles: 27, 50, 80, 100, and 180. For each individual sail area mentioned in Section 5.1.1, Hazen defines sail

Table 5.2: Measured parameters of other rig components

Parameter	Value	Details
EHM	26m	Mast height above sheer Derived from sail plan
Bmax	7.1m	Maximum beam Main dimensions from general arrangement
FA	2m	Average freeboard Difference between depth and draft
EMDC	250mm	Average mast diameter Round diameter assumption

coefficients for lift and drag in every aforementioned apparent wind angles as presented in Tables 5.4 and 5.3 [72].

Table 5.3: Sail coefficients for drag [72]

Apparent wind angle [deg]	Main (Cl_M)	Jib (Cl_J)	Mizzen (Cl_Y)	Mizzen staysail (Cl_{YS})
27	1.5	1.5	1.3	0
50	1.5	0.5	1.4	0.75
80	0.95	0.3	1	1
100	0.85	0	0.8	0.8
180	0	0	0	0

Table 5.4: Sail coefficients for lift [72]

Apparent wind angle [deg]	Main (Cd_M)	Jib (Cd_J)	Mizzen (Cd_Y)	Mizzen staysail (Cd_{YS})
27	0.02	0.02	0.02	0
50	0.15	0.25	0.15	0.1
80	0.8	0.15	0.75	0.75
100	1	0	1	1
180	0.9	0	0.8	0

The sail dimensions presented in Table 5.1 and 5.2 are then plotted for the calculation of lift and drag coefficients. Equation 5.1 calculates the nominal sail area. Equation 5.2 provides the lift coefficient for a designated apparent wind angle. Equations 5.3, 5.5 and 5.6 give the viscous drag, induced drag, and the drag of the mast and topsides. The final drag coefficient is the summation of the three drag coefficients added in equation 5.7.

$$A_n = A_F + A_M + A_Y \tag{5.1}$$

$$C_l = \frac{1.15 * Cl_M * A_M + Cl_J * A_J + Cl_Y * A_Y + Cl_Y * A_Y + Cl_{YS} * A_{YS}}{A_n} \tag{5.2}$$

$$C_{DP} = \frac{Cd_M * A_M + Cd_J * A_J + Cd_Y * A_Y + Cd_Y * A_Y + Cd_{YS} * A_{YS}}{A_n} \tag{5.3}$$

$$AR_{other\ course} = \frac{(1.1 * EHM)^2}{A_n} \tag{5.4}$$

$$C_{DI} = C_L^2 * \left(\frac{1}{\pi * AR} + 0.005\right) \tag{5.5}$$

$$C_{DO} = 1.13 * \frac{(BMAX * FA) + (EHM * EMDC)}{A_d} \tag{5.6}$$

$$C_{drag} = C_{DP} + C_{DI} + C_{DO} \tag{5.7}$$

Where,
$A_n =$ Nominal sail area $[\mathrm{m}^2]$
$C_l =$ Lift coefficient [-]
$C_{DP} =$ Viscous drag coefficient [-]
$C_{DI} =$ Induced drag coefficient [-]
$C_{Do} =$ Drag of mast and topsides coefficient [-]
$C_d =$ Drag coefficient [-]

By interpolating the results, spline interpolation is plotted as shown in Figure 5.4. The chart was created using the series formula in Excel. This was done for both lift and drag coefficients and then compared against each other. This trend line provides an insight into the behavior of this sail configuration in various wind angle conditions.

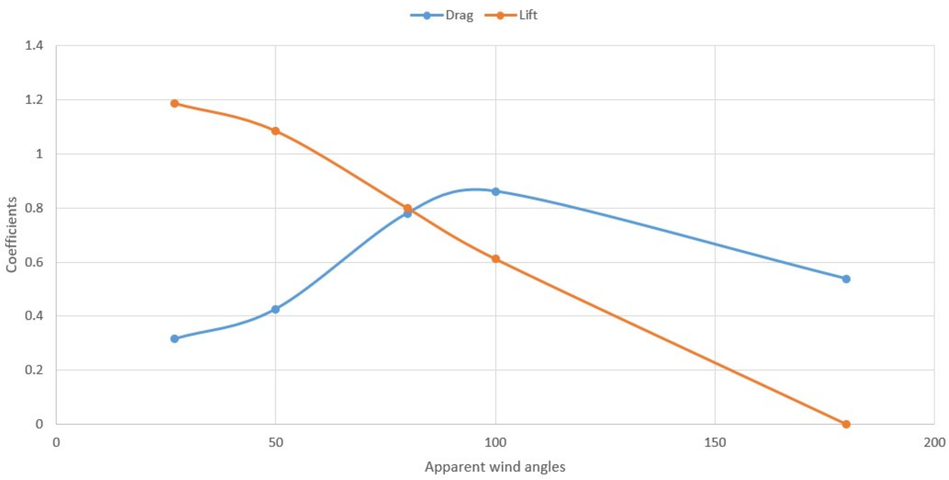

Figure 5.4: Lift and drag coefficients

It can be noted that the behavior of drag and lift is quite different for various apparent wind angles and only intersects around 80 degrees. When sailing downwind, the primary force is the drag, whereas, in upwind conditions, lift force intervenes [75]. The classic soft sails are best suited for downwind sailing to catch as much wind as possible at angles of attack larger than 90 degrees. This stems from the fact that the momentum flux is closely similar to the drag force because it acts in the same direction as the wind force and thus dominates at large angles of attack [76]. The momentum flux permits sailing upwind by projecting the wind force into the sail direction. However, this makes the sailing much more difficult as the boat has to maneuver in large zig-zag directions to generate the required lift . Figure 5.5 depicts the areas favorable for sailing in terms of wind direction and enforces the argument of the predominant use of drag force in sailing for the reference current vessel calculation.

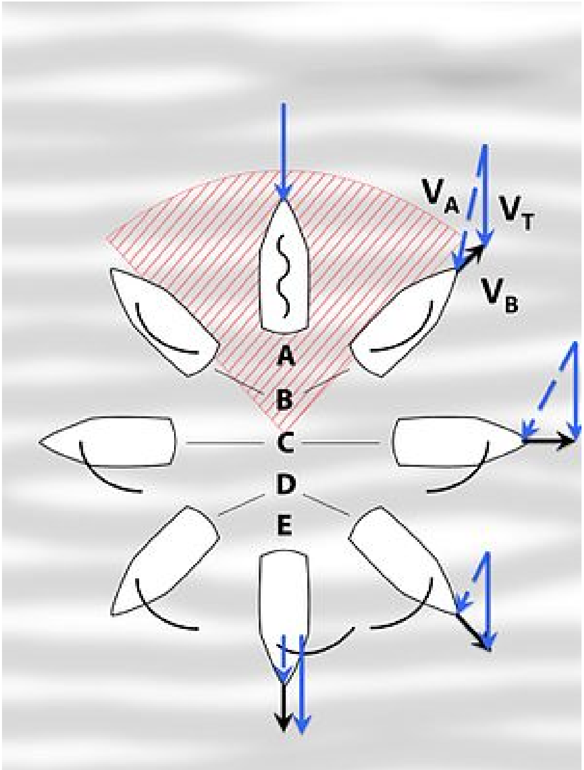

Figure 5.5: Sails angle of attack[77]

5.1.3. SAILING ENVIRONMENT

Before diving into the calculation of the actual thrust delivered by the sails in various operational conditions, an important note is to be made about the wind conditions and potential in the area. However, the estimation of average wind speed and wind direction is strenuous and challenging due to various factors such as weather, temperature, and height. Therefore, the recordings have been made from the consulted sources.

The first study concerns the assessment of wind resources in the South Pacific region to develop wind turbines. The study was conducted in the islands of Tonga and its surrounding regions. These islands were frequently serviced by SV Kwai and thus can provide a reasonable estimate for the potential of sailing wind speed. The data presented in Figure 5.6 for various heights over a year [78].

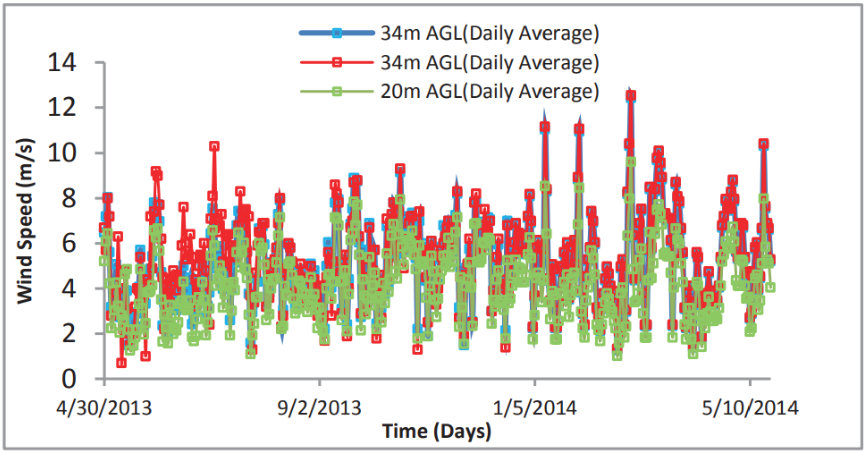

Figure 5.6: Average wind speed estimate, Tonga territory 2013-2014[78]

For the case of a sailing vessel, the most relevant wind speed estimates are the ones that are recorded as close to the water surface as possible. This study's range of height recordings is from 20 to 34 meters. Thus, the average point of recording is set as an average between 20 and 34 meters. The reason for this height choice average is because of the mast height of 26 meters (Table 5.2). It is assumed that at this height, the rig can harness the full potential of the wind. Over a year, the average wind speed has been identified at 6.5m/s, translating to approximately 12.5 knots. A similar study performed in Fiji in the islands of Kadavu and Suva has identified a similar situation with an annual average of 7 m/s (13.6 kn). In both cases, the peak periods of maximum values, excepting the typhoon seasons, reached wind speeds of up to 10.5 m/s (20.41 kn) and minimums of 0.5 m/s (0.97 kn)[79].

5.1.4. POWER LOAD BALANCE IN MOTOR SAILING CONDITION

Motor sailing is the operational mode of the vessel in which sails generate part of the delivered thrust force in addition to the already running diesel engine. As stated in Section 4.4, motor sailing primarily happens in atolls and lagoon areas where wind conditions do not allow for the use of full sailing. Looking at the values displayed in Figure 5.6 and Table 5.5 concerning the wind speed potential and the thrust generation for various wind speeds, a conclusion can be drawn about the proper sailing environment for motor sailing mode.

The calculation logic is as follows. First, the overall necessary thrust was calculated in Section 5.2.2. Then the available thrust force generated by sails for various wind speeds is calculated in Section 5.5. A final necessary thrust is then calculated by deducting the thrust provided from sails from the overall generated thrust by engines for a particular speed. Finally, following the power chain calculation again, the necessary brake power is recalculated with the new values for the motor sailing condition. However, a few remarks need to be made. The load balance between engine and sails is not always a 50/50 ratio since the wind speed almost always shifts. However, according to the "Modern-day Motorsailer" [80], a rule of thumb for the usage of sails in motor sailing conditions is 30/70, 50/50, and 40/60.

5.1.5. PERFORMANCE PREDICTION

Thrust calculation

Before identifying how much the sails can take off the engine load, the next step is to calculate the actual thrust delivered by this sail configuration. As it has been previously mentioned in Section 5.1.2, for this sail configuration, the predominant force acting on the sails is the drag force which also generates the thrust of the vessel only when primarily sailing downwind. Also, the current aerodynamic design of the sails provides more favorable propulsion in downwind sailing, in which drag forces act. Predominant sailing in lift force condition are thus not a viable option for, as it can be seen in Figure 5.4 because they either fall within the "No go zone" or the angle is too small for the SV Kwai's rig system to make use of as previously explained in Section 5.1.2.

Considering the range of 27 to 180 degrees model, the drag force will be predominant in angles higher than 80 degrees whereas lift plays a more important role in the smaller angles. Nevertheless, overall thrust, driving force and side force are a combination of both lift and drag coefficients but on different proportions.

The formula used for this calculation are 5.8 and 5.9.

Table 5.5: Sails generated thrust

Wind speed [m/s]	Average thrust [kN]
5	4.57
6	6.58
7	8.95
8	11.69
9	14.80
10	18.27
11	22.10
12	26.31
13	30.87
14	35.80
15	41.10
16	46.77
17	52.79

The lift and drag coefficient results can then be used for further assessment in performance prediction. The core relationship between lift, drag, side force, and driving force can be seen in Figure 5.7. Lift and Drag forces are calculated. These are further used as thrust force to calculate the total thrust power delivered by the sails and are approached in a separate section.

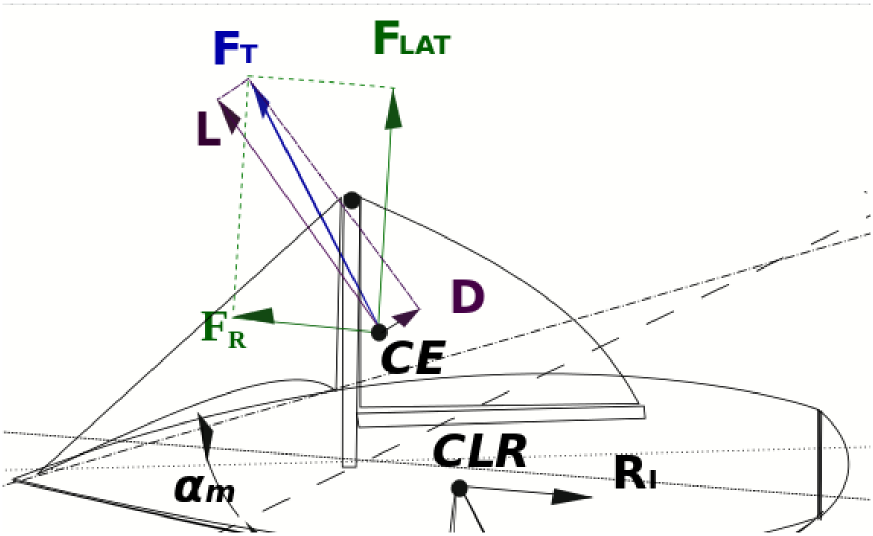

Figure 5.7: Aerodynamic force components [81]

$$L = 0.5 * \rho * V_a^2 * A_{total} * C_l \tag{5.8}$$

$$D = 0.5 * \rho * V_a^2 * A_{total} * C_d \tag{5.9}$$

where
$L =$ Lift [N]
$D =$ Drag [N]
$\rho_a =$ Density of air $[\text{kg/m}^3]$
$V_a =$ Flow velocity [m/s]
$A_{total} =$ Sail area $[\text{m}^2]$

Another measure of performance for sails is through the Side force and Driving force coefficients. These are corresponding forces for lift and drag and decomposed from the total aerodynamic force. The driving force is the component that overcomes resistance to forwarding motions. In contrast, the side force is the lateral component that creates a heeling force but has to overcome resistance from appendices such as the keel, blade, or wheel. With the previously calculated lift and drag coefficients, formulas 5.12 and 5.15 provide the values for the drive, and side force coefficients [72]. Similarly, these coefficients are calculated for the same apparent wind angles as the last lift and drag coefficients.

$$A_S = A * (C_l * \cos(\alpha) + C_d * \sin(\alpha)) = A * A_{SP} \tag{5.10}$$

$$A = 0.5 * \rho * V_a^2 * S \tag{5.11}$$

$$A_{SP} = C_l * \cos(\alpha) + C_d * \sin(\alpha) \tag{5.12}$$

$$A_R = A * (C_l * \sin(\alpha) - C_d * \cos(\alpha)) = A * A_{RP} \tag{5.13}$$

$$A = 0.5 * \rho * V_a^2 * S \tag{5.14}$$

$$A_{RP} = C_l * \sin(\alpha) - C_d * \cos(\alpha) \tag{5.15}$$

where
$A_S =$ Side force [N]
$A =$ Calculation factor [N]
$A_{SP} =$ Side force factor [-]
$A_R =$ Driving force [N]
$A_{RP} =$ Driving force factor [-]

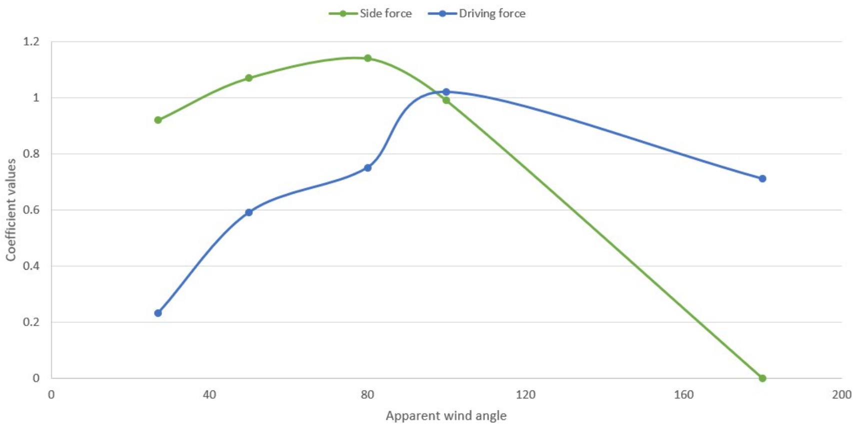

Figure 5.8: Side and driving forces

In Figure 5.8, the results of the calculation are depicted. The figure indicated that the dominant is the driving force for this sailing configuration that acts best in a downwind sailing condition. This stems from the fact that the direction of travel is more aligned with the wind, decreasing the lateral force.

5.2. POWER PLANT DESIGN

In this sub section, the second system from the Operational Cycle Impact Assessment (see Figure 3.5) is analyzed. The calculation flow for the power plant is inspired by the MAN Solutions engine design diagram and the calculation chain described in Power

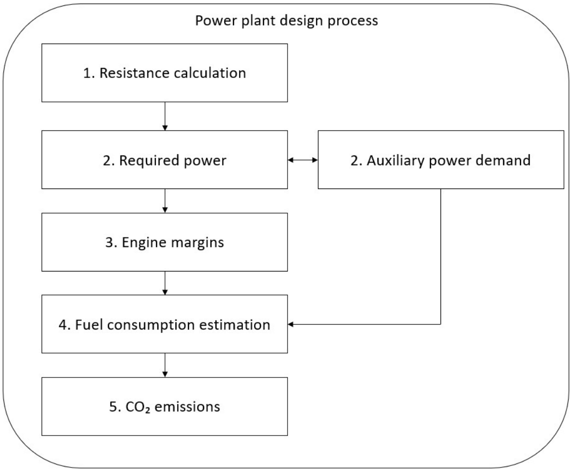

Figure 5.9: Power plant design steps[82][83]

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plant design by Klein Would and Stapersma [82][83]. Thus, the following steps from Figure 5.9 will be followed in this first part of the technical section.

Based on the operational profile described in Section 4.4, the speeds per operational profile are set.

5.2.1. RESISTANCE CALCULATION

For the calculation of the power plant capacity, the first stage is to calculate the total resistance of the vessel. Resistance is one of the most critical indicators for selecting an engine concerning its power capacity, size, and type.

A CFD analysis is not well suited for this project; too complex and time-consuming for an early-stage design prediction tool. A more straightforward computational method was needed, which can be integrated into the Excel tool and yield instant results. Thus, an empirical method was used, such as the Holtrop Mennen method. This method is fitting for regular displacement cargo and container vessels with U-shaped hull. Looking at the SV Kwai transverse section, it can be observed that it fits the standards for the Holtrop Mennen method. For ease of calculation, an academic Java tool developed at "Dunarea de Jos" University of Galati was used, which calculates the total hull resistance of a vessel [84]. In order to calculate the resistance, a series of hull and appendage parameters are needed. The data for calculation is presented in Figure 5.10

Due to lack of data from the original Kwai design documentation, additional coefficients had to be calculated with Formulas 5.16-5.20

$$C_m = \frac{A_m}{B * T} \tag{5.16}$$

$$C_b = \frac{\nabla}{L_{wl} * B * T} \tag{5.17}$$

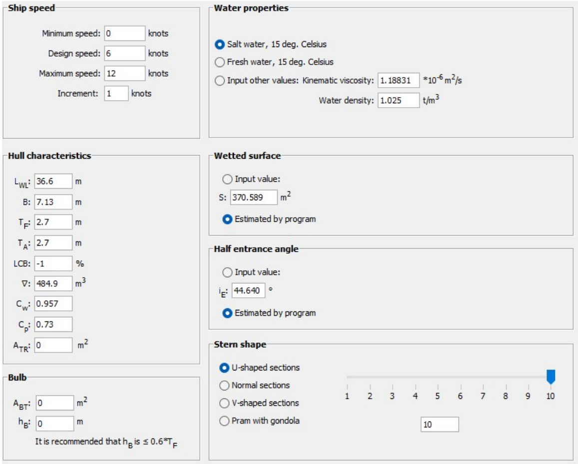

Figure 5.10: Resistance calculation

$$C_p = \frac{C_b}{C_m} \tag{5.18}$$

$$C_{wp} = \frac{A_{wp}}{L_{wl} * B} \tag{5.19}$$

$$L_{cb}\%\ of\ L_{wl} = \frac{100 * L_{cb}\ position - L_{wl}/2}{L_{wl}} \tag{5.20}$$

After compiling all this data together, the software calculates the resistance. The range of speeds to resistance is from 0 to 12 knots due to the ability of the vessel to sail at top speeds. The results cans are seen in Figure 5.11. Considering the operational profile defined in Section 4.4, it can be seen that for a cruising speed of 6 knots, a total of 6.5 kN is identified. With higher speeds, the resistance increases exponentially, and a sharp rise can be seen between 7 and 11 knots.

Even though the engine is not expected to perform at speeds as high as 11 knots, the calculation includes the full-sailing scenarios. According to Captain Brad Ives, in almost ideal calm water and high-speed wind conditions, the SV Kwai was able to reach as much as 10.5 knots hull speed [85]. For additional verification, a comparison was made with the Greenheart project model. The model designed in the Greenheart project is similar in hull dimensions to SV kwai. Thus the resistance calculation has similarities to some extent as well. For the Greenheart project, the resistance for speed ranging between 6 to 9 knots is from 6 to 15 kN [38]. SV Kwai has slightly bigger values. The resistance is between 6.5 to 23.4 kN for the same speed range. The difference at higher speed is due to the more significant displacement of SV Kwai.

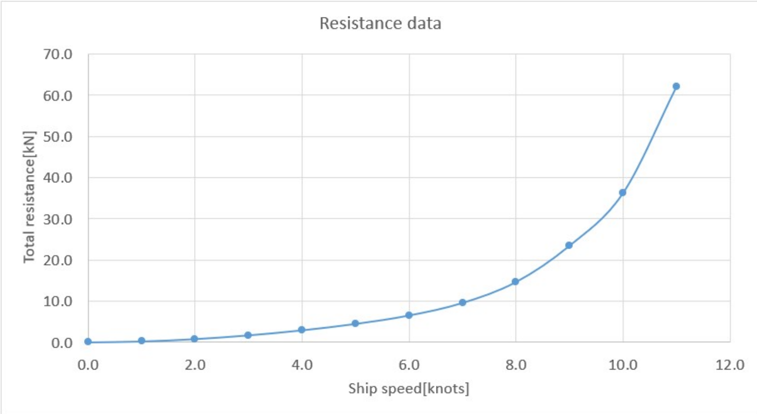

Figure 5.11: Resistance calculation

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5.2.2. POWER CALCULATION

This calculation aims to find the necessary power required to run the vessel in various operational conditions. Estimates can be made based on the power demand regarding fuel consumption and emissions. The calculation chain for the installed power is calculated through empirical methods established by Klein Would, and Stapersma [83]. Calculations are made only for the motoring profile of the vessel. The motor sailing mode is extensively discussed and includes the power balance. Thus, the motoring mode calculation will yield results for the maximum capacity the engine can be operated.

After completing the hull resistance calculation, the adequate power of the vessel can be calculated using the following Formulas 5.21 and 5.22

$$P_E = R \cdot v_S \tag{5.21}$$

From the effective power, the Brake power can be derived as well with:

$$P_B = \frac{P_E}{\eta_D \cdot \eta_{TRM}} \cdot EM \cdot SM \tag{5.22}$$

Propulsion description and additional coefficients

The propulsion of SV Kwai is driven through a single screw propeller configuration. Due to the complexity of the calculus and lack of information regarding the propeller, some assumptions have been made regarding the efficiency coefficients along the shaft line. The calculation of the propeller efficiency is out of the scope of this research. First of all, the rotative and shaft efficiencies have been estimated to be 1 and 0.99, respectively [83]. For the calculation of propeller power, the number of propellers is set to 1. For brake power, the number of engines is set to 1. Even though SV Kwai possesses two additional engines onboard, these are used only for the electric generation of hotel conditions and deck equipment. Finally, the wake and thrust factors have been calculated as 0.183 and 0.173, respectively. This help calculates the hull efficiency as seen in Formulas 5.23 and 5.24.

$$\eta_H = \frac{1-t}{1-w} \tag{5.23}$$

Finally, the propulsive efficiency is calculated in

$$\eta_D = \eta_O * \eta_R * \eta_H \tag{5.24}$$

The final results are an indication of the required power capacity to meet design speed and in sailing and motor sailing in various operational conditions.

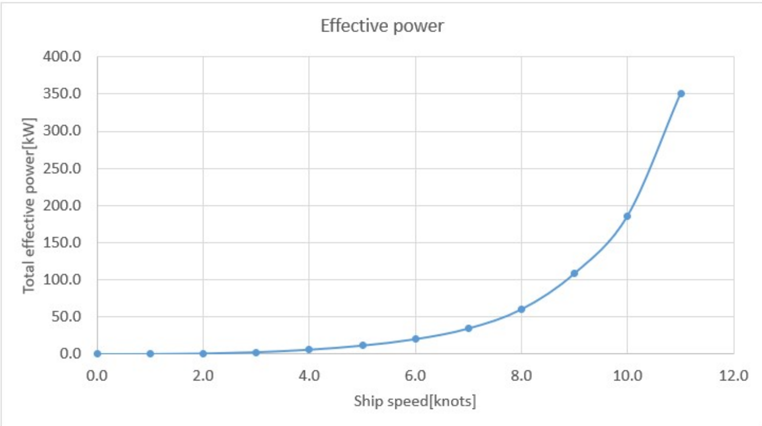


Figure 5.12: Effective power

5.2.3. ENGINE MARGINS

In the design process of an engine, two margins, called, sea margin and engine margin, are added according to the IMO regulations. The sea margin accounts for additional resistance expected from wind and waves and typically lies between 10 and 30%. A similar range is applied for the engine margin because a 100% utilization rate is not desirable and efficient for normal operational conditions. This is because it increases the fuel consumption and emissions drastically [82]. Therefore, a 10% sea margin and a 10% engine margin are applied for the current design. The total engine output is 183 kW. The maximum speed at which the engine can operate safely with the margins mentioned above is 9 knots, at which the engine output is 155 kW.

5.2.4. AUXILIARY POWER DEMAND

In this section, the total energy consumption of the auxiliary generators will be made concerning the operational profile of the vessels. Looking at the documentation provided by Captain Brad Ives, it can be concluded that the auxiliary power generation has a significant influence on the total fuel consumption of the vessel, similar to the engine's running. For example, on trip 39, it can be seen that out of the total fuel consumption over 77 days, approximately 33% is spent only in harbor conditions. Also, fuel consumption information is given for all the sailing and motoring profiles. This includes the fuel used to generate power for auxiliary consumers on board, but no specific data regarding the percentage of the total power demand is given. Considering all these facts, in this section, a breakdown of all the consumers during harbor and navigation will be made to determine precisely what is the typical power consumption just for auxiliary consumers and how these influence the total consumption of the vessel. In order to match the theoretical calculation to the actual power consumption, a first look is given into the existing generators of the case vessel.

Generators data

According to the vessel description, SV Kwai has 3 diesel generators on board with the following specifications:

- Lister Generator- HRW3 26HP- 20kW with a 2kW alternator. This generator ran an average of 4.2 hrs/day
- Mitsubishi Deck generator- 20HP L4S2- 20kW. This generator ran an average of 4.6hrs/day
- Cummins generator 6BTA 5.9 with 160 HP hydraulic pump to power 8HP cargo gear and 5HP Anchor winch. This engine ran while loading and discharging cargo with an average of 2.8hrs/day in harbour

Power by consumer

The power estimation for auxiliary components has been performed for all main operational profiles: harbor, sailing, motoring, and motor sailing. Since the power estimation for the engine has already been performed in Section 5.2.2, the calculation will only display the values of auxiliary consumers during these operation modes. The tool model has a separate section for both auxiliary and engine power demand for the user to understand the vessel energy balance and observe which component of the power plant has a more influencing factor on the overall energy consumption.

The design and calculation of auxiliary consumers is difficult and time-consuming. Therefore an estimation for each consumer was taken from the relevant literature. Additionally, the calculations and research performed in the Greenheart project are also of relevance. The design performed by the BEP group is close in size to SV Kwai, sails in the South Pacific, and has a similar operational profile [38]. Furthermore, Greenheart project authors have identified various consumers for particular conditions in their research. In table 5.6, an overview of the typical consumers for both navigation and harboring conditions are presented.

5.2.5. FUEL CONSUMPTION

Approach

This section will calculate the total fuel consumption for the vessel in the various operational profiles. Thus, fuel consumption is calculated concerning the amount of power spent during a specific time. To better evaluate the ship's fuel efficiency, the fuel consumption is initially calculated for the main propulsion and auxiliary equipment sepa-

Table 5.6: Auxiliary power consumption overview [38]

	Navigation			Harbour		
	Power[kW]	Load factor	24hrs use	Power[kW]	Load factor	24hrs use
Cooling	1.06	1.00	25.44	1.06	1.00	25.44
Freezing	2.12	1.00	50.88	2.12	1.00	50.88
HVAC	18.07	0.30	130.10	18.07	0.30	130.10
Crane	-	-	-	25.00	0.02	12.00
Radar	0.05	1.00	1.20	-	-	-
VHF	0.06	1.00	1.44	-	-	-
CB	0.06	1.00	1.44	-	-	-
Depth finder	0.01	1.00	0.24	-	-	-
Computer	0.07	0.21	0.35	0.07	0.42	0.70
Auto pilot	0.05	1.00	1.20	0.05	-	-
Knot meter	0.00	1.00	0.02	0.00	-	-
Wind speed	0.00	1.00	0.02	0.00	-	-
Bilge pump	0.06	0.08	0.12	0.06	0.08	0.12
Refrigerator	0.06	1.00	1.44	0.06	1.00	1.44
TV	0.30	0.21	1.50	0.30	0.42	3.00
DVD	0.10	0.21	0.50	0.10	0.42	1.00
Satellite rec.	0.14	0.21	0.70	0.14	0.42	1.40
Microwave	0.60	0.08	1.20	0.60	0.08	1.20
Coffee maker	0.50	0.04	0.50	0.50	0.04	0.50
Cabin lights	0.50	0.75	9.00	0.50	0.75	9.00
Total			227.30			236.79

rately. Furthermore, the fuel consumption will be used as an indicator for the emissions release and the ship's finances.

Fuel consumption for SV Kwai has been particularly challenging to calculate due to a series of reasons: engine age, power plant over design, possible inaccuracies in fuel sounding measurements, and difficulty in assessing engine performance in lagoon motoring profile. According to the vessel documents, estimated fuel consumption is given for sailing, motoring, motor sailing, and port profiles. However, as previously stated in Section 5.2.4, the information during the navigation modes includes both propulsion and auxiliary fuel consumption. As a result, the percentages of each primary consumer have to be deduced, and the most realistic pattern for fuel consumption balance was found. This was done by analyzing several trips of equal duration, which included all the aforementioned operational modes in equal proportion. In the analysis, the voyages which were taken into account were the ones that lasted between 70 and 86 days. This is mainly because a voyage lasts, on average, this amount of time, and for this study, these were the only reliable sources of information to use. Trips from 2017 and 2020 were used since they contained the most comprehensive information related to navigation time, time spent in ports, fuel consumption, and assessment for inter-island/sea passage navigation. With all due consideration, the following conclusions have been drawn regarding the fuel consumption:

- On average, out of the total fuel consumed on a trip, roughly 33% is burnt for hotel and loading/discharging operations in ports.
- 45% of the time is spent moored. In this case, the auxiliary engines are used most of the time.
- Fuel consumption is heavily influenced by the sailing environment. Inter-island trade is more fuel consumption than sea passage transits due to the additional electricity generation on board, extra propulsive power during drifting, and tight schedules.
- For the same distance, the fuel consumption in inter-island passage can be 80% higher than sea passage transits.

Calculation

The fuel consumption is calculated with the developed model and then compared with the reported consumption from the ship documents. This model does not follow the standard cross calculation presented in "Design of Propulsion and Electric Power Generation Systems"[83] because that would require additional information about torque, shaft power, and heat input which are unknown. The calculation of these parameters goes beyond the scope of this work. As a result, the choice of fuel consumption calculation was decided to be made as an approximation based on the fuel specifications of the engine. This estimation provides insight into the theoretical fuel consumption of a designated engine and generators when paired with a specific type of sails.

The Detroit 12-71 engine is typically rated at approximately 450 HP (330.9kW), but it only reaches 250 HP(183.9 kW) with the current injectors. In this case, the resources for the engine specification for fuel consumption are not entirely accurate. Thus, a decision has been made to estimate the regression compiled for a range of 250HP engines [86]. A similar case can be made for the auxiliary generators, where information is limited. The reference engine and generators can be seen in Annex B.

Consequently, Formula 5.25 was used to determine fuel consumption:

$$\begin{aligned} Total\,fuel\,consumption = \sum_{sailing} f.cons. * time + \sum_{auxiliary} f.cons * time \\ + \sum_{moored} f.cons * time \end{aligned} \tag{5.25}$$

Given that the most comprehensive information and details have been found on Voyage 39 from 2017, a test case study for fuel consumption has been performed on this particular trip. Pairing the information related to the operational profile, brake power output, and auxiliary energy demand, the following fuel consumption overview has been compiled in Table 5.7

The table presents fuel consumption data for all the operational mode conditions. This detailed breakdown of fuel consumption per operational speed provides a better

Table 5.7: Fuel consumption by operational mode

	Main engines		Electrical gen	
Operational mode	P/P_max[%]	Total[l]	P/P_max[%]	Total[l]
Mooring/Port	0	0	75%	4,784.8
Sailing 6 kn	0	0	90%	130.7
Sailing 8 kn	0	0	90%	130.7
Sailing 10 kn	0	0	90%	29.04
Ms 6 kn	9%	1,869.16	90%	713.05
Ms 8 kn	28%	1,958.17	90%	305.59
M 4 kn	5%	460.98	90%	316.53
M 6 kn	16%	1,936.10	90%	474.81
Sailing 6 kn	0	0	90%	68.46
Sailing 8 kn	0	0	90%	68.46
Ms 6 kn	9%	314.71	90%	120.06
Ms 8 kn	28%	1,538.64	90%	240.12
Ms 9 kn	51%	1,084.04	90%	120.06
M 6 kn	16%	502.03	90%	123.12
M 8 kn	47%	1,075.77	90%	123.12
M 9 kn	84%	1,685.38	90%	123.12
		12,424.98		**7,751.63**

understanding of how efficient the engine is between the sailing, motor sailing and motoring modes. Also, it shows the fuel consumption for various power outputs. The time spent in ports amounts to 40 days, during which roughly 4784.8 liters of fuel are consumed for hotel conditions and cargo loading/discharging. From Sailing 6 knots to Motoring 6 knots, the following items represent the sea passage profile. Here, due to the predominant use of sails for cruise speed, the fuel consumption is much smaller. In sailing conditions, only the auxiliary generators are used. In motor sailing, the sails deliver more thrust, and thus the engine load is significantly reduced, leading to consumption of 8 to 18 l/h. Lastly, there are cases in which pure motoring has to be used to attain the cruise speed of 6 knots.

The total initial estimated fuel consumption from the captain's report is 21,569 liters for a 77 days voyage. With the current model, the total fuel consumption has been estimated to be 20,176 liters. Thus, there is a 5% difference more minor than the original estimation.

5.2.6. EMISSIONS

This section provides the amount of CO_2 emissions for an entire voyage. The CO_2 emissions are a crucial factor in determining the carbon footprint characteristic of the vessel and can be further used to calculate parameters such as EEDI. For the current vessel, the emissions for the main engine and the auxiliary generators are calculated with formulas 5.26 and 5.27. The process of calculation is based on the fuel consumption data previously derived in Section 5.2.5.

Specific fuel consumption:

$$SFC = \frac{Fuel\, consumption * q_{fuel}}{P_B} \tag{5.26}$$

where SFC- specific fuel consumption [g/kWh]
q_{fuel}-fuel density [kg/m^3]
P_B- brake power [kW]
Co_2 calculation

$$C0_2\ emissions\ per\ voyage = SFC * C_f * op.\ mode\ time * P_B \tag{5.27}$$

where $C0_2$ emissions- total emissions emitted [tonnes/voyage]
where C_f is the emissions factor (3.206)
After performing the calculation for each operational profile, the following data results in Table 7.7

Table 5.8: CO2 emissions per operational profile

	Main engines	Electrical	Main engines	Electrical
Operational profile	SFC[g/kWh]	SFC[g/kWh]	CO2[t/voyage]	CO2[t/voyage]
Mooring/Port	0	189.25	0	17.84
Sailing 6 kn	0	175.1	0	0.17
Sailing 8 kn	0	175.1	0	0.17
Sailing 10 kn	0	175.1	0	0.03
Ms 6 kn	442.79	175.1	5.09	0.97
Ms 8 kn	362.01	175.1	5.33	0.41
M 4 kn	493.25	175.1	1.25	0.43
M 6 kn	413.27	175.1	5.27	0.64
Sailing 6 kn	0	175.1	0	0.09
Sailing 8 kn	0	175.1	0	0.09
Ms 6 kn	442.79	175.1	0.85	0.16
Ms 8 kn	362.01	175.1	4.19	0.32
Ms 9 kn	283.17	175.1	2.95	0.16
M 6 kn	413.27	175.1	1.36	0.16
M 8 kn	296.19	175.1	2.93	0.16
M 9 kn	257.59	175.1	4.59	0.16
Total	-	-	**33.85**	**22.05**

The reason why emissions are so high in motor sailing mode is because engine is mostly operating in very low MCR and thus the fuel consumption is high and as a result, increases the emission as well. Also, a consideration has to be made about the over design and age of the engine. For a voyage, SV Kwai can emit a total of 55.8 tones of CO2 per voyage and roughly 220 tones per year.

SO_x emissions

From the specific fuel consumption, the amount of SO_x emmissions can be calculated with formula 5.28. The SO_x emissions are a contributing factor to the human health and does a cap has been imposed for the sulphur content of marine diesel oil. This amount was reduced from 3.5% to 0.5% as of 2020, based on a directive emitted by IMO[87].

$$SO_x = 1.998 * fuel\,rate * (\%\,fuel\,rate\,by\,weight/100) * 1000 \tag{5.28}$$

For the current calculation, the sulphur content of 0.5% will be used. Per voyage, the actual release of SO_x is very small. The main generators emit around 311 grams of SO_x whereas the generators produce just 67.34 grams.

5.3. CONCLUSION

The purpose of Chapter 5 was to calculate the assess the system categories and their subsequent pressure categories. Firstly, an overview of all the important theory, calculations, assumptions and performance characteristics of the vessel's power plant and sails configuration was provided. Section 5.1 introduced the Hazen model with which the total sails thrust is calculated. This is done for a range of wind speeds estimated from weather routing data. The following section presents the resistance calculation and consequently, the power output necessary for various speeds. The auxiliary consumers are estimated as well and thus the whole power plant output is estimated. Finally, the fuel consumption and emissions are calculated and verified. All these pressure categories are further used in the case study for the midpoint impact categories.

6

SOCIAL AND ECONOMIC IMPACT ANALYSIS

The following step of the current methodology from Figure 3.5 is to identify, calculate and analyze the economic and social factors in the midpoint impact category. From an economic perspective, the ship finances of the vessel will ultimately be approached to calculate the price per cubic meter of transported cargo. From a social point of view, a brief analysis of the impact on small local communities will be provided and the impact of such a vessel on regional sustainability policies. The impact on purchasing power and availability for future jobs through fleet increase will be discussed here. The calculations and assessments are intentionally simplified, considering that they represent just a rough estimation for an early-stage design tool.

6.1. SHIP FINANCES CALCULATION

The economic calculation in this section is based on the yearly profit and loss statements and the balance sheets received from Captain Brad Ives. A typical financial document from Island Ventures Limited can be seen in Annex A within the ship finances calculation sheet. A total of ten yearly ledgers have been studied, together with the additional comments and remarks that influenced SV Kwai's revenue over the years. The data from 2017-to 2020 were found to be closest in terms of numbers and results, and thus, the average numbers of these years will be used as entry data in the used formulas.

These calculations and their addition to the tool are to integrate empirical means of financial assessment between various designs. Due to the shortage of time and complexity of a more comprehensive financial assessment, only the ship-related costs will be considered. The four main cost parameters were chosen for this method are[88]:

- CAPEX- costs related to the vessel purchase and building costs
- Cargo handling costs- the expenditure for loading/unloading cargo operations
- OPEX- costs during operation

- VOYEX- all costs related to navigation

These parameters amount to the yearly costs out of which the freight cost is calculated. Consequently, a comparison is made with regional competitors in the area.

Capital expenses

The capital expenses consist of the following parts: the vessel depreciation, loans and the property and equipment. For the current case, CAPEX calculation is simplified without considering any loans for purchase. With these considerations, Formula 6.1 is used

$$CAPEX = PP\&E_{current\,period} - PP\&E_{prior\,period} + Depreciation \tag{6.1}$$

-where

PP and E-change in equipment

The original formula includes depreciation, but it is hard to approximate considering that a regular vessel is scrapped after 30 years and SV Kwai is 71 years old. Therefore, depreciation is calculated for when SV Kwai was sold to the Republic of the Marshall Islands in 2021. The book value, which represents the fixed asset cost, is set to $300 000 as this was the selling price of SV Kwai in 2021. The scrap value can be estimated using a rule of thumb developed in [89]. This is calculated by multiplying $100 with LDT, which is approximated to 25% of the vessel deadweight. With the current state of the vessel, it is approximated that it will be able to perform for roughly five more years before it will be scrapped since the vessel is operating on its limits [85].

6

$$Depreciation\,expense = \frac{Cost\,of\,fixed\,asset - Salvage\,value}{Useful\,life} \tag{6.2}$$

The PP&E for years 2019 and 2020 have not changed and, therefore, will cancel each other. It is left that the total CAPEX for SV Kwai for the year 2020 results in the depreciation, which is $58,615.

Cargo handling costs

Handling cargo in a port can be expensive, especially for harbors and wharves where technology is limited and human resources are the primary source of stevedoring. The cargo handling equation 6.3 considers all the expenses that arise during the loading/unloading process.

$$CHC_{tm} = L_{tm} + DIS_{tm} + CL_{tm} \tag{6.3}$$

-where

CHC-cargo handling costs

L-cargo loading cost

DIS-cargo discharge cost cost

CL-cargo claims

SV Kwai possesses a hydraulic crane on board. This ship design characteristic can significantly reduce this type of expense and can achieve faster and more economical cargo operations. However, this is true in major ports such as Port of Suva, Fiji, or Nuku'alofa, Tonga. In addition, even the mooring conditions are not suitable at the shore for many of the wharves in the tiny Pacific islands. Therefore, cargo delivery is done by dingies.

Considering these limitations, the expenses for cargo handling can reach up to $150,562 per year.

Operating expenses

The operating costs are estimated using formula 6.4 and are calculated on a yearly basis. The manning and maintenance costs are prone to variation due to unforeseen circumstances which could appear because of the vessel age. Thus, these have been estimated from 2020 as a one-off cost. On the other hand, administration and insurance were averaged for the 2017-2020 period, and an approximation was made. An average of $15,000 were spent per year for insurance, and administration was $131,250.

$$OPEX = M_{\text{im}} + MN_{\text{tm}} + I_{\text{tm}} + AD_{\text{tm}} \tag{6.4}$$

-where
M-manning cost
MN-routine repair and maintenance
I-insurance
AD-administration
The total operating expenses per year amount amount to $554,192.

Voyage expenses

The voyage expenses calculated in Formula 6.5 represent the variable costs which occur during a voyage. The fuel costs are calculated in the tool at a price of $0.85 per liter at the time of the calculation [90]. Canal dues and pilotage are not applicable for the case of South Pacific vessels as they don't pass through any canals or straits. The total voyage expenses per year are $72,405.

$$VOYEX = FC_{tm} + PD_{mw} + TP_{mw} + CD_{tm} \tag{6.5}$$

-where
FC-fuel costs of main engines and auxiliary generators
PD-port and light fares
TP-pilotage
CD-canal dues

Average price per cubic meter transported

In Figure 2.2, Section 2, the average cost per shipping unit and cubic meters are presented for various continental-island, and inter-island routes are provided. This shows the prices of competitors which operate in the South Pacific region and navigate with diesel engine container vessels. Because SV Kwai only transports cargo in bulk, a comparison is made with the prices by cubic meter. As highlighted in the graph, it can be observed that the PICT are paying a premium price in comparison to the South East Asian countries. For instance, the average price for transportation between Fiji and Tonga can reach $100 per cubic meter and increase up to $270 to destinations such as Kiribati or Tuvalu. It speaks for itself that servicing even smaller communities than the regular ports can increase the price even more.

This is calculated by dividing the yearly costs calculated in the previous sections by the average volume of cargo transported in a year. It was discovered that SV Kwai is a competitor in the region with an average price of $88.88 per m^3

6

6.2. SOCIAL IMPACT ANALYSIS

This section will discuss the Influence on society of sustainable shipping across the South Pacific. Firstly, the Influence over the decision-making process using international indexes will be discussed. The second part will approach the impact on local communities based on the Needs analysis.

6.2.1. INFLUENCE OVER POLICY MAKING

Recounting the conclusions from Section 2.2, empirical methods for assessment of abatement measures have yet to be applied in research on the sustainability policies of PICT. This thesis will contribute to the research by providing an insight into the efficiency of the present abatement measure, i.e., soft sails for Pacific vessels. The following tools will be used: EEDI, CII and CATCH.

EEDI

EEDI is commonly applied to a vessel whose operational profile focuses on the transportation of various cargo and has a net tonnage of over 400GRT. The IMO has not yet considered vessels below this threshold for the time being. However, the need for such an indicator might prompt the organization to develop an appropriate index to quantify the emissions efficiency for the range of vessels suitable for the PICT. Thus, this work advocates for the development of an indicator that can quantify the CO_2 emissions per transport work for small-sized vessels as well[12].

6

In the present model, EEDI is calculated for SV Kwai and compared to the smallest group of vessels defined by the IMO. Formula 3.1 from Section 3.2 is applied. This results in a score of 28.25 grams/tonne-nautical mile. SV Kwai fits within the standards imposed by the IMO. This can be validated with the reference line formula proposed by the IMO for general cargo vessels:

$$y = a * x^{-c} \tag{6.6}$$

where x- DWT

a- 107.48-reference line factor

c=0.216-reference line factor

The result is 28.26 gr/t-nautical mile and SV Kwai is under the reference line as can be seen in Figure 6.1. Consequently, SV Kwai attains a reduction factor of 34% which fits within the IMO standards for Phase 3(1 January 2025 and onwards) for general cargo vessels.

Carbon intensity indicator

Following Formula 3.2, the CII is calculated. From an operational perspective per one year of navigations, SV Kwai scores a 36.09 gr/capacity-nautical mile on the CII scale. Nevertheless, the score is under the reference line as it can be seen in Figure 6.2.

The graph also indicates that SV Kwai is within the IMO standards.

CATCH index

Following the method described in Section 3.2, the CATCH parameter is calculated. The operational life of SV KWAI, from purchase and refitting to scraping, has been assumed to be twenty years. The cost of retrofitting is assumed as a one-time investment

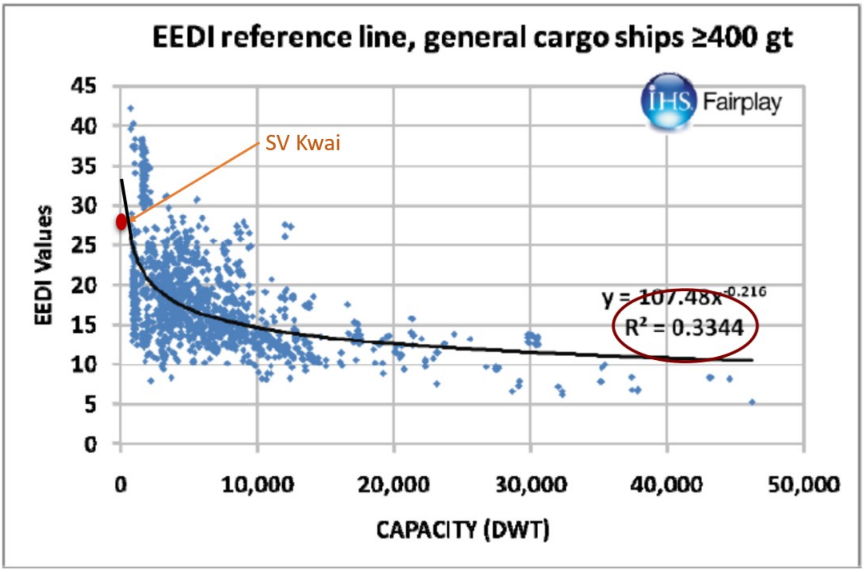


Figure 6.1: Adaptation of EEDI results with SV Kwai reference line and point of calculation [91]

and was calculated at 131,400 USD. The fuel cost savings are $40,558 per year, and the expected CO_2 emissions are roughly 3,393 t per year. Using the defined input parameters, it results that the final CATCH indicator is 34.93 $/t of CO_2. The study performed by Eide et al. suggests that the optimal CATCH value should be <50 %tonne CO_2 in GHG emission reduction assessment for shipping. This value is based on the global cost-effectiveness data from IPCC and aligns with the norms from the Formal Safety Assessment from IMO [61]. The calculated CATCH value shows that SV Kwai follows this international norm as well.

The CATCH indicator can be further implemented in a MACC curve, which compares various abatement measures on cost and emissions efficiency. A MACC curve will not be drawn for the current work, considering that only one abatement measure has been analyzed. However, the present work contributes by providing an insight into the cost-benefit of the soft sails and can be further implemented in a MACC graph. Furthermore, if future studies are conducted on other WASPs, alternative fuels, control strategies, or other emissions reduction technologies, the present results can be compared against these novel abatement measures.

6.2.2. REFLECTION ON THE SOCIAL IMPACT OF LOCAL COMMUNITIES

In the needs analysis performed in Section 2.2, several key areas were chosen for assessment: inter islands transportation, local infrastructure, population financial well-being, and job prospects. Each need could be the subject of a separate work more suitable for a social assessment, disaster relief, or port logistics research. As a result, the present work

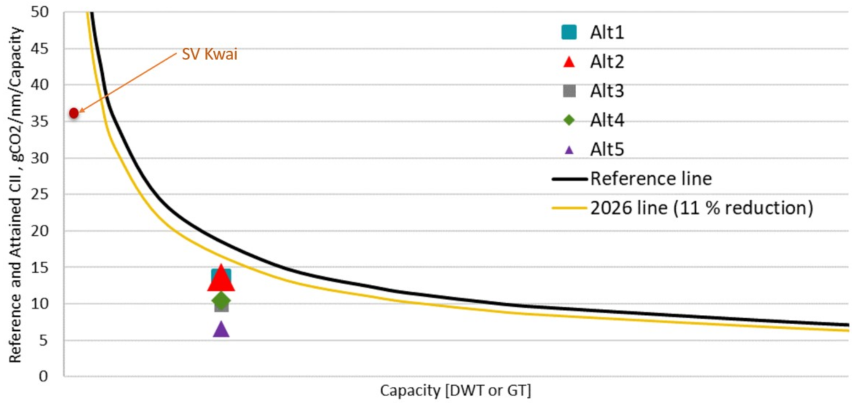


Figure 6.2: Adaptation of CCI results with SV Kwai point of calculation

will only touch briefly on the subject through a reflection based on the social research done by the Asian Development Bank and the University of South Pacific.

Inter-island transportation

The means of passenger transportation are limited between the islands of the Pacific, and for most of them, marine transportation might be the only solution for a good connection. The problem lies in the high transportation costs which result from the high costs incurred by the vessels. In addition, more often than not, the passenger's vessels are old, poorly maintained, or not suitable for passenger transportation[11].

The introduction of vessels such as SV Kwai could bring about a positive change in this situation. This thesis proved that sails could bring down fuel costs by $40,558 USD per year. These reductions can bring down passenger ticket costs and be competitive in a market dominated by diesel engine-driven vessels.

Before the outbreak of the COVID-19 Pandemic, SV Kwai performed well in the passenger transportation sector with an average net profit of over $54,579 USD per year, as it can be seen in Figure 6.3

This vessel was "the choice of inter-island travelers from Cook and Kiribati." The passengers ranged from Government workers and business people to families and tourists[85]. SV Kwai has a passenger capacity of up to 62 [70].

Local infrastructure

As highlighted in the Needs Analysis, the small islands serviced by SV Kwai have limited port infrastructure with wharves and hardstands in shallow waters, which lack proper cargo handling equipment. In these circumstances, SV Kwai is moored in deeper waters, and cargo transportation onshore is performed by dinghies. Then additional people from the island have to be employed for distribution. From practical experience, Captain Brad Ives recommends modernizing these facilities by extending the wharf length and fitting with crane equipment, provided the moored vessel does not already possess it. It stands to reason that a cargo handling operation would be more time-efficient by switching to crane cargo handling than dinghy transportation.

Figure 6.3: Yearly passenger transport profit

Population well-being

The income for people from the remote Pacific islands is small and ranges between $1,000 per year and $10,000. However, as emphasized in the Needs Analysis, even with these low incomes, people pay premium prices for product delivery, up to five times more by a cubic meter than on South Asian routes. Therefore, a comparison between regional shipping services and SV Kwai was devised in Figure 6.4.

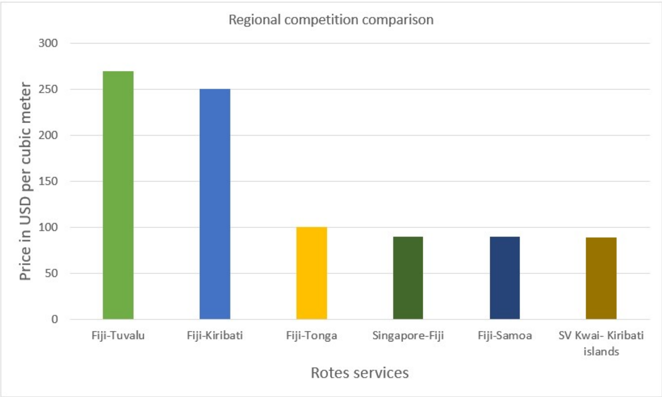


Figure 6.4: Regional price comparison

The price per cubic meter of cargo for the competition results from the economy of scale. The competitors in the South Pacific region are companies such as Matson shipping and Kyowa shipping ltd., which operate on diesel engine propulsion container vessels. From Figure 6.4, it results that SV Kwai was at least competitive with these shipping companies. The advantage for the local population is that trading has a more natural characteristic, meaning that it is directly delivered to the customer. In contrast, more prominent companies inquire about the additional price for the delivery of containers to remote communities. In conclusion, the local population's purchasing power could greatly benefit from the operation of vessels such as SV Kwai in the region; It can be assumed that the cargo costs can decrease by the economy of scale with the introduction of a fleet of WASP vessels.

Job prospects

A numerical prediction for the job prospects with the introduction of WASP vessels in the region is difficult to make because of the lack of social research in this particular area. The Needs Analysis mentioned that various maritime training institutions exist in the region, but the extent of soft sailing training within these is unknown. As a result, no further analysis is conducted on whether the local population could benefit from a job increase from implementing more sustainable technologies on local fleets.

6.3. CONCLUSION

Chapter 6 encompassed the economic, social and one environmental midpoint impact categories. The theory, formulas and estimations for these categories were provided in this chapter. From an economic standpoint, the following parameters were calculated: CAPEX, OPEX and VOYEX. These amount to the yearly costs from which the transportation cost for cargo can be derived. From a social perspective, no parameters were derived. Instead, a a critical assessment of the pressure categories impact on inter-island transport, infrastructure and job prospects was devised. Lastly, for the policy making, the EEDI, CII and CATCH indicators were calculated.

7

CASE STUDY AND RESULTS ASSESSMENT

In this chapter, the case study of SV Kwai on Voyage 39 is discussed. The first part of the chapter will expand on the Excel tool development, and the breakdown of each calculation and datasheet is presented. In the following section, the case study of SV Kwai and its output parameters are going to be presented through the designed methodology described in Chapter 3. Then, conclusions are drawn and quantified regarding the overall impact. In the last part of the chapter, a sensitivity analysis is conducted for various output parameters.

7.1. TOOL

The case study is conducted with the help of an Excel tool that automatically calculates various technical, environmental, and economic parameters. The tool has eight tabs, each with a specific function: input tab, operational profile, data for resistance calculation, power calculation, sails calculation, environmental, economic-social calculation, and output data. Figures 7.1 and 7.2 display the dashboards for the input and output data. Further details about the other tabs can be seen in Annex A.

The initial data for the calculation is introduced in the input tab. Here, information such as the vessel dimension, hybrid propulsion characteristics, and estimated voyage details are introduced. For the technical calculation, additional data is required such as hull resistance, weather routing and approximate sails area. Further details and estimations are made in the propulsion, sails, and economic tabs. The output data tab presents the critical performance indicators chosen for this case study. From a technical standpoint, the tool user can assess the hybrid propulsion and fuel efficiency and visualize the predicted saving. The environmental section displays the total emission output and the compliance with the EEDI, CII and CATCH indicators. Lastly, the economic part automatically calculates a yearly cost and cargo price estimation.

Input details

Item name	Input value	unit
Vessel details		
Length overall	36.6	m
Breadth moulded	7.1	m
Depth to main deck	3.0	m
Design draught	2.7	m
Deadweight at max draught	277.0	t
Cruise speed	6.0	kn
Net tonnage	179.0	t
Propulsion details		
Sail area	434.0	m^2
Rig height	21.4	m
Engine output	186.4	kW
Propeller diameter	1.2	m
Voyage details		
Estimated days at sea	41	days
Estimated days in port	37	days
Inbout cargo	527	metric tonnes
Outbound cargo	620	metric tonnes
Total cargo moved	1147	metric tonnes
Cargo volume	2586	m^3
Total transported passengers	99	-

Figure 7.1: Tool input tab

7

Output values

Item name	Input value	unit
Technical performance		
Average wind condition	15	kn
Average sails thrust	16.01	kN
Average SFC	376.63	g/kWh
Fuel consumption/voyage	20517.45	liters
Predicted fuel saving	37%	-
Environmental		
CO2 emissions	55.9	tonnes
Predicted CO2 reduction	37%	-
SOx emissions	379.62	grams
Predicted SOx reduction	0.34	-
CII	36.1	gr/t*nautical mile
CII no sails	57.1	gr/t*nautical mile
EEDI	28.3	gr/t-nautical mile
EEDI no sails	36.5	gr/t-nautical mile
CATCH	34.9	$/Tonne CO2
Economic		
CAPEX	58615	USD
OPEX	632267	USD
VOYEX	76460	USD
Yearly costs	917904	USD
Cargo price/cubic meter	88.7	USD

Legend	(green)	compliant
	(red)	non compliant

Figure 7.2: Tool output values

7.2. CASE STUDY

The purpose of the case study is to analyze and validate the designated vessel and its parameters, namely SV Kwai and to develop a future model that can be implemented on other similar types of vessels (new builds or retrofits). The study is based on the documents received from captain Brad Ives. Voyage 39 from 2017, elaborated in Section 4.3, is the baseline model which is then compared to other case scenarios: increased and decreased sailing time and decreased mooring time. However, additional information and rules of thumb have been derived from Voyage 55 of 2020 (see Section 4.3), given the similarities in terms of fuel consumption and duration of trips. The information thus converges and creates a unique case study to identify and validate the design characteristics, fuel consumption, emissions release, economic data, and social impact for this particular voyage.

7.2.1. CALCULATION BOUNDARIES

Before diving into actual results and interpretation of the results, it is essential to mention the boundaries set when conducting the analysis. Therefore, the following aspects have been implemented:

- The case study is performed for one voyage, which lasts roughly 78 days, out of which 41 are spent at sea and 37 moored. The total covered a distance of the vessel during the whole voyage is 5,592 nautical miles. All results presented in the case study were calculated with regard to the voyage timeline. An overview of the established operational profile of the vessel during the voyage can be seen in Figure 7.3

- The navigation profile of the vessel has been divided into sea passage and inter-island navigation, each with its characteristics. According to the voyage report, a rule of thumb was created. The sea passage had a predominant sails usage with almost 50% of the time motor sailing and roughly 14% pure sailing up to 11 knots in ideal wind conditions. The maximum speed attained with motoring is 6 knots. A similar pattern has been considered for the inter-island in terms of sailing and motor sailing time but at lower speeds and predominant engine use. The difference consists in the propulsion power and time spent in motoring conditions. Both operational profile can be seen in Figures 7.4a and 7.4b.

- Sailing in lagoons and atolls was integrated into the inter-island traveling, which means that motoring was used more often than in sea passages. As a result, the maximum sailing speed with sails was set to 8 knots, and the motoring and motor sailing were increased to up to 9 knots.

- It should be noted that the time spent in sea passage and inter-island sailing are also different. According to the fuel report from Voyage 39, some ratios were estimated for the two different sailing profiles. In the calculation, an emphasis was put on following the ratios to achieve the correct model—the ratios regarding fuel consumption, time, and distance described in Section 4.3.1.

- from a fuel calculation perspective, both voyages have an interesting main engine to auxiliary ratio. It was discovered that generally, the auxiliary fuel consumption is around 66% of the propulsion consumption. Moreover, out of the total fuel consumption, the auxiliary represents 40%, whereas propulsion burns 60% of the fuel. These created rules of thumbs have been used as the criterion for calculation and verification of results accuracy.
- Based on the wind speed estimates in Section 5.1.3, the potential wind speed was set between 10 and 30 knots.

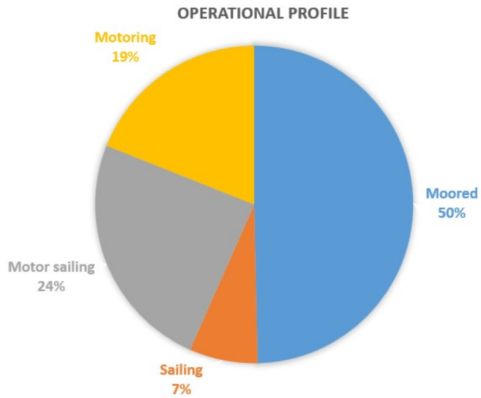
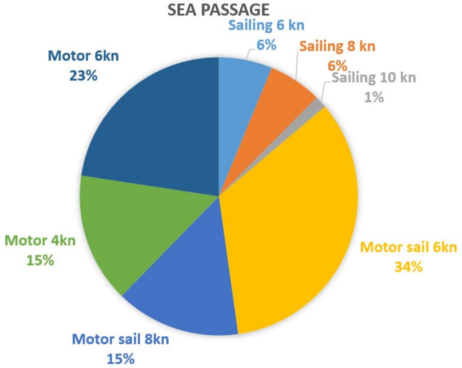
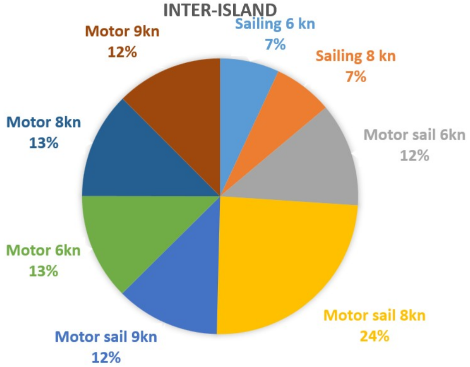


Figure 7.3: Operational profile



(a) Sea passage transit



(b) Inter island transit

Figure 7.4: Navigation profile breakdown

7.2.2. FUEL PERFORMANCE ANALYSIS

From a fuel consumption perspective, the present tool model calculated the total fuel burnt during a voyage within a 5% margin. Thus, the calculated fuel consumption with sails is 20,517.4 liters per voyage. The vessel documentation from captain Brad also provides an estimate for the scenario in which no sails are used. The amount was estimated to be 30,679 liters. For verification, the present tool iterated a scenario with no sails to prove the accuracy of the calculation. The result is that the present tool estimated 32,446 liters for the entire voyage, roughly 5% more than the original estimate. A representation can be seen in Figure 7.5

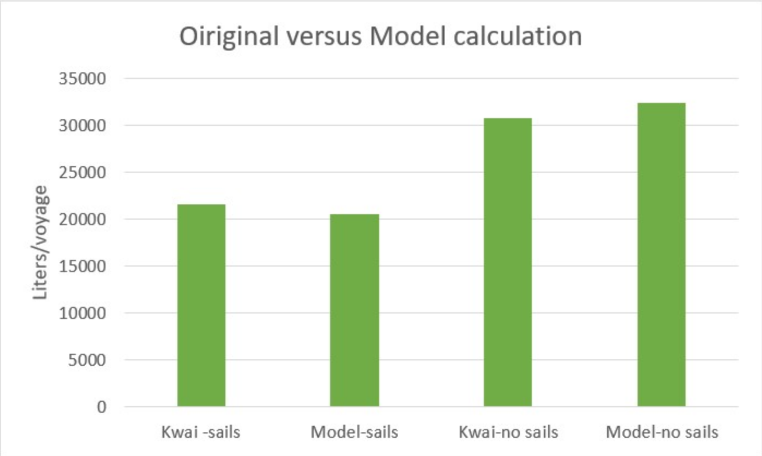


Figure 7.5: Original estimation versus model calculation

The graph also highlights the fuel consumption efficiency attained by this propulsion configuration which is 37%. Furthermore, a breakdown per operational profile is presented in Figure 7.6

As can be seen, only the auxiliary engines consume fuel during the pure sailing time. However, fuel consumption during mooring is a significant contributor considering the demand for auxiliary equipment. In this case, much of the fuel consumption is due to the hotel conditions and loading/discharging of cargo in ports. Lastly, the motor sailing and motoring modes are the most fuel-demanding consumers on board. At first glance, looking at the hours to fuel consumption rate, there is not a staggering difference between sailing and motor sailing. Motor sailing is more fuel-efficient but only by a slim margin. Part of the reason for this slight difference is the integration of atoll and lagoon navigation. In these sailing circumstances, the motor sailing condition has a 70/30 percent load operation, meaning that the engine takes 70% of the load whereas the sails take just 30%.

The engine also operates in a low running condition below its operational point, 8-16 kW, which means under performing and uses a high amount of fuel for more extended periods. The reason for these low efficiencies has been attributed to the old age of the vessel and its over design for the actual vessel needs. It is expected that a lower-powered

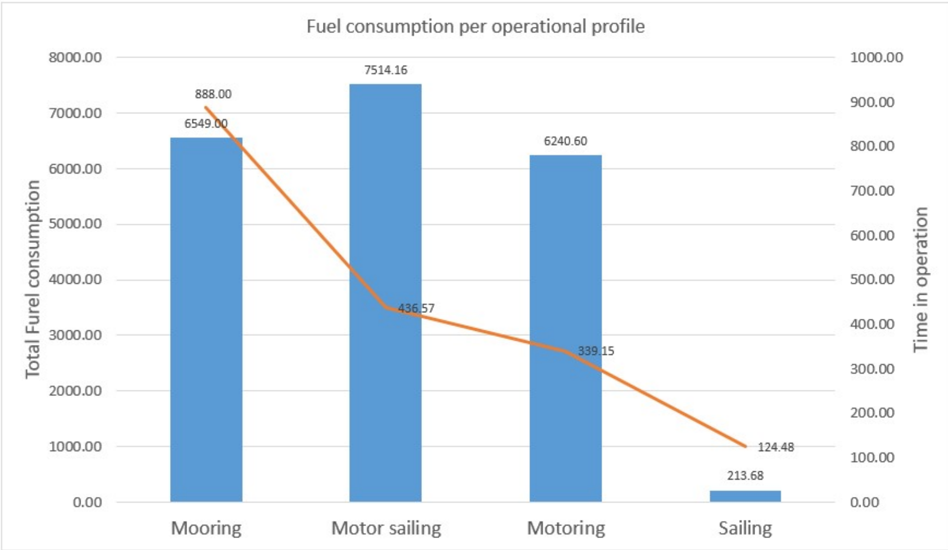


Figure 7.6: Fuel consumption per operational profile

engine with higher fuel efficiency could achieve more efficient results.

With all facts considered, the question is not by what percentage the motor sailing mode is more efficient but what would happen if hybrid propulsion was not installed altogether. The answer is the 37% difference in fuel consumption detailed in the previous paragraphs.

7.2.3. ENVIRONMENTAL OUTPUT

From an environmental standpoint, the situation follows a similar trend line as the fuel consumption discussed in the previous section. A comparison was made between the emissions released in hybrid propulsion and motoring propulsion. The results yield a 37% CO_2 emissions reduction. The total emissions CO_2 for a voyage amount to roughly 55.9 tonnes, whereas without sails, it would be around 88.4 tonnes. A breakdown of the CO_2 emissions per operational profile can be seen in Figure 7.7

Another emission substance studied in this work is the release of SO_x, known to be a threat to human health. The calculated SO_x per voyage is around 379 grams. Consequently, with the hybrid propulsion, the SV Kwai fits within the standard norms imposed for 2025 and onwards by calculating EEDI, CII and CATCH indicators. The EEDI value is 28.26, compliant with the bulk carrier standards for future vessels. The CII is 36.10. Similarly, the CATCH indicator shows an expected \$34.93 per tonne of CO_2 which is below the threshold indicated by Faber et al. [62].

7.2.4. ECONOMICAL OUTPUT

From an economic standpoint, the finances of the vessel were studied and calculated with the current tool. The CAPEX, OPEX, and VOYEX parameters were calculated for

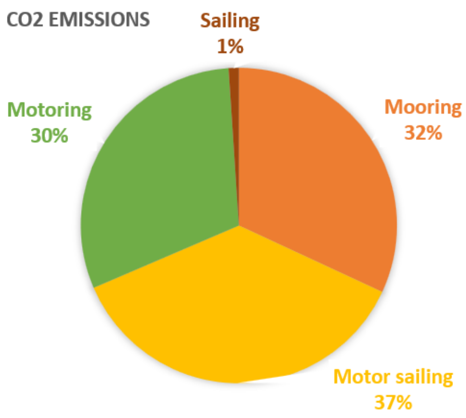


Figure 7.7: Breakdown of emissions per operational profile

a year, assuming four voyages during the entire year. The distribution of the costs is presented in Figure 7.8.

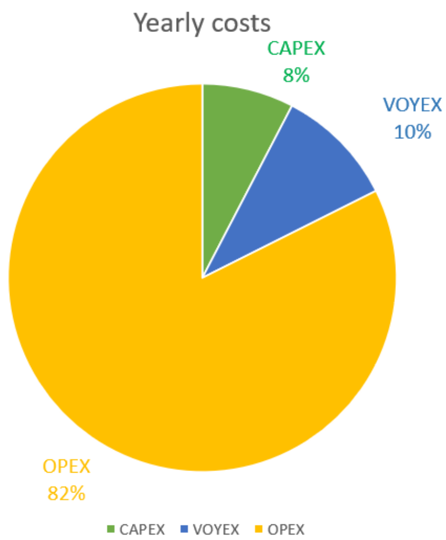


Figure 7.8: Breakdown of yearly costs

The calculation of these parameters had two purposes: to estimate the financial indicators for future WASP new builds or retrofits of similar size and to calculate the cargo price per cubic meter. The latter parameter is essential to assess the commutativity of a WASP vessel with other shipping companies in the region. The result was that SV Kwai has an average price of shipping of approximately \$89 per m^3. Provided a more efficient engine and sail configuration would be installed onboard, and fuel consumption would be lower, the price would be expected to drop even lower. In conclusion, SV Kwai is an important market player in the South Pacific region and can stand the economy of scale of other container ship fleets in the region. An analysis for OPEX and VOYEX reduction is further conducted in Section 7.5.

7.2.5. SOCIAL IMPACT

The tool does not directly calculate any social parameters derived from the operation of SV Kwai in the South Pacific region. Instead, the environmental and economic output of the vessel indirectly affects other areas of the social spectrum, ranging from sustainable policies to population well-being. From a policy perspective, the calculation of EEDI, CII and CATCH previously discussed provides a valuable insight into the compliance of WASP vessels with the regulatory norms of the IMO.

The inter-island transportation study has shown that WASP vessels can also diversify their services with passenger transportation. Therefore, there is a demand for it as an alternative to other means of transportation. The future implementation of WASP vessels demands better port infrastructure for cargo handling to save time and fuel. From a job prospect standpoint, a conclusion could not be reached due to the lack of information on maritime employees' unemployment rates and demand for future vessels. Lastly, it is expected that the population's well-being can increase by introducing a fleet of WASPs in the region from the decrease in shipping costs. Moreover, a decrease in CO_2 would help mitigate the climate change, increasing sea levels and thus prevent land loss and weather change. Lastly, a minor contributing factor for major ports in the Pacific such as Fiji is the decrease of SO_x emissions, which directly impact human health.

7.2.6. MODEL CHALLENGES AND LIMITATIONS

So far, the benefits of WASP vessels within the South Pacific shipping context have been studied. However, the technical, economic, and social challenges of vessels in this environment are unique and require adapted critical thinking to devise a practical solution for assessment. This section will present challenges and limitations encountered during the study, research, and creation of the tool.

From an informational standpoint, the following gaps were found in the research:

- Wind propulsion on target vessels The literature research on WASP technologies in Chapter 2.6.1 has proved that there is a knowledge gap in the studies of wind-assisted ship propulsion for small cargo vessels such as the SV Kwai. This has prompted the decision to further look into the yachting sector for alternative methodologies to assess sails performance. Thus, the Hazen model for sailing leisure vessels was used. The model is crude and robust but provides an essential insight into sails performance. In addition, future aerodynamics studies of sails on cargo vessels ranging from 100GT to 400GT should provide a clearer view of the performance of sails in this sailing environment. Up to this point, only some results from the SV Kwai case study have been compared against the sailing Greenheart Project, a vessel in its design stage.

- Wind propulsion alternatives.

The literature research highlighted that other wind propulsion alternatives such as rigid sails, Flettner rotors, or towing kites have the potential for fuel efficiency and emissions reduction. However, no research on these technologies has been conducted on this case study's range of vessels of interest(25-45m). Therefore, the results could not be compared against other viable WASP solutions.

- Social studies applicable to the case study

  When performing the needs analysis and social impact assessment, it was discovered that there is a research gap in the social analysis of the local population and the impact of maritime economics in the region. This hindered an in-depth analysis of the impact of SV Kwai on aspects such as purchase power, job prospects, development of port infrastructure, and improvement of transportation between islands. As a result, the present work resorted to a brief reflection on the impacts a WASP vessel could have on local communities based on the calculated environmental and economic parameters.

- International standards for climate change mitigation

  It was highlighted by Nuttal et al. [12] that the WASPs which were studied throughout the years have not been subjected to the environmental method of assessment and that there is a dire need to do so. In the present work, the EEDI and CATCH parameters were calculated. Therefore, the first option is not applicable. However, a calculation showed that the current case study vessel fits the EEDI,CII and IMO norms. From the CATCH indicator, a MACC curve(demanded such a vessel) was not able to be drawn because there are no other abatement measures to compare the soft sails against.

A series of practical limitations have been encountered throughout the tool development process. These issues have been accounted for, and assumptions have been made in order to make an accurate technical prediction for the hybrid propulsion performance:

- Vessel age.

  The Kwai is roughly 71 years old, which posed a problem to the overall calculation. The vessel is an old Norwegian fishing vessel retrofitted into a sailing cargo vessel. Thus, considering that the boat was designed for a completely different sailing environment and purpose, it can be expected that the hull efficiency would decrease. In turn, this can have consequences on increased resistance and fuel consumption. The assumption was made for a U-shaped cargo vessel design in the Holtrop Mennen resistance calculation. A CFD analysis of future models can better understand hydrodynamic performance.

- Old engine

  The engine of SV Kwai was adapted from an old 12V-71 Detroit (Peak power:335kW). By reconfiguring the engine with new parts and reducing the number of injectors, the output power was scaled to 183 kW. However, the power calculations of the model have shown that this engine is, in fact, over-designed for the power necessities of the Kwai. As a result, the Kwai is mostly under-performing in cruise speed conditions due to the low fuel efficiency. A new engine with lower power and higher fuel rate efficiency would significantly decrease the total fuel consumption.

- Lagoon and atoll integration

  Sailing in lagoons and atolls can considerably affect fuel consumption due to the drifting of the vessel from the ocean currents. As to this, the engine has to increase its output power to reach the desired cruise speed. Therefore, the study of drifting influence overpowers and fuel consumption has not been considered. However, the lagoon and atoll sailing time have been integrated into the calculation by adding additional motoring time at high speeds.

- Accuracy of baseline fuel consumption from Kwai Fuel Report

  The final fuel consumption calculated in the model was compared against the manually collected data by the crew during a voyage. However, the author of the Kwai report notes that the calculation and measurements are influenced by a variety of errors such as: sounding by dipstick, the impossibility of evaluation of fuel consumption per engine, and inaccuracy in data collection during various operational modes and listing during the measuring. These errors are difficult to quantify in a percentage that influences the actual fuel consumption of the vessel.

7

Part of the limitations and assumptions explained in the previous paragraphs are further elaborated in the sensitivity analysis performed in Section 7.3

7.3. SENSITIVITY STUDY

In order to test the accuracy of the model, a sensitivity study is carried out on top of the case study discussed in the previous Sections. The test aims to investigate the impact of 10% and 20% decrease and increase in sailing time on the most crucial output parameters of the model. Sailing time is chosen as the variable parameter because it has an influence the majority of the impact categories of the operational cycle assessment such as power load balance, fuel efficiency, emissions and finances. Thus, the following output will be assessed through the study: CO_2 emissions, SO_x emissions, fuel price, and cargo transportation cost. All the parameters are tested per voyage except for the cargo cost assessed per year.

Sail thrust variation

Before analyzing the five parameters, a sensitivity analysis for the wind thrust potential is performed. Figure 7.9 illustrates an estimation of wind harness potential for wind speeds between 10 and 33 knots. Generally, the Kwai sails configuration requires 20 to 23 knots of wind to generate enough thrust for cruise speed. The calculation in the model was verified with the actual logs of the vessel. Captain Ives notes that around 20 knots of wind were required to sail the ship without the help of the engine[85].

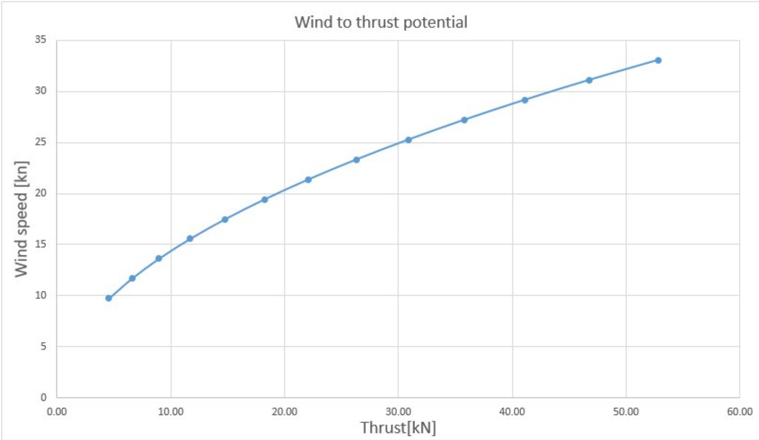


Figure 7.9: Wind to thrust potential for current configuration

Most of the time, the Kwai will spend sailing and motor sailing in the region of 10 to 20 knots to reach the desired cruise speed. The 10% and 20% variation of the sensitivity study accounts for the lower and upper limits of the wind thrust potential. At the lower end of the wind spectrum, sailing without engines at cruise speed is virtually impossible, and thus motor sailing is prioritized with the bit of wind available. On the other hand, the gust of wind in the upper limit is favorable for pure sailing, where the Kwai can reach top speeds of up to 11 knots.

Considering the following time and wind thrust estimates, the following output parameters change in the 10% to 20% margin. Sail time in the following figures incorporates sailing as well motor sailing time.

Fuel consumption per voyage

It comes as little to no surprise that the fuel consumption presented in Figure 7.10 has an even distribution of fuel consumption. A 10% and 20% decrease/increase does not automatically translate to a 10%-20% fuel saving. Instead, it can be observed that with a 10% decrease in pure diesel engine use, around 250 liters worth of fuel is saved. In 20% increased sail time, more than 500 liters can be achieved. A similar situation is encountered when switching the sailing to pure motoring time. The reasons for the low fuel efficiency have already been discussed in Section 7.2.6

However, provided that a proper sailing hull, new fuel efficient engine and better sailing configuration would be installed, than there is no doubt that for the same increased sailing times, a considerable more amount of fuel would be saved.

CO_2 emissions per voyage

Similarly to the previous fuel consumption analysis, the CO_2 follows a similar trend line as it can be seen in Figure 7.11.

By increasing the sailing time of the vessel, around 0.7 tonnes of CO_2 are less emitted

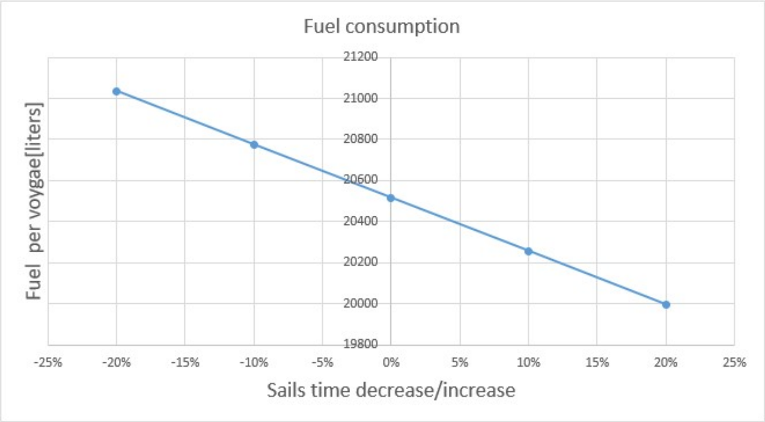


Figure 7.10: Total fuel consumption variation per voyage

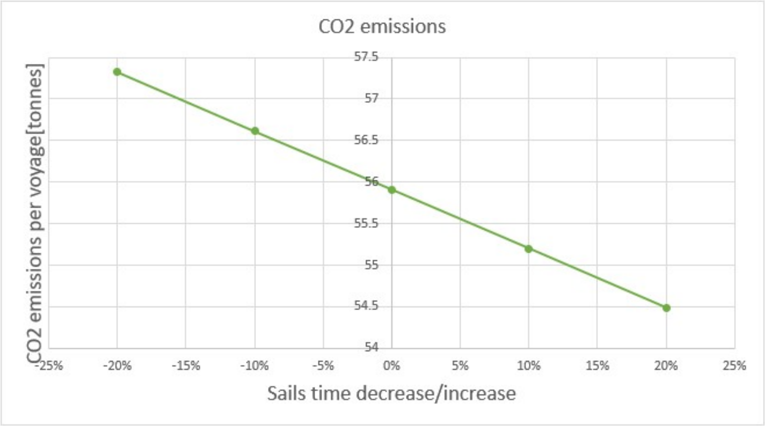


Figure 7.11: Total CO2 variation per voyage

for every 10% increased in sailing time. On a similar note, around 0.7 more tonnes of CO_2 are released if sailing time is reduced.

SO_x emissions per voyage

The SO_x emissions for the vessel scale of SV Kwai can be considered insignificant with only 379 grams emitted for an entire voyage as seen in Figure 7.12. The shift in sailing time barely changes the total emissions per voyage and cannot be considered more harmful.

Fuel price per voyage

The fuel price per voyage was calculated with the international bunker price of the day, which was set to $ 0.85 per liter (10.05.2022). The fluctuation in fuel price presented in Figure 7.13 shows that the use of sails plays an essential role in fuel expenditures as

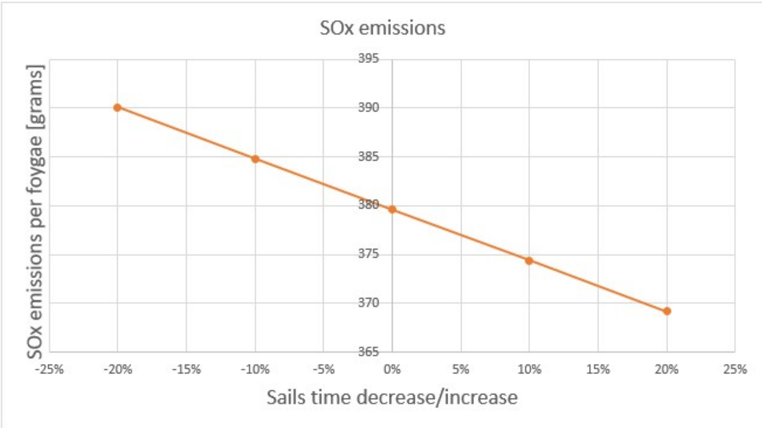


Figure 7.12: Total SO_x variation per voyage

well. For example, from a 20% increase in sailing time, the KWAI would save up to % 500 per voyage, but in a whole year, this could increase to more than % 2000.

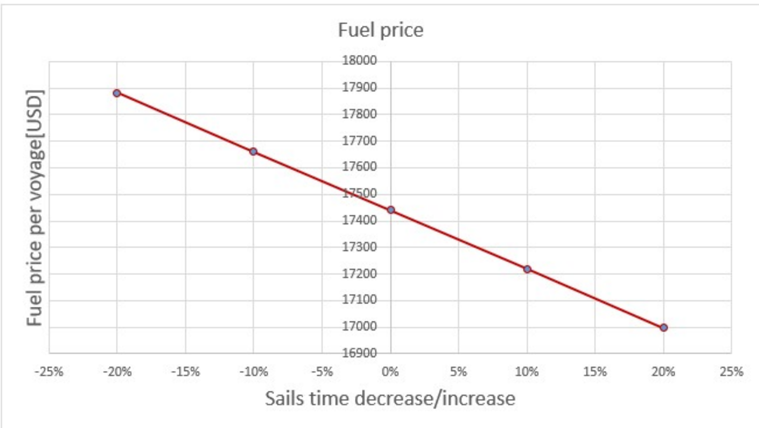


Figure 7.13: Total fuel price variation per voyage

Cargo price

The cargo price presented in Figure 7.14, shows that the use of sails does not have a considerable influence on the total cargo transportation price. In fact, between the -20% and +20% sailing time, the cargo price difference is only % 0.46. The main reason for this is that the fuel does not play a significant role in the overall yearly costs calculation of the vessel and, as a result, does not influence the cargo price either. However, for future decrease in cargo price and increase in competitiveness with other companies, a more comprehensive study on the yearly transportation costs of SV Kwai should be performed.

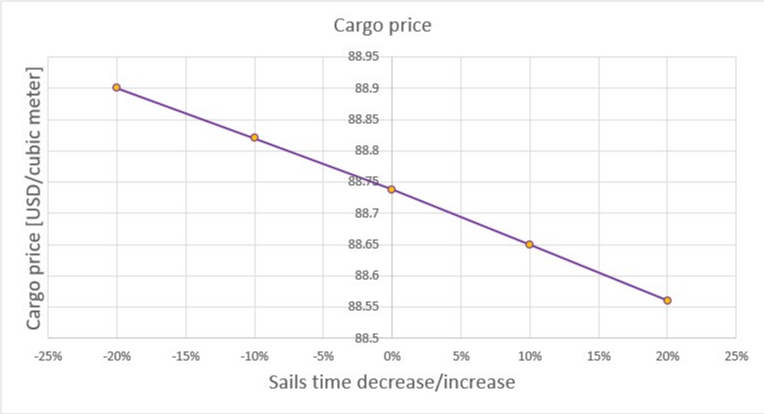


Figure 7.14: Cargo price variation

7.4. SCALABILITY AND REPLICABILITY

In Chapter 3, the LCIA method and its various side tools and applications have been discussed. However, it was concluded that the present work would not conduct a full-scale LCIA due to the following reasons: missing information, missing specialized LCIA tool, and complex calculations. Nevertheless, a more in-depth assessment such as the LCIA will be needed for vessels such as SV Kwai.

The present work, through the assessment of fuel consumption and calculation of CO_2 and SO_x emissions, can contribute to a future LCIA. Thus, the current work only provides the operational side of the assessment and its output. The precise impact on the LCIA KPIs is not performed for the reasons mentioned in the previous paragraph. However, the previous chapters discussed various impacts of the calculated parameters that have been discussed and augmented.

In order to touch upon the last requirements of the USP partners, namely the scalability and replicability characteristic of a WASP vessel, the output parameters are expanded for the 20 years vessel cycle. As previously mentioned, the 20 years of operation life is the estimated operational lifespan of the vessel from the moment of purchase and retrofit. The vessel sailed under the ownership of Island Ventures LTD for 15 years and is expected to operate for 5 more years. The assumption is that four voyages are undertaken on average per year. Each voyage lasts around 80 days. In Table 7.1, the results of a 20-year operational cycle can be seen.

Table 7.1: 20 years operational cycle

SV KWAI 20 years operational cycle analysis						
Pressure category	No sails	-20%	-10%	Baseline and decrease	10%	20%
Fuel consumption[liters]	2,595,718	1,682,927	1,662,162	1,641,395 - 37%	1,620,630	1,599,865
Fuel price[USD]	2,206,360	1,430,488	1,412,837	1,395,186 - 37%	1,377,535	1,359,885
CO2 emissions[tones]	7,074	4,586	4,529	4,472 - 37%	4,416	4,359
Sox emissions[grams]	46,097	31,203	30,786	30,369 - 34%	29,952	29,535

The table presents results for various case scenarios: no sails installed, baseline, and sensitivity to wind time harnessing. For 20 years of operation, the impact of an entirely diesel-driven SV Kwai has had massive environmental and financial consequences. For example, in 20 years, the SV Kwai in a baseline case scenario can save as much as 954,322 liters of fuel which would cost USD 811,174. Moreover, the resulting CO_2 and SO_x emissions would be 2,601 tonnes and 15,727 grams less, respectively.

A comparison can be made between the baseline model and the +20% sailing time, where a year and a half worth of fuel and money can be saved from just a 20% increase in sails time. The emissions difference is negligible in this case. The other case scenarios follow a similar trend line.

Applicability to future vessels

In conclusion, the present tool will be able to assess future vessels and can give an indication on the operational life span of a vessel and its impact on the target categories. Through an iteration process, the tool calculates some of the KPIs important for both a designer and a ship operator to make a decision about the long-term viability of the considered design.

The SV Kwai example, assessed in this section, shows positive results and the potential for emission reduction and financial savings. The projection for a 20 year life span is also favourable. With a better engine, rig system and improved hull design, it can be safely assumed that the parameters would be even more consistent. Consequently, scaling the vessel to an entire fleet and replacing the old current diesel driven vessels would bring tremendous benefits and contribute to the local carbon reduction goal. The long-term analysis is prone to errors considering that a vessel will not be servicing the same line of islands, transporting the same type of cargo or navigating the same distances every year. Nevertheless, it cannot be overlooked that no matter what route the vessel is taking in the South Pacific region, ideal sailing conditions, fuel reduction, financial savings and constant cargo demand for isolated communities can justify a large scale investment for WASPs.

7.5. CASE SCENARIOS FOR POTENTIAL OPERATIONAL SAVINGS

The current developed model can also be further used to assess the possibility of decreasing other operational indicators such as OPEX and VOYEX. As it can be seen in Figure 7.8, OPEX is the predominant of the yearly costs out of which crew wage and maintenance make up the majority of these expenses. This stems from the fact that almost 50% of the operational time of the vessel is spent moored in ports.

In contrast to other companies in the region, Island Ventures LTD. performed commercial business besides shipping. This means that the company took in orders, transported and then delivered and sold cargo on location for all its customers. Moreover, the shipping logs indicate that the company set up its own mobile distribution centers called "Kwai Shops" on location[71][85]. This led to considerable amount of time spent on stevedoring, selling, purchasing and negotiating on location for further delivery services. As a result, additional time and money were spent for these operations which increased the overall OPEX and VOYEX.

Through the current tool, several case scenarios are conducted in which the mooring time is reduced by 90%, 70% and 50%. The assumption for these percentages is that the time spent for the above mentioned operations can be outsourced to local agents on the islands , allowing SV Kwai to focus solely on transportation. Time spent in ports could be instead used to service other neighbouring islands. In Figure 7.15, the assumed case scenarios are compared to the current voyage baseline model.

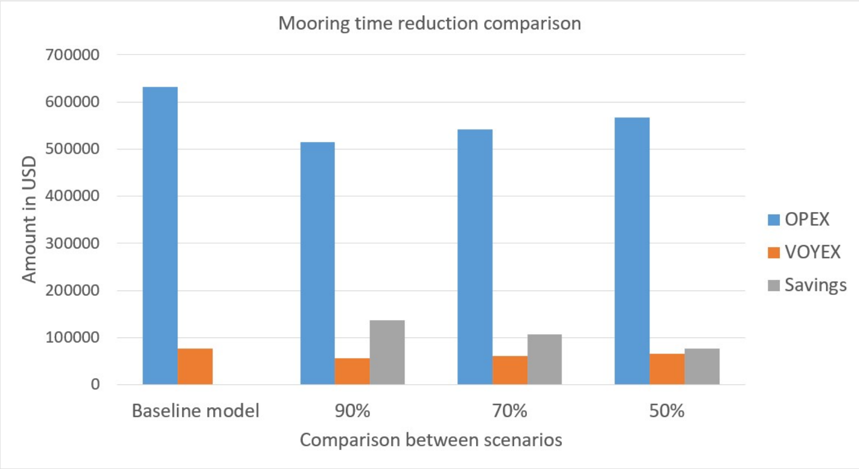


Figure 7.15: Mooring time reduction

The indicators for OPEX which were decreased for the specific deducted mooring time were: crew wages, food stewart and professional fees. The VOYEX parameter influenced by these reductions is the fuel consumption derived from auxiliary engines.

The chart indicates that a considerable reduction can be achieved in terms of OPEX. Thus, in comparison to the baseline model, the reduction can range from $117,121 (90%) to $65,067(50%). In terms of fuel costs, up to $20,039 can be saved in the major reduction scenario whereas only $11,133 are saved in the 50% case. Lastly, the overall savings from each individual scenario are: $137,160(90%), $106,680(70%) and $76,200(50%) per year.

In conclusion, these savings can be potentially used to employ agents in a region (island or cluster of smaller islands) who already have local distribution centers and who can contact the local residents for their orders. Furthermore, the agent would be able to strike future deals in the name of the company so that the ship leaves loaded with raw materials such as copra seaweed. As a result, by employing an intermediary, the company would be able to save time which in turn could be used for other charters in the area, thus making the operations more efficient and possibly more profitable. The current calculations have not included the actual costs of the agents per year but savings are a good indication that enough money could be used in order to outsource this service. The massive OPEX reduction can lead to a decrease in cargo price as well. However, since the agent costs are unknown, a prediction on the new cargo prices is not made

8

CONCLUSIONS AND RECOMMENDATIONS

In this final chapter, the conclusions of the overall work and the recommendations for future research are presented.

8.1. THESIS CONCLUSION

The main objective of the research in the present work is to answer the following question:

"To what extent is it possible to assess the social, economic, and environmental impact of a WASP vessel in the Pacific island region in order to justify investment in large-scale production?"

To answer this research question, answers are provided to the sub-questions presented in Section 1.2. Each sub-question stands for the topics of each of the chapters elaborated in this work.

- *How will an improved shipping service influence the region from a technical, environmental, economic and societal points of view, and what are the needs for future improvements?*

  The overview of the maritime sector in the Pacific and its impact on society, ship economics and environment was performed in Chapter 2. The result of this literature review was a needs analysis. With this, key issues have been identified from the three aforementioned perspectives. Thus, the analysis shows what effect will the introduction of sustainable vessels have on the defined problems. From a social perspective, it is believed that a new vessel will improve the local transport and cargo services by increasing the frequency of maritime commerce, passenger transport and lower price. Consequently, the improvement in these areas could trigger the development of better port infrastructure and demand of skilled labour. However, the two latter issues have not been studied in-depth and additional research is needed to draw a conclusion.

From an economic standpoint, a better vessel will also have an improved financial output. The investment costs should be minimal and the operational costs should be kept as low as possible. These factors will cause a decrease in cargo price.

Lastly, the environmental and technical necessities were highlighted in the needs analysis. The main targets of regional organization is to decrease CO_2 emissions in shipping with 40% by 2030 and bring down SO_xcontent in fuel to 0.05%. These can be achieved by research and implementation of alternative and hybrid propulsion and validation to international standards and indicators.

The conclusions of the needs analysis were used as the drivers for the development the tool and methodology.

- *What are the most suitable WASP options for a medium-sized Pacific cargo vessel?*

  A variety of WASP technologies have been discussed in Chapter 2 by means of literature review. The needs analysis showed that WASPs are the most optimal technology for the current problem since it checks the economical and deployability criteria. A total of six deployed and concept technologies have been review: soft sails, rigid sails, towing kites, suction winds, hull sails and Flettner rotors. All technologies were assessed from their working principles, application, performance and limitations. Based on these criteria, grades were given according to the Technology Readiness Scale. The results of the review indicated that soft sails are for the time being the optimal choice for the Pacific vessels. The reasons are the solid research behind the technology, the vast proven application in yachting and Pacific cargo vessels (SV Kwai, Tai Kabara and Cagidonou) and the low cost of implementation and operation. Other technologies such as : Flettner rotors, towing kites and rigid sails displayed considerable potential but further research is needed.

- *What are the applicable impact assessment methods currently in use in the maritime world and what is applicable to the current Pacific Islands case?*

  In Chapter 3, a total of five methodologies for impact assessment have been reviewed. Each method presented various calculations and examples which could be implemented on the Pacific case study. It was decided that a custom framework for the present case will be created. This has the Life Cycle Impact Assessment approach as its foundation but borrows elements from the other methods to cover the societal and economic perspectives as well. Thus, the Operational Cycle Impact Assessment was created to test the effects of the proposed vessel during its operational lifespan, using the the engine and WASP as its prime pressure categories. Any other impacts derived from building, scrapping or pollution of other systems on board were intentionally left out.

- *Are there past and current proven applications of WASPs in the South Pacific region, and how relevant are they for developing future WASP vessels?*

  The collaborators from the University of South Pacific have provided various documentation and research on proven WASP vessels. It was discovered that vessels such as Na Mataisau, Cagidonou and Tai Kabara were built and operative in the 1980s and 1990s and displayed impressive fuel reduction of 20% to 37%. A proven vessel which is still in operation is SV Kwai. The comprehensive voyage and fuel data received from the USP counterparts have prompted the use of this vessel as case study subject.

- *How can a case study vessel be used to develop an assessment tool?*

  In Chapter 4, an in-depth description of the SV Kwai documents is provided. These include voyage logs, fuel reports, cargo lists and technical details reports. All the data from the voyage logs has been used to define the operational profile of the vessel and the sailing pattern of the hybrid propulsion. Consequently, the fuel reports were used to verify the accuracy of the assessment tool.

- *Which are the technical and environmental considerations of the hybrid propulsion calculation?*

  The sails and engine calculations chains and theory were elaborated on in Chapter 5. The novelty of the study consists in the application of empirical performance assessment methods to SV Kwai in various operational conditions. Consequently, the engine load balance was compiled to understand what is the thrust delivered by sails and how much of this potential power can be harnessed at various wind speeds. Moreover, this technical chapter includes the estimates of auxiliary power demand and its influence over the overall fuel consumption.

  The calculations were integrated in the Excel tool to calculate the performance indicators of vessel propulsion. The methods used in this work are optimal for an early-stage design phase to calculate engine load balance with the sails, to estimate an initial fuel consumption and to make a prediction about CO_2 and SO_x emissions.

- *Which are the social and economic parameters and how are they calculated?*

  Chapter 6 encompasses the social and economic impacts of a WASP vessel. From an economic perspective, the current work focused on the calculation of ship financial parameters: CAPEX, VOYEX and OPEX. These were estimated with the help of the documents provided by captain Brad Ives. Based on these parameters, the total yearly costs were calculated, and consequently, the average cargo price was estimated as well. The economic calculation can help in assessing the SV Kwai competitiveness in the regional market.

  From a social standpoint, several issues were identified in the Needs analysis such as policy making, inter-islands transport, local infrastructure, population well-being and job prospects. However, the nature of societal analysis was found to be too difficult and too complex for the scope of the current research. As a result, only a brief critical assessment of the impact of a WASP on local societies was made. On the other hand, it was discovered that the policy making can be influenced by various parameters and standards such as the EEDI, CII and CATCH. These were calculated for SV Kwai and displayed positive results which could aid in the decision-making process of regional policies for fleet renewal and technology implementation.

- *What is the impact of operational cycle for hybrid propulsion and what effect will it have on the vessel's scalability and replicability characteristics?*

The case study of SV Kwai was performed in Chapter 7 and aims to provide an overview of the vessel performance, output parameters and case scenarios for a 20 years operational cycle. The following conclusions can be made for the various perspectives approached in this thesis:

Technical:

With the current tool model, the prediction of the propulsion performance can be achieved. The results are within 5% error margin of the collected data. Fuel consumption can be reduced by 37% with the current hybrid configuration. It is believed that with a better engine, improved sails and better hull design, the reduction would be far greater. Nevertheless, the installation of sails on retrofits can have a positive impact as well. If implemented on a fleet of similar vessels, it can be concluded that at least the 37% can be achieved at wide scale.

Environmental

From an environmental perspective, the, total CO_2 and SO_x emissions were calculated for the entire operational cycle of the vessel. Similarly to the fuel consumption, an overall reduction of 37% decrease can be achieved. If implemented on a large scale within a fleet, the emission reduction would greatly contribute to the 2030- 40% target of the local region.

The social results discussion for policy making are incorporated in the environmental conclusion. From a policy making perspective, the EEDI, CII and CATCH indicators display promising results. The implementation of soft sails on the current case study vessel already proves that mitigation of climate change is possible.

Economic

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Decrease in fuel consumption can have an influence over the cargo price in the long run, but it is not the main culprit when it comes to decreasing it. The USP requirement was to keep the OPEX as low as possible while still maintaining similar operations. Modifications were not made to the profit and loss statement items and thus, no reduction could be achieved in any other category than the fuel costs. A case scenario for OPEX reduction shows potential of decrease in this area but more studies are needed. For future research, more in-depth analysis and information is needed to conclude whether VOYEX and CAPEX can be decreased.

Overall outlook

The present work has filled in the gap in the Literature by providing an insight into performance of a WASP vessel in the South Pacific Region. The research has shown that the introduction of WASP technology on new builds or retrofits has the potential to considerably decrease fuel consumption, emissions, costs while complying with international standards and regulations. The present developed tool can be further used for other new build designs or retrofits. Thus, the goal of this work has been achieved and the customer requirements from the USP-MCST partners were solved as well. It is firmly believed that soft sails WASPs can be the potential solution towards the 2030 40% emissions reduction and a potential aid in the full decarbonatization target of 2050.

8.2. Recommendations for Future research

Prospects of alternative WASP technologies:

The present study has considered the soft sails as the optimal technology applicable to the Pacific study case due to the solid research and widespread applications which prove the fuel and emissions reduction. The literature review performed in this thesis has shown that there are other viable solutions such as Flettner rotors, wing sails or towing kites. The application of these technologies is however limited and inconclusive for a wide range of vessels and thus were omitted from the present research. A recommendation in this regard for future research is the study of the aforementioned technical solutions on vessels of the SV Kwai's size in order to get an insight into the best abatement measure. Flettner rotors particularly are believed to be 10 times more efficient than traditional sails and could bring considerable fuel and emissions reductions. Consequently, the study of more abatement measures and calculation of the CATCH indicators can aid in creating the MACC curve for comparison purposes.

Market analysis and competitiveness:

Island Venutres LTD, the owner of SV Kwai had various competitors in the South Pacific region. Most of these companies are container shipping vessels which take advantage of the economy of scale to generate profit. The present work has concluded that SV Kwai is a competitive player in the region but this has only been proven in the model for a particular voyage. An in-depth market analysis research paired with the design tool developed in this thesis could a provide a better insight on how competitive can a company with WASPs vessels be for various other shipping routes.

Study on social impact

The needs analysis in this thesis has identified potential sectors on which the introduction of WASP vessels can have an impact on the local communities. Due to the lack of data, time and complexity of empirical methodologies, the port infrastructure, job prospects and population well-being have not been elaborated in detail. Further studies on these aspects could help to give an insight into how these needs of the local communities can be addressed properly through he improvement of maritime transportation.

Life cycle Impact assessment

The present work has employed an adaptation of the LCIA method by assessing the operational cycle of the vessel and its impacts. In order to complete the study, a full LCIA is needed to estimate the total impact of a WASP vessel from conception to scrap. Thus, further research and impact analysis should be conducted into: manufacturing, fuel, retrofit and residue (coating, waste water). Pairing these with the operational results from the present work can provide an insight into the damage to human health, biotic and abiotic natural environment, biotic and abiotic natural resources and biotic and abiotic man made environment.

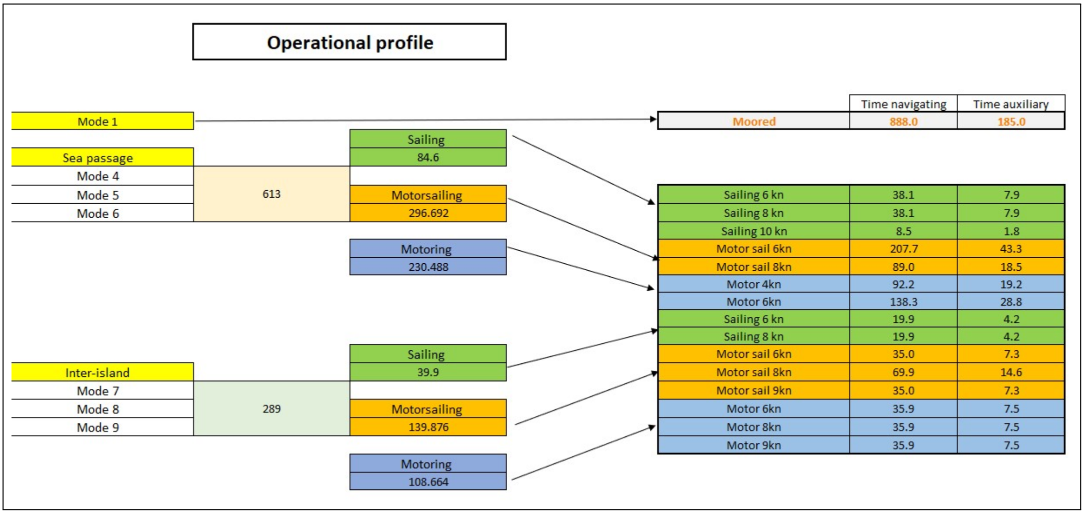
Personal reflection

My master thesis has proved to be a challenging but rewarding experience from which I have learnt a great deal of knowledge. The work encompasses technical, environmental, economic and social perspectives and considerations for the design of a sustainable vessel. With that, the topic has a unique characteristic to it and a complexity which made the final result much more fulfilling. My journey began in 2021 when my mentor Dr. A.A.Kana, provided a list of topics out of which this specific one "Methodology for sustainability assessment of marine transport in the South Pacific region" stood out for me. I pursued this path and in my initial project definition stage I met Dr. Peter Nuttall and Andrew Irvin. Their insights, knowledge, recommendations and research shed light over the complex issue that I had to deal with. After our conversations, I decided to develop a methodology which assess the impact of WASP vessels on the triple-bottom line aspects: social, economic and environmental. The first four months of my thesis consisted in the Literature review writing. Here, I conducted a needs analysis, a rundown of all available WASP technologies and an overview of applicable methodologies to the current case. The needs analysis was particularly hard to do because the literature on the chosen needs aspects was scarce. This prompted me to scope down my socio-economical approach and only study more tangible subjects such as: inter-island transport, cargo prices and ship finances. Other subjects like local port infrastructure, job prospects or shipping competition were slightly touched upon but more under the shape of a reflection of the WASP vessel influence rather than a conclusive quantification of parameters. From a methodology perspective, I decided to create my own unique framework which I considered to be fitting for this particular situation. I bumped into a problem when I discovered that the original LCIA actually requires a complex tool in order to calculate all the impact categories. Due to lack of time and knowledge on how to use the tool, I decided to adapt the LCIA philosophy to my particular situation and add economic and social elements, besides the environmental categories. As a result, I blended various frameworks to create the Operational Cycle Impact Assessment, which studies a vessel's propulsion technology only from its operational side. The following stage of my thesis was the the exploration of proven sustainable vessels in the region. This is where I was introduced to Captain Brad Ives, the owner of Sailing Vessel Kwai. Because of its proven sustainable navigation history, I chose this vessel as my case study to develop a tool for the methodology. I have elaborated on the sailing profile and the technical details of the vessel but what I found fascinating is how this ship could attain such fuel consumption and emission reduction considering the old age of the vessel and engine. These two factors have been on the other hand my biggest challenges as well because it was difficult to calculate the engine load balance with the soft sails. My calculations showed that the engine is overdesigned and is actually operating in very low efficiency which in turn increases fuel consumption and emissions. This low efficiency in motor sailing mode has been confusing during the calculation process because the specific fuel consumption was much higher than expected. Nevertheless, the calculations showed that the amount of time spent in motor sailing is more fuel efficient than the time spent motoring, even with this low power fuel efficiency. As I have highlighted in my thesis, I strongly believe that a more efficient fuel engine would work wonders for the overall fuel consumption and emissions release of SV Kwai. Lastly, I conducted a case study on this vessel in order to verify that my tool is working. I am proud to say that with assumptions and created rule of thumbs of the operational profile, I was able to create a tool which can be used for assessment of future WASP vessels. The rules of thumb were particularly tricky to create and required a few iterations before I could find the rule that applies to the operational profile of the vessel. The rules of thumb had to check two individual voyages, with two different routes and slightly different fuel consumptions. This was a difficult and time-consuming process but once I managed to establish the rule, the calculations that connect the operational profile to power load balance, fuel consumption and emissions were much easier to make. As a conclusion of the overall work, I believe my tool is a good method for an early stage design of WASP for the South Pacific environment and can be applied for future vessels in the region. It gives an estimation of fuel consumption, emissions, cargo price, finances, and compliance to international standards and is helpful in deciding between various soft sails designs. The tool is not yet entirely user-friendly and requires my help for utilisation. I hope my work can contribute to the climate change mitigation in the South Pacific region and my results can inspire other researchers to further explore the possibilities of sustainable shipping in the region.

ANNEX

A. TOOL SHEETS

The Excel tool was compiled by Laurentiu Lupoae. Each individual screenshot represents the general calculation and the methods. The tool contains several other hidden sheets with more detailed calculation. All screenshots display the simplified version of the tool in order to show the calculation mechanism. In conclusion, the tool is not considered to be yet user-friendly.



Resistance calculation data

General data		
g	9.81	m/s
rho	1.03	t/m^3
Length BP	33.50	m
Breadth moulded	7.13	m

Calc. coefficients		
D_p	1.20	m
k_p	1.00	-
w	0.18	-
t	0.17	-
eta_trm	1.00	-
eta_d	0.50	-
eta_h	1.01	-
eta_R	0.99	-
eta_o	0.50	-
gearbox ratio	1.00	-

Engine		
PB	250.00	hp
Pb	183.87	kW
n_e_nom	20.00	rps
n_e_nom	1200.00	rpm
P_B_nom	0.00	kW
M_B_nom	0.00	kNm

Design/summer		
Draft	2.74	m
Design speed	6.00	kts
Design speed	3.09	m/s
C_b	0.70	[-]
Deadweight	277.00	t
Displacement	484.88	m^3

Resistance data		
P_b	183.87	kW
c1	4.38	-
eta_trm	1.00	-
eta_d	0.70	-
P_E	128.71	kW
C_E	0.07	-

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WASP Calculation

WASP-Kwai		
Nominal sail area (TOTAL)	434	m2
Foretriangle sail area(Af)	0	m2
Main sail area (Am)	165	m2
Mizzen sail area (Ay)	77	m2
Jib sail area (Aj)	112	m2
Mizzen staysail area (Ays)	80	m2

AR	1.884700461
density air-q	1.293
Thrust	C*A*(ro/2)*(v^2)
Calculation factor-A	7.014525

Parameter		
EHM	26	m
BMAX	7.1	m
FA	2	m
EDMC	0.25	m

Lift				
Apparent wind angles [deg]	Main(CLm)	Jib(Clj)	Mizzen(Cly)	Mizzen staysail(Clys)
27	1.5	1.5	1.3	0
50	1.5	0.5	1.4	0.75
80	0.95	0.3	1	1
100	0.85	0	0.8	0.8
180	0	0	0	0

Drag				
Apparent wind angles [deg]	Main(Cdm)	Jib(Cdj)	Mizzen(Cdy)	Mizzen staysail(Cdys)
27	0.02	0.02	0.02	0
50	0.15	0.25	0.15	0.1
80	0.8	0.15	0.75	0.75
100	1	0	1	1
180	0.9	0	0.8	0

	Lift(kN)	Drag(kN)	Asp(-)	Arp (-)	As(kN)	Ar(kN)
27	5.3333664	1.417535269	0.92	0.23	3.68	0.92
50	4.8751272	1.910883431	1.07	0.59	4.28	2.36
80	3.5929884	3.499444095	1.14	0.75	4.56	3
100	2.7499524	3.865789775	0.99	1.02	3.96	4.08
180	0	2.415230904	0	0.71	0	2.84

	Lift coefficient(Cl)	Visc. Drag coefficient(Cdp)	Induced drag coeff(Cdi)	Drag of mast(Cdo)	Drag coefficient(Cd)
27	1.188	0.016	0.246	0.054	0.316
50	1.086	0.167	0.205	0.054	0.426
80	0.800	0.614	0.111	0.054	0.780
100	0.613	0.742	0.065	0.054	0.861
180	0.000	0.484	0.000	0.054	0.538

50	80	100	180	Average Thrust(N)	Average thrust(kN)	Vair(m/s)	Vair (knots)
2985.8	5467.9	6040.3	3773.8	4566.9	4.6	5.0	9.7
4299.5	7873.7	8698.0	5434.3	6576.4	6.6	6.0	11.7
5852.1	10717.0	11839.0	7396.6	8951.2	9.0	7.0	13.6
7643.5	13997.8	15463.2	9660.9	11691.3	11.7	8.0	15.6
9673.8	17715.9	19570.6	12227.1	14796.9	14.8	9.0	17.5
11943.0	21871.5	24161.2	15095.2	18267.7	18.3	10.0	19.4
14451.1	26464.5	29235.0	18265.2	22104.0	22.1	11.0	21.4
17198.0	31495.0	34792.1	21737.1	26305.5	26.3	12.0	23.3
20183.7	36962.9	40832.4	25510.9	30872.5	30.9	13.0	25.3
23408.3	42868.2	47355.9	29586.6	35804.8	35.8	14.0	27.2
26871.8	49210.9	54362.7	33964.2	41102.4	41.1	15.0	29.2
30574.1	55991.1	61852.6	38643.7	46765.4	46.8	16.0	31.1
34515.3	63208.7	69825.8	43625.1	52793.7	52.8	17.0	33.0

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Power calculation

Op. profile		V[kn]	V[m/s]	Va[m/s]	R(kN)	PE(kW)	PB(kW)	PT(kW)	Thrust (kN)	Vair thrust	PD(kW)	Motorsailing thrust(kN)	PT-motor sailing(kW)	PE-motorsailing(kW)	PB-motorsailing(kW)
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00				
		1.00	0.51	0.51	0.22	0.11	0.16	0.11	0.22		0.06				
		2.00	1.03	1.03	0.80	0.82	1.17	0.81	0.79	6.58	0.41				
		3.00	1.54	1.54	1.71	2.64	3.76	2.61	1.69	11.69	1.32				
		4.00	2.06	2.06	2.93	6.03	8.62	5.97	2.90	18.27	3.03				
		5.00	2.57	2.57	4.49	11.54	16.48	11.42	4.44	22.10	5.79				
Cruise speed		6.00	3.09	3.09	6.53	20.16	28.79	19.96	6.47	26.31	10.12	3.88	11.97	12.09	17.28
		7.00	3.60	3.60	9.58	34.49	49.27	34.15	9.48	30.87	17.31	5.69	20.49	20.69	29.56
		8.00	4.12	4.12	14.64	60.26	86.09	59.67	14.50	35.80	30.25	8.70	35.80	36.16	51.66
		9.00	4.63	4.63	23.45	108.56	155.09	107.49	23.22	41.10	54.49	13.93	64.49	65.14	93.05
		10.00	5.14	5.14	36.19	186.18	265.97	184.33	35.83	52.79	93.45	21.50	110.60	111.71	159.58
Max by sails		11.00	5.66	5.66	62.01	350.87	501.25	347.39	61.39	65.95	176.12				

					Vair (m/s)	kN
				1	1	0.182677316
				2	2	0.730709263
				3	3	1.644095841
				4	4	2.922837051
				5	5	4.566932893
	2.0	0.8		6	6	6.576383366
	3.0	1.7		7	8	11.69134821
	4.0	2.9		8	10	18.26773157
	5.0	4.4		9	11	22.1039552
Cruise speed	6.0	6.5		10	12	26.30553346
	7.0	9.5		11	13	30.87246636
	8.0	14.5		12	14	35.80475388
	9.0	23.2		13	15	41.10239604
	10.0	35.8		14	17	52.79374424
Max speed	11.0	61.4		15	19	65.94651097
				16	21	80.56069623
				17	22	88.41582081
				18	23	96.63630001
				19	24	105.2221339

	Good wind time	Average wind time	Poor wind time	
	Ms-Sailing	Ms-Sailing	Ms-Sailing	
Air speed [knots]	60/40	50/50	70/30	Average thrust [kN]
6 knots- 7.9 kN	3.88	3.23	4.53	3.88
7knots- 11.6kN	5.69	4.74	6.64	5.69
8 knots- 17.7kN	8.70	7.25	10.15	8.70
9knots-28.4kN	13.93	11.61	16.25	13.93
10 knots-43.8	21.50	17.92	25.08	21.50

Motoring		
6	2.59	1.94
7	3.79	2.85
8	5.80	4.35
9	9.29	6.97
10	14.33	10.75

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Environmental calculation

Port	Mooring/Port	Main Engines P / P_max [%]	L/h	Total [l]	Eletrical Gen P / P_max	L/h	Total [l]
Port	Mooring/Port			0.00	0.75	35.40	6549.00
Sea passage	Sailing 6 kn	0.00	0.00	0.00	0.90	8.24	65.35
	Sailing 8 kn	0.00	0.00	0.00	0.90	8.24	65.35
	Sailing 10 kn	0.00	0.00	0.00	0.90	8.24	14.52
	Motor sail 6kn	0.09	9.00	1869.16	0.90	8.24	356.52
	Motor sail 8kn	0.28	22.00	1958.17	0.90	8.24	152.80
	Motor 4kn	0.05	5.00	460.98	0.90	8.24	158.27
	Motor 6kn	0.16	14.00	1936.10	0.90	8.24	237.40
Inter island	Sailing 6 kn	0.00	0.00	0.00	0.90	8.24	34.23
	Sailing 8 kn	0.00	0.00	0.00	0.90	8.24	34.23
	Motor sail 6kn	0.09	9.00	314.72	0.90	8.24	60.03
	Motor sail 8kn	0.28	22.00	1538.64	0.90	8.24	120.06
	Motor sail 9kn	0.51	31.00	1084.04	0.90	8.24	60.03
	Motor 6kn	0.16	14.00	502.03	0.90	8.24	61.56
	Motor 8kn	0.47	30.00	1075.77	0.90	8.24	61.56
	Motor 9kn	0.84	47.00	1685.38	0.90	8.24	61.56
				12424.98			8092.47

CO2 saving	55912100.24 g
Total with sails	55.91210024 t
	88419878.31 g
Total withtout sails	88.41987831 t
carbon reduction	0.632347627
	37%
Total Sox	379.6203297
Sox no sails	576.2106186
	0.658822169

	Main Engines SFC (g/kWh)	Electrical genearation SFC (g/kWh)	Main Engines CO2 (g/kWh)	Generators CO2 (g/kWh)
Mooring/Port		189.25		606.72
Sailing 6 kn	0.00	175.1	0.00	561.37
Sailing 8 kn	0.00	175.1	0.00	561.37
Sailing 10 kn	0.00	175.1	0.00	561.37
Motor sail 6kn	442.79	175.1	1419.57	561.37
Motor sail 8kn	362.01	175.1	1160.62	561.37
Motor 4kn	493.25	175.1	1581.37	561.37
Motor 6kn	413.27	175.1	1324.94	561.37
Sailing 6 kn	0.00	175.1	0.00	561.37
Sailing 8 kn	0.00	175.1	0.00	561.37
Motor sail 6kn	442.79	175.1	1419.57	561.37
Motor sail 8kn	362.01	175.1	1160.62	561.37
Motor sail 9kn	283.17	175.1	907.83	561.37
Motor 6kn	413.27	175.1	1324.94	561.37
Motor 8kn	296.19	175.1	949.60	561.37
Motor 9kn	257.59	175.1	825.83	561.37
Total	3766.337533	2815.745283	12074.88	9027.28

Main engines CO2 per voyage	Generators CO2 tone total per voyage	Main engines Sox(grams)	Generators Sox(grams)
	17.8466799		34.97536698
0.00	0.18	0.00	1.39
0.00	0.18	0.00	1.39
0.00	0.04	0.00	0.31
5.09	0.97	91.87	7.57
5.34	0.42	32.19	3.24
1.26	0.43	45.43	3.36
5.28	0.65	57.09	5.04
0.00	0.09	0.00	0.73
0.00	0.09	0.00	0.73
0.86	0.16	15.47	1.27
4.19	0.33	25.29	2.55
2.95	0.16	9.89	1.27
1.37	0.17	14.80	1.31
2.93	0.17	10.61	1.31
4.59	0.17	9.23	1.31
33.8593	22.05279291	311.8790013	67.74132842

Kwai w sails	21569
Kwai no sails	30796
fuel saving	9227.00
Kwai cost saving	7842.95
My estimate with sails	20517.45
My estimate no sails	32446.47
fuel saving	11929.02
My cost saving	10139.67

CII	36.10
EEDI	28.26
CATCH	34.93

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Ship finances

Investment costs-ship	$700,000.00
Sails cost	$131,400.00
Book value	$300,000.00
Vessel age	71
LDT	69.25
2nd value	6925
Useful life	5
Depreciation	$58,615.00
PP&e current	$1,237,329.00
PP&e prior	$1,237,329.00
total cargo moved per voyage	2586
total cargo moved per year	10344

Comparison	Price per m3
Fiji-Tuvalu	$270.00
Fiji-Kiribati	$250.00
Fiji-Tonga	$100.00
Singapore-Fiji	$90.00
Fiji-Samoa	$90.00
SV Kwai- Kiribati islands	$88.74

Voyage expenses	
Canal passage	-
Fuel costs	$69,759
Port and light fees	$6,701
Total	**$76,460**
Operational expenses/year	
Crew costs	$187,169
Maintenance costs	$296,058
Administration	$131,987
Insurance	$17,053
Total	**$632,267**
CAPEX	**$58,615**
Cargo handling	**$150,562**
Cash flow	$917,904
Price per m3	**88.74**

	Fuel consumption [liters]	Cost
Voyage 1	20517.45	$17,439.83
Voyage 2	20517.45	
Voyage 3	20517.45	
Voyage 4	20517.45	
Total	**82069.80**	**$69,759.33**

Cargo operation		
		2020
Charters		$642,000.00
Freight		$204,770.00
Passengers		$6,929.00
Interest		-$596.00
Sales	$447,191.00	
Purchase cargo	-$291,826.00	
Commissions	-$5,462.00	
Profit from sales		$149,903.00
Exchange/Earnings/Loss		-$32,724.00
Cargo Costs		
Agency	-$10,433.00	
Bad Debts	-$75,413.00	
Claims	-$873.00	
Port Costs	-$6,701.00	
Stevedores	-$57,142.00	
Total Cargo Costs		$150,562.00
Gross profit		$1,120,844.00
Ship Administrative Costs		$679,238.00
Operating Profit		$140,482.00
Dividents Paid		
Accummulated Bad Debt		-$247,980.00
Net profit		-$107,498.00
Investment		$0.00
Divident Reinvestment		$0.00
Operating Costs per day		$1,861.00
Ops Cost no CPS or Fuel		$1,493.00
Operating Profit Return on Investment		11%

Ship and admin expenses	
Ship expenses	2020
Cargo profit sharing	$87,235.00
Crew's wages	$187,169.00
Deck	$45,554.00
Engineering	$22,579.00
Food & Stewart	$64,482.00
Fuel, oils propane	$46,971.00
Materials	$3,039.00
Medical	$2,278.00
Paint	$7,122.00
Professional fees	$10,246.00
Safety equipment	$17,286.00
Sails and rig	$285.00
Shipyard	$31,783.00
Tool	$4,169.00
Total	$530,198.00
Administrative costs	
Insurance	$17,053.00
Licenses and Certificates	$8,260.00
Office	$2,435.00
Shore	$12,210.00
Shore crew	$65,865.00
Taxes	$0.00
Travel	$12,753.00
Utilities	$9,511.00
Warehouse	$20,953.00
Total	$149,040.00
Ship& Shore	$679,238.00

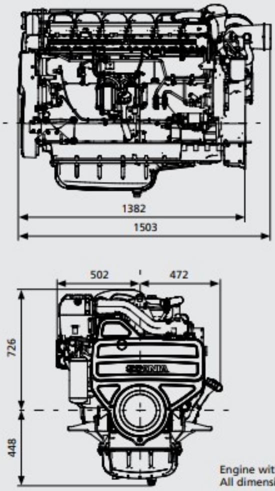
B. REFERENCE ENGINE DETAILS

DI13 080M. 184 kW (250 hp)

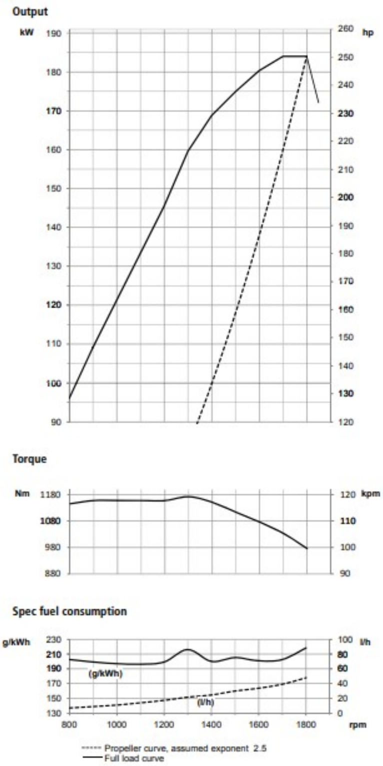
US Tier 3, IMO Tier II, CCNR II

Engine description

No of cylinders	6 in-line
Working principle	4-stroke
Firing order	1 - 5 - 3 - 6 - 2 - 4
Displacement	12.7 litres
Bore x stroke	130 x 160 mm
Compression ratio	17.3:1
Weight (excl oil and coolant)	1285 kg (Engine with heat exchanger) 1180 kg (Engine with keel cooling)
Piston speed at 1500 rpm	8.0 m/s
Piston speed at 1800 rpm	9.6 m/s
Camshaft	High position alloy steel
Pistons	Steel pistons
Connection rods	I-section press forgings of alloy steel
Crankshaft	Alloy steel with hardened and polished bearing surfaces
Oil capacity	28-34 dm³ (standard oil sump)
Electrical system	2-pole 24V



Engine with heat exchanger
All dimensions in mm



Test conditions Air temperature +25°C. Barometric pressure 100 kPa (750 mmHg). Humidity 30 %. Diesel fuel acc. to ECE R 24 Annex 6. Density of fuel 0.840 kg/dm³. Viscosity of fuel 3.0 cSt at 40°C. Energy value 42700 kJ/kg.
Power test code ISO 3046. Power and fuel values +/-3%.

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