EVALUATION AND ADAPTIONS TO THE GREENHEART PROJECT ZERO-EMISSION VESSEL FOR SERVICE IN THE PACIFIC ISLANDS

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SUMMARY

This paper provides an evaluation on the suitability of the Greenheart Project vessel design for the Pacific Islands and proposes adaptations for an improved design that is specifically tailored to an updated set of requirements. The Greenheart Project vessel design was developed by an open-source design process and is part of an initiative to develop zero-emission sail and solar ships for remote island locations. The original vessel design stands unaltered since 2014 and the design has now been tested against an updated set of client requirements which were developed in cooperation with local stakeholders. Proposed adaptations to the design are described and an alternative design is proposed that specifically matches with the proposed client requirements. Three types of requirements are developed and discussed: technical, operational, and economic. The research results in adaptations which are integrated into a final design. This paper discusses the evaluation of the Greenheart Project, the considered adaptations and elaborates specifically on the propulsion system.

1. INTRODUCTION

This paper presents a third-party evaluation and assessment of the Greenheart Project vessel design against a set of specific client requirements in order to clearly define the deficiencies in the design and to provide guidance on an improved concept. The Greenheart Project is a non-profit organisation with a mission to develop new types of simple, sustainable, low-cost, zero-emissions, sail/solar-powered ships.

The evaluation was performed by a group of student researchers at Delft University of Technology in close collaboration with regional stakeholders from the University of the South Pacific. During the problem discovery phase, it became clear that key differences existed between the visions of the original Greenheart Project and the current needs of the local stakeholders. For example, one of the features of the original design was its ability to perform beach landings. However, while formulating the updated requirements with the stakeholders, from communication with the end user it became clear that performing beach landings in the Pacific was neither desired nor practical. It was therefore important to maintain close contact with the client in the region during the entire project. The main focus was to ensure the revised vessel was both operationally suitable and tailored to the specific requirements of the region.

In this region, low financial investments both CAPEX and OPEX, robustness, and reliability are particularly important. Harbor and maintenance facilities are limited, and the weather conditions in the Pacific can be challenging. Despite this, these vessels are key to the region, as many islands fully depend on them to provide food and other necessary supplies. It is thus necessary to develop suitable vessel solutions for this region which meet the unique technical, economic, and operational needs.

In the past decade there has been a lot of interest in green and sustainable shipping and many projects and studies have been undertaken concerning this topic. For example, the Transitioning to Low Carbon Sea Transport (TLCSeaT) project provides operational and technical options to reduce emissions and fuel consumption (Vahs *et. al*, 2019). The TLCSeaT project is being carried out for the Marshall Islands. This project is thus not only focused on reducing the carbon footprint of sea transport, but is also focused on the Pacific Islands, and their unique complex characteristics. The Micronesian Center for Sustainable Transport has published several studies on zero- or low-emission vessels. For example, the Cerulean Project by the Micronesian Centre for Sustainable Transport (2019) focuses its attention on the cargo and routing in the South Pacific region. Its analysis covers the most optimal routes and most common cargo types transported within the region based on demands.

Reducing carbon production requires smart and inventive ideas. However, the end user demands a robust and simplistic vessel for operation and maintenance in the region. This contrast outlines the complexity of this project. The need for a 'greener' vessel is clear, but the ship being able to sail in all conditions at any time is important from a safety and performance perspective. Cargo handling must be simple and even more important, the project must be economically viable. Only when these conditions are met, a cleaner and more environmentally friendly vessel can be realized. Within the TLCSeaT project, a lot of attention is given to the wind flows in the Pacific and the different options to sail vessels when taking performance and emission reduction into account. In the project, numerous design options are given together with their logistical capabilities. Furthermore, study has been done into how the local population can be trained and how the Pacific as a region can develop smarter and better sea transport. This means the project will be very useful for this evaluation and adaption of the Greenheart Project design.

The analysis of routes and cargo provided by the Cerulean project allows for a clear overview of what the demands are within the region and how these can be met in an efficient manner. Routes and cargo types are analysed upon their strengths, weaknesses, opportunities, and threats. This analysis, while not a technical analysis of any specific vessel, does provide good insight for the development of a vessel design for this region. More common and necessary cargo types within the region are clearly presented leading to possible alterations to cargo hold layouts for vessels within the regions. For example, instead of having to fit a 20-foot container into the cargo hold, extra space may be more efficiently utilized for a cooled/freezing cargo compartment. The more optimal routes analysed in this report can be used as a basis for the technical and operational requirements of the vessel. A separate study of the Cerulean Project took into consideration the Greenheart Project vessel as this paper also does. The Cerulean Project started with the general features of the Greenheart Project and used them as a starting point to determine the general characteristics of a new vessel, more practical and suitable for the Pacific Islands.

This paper can be viewed as an exercise parallel to the TLCSeaT project and the Cerulean project due to the fact that within the project a good framework is outlined for the situation in the Pacific. Not only are regional infrastructure and economics discussed, but attention has also been paid to different options on how emissions can be reduced, and sea transport can be improved. Creating a final design, suited for the region is the next big challenge. Every detail needs to be worked out, so that one engineered vessel together with its costs and operational characteristics can be presented. The Greenheart Project was developed as an open-source design. This means that, already during the design phase, different ideas were discussed on a forum and taken into consideration for the design. This led to an interactive design process.

The study presented in this paper, took the Greenheart Project as a base and adapted several of its features. A systematic third-party evaluation of the Greenheart Project for the Pacific Islands and an implementation of adaptions has been done in order to create "an adapted version" of the design. Section 2 will present the methodology that has been used. The main features of the Greenheart design, the end user requirements and the evaluation of the Greenheart design are also presented in this section. In section 3, the possible adaptions to the design are given. In sections 4 and 5, an analysis of the obtained results is shown together with the conclusion and the discussion.

2. EVALUATION OF THE GREENHEART PROJECT DESIGN

This section describes the three steps performed for this evaluation: 1) definition of Greenheart Project design (Section 2.1), 2) development of client requirements (Section 2.2), and 3) evaluation of Greenheart Project design according to requirements (Section 2.3).

2.1 GREENHEART PROJECT DESIGN

In order to provide a clear basis for the analysis, the main features of the original Greenheart design are presented. The ship was designed as a "sustainable, low-cost, zero-emission sail/solar-powered ship designed to fill current weaknesses and gaps in the global shipping industry", (Greenheart Project, 2014). One of the main design features was to be a completely sustainable vessel with zero fuel emissions, which in turn was one of the leading design drivers behind many of the design decisions of the Project. Figure 1 shows the Greenheart Project design, where the dots represent the main features of the original design (Greenheart Project, 2014). Table 1 and Table 2 list the main features, dimensions and parameters of the vessel (Greenheart Project, 2014).

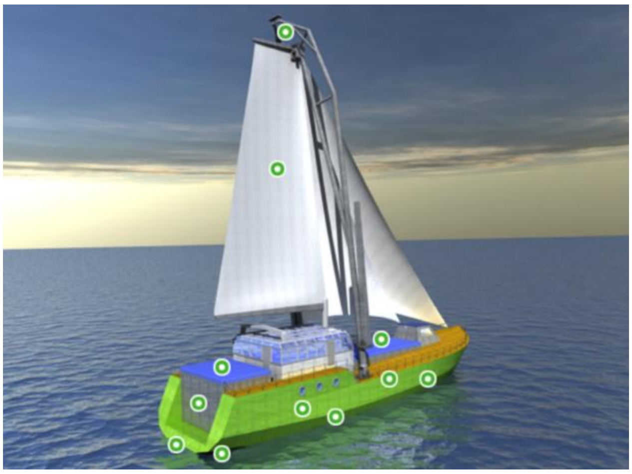

Figure 1. Greenheart Project Design (Greenheart Project, 2014)

Table 1. Main features of the original Greenheart vessel

Main Feature	Details
Shallow hull	Steel, shallow for beach landing and travel in shallow waters
Sails	Primary propulsion system with sail area of approximately 400 m^2
Folding mast/crane	Mast designed to pivot on an axis
Solar panels	Rooftop-style panels
Batteries/ballast	Lead-acid traction batteries of 600 kW; weight acts as 20 tonnes of ballast
Motors	Two electric driven motors of 150 kW
Cargo hold	3 TEU or 70 tonnes loose cargo
"Twin" bildge keels	For extra stability
RORO ramp	"Roll-On, Roll-Off" access to stern

Table 2. Main dimensions and parameters of the original Greenheart vessel

Parameter	Value
Length, LOA	32 m
Beam, B	7.5 m
Draught, T	2.4 m
Displacement, Δ	220 tonnes
Hull Speed, v [1]	10-11 knots

[1] Given projected hull speed (Greenheart Project, 2014).

2.2 UPDATED VESSEL REQUIREMENTS

In order to provide a well-founded evaluation of the main features of the Greenheart Project design, an updated set of end user requirements has been developed. Setting these requirements creates better insight into the wishes and concerns of the end user and forms a sound framework to assess the design. These updated requirements were necessary because of the misalignment of objectives of the original vessel and the local stakeholders. For example, the stakeholders were focused on developing a vessel that satisfied various requirements for the region, while the Greenheart project was more focused on creating a fully 'green' vessel. The Pacific is a complex region with many limitations, making the original design not a viable option. These limitations include geographical characteristics such as shallow shores making access by ship difficult as well as remote location of islands making bunker transport costs significantly higher.

These updated requirements have been listed as directly and quantitatively as possible as this ensures they are easily measurable and leave as little room for interpretation as possible. Three types of client requirements have been defined: technical, operational and economical, as given in Table 3.

Table 3. Client Requirements

Technical requirements	Operational Requirements	Economical Requirements
Length < 40 m	Sea State = 11 Bf	Vessel building costs < 2M US $ [2]
Draught < 3.5 m	Capable of ship-to-ship cargo transfer	Design Costs < 50,000 US $
Cargo capacity about 70 tonnes	Capable of low and deep draught port cargo transfer	Maintenance Costs < 50,000 US $/year
Minimum Speed = 6 kts	Crane Capacity = 5 tonnes, port side and starboard	Profit > 16,000 US $/week
Cruise Speed = 8 kts	Loose cargo of two types, dirty and clean	Fuel Costs < 70,000 US $/year
Accommodate 6-8 crew	Frozen cargo = 8 m^3	Payback < 3 years
Accommodate up to 8 passengers, such as a research team	Refrigerated cargo = 8 m^3	Reduced fuel consumption compared to existing fleet
Ability to be dry-docked close to shipping route	Ability to transport passengers and livestock	
Flagged in the Pacific region	400 nm on reserve power	
Meet all SOLAS, UNCLOS and IMO regulations	Ability to secure one TEU is optional	
Able to be produced and maintained by small-scale shipyards local to region		

For the technical requirements, the most relevant factor is dictated by the limited harbour facilities. This explains the maximum length and draught, based on small harbours and shallow water conditions, in which the vessel mostly operates. Furthermore, requirements have been set for the crew and passenger capacity along with ship speed.

The operational requirements are based on the variety and type of the cargo. Most of the cargo is transported loose, in sacks or pallets, and consists of necessities for the people living on the islands. The sea state must also be considered, meaning that the vessel must be able to travel in almost any weather condition whilst remaining on schedule. Because of this, the design must be capable of enduring the strongest sea states and wind speeds that occur in the region.

For the economical requirements, the design should comply with low building and low fuel costs. This last aspect is particularly important, because of the remote location of the region the fuel importation costs are very high. Therefore, a design in which the fuel consumption compared to the current fleet is reduced, is of high importance.

2.3 EVALUATION AND ASSESSMENT

After setting the end user requirements, the evaluation and assessment of the Greenheart Project was performed. For the evaluation, different features of the Greenheart Project were considered as stated in subsection 2.1. These are the features that will be discussed in more detail and can be classified into three main categories: hull design, propulsion system, and general arrangement. In the following subsections the features of the design belonging to the specific category will be discussed shortly.

2.3 (a) Hull design

The type of hull, the resistance of the hull and the building material were all analysed to determine areas of improvement. The original hull design was a steel monohull. After examining other options such as aluminium, composites, or multi-hulls, with the requirements for robustness and costs a steel monohull was again considered the most suitable decision. The steel monohull is the most accessible and common hull form for this application. The Greenheart Project added a RORO-ramp to the stern for beach landing, creating a flat afterbody. This feature negatively influences the resistance and was not required nor requested by the end user. Thus, the RORO-ramp has been removed resulting in an improved afterbody (see Section 3.1).

The original design also included a "twin” bilge keel for both extra stability and to ease the beach landings. Seeing as beach landings are not feasible, the bilge keels can be adapted accordingly. The original bilge keels are long, thick, and stick out below the bottom of the ship to act as supports for the beach landings. This increases the draught of the ship and increases resistance due to the large thickness and surface area of the bilge keels. The new bilge keels can be designed purely for stability in sailing conditions which will result in different dimensions.

[2] Following from limited resources in the pacific region.

2.3 (b) Propulsion system

In the original Greenheart Project vessel, the sails were the prime movers of the vessel which were supported by two electric drive engines used for approach and departure from harbours and for emergency manoeuvres, (Greenheart Project, 2014). These electric engines were powered by 600 kWh of batteries resulting in a range up to 55 nautical miles when sailing on the engines only, (Greenheart Project, 2014). The updated requirements, however, state that the vessel should be capable of travelling 400 nautical miles without sails, which is a much longer range than considered by the Greenheart Project. Thus, the vessel should not only be capable of doing the manoeuvres in and from harbours but should also be able to travel between harbours on the engine propulsion system only.

The sails will remain as the prime movers of the vessel when the weather conditions allow. In-ideal conditions the vessel will be propelled fully by the sails. In other conditions, the vessel would be able to motor-sail, even using both sail and engine power. However, the vessel must be able to reach its next port of call, even when the weather does not permit sailing. Thus, the engine propulsion system should also be capable of providing the full power necessary to achieve the designed speed and range.

In order to minimize the need for an alternate propulsion system, the sails and the mast have been analysed. The Greenheart Project designed a foldable A-frame mast which also could be used as a crane. The end user requirements specify no height restriction and require cargo handling on port side and starboard which make the folding, dually used crane too complex and less robust. However, the A-frame is a practical design feature and allows for variable sail-configurations. The current design gives two options when it comes to sail-configurations: cutter rig and schooner rig. If the mast configuration is changed, the variable sail-configurations could also be investigated further with respect to sail areas and performance for various wind angles. The Greenheart Project features Dacron or Ripstop sails. Dacron could be used but only certain types and qualities as it is applied to large sail areas and under challenging conditions like UV exposure and instantaneous high loads.

The current electric propulsion system of the Greenheart ship does not meet the end user requirements. In order to extend the sailing range up to 400 nautical miles without the sails, while maintaining the current electric drive motors and the batteries, an additional generating system should be installed to power the electric engines. This system is needed because the solar panels provide approximately 20 kWh, which is not enough power to sail the vessel on the electric motors alone. Furthermore, the vessel will also need climate control systems for both personal spaces as well as cargo spaces which need cooling and refrigeration. Heating and cooling systems are very power consuming, so an alternative power generator is certainly needed. However, the more energy that can be generated from the solar system the better.

For this reason, a closer look has also been taken at the solar panel configuration. Already addressed on the forum of the Greenheart Project, (Greenheart Project, 2014), the position and number of the solar panels have been a subject of discussion. A balance was needed between creating a large enough surface area for the solar panel system without making the panels a practical hindrance. The latter is especially important, since the Greenheart vessel will become a sailing vessel and walking and working around the deck is important for safe operation. Furthermore, the vessel is also a cargo vessel so safe operation when loading and unloading cargo is just as important. In a next phase, the available solar panel space will be assessed so that an optimum balance can be found between maximum panel surface area and safe operation considerations.

The last element of the propulsion system that was analysed were the batteries. As stated in subsection 2.1, the batteries were used for two main purposes: store power from the solar panels to feed the engines and as ballast. Lead-acid batteries were considered by the Greenheart Project as they are a good option because these are widely available in the Pacific Island region and easy in use and maintenance. The addition of a diesel motor as a main power source prompts an evaluation of the size of the batteries as the power demand for the batteries change from providing additional propulsion to providing auxiliary power.

2.3 (c) Cargo hold

The final aspect to be evaluated was the cargo hold. As stated in subsection 2.1, the original capacity of the Greenheart Project is 3 TEU (Twenty-foot Equivalent Unit) or, alternatively, 70 tonnes in pallets. In this design, two cargo holds were present. However, from drawing up the end user requirements it became clear that the vessel does not need 3 TEU of container space and that in total four different types of cargo must be transported: clean and dirty lose cargo and refrigerated and frozen cargo. Here it must be noted that most of the islands, outside of capital/urban ports, do not have the infrastructure to handle twenty-foot containers. This means that the entire cargo space must be re-designed so that four new cargo spaces can be accommodated.

In connection with the cargo, the general arrangement of the ship must also be taken into consideration. The general arrangement of the original vessel is given in subsection 3.1, together with the new adaptions apported to the design. The cabins, the tanks and other facilities were also analysed, in correlation with the cargo arrangement. With this evaluation it should be noted that in the original design only a fresh and black water tank was installed since no fuel tanks were necessary. However, it will be likely that in order to meet the end user requirements an additional propulsion system will be necessary. Therefore, the vessel will be partly dependent on fuel. Regarding the cabins, the original Greenheart design does meet the end user requirements Table 2.

3. ADAPTIONS FOR IMPROVED DESIGN

After analysis of the existing Greenheart vessel, this section proposes modifications for improvement. To do so, the features discussed previously are modified and tailored to fit the requirements set by the end user and to optimize the vessel for its ultimate goals.

3.1 MAIN FEATURES

In the initial evaluation of the design, it became apparent that there were aspects of the design that were missing, some aspects that were not necessary, and others that had significant room for improvement. To address these, this research paid particular attention the hull design, bilge keels, RORO ramp, and the cargo hold.

For the hull design different options were studied: a monohull, a catamaran, and a trimaran, which is a common hull form in the region. Based on these requirements, the monohull was chosen. As a general cargo vessel, it will need significant displacement as well as space for accommodating a large number of crew and passengers. In addition to these requirements, the vessel has to have enough space for the necessary equipment such as a big enough engine room and the cooling system for the frozen and cooled storage rooms. Altogether, the current form of the vessel appears to be the optimal choice with the available information.

However, this current hull leaves significant room for improvement. As previously discussed, the original design is suited for beach landings by using the RORO ramp and has twin bilge keels designed, in part, to support this. As a relatively slow speed cargo vessel, viscous resistance dominates, thus necessitating a need to reduce wetted surface as much as possible to reduce frictional resistance. However, the original RORO ramp adds significant wetted surface to the aft of the vessel, adding unnecessary resistance. In the new final design, the hull shape has been modified to both reduce the wetted surface area and improve the flow. The lines plan was created following examples of existing similar ships given in (Versluis, 2009) and the indications given by (Larsson *et. al*, 2010). For the adaption of the keel, the length, position, and thickness were analysed. As stated in subsection 2.3, these adaptions were made taking only sailing condition into account and not beach landing. This re-dimensioning was done following the method presented in (Larsson and Eliason, 2000). The length of the fins across the hull as well as the keel draught and thickness of the fins were considered as main parameters, in order to determine the necessary adaptions. The length, thickness, and draught of the fins was significantly reduced with respect to the original vessel. The adaptions to the keel are based on the sail area and position and on the characteristics of the bilge radius.

At last, the main dimensions of the ship were changed according to the end user requirements. The ship was scaled in order to have a length over all of 40 meters. Taking the main scope of the project into account, the scaling was done without major changes to the hull-form. In figure 2 the proposed hull design is presented, as a 3D design as well as the lines plan. As visible in the figure, the bow is more rounded in order to decrease the wetted area, while the stern is slenderer. Also, no Ro-Ro ramp is present, and the keel is redesigned in order to better fit the new hull design. Last, it can be noted that in the proposed hull design, a submerged transom area is no longer present. In figure 3 the original hull shape of the Greenheart vessel is given (Greenheart Project, 2014). In order to compare the new design to the one of the Greenheart vessel, a resistance calculation was performed. For the original design, a CFD calculation was done (Greenheart Project, 2014) showing a resistance of about 14.8 kN for a speed of 8 knots. For this later determined design speed, a simple resistance calculation was done using the method of Holtrop & Mennen. This showed a resistance of about 10.9 kN. This method is not very precise, but is enough to give a first estimate of the gain that can be achieved with an improved design.

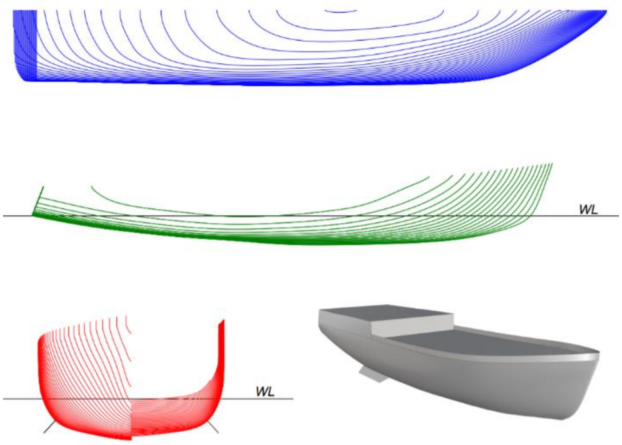

Figure 2. Proposed improved hull form with smaller bilge keels and modified underwater transom area.

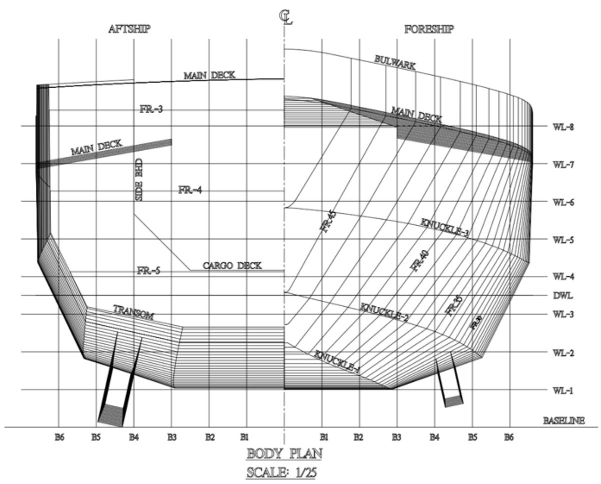

Figure 3. Hull form of the Greenheart vessel, (Greenheart Project, 2014) – see complete image in Appendix

The last element analysed is the cargo hold and the general arrangement. As stated in section 2.3, the original design only contained two separate cargo spaces and space for container, which were deemed insufficient and unnecessary respectively, according to the updated requirements. Two special holds, for frozen and refrigerated cargo, are needed on board as well as a space for potential livestock. It also became necessary to add or modify the diesel generators, engines, batteries (both configuration and number), fuel, lubrication oil, and ballast tanks to the proposed design.

In figures 4 and 5 the original general arrangement and the modified design are presented (Greenheart Project, 2014). Only the accommodation deck and the bottom deck are presented. In figure 4 the modified arrangement of the cargo spaces is visible. All the four needed holds are present and an extra space for livestock is included. In figure 5 the changes in the engine room and the changes in the tanks are visible.

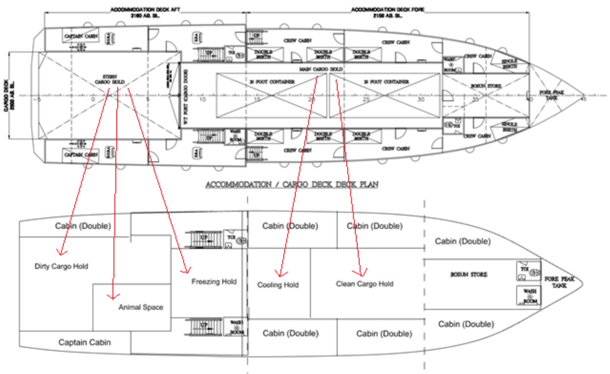

Figure 4. General arrangement of the Greenheart project (above) and adaption (below); Accommodation deck - see detailed image in Appendix (8)

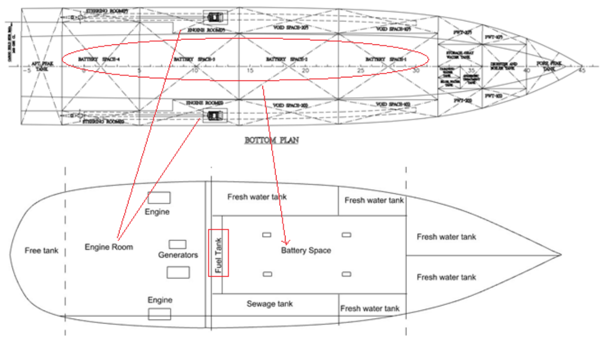

Figure 5. General arrangement of the Greenheart project (above) and adaption (below); Bottom deck - see detailed image in Appendix (8)

3.2 INSIGHT INTO THE ADAPTION OF THE MAST CONFIGURATION, SAILS AND ENGINE

3.2 (a) Mast configuration

During the open-source design of the Greenheart project, three different sail and mast configurations were developed by different designers. For these, the mast configuration, material, sail area and configuration, and crane capacity in longitudinal and transversal direction was analysed. The main characteristic of this part of the design is the dual use of the mast as crane and mast.

Taking into consideration the end user requirements, no maximum height is specified for the vessel. This is the case because a majority of the time the vessel will not enter a physical port in the Pacific. Most of the outer islands in the Pacific do not have a port, so cargo transferring will be done close to the coast of the islands. The ports that exist were mostly constructed during the Second World War and do not have any bridges that should be passed for entrance. This means that a folding mast is not necessary and makes the design both more complex and less robust. Another important parameter for the choice of the mast is the weight and location of the centre of gravity. This choice can be determined by analysing the material. Aluminium, even if it is more expensive, in the end makes for a better option than steel as it is a lighter material and needs less maintenance. The A-frame can be used as a crane for longitudinal cargo operations but not for transversal cargo operations. This last aspect, as stated in the end user requirements, is necessary since cargo will also be transferred from ship to ship.

3.2 (b) Sail configuration

From the analysis of the three designs and the end user requirements, various modifications have been proposed. A design with two masts is the most advantageous solution as it provides redundancy and the possibility to use different sail configurations. Different sail-configurations (figure 3) like a gaff rig or IndoSail, were considered using Hazen's model. This model was chosen as an easy available and fast approach to give a rough indication of sail performance. The sail areas of these configurations are given in table 4. The total sail area is smaller than the sail area of the original Greenheart design. Together with the increased displacement of the new design, this results in a lower sail/displacement ratio. Extensive discussion with the client led to smaller and more manageable sails in combination with propulsion redundancy by diesel generators. This was done in order to provide a robust and reliable design suitable for the pacific region. Other's wind-assisted propulsion options were studied but considered not applicable. This is for example the case for a Dynarig or a kite system since these systems proved to be either too expensive, too complex, or not robust enough to deal with the conditions in the Pacific region.

The lift and drag coefficients were calculated for the different configurations using Hazen's model found in (Larsson *et. al*, 2000). Also, the side force and driving force of the configurations were determined using apparent wind angles, lift coefficients and drag coefficients. The configurations with two jibs resulted in a higher driving force than the configuration with a foretriangle. Figures 7 and 8 provide the drive and side force, as a factor, for the configurations with two jibs. It can be seen that configuration 3B gives a higher driving force for a large range of apparent wind angles compared to the other configurations. This sail configuration features a mizzen, staysail, fisherman and two jibs as displayed in figure 9. After careful consideration, Clipper Canvas or Oceanus were chosen as the sailcloth because they are suitable for large sail areas, have high UV-resistance and a long lifespan.

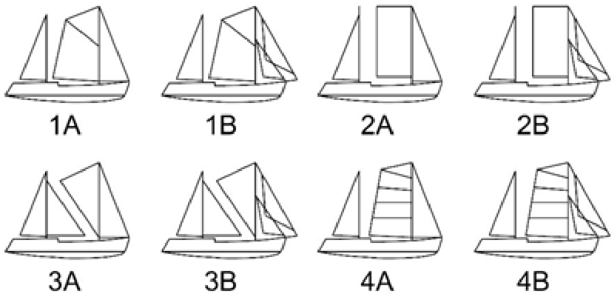

Figure 6 Studied sail-configurations

Table 4. Sail areas in parameters used in Hazen's model

Sail area [m^2]	1A	1B	2A	2B	3A	3B	4A	4B
Foretriangle A_F	75	0	75	0	75	0	75	0
Main sail A_M	130	130	160	160	100	100	170	170
Mizzen A_Y	55	55	55	55	55	55	55	55
Jib A_J	45	105	0	60	0	60	0	60
Mizzen staysail A_{YS}	0	0	0	0	70	70	0	0

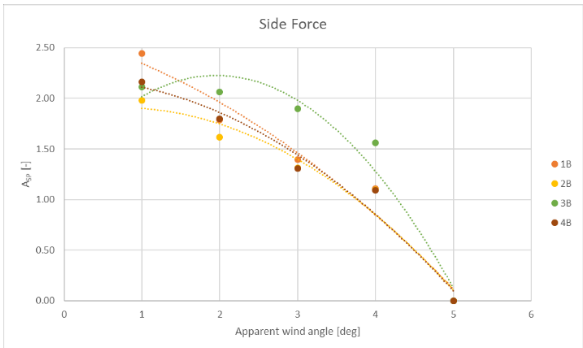

Figure 7. Side force coefficients for sail-configurations with two jibs

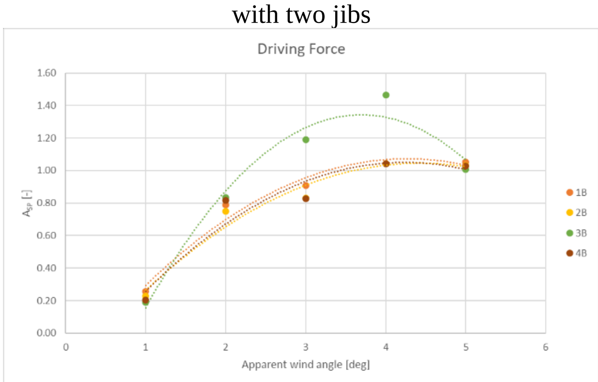

Figure 8. Drive force coefficients for sail-configurations with two jibs

Figure 9. Chosen sail and mast configuration

3.2 (c) Engine

From the evaluation of the Greenheart Project, it has become clear that the existing propulsion system does not meet the end user requirements. For the propulsion system the following end user requirements applied: minimum required speed of 6 knots and desired cruise speed of 8 knots, capability of travelling 400 nautical miles without sails, current estimated fuel costs per year about 70,000 US Dollars. This last requirement is a maximum that should be reduced as much as possible. Several alternative solutions have been taken into consideration in order to make the propulsion system comply with the requirements: diesel engines, a hybrid installation and diesel generators. Eventually, the most suitable solution needs to meet the requirements of the end user, has the highest degree of sustainability, and is designed to fit the needs and resources of the Pacific Islands region.

The first option requires removing the electrical engines and substituting them with two diesel engines. This is a very reliable and robust solution; however, it does mean a high increase in emissions. With a hybrid installation, the vessel would keep its low-emission profile. This solution consists of integrating a diesel engine with an electric motor powered by batteries. The maintenance and operation of the diesel electric hybrid system is complex and requires special skill, meaning special training for the crew and extra control systems. The last option consists of adding two diesel generators on board. This way the generators are linked directly to the electrical engines and can also generate all the power necessary on board.

Furthermore, generator sizes should be chosen smartly so that generators can work efficiently in different scenarios. For example, one smaller generator can be used when only power onboard is necessary, while another larger generator can be run in addition when the vessel also needs supplementary propulsion with the electrical engines. For the modified vessel installing diesel generators seems like the most suitable solution. In order to have efficient working points in different scenarios and for redundancy reasons, the decision has been made to install two generators. The solution is practical and suitable for the Pacific Islands region. Furthermore, the solution is still based on the electric drive engines. Since the propulsion system is only partly needed with the sails onboard and solar power can also be used for the engines, this alternative has a reduced fuel consumption compared to the current fleet in the Pacific Islands.

With the batteries not being the power supplier of the electric engines anymore, a closer look has also been taken at different types of batteries available for use in marine vessels. In the original Greenheart Project design, lead-acid battery banks were used. Next to lead-acid battery types, lithium-ion batteries are commonly used for electric motor drives. When choosing an appropriate battery type, suitability for use in the Pacific Island region is the most important factor. The conditions in this region differ in terms of availability of battery types and skills in the field of maintenance and service. Analysing these aspects, it was determined that lithium-ion batteries are currently not a suitable option. Also, disposal, recycling and acquiring of these batteries is not easy in the region. After making a trade-off between the different battery types which were studied, it was determined the use of a wet cell lead acid type as a starting battery for the electrical engines, and to use an AGM types as a deep cycle for the hotel services. Last, the adaption made for the batteries onboard is one of the more significant changes regarding stability. To reassure vessel stability, ballast tanks have been added to the design as shown in figure 5.

It should be noted that due to the diesel generators the design will not be a zero-emission vessel like the original Greenheart Project design. However, this decision has been made consciously. From the contacts with the end user, it became clear that the ship must be functional and practical in all conditions with a zero-emission profile as only an additional feature of the design. In current circumstances in the Pacific region, creating a zero-emission vessel that fits the end user requirements just is not feasible. The goal is to maximize efficiency for expanding service range and reducing fuel cost. In the future, if biofuel should be integrated into the operations, the vessel could achieve zero-carbon propulsion and regain a zero-emission profile.

Table 5. Summary table for the main dimensions

Parameter	Original Greenheart vessel design	Adapted Greenheart vessel design
Length, LOA	32 m	40 m
Beam, B	7.5 m	9.5 m
Draught, T	2.4 m	2.2 m
Displacement, Δ	220 tonnes	388 tonnes
Speed, v	10-11 knots [3]	8 knots [4]

Table 6. Summary table for the Evaluation and Adaptation

Parameter	Evaluation	Proposed modification
Shallow Hull (steel)	The maximum draught of the design is smaller than the one allowed and can be thus increased. The shallow hull, necessary for beach landing and useful for shallow waters can be made deeper as well.	The draught is increased, and the hull is made deeper in order to decrease the resistance of the vessel and reduce propulsion power. The dimensions are changed in order to maximize the cargo spaces but still stay within the requirements and limitations of the region.
Sails	Cutter or Schooner rig. Dacron could be used as sailcloth, but suitability depends on the type and quality; configuration to be modified for the choice of the mast.	Configuration with mizzen, staysail, fisherman and two jibs. Use Contender Oceanus or Clipper Canvas as sailcloth.
Folding Mast/Crane	A-frame is useful, but the foldable mast used as a crane is too complex and does not match with the end user requirements	Two non-pivoting A-frames from aluminium, for redundancy and flexible sail configuration; derricks for transverse cargo operation
Solar Panels	Charging method for the batteries. This was considered not enough to sail the required range and requires changes.	In order to sail the 400 nautical miles required, two diesel generators are added. Those are the energy source of the two electric motors. The solar panels are still present but in a lower number. They are still used to charge the batteries, now only necessary for the HVAC system and cargo spaces.
Batteries/ Ballast	Lead acid batteries are most suitable for availability in the region and ease of use. For ballast, tanks should also be considered and, if necessary, added to the design instead of using only the batteries for the purpose.	Fewer batteries installed since the electric engines are no longer powered by them. The ballast function is done by the electrical installation as well as by tanks added for the purpose.
Motors	Electric motors can be good for zero fuel consumption, emissions, and redundancy.	Two electric motors driven by batteries and diesel generators. No changes were made to the motors.
Cargo Hold	Suitable for 20' containers, not really handled in the Pacific islands. It does not suit the 4 necessary cargo holds required by the end user.	Four separated cargo holds with adjusted volumes are created. A dirty, clean, frozen, and cooled space are created. The volumes are adjust based on the average shipped cargo in the Pacific Islands.
"Twin" Bilge Keel	Important for the stability. To be modified for the new design if the sail and hull are changed.	Adapted for the new sail configuration and hull design, disregarding beach landing which is not present anymore in the design.
RORO Ramp	Not necessary. Designed for the beach landing, which is of no use in the Pacific Islands.	Not present anymore. Substituted by a sharp stern, more efficient from a resistance point of view.

[3] Hull speed
[4] Design speed

3.3 SUMMARY TABLES

As mentioned in the previous sections, several modifications were studied based on the original Greenheart Project vessel's features and the end user requirements. Tables 5 and 6 present a summary overview of the discussed evaluations and modifications.

4. CONCLUSION

In this project a third-party evaluation and assessment on the Greenheart Project vessel has been made to come up with a design more suitable to operate in the region of the Pacific Islands. A set of end user requirements has been developed for a better understanding of the necessities. Through use of these end user requirements, an evaluation of the main futures of the Greenheart Project was performed, including: the RORO ramp, the twin bilge keels, the shallow hull, the cargo hold, the motors, the solar panels, the batteries which also serve as ballast, the sails and lastly, the folding mast/crane.

For the hull, the beach landing was considered of no real benefit and removed. The RORO ramp was also removed from the design and the twin bilge keels along with the hull shape were adjusted to reach a more optimal hull design. The cargo hold, originally designed to fit three 20' containers, was split up into 4 different cargo holds, dirty, clean, cooling, and freezing space. The original two electric engines powered by batteries and solar panels were modified to cover the range of 400 nautical miles required by the end user, the air-conditioning, the freezing and cooling capacity for the cargo. For these reasons, two additional diesel generators were installed. These generators were chosen in order to work efficiently in different scenarios and have redundancy. The solar panels were not heavily investigated, but still added to the design to reduce fuel consumption. The batteries, lead acid type, no longer serve to power the engines but now they are used for hotel services and starting the engines. Lastly, the sails, the crane and the mast were modified. Two non-pivoting A-frames equipped with derricks were considered for the mast. A new sail configuration was also designed based on the study of the d rag and lift coefficient of different possible configurations. Integrating the modifications described into the new design, the vessel should now comply with the end user requirements set and be more suitable for needs of the Pacific Islands.

5. FUTURE WORK

As stated in the adaption and evaluation sections, only the most important features of the Greenheart vessel were studied. Many others could be considered and, if necessary, improved. This is for example the case for the propeller. This aspect was not mentioned further, although it plays an important role in determining the necessary power. A deep study into the most suitable propeller could result in smaller, cheaper and more efficient diesel generators. Also, a deeper analysis of the different studied features could reveal more possible modifications. This is the case for the main dimensions of the ship. Some changes were made, and the requirements allowed larger parameters than the ones used by the original Greenheart Project. A deeper analysis of the main dimensions could have brought a more efficient hull form. These are only two examples of the possible improvements that could still be done to the design. The choice to focus on the main features of the vessel has been made because of the limited time available for this project. Furthermore, a better view has been created of what this vessel should look like in order to operate within the Pacific Islands. The next step would be to dive deeper into the design and look at more specific parts, in order to bring this vessel another, step closer to sailing within the region.

6. ACKNOWLEDGEMENTS

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8. APPENDIX

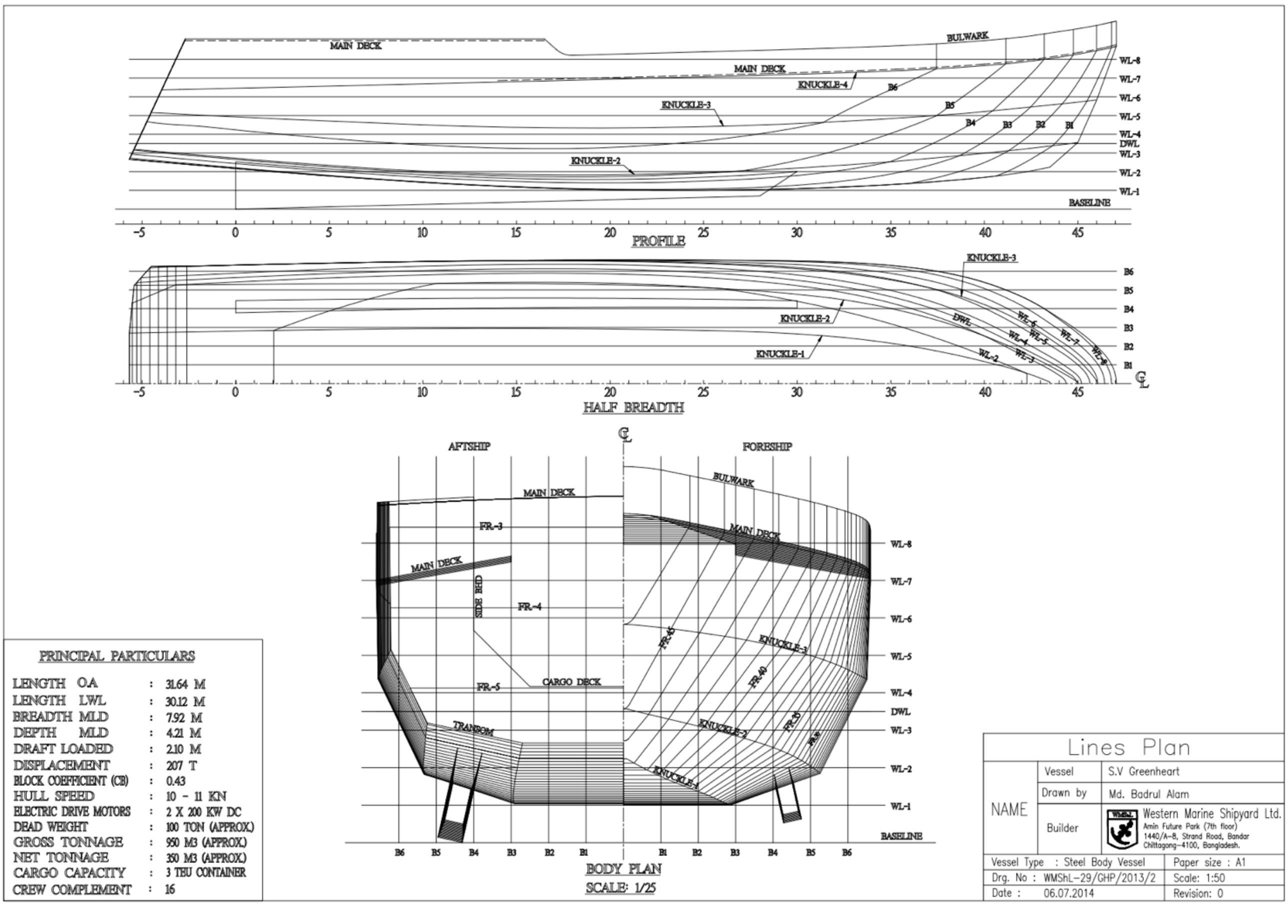

Figure 3. Hull form of the Greenheart vessel, (Greenheart Project, 2014)

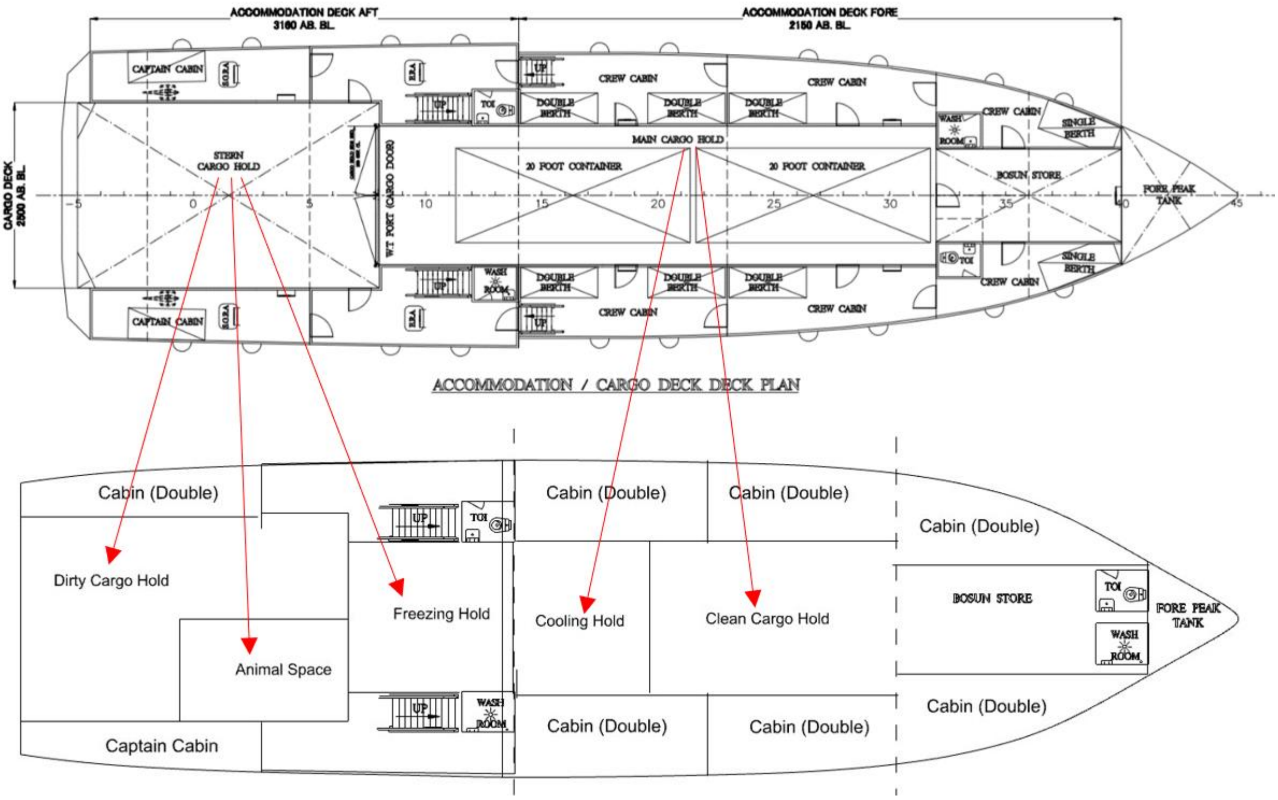

Figure 4. General arrangement of the Greenheart project (above) and adaption (below); Accommodation deck

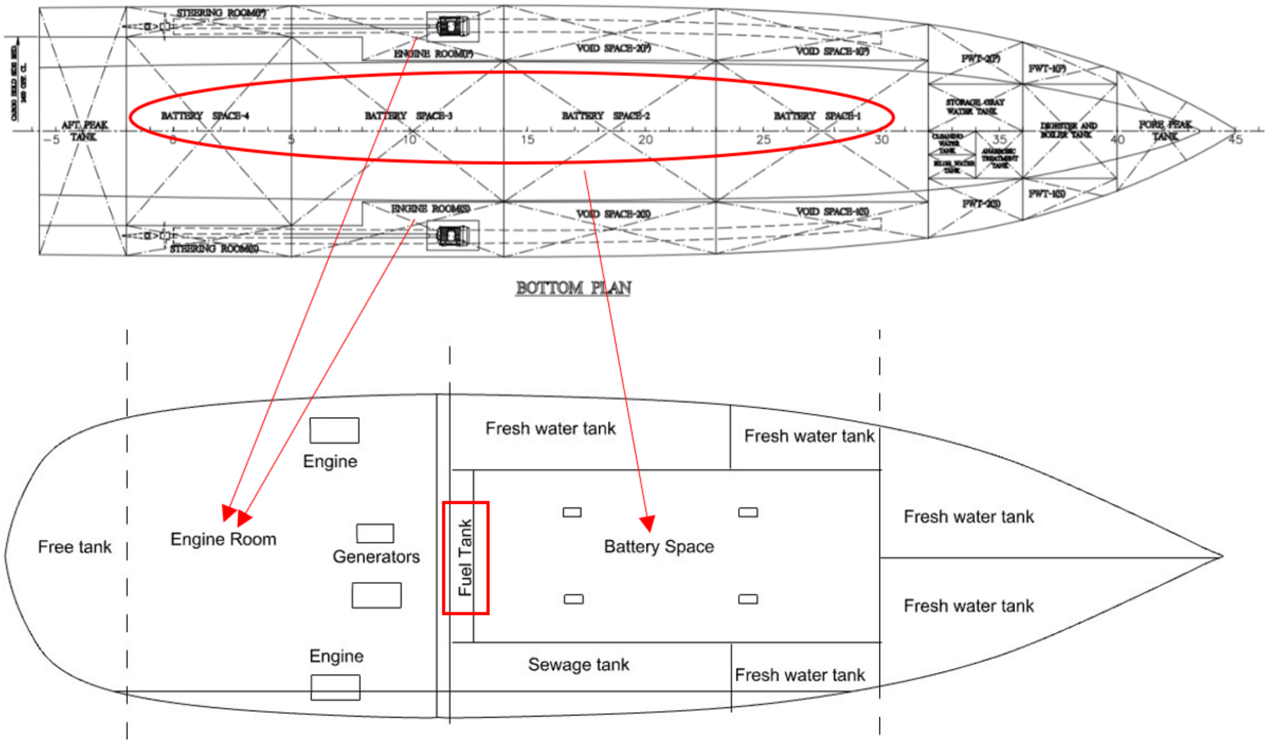

Figure 5. General arrangement of the Greenheart project (above) and adaption (below); Bottom deck