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Contents

1. Transitioning to Low Carbon Sea Transport (LCST) in the Republic of the Marshall Islands 1
   1.1. Background of the LCST Project . . . . . . . . . . . . . . . . . . . . . . . 1
   1.2. Current Situation of Domestic Shipping in RMI . . . . . . . . . . . . . . . 1
   1.3. WAM Prototype Construction Workshop 2020 . . . . . . . . . . . . . . . . . 2

2. Approach and Methodology 5
   2.1. Methodology and Educational Approach of the Training Program . . . . . 5
   2.2. Pedagogical Analysis of the Training Program . . . . . . . . . . . . . . . . . 7

3. The Prototype Designs 8
   3.1. Building Process and Materials . . . . . . . . . . . . . . . . . . . . . . . . 8
      3.1.1. Tools . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
      3.1.2. Materials . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
      3.1.3. Construction Techniques . . . . . . . . . . . . . . . . . . . . . . . . 14
      3.1.4. Beams . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22
      3.1.5. HarryProa . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
      3.1.6. WAM Catamaran . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
      3.1.7. Ailuk Catamaran . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36
   3.2. Commissioning and Sea Trails . . . . . . . . . . . . . . . . . . . . . . . . . 40
      3.2.1. HarryProa . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40
      3.2.2. WAM Catamaran . . . . . . . . . . . . . . . . . . . . . . . . . . . . 41
      3.2.3. Ailuk Ferry . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45

4. Evaluation and Recommendation for Future Workshops 46
   4.1. Evaluation according to LoR . . . . . . . . . . . . . . . . . . . . . . . . . . 46
   4.2. Lessons Learned . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47
   4.3. Recommendation for Future Workshops . . . . . . . . . . . . . . . . . . . . 48
A. Appendix

A.1. Construction Techniques .................................................. 50
A.2. Figures Construction ..................................................... 57
  A.2.1. Beams ................................................................. 57
  A.2.2. HarryProa ............................................................ 62
  A.2.3. WAM Catamaran ..................................................... 74
  A.2.4. Ailuk Ferry ............................................................ 136
A.3. Commissioning and Sea Trials .......................................... 149
  A.3.1. HarryProa ............................................................ 149
  A.3.2. WAM Catamaran ..................................................... 152
A.4. Materials ................................................................. 158
A.5. Tools ........................................................................ 159
  A.5.1. Figures Tools .......................................................... 159
A.6. KIR 5A Original Drawing ................................................. 164
A.7. HarryProa Mini Cargo Ferry Plans ...................................... 165
A.8. WAM Catamaran Study Plan (2018) ..................................... 183
A.9. List of Requirements ....................................................... 197
  A.9.1. 2018 Version .......................................................... 197
  A.9.2. 2020 updated Version ............................................... 198
A.10. Design Evaluation .......................................................... 198
  A.10.1. 2018 Evaluation ....................................................... 198
  A.10.2. 2020 Evaluation ....................................................... 201
1. Transitioning to Low Carbon Sea Transport (LCST) in the Republic of the Marshall Islands

1.1. Background of the LCST Project

The Republic of the Marshall Islands (RMI) is leading the global international effort to drastically reduce carbon dioxide emissions from sea transportation. As an atoll nation highly vulnerable to the devastating effects of climate change, the RMI successfully lobbied the International Maritime Organization members to agree to (1) reduce shipping greenhouse gas emissions by 50% by 2050, and (2) work towards phasing out carbon dioxide emissions entirely. As the second largest shipping registry in the world, the RMI is at the forefront to demonstrate how a country can meet the global 1.5 °C temperature rise limit set by all nations in the United Nation’s 2015 Paris Agreement on Climate Change. In the official communications on Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), the RMI aspires to reduce transportation emissions by 16% in 2025 and by 27% in 2030. The Transitioning to Low Carbon Sea Transport (LCST) Project, an innovative, 9.5 million collaboration between the Government of Germany and the Government of the RMI, directly contributes to achieving the RMI’s NDC targets. The project (effective until 2023) will operationalize two low-carbon shipping solutions: (1) lagoon-based transport vessels, and (2) larger offshore cargo ships. With the combined technical expertise of the Marshall Islands Shipping Corporation (MISC), the University of Applied Science Emden/Leer (HEL), Waan Aelōn in Majel (WAM), the German Agency for International Cooperation (GIZ), and other relevant stakeholders, the LCST Project aims to demonstrate to the world that a small Pacific Island Country (PIC), whose contribution to global warming is negligible, is leading the way in reducing carbon dioxide emissions.

1.2. Current Situation of Domestic Shipping in RMI

The Marshallese people (Ri Majol) have been known for their superior boat-building and sailing skills for centuries. In the past, Ri Majol traveled frequently between their atolls (for trade and war) on large offshore canoes called walap (some as long as 100 ft). The
lagoons of the low-lying coral atolls were also crested by the sails of smaller outrigger canoe designed for rapid inside lagoon transportation, food gathering, and fishing.

Today, the traditional outrigger canoe designs are no longer used for inter-atoll voyages in the RMI. These voyages likely stopped with the appearance of foreign colonizers and the introduction of motorized means of transportation. None of the traditional inter-atoll canoes (i.e., *walap*) remain today.

Nowadays, offshore transport tasks are mainly carried out by the government-owned Marshall Island Shipping Corporation (MISC) and private contractors with conventional monohull freighters.

Inside lagoon traffic and artisanal fishing differs from atoll to atoll in the Marshall Islands. These differences are due to factors such as the shape of the atoll, population density and concentration, as well as the extinction of canoe-building skills. Unfortunately, most of the island communities have not maintained their traditional canoe-building skills and depend on motorized, fuel-consuming boats for fishing and transportation. In addition to significant greenhouse gas emissions by the lagoon shipping sector, the dependency on engine-powered boats causes additional problems for the outer islands:

- Fuel is expensive and not always available. This limitation on lagoon transportation and fishing results in:
  - Reduced availability of local seafood
  - Obstruction of local economy

- Limitations on obtaining local seafood compromises an island’s overall food supply security. This can impact an islander’s sense of identity as providers for family, resulting in lower self-esteem. Additionally, the younger generation does not have the opportunity to witness examples of local islander capacity; instead, young people are enculturated toward a dependency (on imported goods) lifestyle.

- The dependency on imported food, often highly processed and high in salt, fat, and sugar, results in health problems caused by an unbalanced diet.

### 1.3. WAM Prototype Construction Workshop 2020

The LCST Project aims to tackle the challenges introduced by motorized boat dependency by supporting greenhouse gas (GHG) neutral lagoon crafts.

After analyzing the local conditions and requirements, as well as similar past and current
projects around the Pacific, a comprehensive project manual, including a detailed List of Requirements (LoR, see [A.9.1]) for lagoon crafts, was prepared in close collaboration with the local NGO and project partner *Waan Aelōn in Majel* (WAM). To achieve a significant reduction of GHG emissions in the lagoon shipping sector, the collaboration between WAM and the LCST Project aims to revitalize and build upon the traditional marine capabilities of the Marshallese island communities. Therefore, a comprehensive canoe-building, knowledge transfer, and training program has been implemented at WAM. This program to revitalize canoe-building uses new sustainable lagoon vessel designs, together with traditional canoes, as flagships and the mainstay of future lagoon shipping in the RMI.

By teaching small delegations of outer islanders how to be boat-building trainers in their community, the LCST Project, with its training of trainers (ToT) approach, aims to demonstrate how a small program with limited resources can create a larger national impact for a PIC. The outer islanders, who are trained by WAM, learn contemporary boat-building methods that can be applied to different types of marine crafts, including traditional canoes. At the end of the training program, the outer island communities will have members who are skilled boat-builders and sailors, in addition to receiving a sustainable canoe. The LCST Project incorporates both land and on-the-water training to ensure that islanders can optimize their newly built canoe’s potential for sailing and fishing, while utilizing appropriate safety guidelines. For a comparably low investment (when compared to motorized boats associated costs), the island communities will have the opportunity to reestablish their former seafaring capabilities, which in turn will decrease their dependency on fuel, increase their food security, and boost in their local economy.

To begin the LCST Project, a prototype design study was developed (the WAM Catamaran, see [A.8]) in accordance with gathered baseline information and the List of Requirements (see [A.9.1]). To allow for a comparison of different prototypes, the program included a design from HarryProa (see [3.1.5] [A.2.2] and [A.7]) and a refit project (i.e., the Ailuk Catamaran, for more details see [A.6] [3.1.7] and [A.2.4]). Along with these designs, a three-month training workshop was developed for the ToT part of the project (see [2]). To host this three-month training, and in preparation for future workshops, the WAM campus was equipped with the following upgrades:

- New workshop (extension of the main building)
- Widened slipway
- New water catchment
- New locker and wash rooms (extension of the canoe house)
2. Approach and Methodology

2.1. Methodology and Educational Approach of the Training Program

Given the limited time frame of a three-month workshop to teach comprehensive boat-building skills and to train trainers, the program focused on the most crucial skills:

- Stitch and glue technique
- Plywood - Epoxy technique
- Rot prevention
- Safety and maintenance

These topics were taught with the methodical approach of *See One - Do One - Teach One*.

SODOTO is a methodology of teaching and learning skills and best practices through (a) direct observation of a task, (b) hands-on experience performing the task, and (c) teaching the task to another person.

While SODOTO might imply watching a solitary example in the *See One* phase, i.e., the first phase, can include lessons from experts, texts, and interactive media. The *See One* step is achieved when the student has successfully completed the necessary observations in preparation for practical experience (i.e., *Do One phase*).

In the *Do One* phase, the student applies the theoretical lessons learned in the See One phase via practical applications. The student performs the task, often under supervision of more experienced individuals. Learning is developed through the experience of using real world variables and assessments by mentors.

In the *Teach One* phase, the student uses their cumulative learning and experience and transfers it by teaching another student. Teaching the skill, or task, helps to reinforce the knowledge learned and assists the student in moving toward skill and knowledge mastery.

The first group of trainees (four from WAM and five from the Marshall Island Shipping Corporation [MISC]) were very heterogeneous in terms of their experience with boat-building, carpentry, and sailing. While most of the trainees had no prior knowledge of

\[1\text{SODOTO is widely used for the training of medical professionals and engineers.}\]
boat-building, some were familiar with tools used in canoe-building. Two of the nine participants possessed the knowledge and skills akin to a master canoe-builder, carpenter, and sailor.

To ensure the trainees shared a common baseline of knowledge, basic theoretical and practical lessons were included during the program’s first two weeks. The theoretical lessons were held as auditoriums with visual support. The practical training focused on introducing tools, a safety briefing, and supervised hands-on practice. Because of epoxy’s critical role in modern wooden boat-building, an overview of epoxy was included during this training phase. Specifically, the first samples of epoxy applications (glued joint, fillet, fiberglass sandwich) were prepared to demonstrate the strength of epoxy in breaking tests (see A.124, A.5, A.6 and A.7).

In this first training program, the WAM Catamaran and HarryProa were built simultaneously in the same workshop. The work on both prototypes was organized according to SODOTO. This approach was especially applicable to WAM Catamaran and, to a smaller degree, the HarryProa because of the opportunity to build certain parts more than once. In fact, the SODOTO methodology was reinforced not just by the repetitious work involving one boat, but by the opportunity to build two vessels with similar hulls, i.e., the first hull was used for explanations and demonstrations during the See One phase, the second hull allowed for independent practice by the trainees during the Do One phase. A modified Teach One phase was executed when one group of trainees explained what they had done in the construction for their vessel to the other group of trainees who worked on other prototype; the second group of trainees then engaged in the Teach One phase by providing reciprocal information about their vessel to the first group.

After a few weeks in the training program, the trainees were gradually given more responsibility for certain tasks when they built the second catamaran’s hull. This approach led to the development of a more autonomous group of trainees, who by the end of the workshop, required very little guidance.

After the WAM Catamaran and HarryProa were successfully launched, construction on the Ailuk Catamaran began; work on this catamaran further reinforced the canoe-building techniques utilized on the first two prototypes.

In addition to canoe-building, sea trials, which included sailing training, were conducted on the WAM Catamaran and HarryProa. While sailing the HarryProa required very little to no training for those familiar with sailing a Marshallese canoe (the operation is very similar to traditional canoes), more direction was needed to demonstrate the full sailing.

\[2\text{A catamaran has two similar hulls.}\]
potential of the WAM Catamaran, which is tacking catamaran. Tacking catamarans are not commonly used in Micronesia\textsuperscript{3} therefore, the new sailing maneuvers, i.e., jibes and tacks, had to be practiced first. After a relatively short training period, all trainees (and even invited guests) were able to operate the catamaran safely and single-handedly; the catamaran’s simple and effortless operation was positively received.

2.2. Pedagogical Analysis of the Training Program

Overall, SODOTO proved to be an effective workshop approach, despite some pedagogical concerns prior to the LCST workshop. All trainees were able to apply the key skills (as listed under 2.1) and attained basic to more advanced sailing skills (ranging from basic to advanced) by the end of the program. In sum, the vocational approach taken, especially the hands-on practical application, was very effective. Furthermore, the inclusion of sailing trips (scheduled towards the earlier in the program) likely contributed to the participants sense boat-building ownership and increased their dedication to the project. The biggest constraint of a comprehensive training program was the language barrier. Using English as the workshop’s training language was problematic due to the varying English fluency of the trainees; as a result, theory lessons (e.g., classroom presentations) presented in English had limited impact pedagogically. The workshop’s quality and overall effectiveness would have been enhanced if the theoretical and practical information were fully comprehended by all the trainees. Therefore, a bilingual approach, which includes basic Marshallese language training for non-Marshallese project facilitators, is highly recommended for future workshops.

\textsuperscript{3}Traditional canoes shunt (change the direction of travel like a train) to get where they want to go instead of turn around (like a car). The concept of tacking and jibing is as unknown in Micronesia as shunting is in the western world.
3. The Prototype Designs

3.1. Building Process and Materials

3.1.1. Tools

For the workshop, a minimal number of simple and inexpensive hand-held tools were used. Figure A.125 gives an overview of each tool used during the three-month training workshop; detailed photos of each tool can be found in Appendix A.5. It should be noted that, if necessary, all construction work could be done without the use of powertools; however, it would take a significantly longer amount of time.

3.1.2. Materials

Lumber

Wooden boat-building requires high-quality lumber. Lumber of this quality is not readily available in the RMI, and if available, it is very expensive. For cost-effective boat building during the workshop, lumber was obtained from local suppliers. In the RMI, the lumber available from local suppliers is generally used for construction work and is not ideal for boat-building because of its heavy rot prevention treatment (i.e., epoxy does not stick to most treatments). The untreated lumber available from local suppliers is usually used as cast material for concrete constructions; therefore, it is very low-quality lumber. Lumber quality issues affecting wooden boat-building are:

- Knots in the wood
- Irregular grain
- High moisture content

To ensure optimal lumber quality, suitable lumber should be hand-picked from local suppliers stockpile (see figure A.10 a). The quality of the wood should be prioritized over the lumber’s dimensions. Only dry pieces with strait grain and very few knots should be selected (It should be noted that a stockpile will only contain a few pieces of suitable lumber). Using a table saw, the selected lumber should be cut lengthwise into battens (see A.10 b, c and d). The dimension of these battens should be based on the lumber’s original dimensions to minimize waste.1 All exposed knots should be removed from the

11 x 1” is a suitable size.
battens, and the remaining lumber should be planed if necessary. If some battens are not long enough for their intended purpose, a scarf bevel should be cut using table saw fixture (see figure A.10 b and c). These scarfed battens are the raw material for all wooden parts, such as stringers, frames, keels, and beams.

**Plywood**

Plywood panels are made from peeled lumber veneers glued on top of each other. When a plywood panel is constructed, the number of plies is always uneven (i.e., 3, 5, 7 layers etc.), and the individual layer’s grain is orientated 90° to each other. This placement approach (1) stabilizes the wood’s potential shrink and swell, and (2) balances its mechanical properties.

Plywood is almost always sold in 4 ft x 8 ft (1200 mm x 2400 mm) sheets, in various thicknesses and with different numbers of plies. Larger sheets are available, but usually more expensive. When larger plywood panels are required, regular sheets are scarfed to size (see 3.1.3).

One-quarter inch plywood may be constructed with three or five plies of veneer. The 5-ply is more difficult to make, and therefore, it is more expensive. However, 5-ply is more evenly balanced when compared to 3-ply because of the 5-ply’s higher degree of stiffness and strength in both directions\(^2\). The thickness of imported plywood may be listed in millimeters. A 6 mm panel is roughly equivalent to a \(\frac{1}{4}\) in panel, while a 9 mm is slightly thinner than \(\frac{3}{8}\) in.

In general, all exterior and marine-grade plywood is suitable for boat-building to a certain degree. The important characteristics to consider are as follows:

- Type of wood
- Straightness of the grain
- Quality of the plies (with regard to knots and voids)
- Waterproof glue

For boat-building, the most suitable wood includes soft woods, such as Douglas fir, cedar, spruce, and pine. To a lesser degree woods, such as poplar (light but weak) and birch (strong but heavy), can be considered. Medium-density tropical woods like okoume (gaboon), utile (sipo), lauan (Philippine mahogany), meranti, and mecore are generally more

\(^2\)The more layers the better for boat-building.
desirable for boat-building than Douglas fir and pine because these tropical woods do not have distinct growth rings and the problems associated with growth rings.

Voids and other irregularities within the plywood may cause failure and rot. Accordingly, the glue used in marine applications should be waterproof (often referred to as water boil proof).

Grading rules for plywood differ according to the country of origin; the most popular standards are the British Standard (BS) and the American Standard (ASTM). The following table lists some general wood grade descriptions:

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Face and back veneers practically free from all defects.</td>
</tr>
<tr>
<td>A/B</td>
<td>Face veneers practically free from all defects. Reverse veneers with only a few small knots or discolorations.</td>
</tr>
<tr>
<td>A/BB</td>
<td>Face as A but reverse side permitting jointed veneers, large knots, plugs, etc.</td>
</tr>
<tr>
<td>B</td>
<td>Both side veneers with only a few small knots or discolorations.</td>
</tr>
<tr>
<td>B/BB</td>
<td>Face veneers with only a few small knots or discolorations. Reverse side permitting jointed veneers, large knots, plugs, etc.</td>
</tr>
<tr>
<td>BB</td>
<td>Both sides permitting jointed veneers, large knots, plugs, etc.</td>
</tr>
<tr>
<td>C/D</td>
<td>For structural plywood, this grade means that the face has knots and defects filled in and the reverse may have some that are not filled. Neither face is an appearance grade, nor are they sanded smooth. This grade is often used for sheathing the surfaces of a building prior to being covered with another product like flooring, siding, concrete, or roofing materials.</td>
</tr>
<tr>
<td>WBP</td>
<td>Weather and Boil Proof glue as used in Marine Ply.</td>
</tr>
</tbody>
</table>

Marine plywood is manufactured from durable face and core veneers with few defects, so the plywood performs longer in humid and wet conditions and resists delamination and fungal attack. Marine plywood’s properties make it ideal for boat-building, where the wood is exposed to moisture for long periods. Generally, wood veneer from tropical hardwoods has a negligible core gap, which limits the chance of trapping water in the plywood while allowing for a solid and stable glue bond. It is recommended that an exterior Weather and Boil Proof (WBP) glue be used, which is the preferred choices when working with exterior plywood.

Marine plywood is graded as being compliant with BS 1088 (British Standard for marine plywood) and IS:710 (Bureau of Indian Standards, BIS, for marine grade plywood). There are only a few international standards for grading marine plywood, and adherence to the
standards is voluntary (e.g., Lloyd’s of London stamp certifies that the marine plywood is BS 1088 compliant.) For the prototype workshop at WAM, marine-grade plywood compliant with BS 1088 was used.

**Epoxy**

Epoxy refers to any of the basic components or cured end-products of epoxy resins. Epoxy is widely used in modern boat-building for coats, fiber-reinforced plastics (i.e., fiberglass), and structural adhesives.

<table>
<thead>
<tr>
<th>Typical mechanical properties of epoxy resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity ($E$):</td>
</tr>
<tr>
<td>Tensile strength ($R_m$):</td>
</tr>
<tr>
<td>Deformation ($\epsilon$):</td>
</tr>
<tr>
<td>Density ($\rho$):</td>
</tr>
</tbody>
</table>

The mechanical properties of epoxy resin make it ideal when working with the common woods used for boat-building. Epoxy resin is an excellent adhesive for structural joints and allows for constructions that do not require metal fasteners like nails or screws. Epoxy is durable and waterproof; therefore, it is used as coating and protective layer to encapsulate lumber and plywood from water and other aging influences. In combination with fiberglass (see 3.1.3), epoxy’s mechanical properties can be enhanced significantly. Epoxy surfaces must be protected from exposure to sun light as epoxy is not UV resistant over the long term.
Toxicity and Safety

The primary risk associated with epoxy use is related to the hardener component and not to the epoxy resin itself. Amine hardeners are generally corrosive and can be classified as toxic or carcinogenic/mutagenic.

In their uncured state, liquid epoxy resins are classified as irritants to the eyes and skin, as well as toxic to aquatic organisms. Solid epoxy resins are generally safer than liquid epoxy resins, and solid epoxy resins are classified non-hazardous. One risk associated with all epoxy resins is sensitization. Exposure to epoxy resins can, over time, induce an allergic reaction. Sensitization generally occurs because of repeated prolonged epoxy resin exposure (e.g., through poor work hygiene or lack of protective equipment). This allergic reaction is often visible in the form of dermatitis, particularly in areas where the exposure has been highest (usually on the hands and forearms). To reduce this carcinogenic hazard and the risk of sensitization, direct exposure to uncured epoxy resin must be avoided.

The use of disposable gloves should be mandatory for all tasks involving uncured epoxy. Acetone works as cleaner for tools; however, vinegar is a safer alternative for the skin. Spilled hardener, resin, or a mixture of the two, can be removed by saturating the substance with sawdust and then cleaning the spill with acetone.

Resin and hardeners are toxic to aquatic organisms; therefore, empty containers and leftover components should be disposed with care according to the local law.

The curing of mixed epoxy resin causes an exothermic reaction, and in some cases, produces sufficient heat to cause thermal degradation, which ignites if not controlled. Fire safety guidelines should be followed when working with combustible agents.

Mixing and Curing

Epoxy resins may be reacted (cross-linked) with a wide range of co-reactants. These co-reactants are often referred to as hardeners or curatives; the cross-linking reaction is commonly referred to as curing. Curing may be achieved by forming a copolymer with resin (component A) and polyfunctional curatives or hardeners (component B); i.e., component A (resin) reacts with component B (hardener) to form a solid state. For a full cure (or copolymerization), the correct ratio of A and B must be carefully mixed. If the mixture contains too much of either component A or B, then some uncured resin or hardener will be leftover (i.e., because of having no reaction partner), and the mixture
will not fully cure.

An increased ambient temperature accelerates the reaction of epoxy mixtures. Generally, an increase of 10°C (18°F) results in a reduction of the pot-life and the curing time by 50%. The curing of epoxy resins is an exothermic reaction, and in some cases, sufficient heat is produced to cause thermal degradation if not controlled.

**Blushing and Blooming**

Ambient-cured epoxy can appear sticky, tacky, and less clear when compared to oven-cured samples. This difference can most likely be attributed to the side reaction of the curing agent reacting with moisture in the air (i.e., humidity). This chemical phenomenon is known as *amine blush* or *amine bloom*.

*Amine blush* results in a sticky, oily, or waxy appearance on the surface of a cured epoxy; alternative appearances include greasy white spotting or salt-like crystalline deposits. *Amine blush* can also appear cloudy, milky, or gray-colored, with opacity and dullness.

Amine blush and bloom generally yield the same unwanted cured appearance, but differ in their chemical properties. Whereas *blush* refers to moisture condensing on the surface of the epoxy, *bloom*, or *leaching*, is the result of the converse reaction, where water-soluble compounds migrate (or leach) to the surface. *Amine bloom* results in sticky deposits or patches (similar to watermarks in the sand).

Amine cure agents being hygroscopic (absorbing moisture), can react with moisture in the air to form ammonium carbamate by-products.

The result of these side reactions with water is that amine compounds, which were intended to react with the epoxy compounds, are consumed. If all the epoxy groups do not react with the curing agent, then the stoichiometry (mixing ratio) is compromised, resulting in under-curing.

Due to its hygroscopic characteristics hardener must always kept dry and stored in air tight containers. As soon as it gets exposed to the ambient atmosphere, side reactions with moisture of the air starts, as explained above.

The ambient humidity is a major factor whether blooming occurs or not. Obviously, high humidity encourages the risk for blooming, same do slower hardeners as the system has more time for unwanted side reactions before it is cured.

---

3 Unlike polyester more hardener doesn’t mean faster cure!
4 Time to work with the mixture.
Practical Application in the Workshop

For the prototype workshop at WAM, a locally available marine epoxy system (imported from New Zealand) was used. Under the workshop conditions in Majuro (30°C resp. 86°F) the hardener had a pot life of 20 minutes for small batches. Although it was possible to work within this timeframe, a resin system with a longer pot life of at least 60 minutes would have been more appropriate for training and teaching purposes.

In the local humid conditions, blooming was inevitable, especially on rainy days. Wet-in-wet layers had to be applied within a one-hour timeframe to ensure chemical bonding. To reach a grindable state, curing for 12 hours at ambient temperature (i.e., overnight) was sufficient.

3.1.3. Construction Techniques

Epoxy as Glue

As introduced in 3.1.2, epoxy resin is an excellent structural adhesive for lumber and plywood because of epoxy resin’s superior mechanical properties. Pure epoxy resin (such as the ready-to-use mixture of resin and hardener) has a comparably low viscosity (i.e., liquid and runny), compared to substances like fiberglass, and works as a coating material. For structural bonds, a higher viscosity substance (i.e., consistency of ketchup and peanut butter) is needed to fill gaps in the joint and prevent resin runoff. The viscosity of epoxy can be adjusted by adding colloidal silica and/or cotton fibers to the mixture. Horizontal and flat joints require glue that is treated with a few additives, while vertical and imprecise joints require fully thickened glue that is not runny.

The surfaces for structural bonds must be well-prepared to ensure proper bonding strength and stability. In general, surfaces should be sanded and cleaned (i.e., free of dust, grease, and oil). End grain or porous wood may require a coat of unthickened resin before the glue is applied in order to avoid the absorption of resin, resulting in a dry joint. Lumber and plywood must be dry before epoxy resin is applied to avoid the unintended, weakening side reactions between the hardener and moisture (see 3.1.2 on Blushing and...
**Blooming**

The strength of epoxy joints can be tested by gluing to blocks of lumber together and splitting them apart at the joint (after the resin is fully cured); a chisel is used for this test (see A.124). The epoxy, and its adhesion to the wood, should be stronger than the wood. If this is the case, the test will result in the wood splitting next to the joint. Treated lumber is generally not suitable for epoxy bonds because the epoxy might not adhere to the treatment; however, some treatments may work with epoxy. If treated lumber is used, the strength of the bond should always be confirmed by conducting wood-splitting tests (as described above).

For the prototype workshop at WAM, baking flour was used as a thickening agent instead of colloidal silica because colloidal silica was not available on island. Tests with flour used as a thickening agent indicated no negative effect on the adhesive strength.

**Scarfing**

Scarfing is a special technique to connect lumber and plywood pieces to each other. In modern boat-building, scarfing is widely used with epoxy resin as an adhesive to create long boards and plywood panels out of shorter pieces. A well-made scarf joint bonded with epoxy can be as strong as the material it joins.

Although there are several different kinds of scarf joints, only the simplest and most reliable one was taught in the workshop (see A.1): Identical bevels were machined at the ends of the pieces to be joined, these matching bevels were fit together, and then permanently bonded with epoxy. The main goal when working with the bevel was to develop enough surface bonding area to exceed the strength of the wood itself. In general, the correct size of the scarfing bevel depends on the thickness of the parts to be joined. For most boat-building needs, a ratio of 8-to-1 is sufficient; therefore, a 1 in (25 mm) thick board will have a bevel 8 in (200 mm) long.

**Lumber**

It is difficult to get lumber, without the quality issues discussed in 3.1.2, but it is almost impossible (and cost-prohibitive) to get high-quality lumber in the desired length required for boat-building. Scarf joints can be used as a work-around to overcome these lumber issues, i.e., long, knot-free boards can be created out of shorter ones. When lumber of a particular length is needed, the required size is simply glued and scarfed together from prepared 1 in (25 mm) battens as described in 3.1.2.
The fastest and easiest way to make the 8-to-1 bevel is to use a scarfing jig for the table saw as shown in A.10. Before the glue (thickened epoxy resin as described in 3.1.3) is applied, the bevels (usually end grain) should be wet with unthickened resin to avoid too much resin getting absorbed out of the glue mixture by the dry wood. Scarfs can be kept in place with clamps; however, the bevels will slide if too much pressure is applied; therefore, it is important to keep the structure in place until the glue is dry.

Plywood

The process of scarfing lumber and plywood panels is comparable; however, one significant difference is in dimension: a 6 in or 8 in (150 mm or 200 mm) wide scarf joint in lumber is considered large, but a 4 ft (1200 mm) or even 8 ft (2400 mm) wide scarf joint in plywood is standard. Plywood is usually much thinner than lumber; therefore, plywood bevels are usually shorter. Accordingly, the table saw jig used to cut bevels for lumber is not appropriate for plywood panels. One option is to cut the bevel manually with an electric planer as shown in A.12; another option involves using a jig for a router. Scarfing plywood is only necessary if a panel with no increase in thickness is required (e.g., plywood for the beams of all three prototypes). For all other purposes, a butt-joint with a doubler on one side and fiberglass tape on the other is a sufficient connection (e.g., side panels of the WAM Catamaran hulls).

Laminating of Lumber

A technique to generate high-quality lumber out of low-quality supplies is described in 3.1.2. For every application that requires a lumber cross section larger than a single batten, a number of battens (scarfed to full length if necessary) is laminated (glued) together with epoxy glue (laminating of lumber, see A.10 and A.11). The resulting constructed laminated wood is free of knots and contains only selected strait grain. By changing the orientation of the battens within the laminate, shrinking is limited and the risk of cracks is reduced. An advanced technique is to force the uncured laminate into a mold to create a bent wooden bar with uncut grain and desired quality.
Fillets

The fillet has become one of the most versatile methods of bonding wood, especially for joining parts at or near right angles to each other. A fillet is a continuous bead of thickened epoxy mixture applied to the angle between two parts to be joined (see A.2). This technique increases the surface area of the bond and serves as a structural brace. Filleting requires no fasteners and results in a joint that is as strong as the parts being joined together.

When working with fillets, the following limitations need to be considered: The fillet cannot join two materials end-for-end; the fillet is appropriate for joining parts at roughly right angles. The fillet also works best when joining thinner wood material, such as plywood up to 1/4 in (6 mm) thick. At this thickness, it is relatively easy to manufacture a joint that is equal to the material’s strength. As the material joined becomes thicker, the fillet’s size must increase accordingly. Using a large fillet is not optimal for two reasons: (a) material expense (i.e., securing more optimally-sized wood is usually cheaper than using substantial quantities of epoxy to create large fillets), and (b) application difficulties (i.e., a large fillet becomes very unwieldy as its mass increases).

All joints that will be covered with fiberglass cloth will require a fillet to support the cloth at the inside corner of the joint.\[02\]

For a filleting mixture, epoxy resin should be thickened with fillers so that it achieves the viscosity of peanut butter (i.e., not runny). The density of the filler determines whether the mixture will result in high- or low-density fillets (see figure A.2 for differences). Colloidal silica creates a very strong but heavy high-density fillet, while micro balloons create a light but weaker, low-density fillet.\[8\] Whether a high- or low-density fillet is required for a specific application depends on the materials to be joined; the higher the fillet’s density, the stronger the joint. In addition to density, another important factor is the fillet’s size; i.e., larger fillets are stronger than smaller ones.

The design goal is to create a bond which is slightly stronger than the wood it connects. Given that lumber and plywood differ in their properties, a fillet’s size and density must be determined by utilizing break test samples (see figure A.5 and A.6). If the sample breaks outside of the joint, and the fillet remains clean and smooth, then the bond exceeds the material strength, and the fillet’s size and density can be assessed as strong enough.

\[8\]Colloidal Silica and micro balloons are often blended to medium density filler.
The application of fillets is explained in three steps by figure A.3.

For the workshop at WAM, neither colloidal silica nor micro balloons were available; instead, baking flour was used for glue and fillet mixtures. The strength of the flour fillets was determined by break test samples (as explained above). The flour fillet mixtures were slightly more difficult to work with, compared to colloidal silica/micro balloon mixtures, because there was a lack in viscosity variation between flour mixtures runny and dry stages.

**Glass fiber Reinforced Epoxy**

Pure or thickened epoxy resin is exceptionally durable and strong for bonding, sealing, or filling. On a larger scale, however, pure or thickened epoxy is unsuitable due to its brittleness and limitations in applying thick layers (due to curing heat).

The solution to this problem is to use a composite (mixed) material made from epoxy and fiberglass. In theory, the mechanical properties of fiberglass are superior to other common material, matched only by high-tech fibers like carbon or Kevlar. Unfortunately, fiberglass, like all fibers (e.g., ropes or strings), carry tensile load well but do not handle other directional loads well because of the fibers bending and displacement. Combined with epoxy, however, the cured resin keeps the fibers in place and allows them to carry loads in all directions. The combination of fiberglass and epoxy (also referred to as composite material or fiberglass reinforced plastic or GRP) offers improved properties compared to each material alone. Accordingly, this combination of fiberglass and epoxy is widely used in modern boat-building (a demonstration of the strength of a single layer of fiberglass cloth is documented under A.7).

Common applications of GRP are as follows: (1) reinforcement/stiffening of panels, (2) local reinforcements, and (3) protection against abrasion, impact, and damages (e.g., in the workshop, the prototype’s entire outside surface was glassed. Edges, corners, and exposed areas, like the keel, were doubled up by additional patches).

Working with GRP takes practice but can easily be mastered over time. During the WAM workshop, only the hand layup process (the most basic technique) was used. Fiberglass cloth was wet out manually with epoxy resin until the white fibers became clear and almost invisible (see A.14). The surface was prepared for glassing the same way as for any bonding.
Rot Prevention

Rot prevention measures are a crucial part of plywood boat-building and play an important role in determining the craft’s lifetime. Well-made, well-maintained boats can survive for 50 years or more, whereas poorly constructed, poorly maintained boats have a lifespan of only 5 years.

Rot is mainly caused by fresh water. To keep a boat rot-free, the wood’s exposure to water must be prevented. The following aspects of boat-building play a critical role in rot prevention and should be always kept in mind:

Design

- Deepening or beading of the wood, which leads to the collection of rainwater (e.g., toe rails without drain holes on the deck or puddles on flat deck or roof panels), should be avoided.
- Sustained abrasive contact between wooden parts will eventually break through the protection layer of epoxy and expose the wood to water; therefore, such contact should be avoided.

Ventilation

- Sustained abrasive contact between wooden parts will eventually break through the protection layer of epoxy and expose the wood to water; therefore, such contact should be avoided.
- Flat surface contact (e.g., beams directly mounted on top of a flat deck) should be avoided because water trapped in small gaps does not usually vaporize.

Surfaces

- Surfaces should be covered with at least three layers of epoxy, or a 6 oz fiberglass cloth and one layer of epoxy, as proper sealing against water.
- Fiberglass reinforces the surface and makes cracks or scratches less likely; if appropriately applied, the wood is less exposed to the elements and lasts longer.

Edges

- Edges, especially if they expose end grain, must be treated the same way as surfaces (i.e., with at least three layers of epoxy or a layer of 6 oz fiberglass cloth plus an epoxy coat).
- All edges must be rounded (the rounder, the better) because sharp edges cannot be properly coated by resin and risk impact damage.
- If possible, rounded edges should be covered by a fiberglass cloth tape for additional reinforcement.

Holes

- The inside of any hole must be sealed waterproof. It is recommended that holes be pre-drilled larger than needed and filled entirely with epoxy resin. The holes should be drilled again after the epoxy cures with the required (smaller) diameter so that the wood is not cut thus risking exposure.
- If pre-drilling is not an option (e.g. very deep holes), holes can be coated from inside by closing one end and filling the hole with unthickened resin. After a predetermined waiting period based on the hole size and grain of wood, (i.e., holes usually expose end grain which absorb larger amounts of resin), the closed side should be opened again and so that the excess (i.e., unabsorbed) resin can run out.

Nails and Screws

Nails and screws should be avoided as they are potential rot starters. Furthermore, a
properly made epoxy joint is superior to metal fasteners when it comes to strength.

**Internal Barriers**

Between each part of a bonded structure should be an impermeable layer of glue. The glue layers act as internal rot barriers and separates all wooden parts from each other. For example, if the protection coating of one part gets cracked, only that part will rot, and the surrounding structure will not be damaged. Nails and screws usually penetrate these internal barriers and should be avoided whenever possible.

**Maintenance**

- Epoxy resin is not UV stable and must, therefore, be protected from sunlight. A coat of paint (exterior house paint is adequate) must be applied and maintained.

- Cracks or damages which expose any wood must be repaired as soon as possible; otherwise, the wood will absorb water at the damaged spot and rot will potentially spread inside.

**Stitch and Glue**

Stitch and glue is a simple boat-building method, where plywood panels are stitched together (usually with copper wire or wire straps) and then glued together with epoxy resin. The stitch and glue method combines all the basic techniques described above and is the backbone technique of the WAM Catamaran. This type of construction eliminates much of the need for frames or ribs. Plywood panels are cut to shape and stitched together to form an accurate hull shape without the need for molds or special tools. Seams between panels are reinforced with thickened epoxy (see 3.1.3) and/or fiberglass tape (see 3.1.3). See figure A.4 for further information.
Rope Hinges

Hinge lashings connect the edges of two panels by a rope in a figure eight style tighten to holes in each panel (see A.8).

3.1.4. Beams

To minimize additional work, all three prototypes share the same basic beam design and have similar dimensions. The fundamental steps of construction described in this section is applicable to all three prototypes. The beam subsection of each prototype design describes specific features of each design to supplement the basic beam construction provided.

Multihulled boat beams are mainly designed to absorb the bending forces between the hulls moving in the water or crew walking on the beams. In the workshop, the 11 ft crossbeams for all three prototype designs were made from hollow and rectangular plywood-lumber cross sections (see A.9). Knot-free lumber was glued to boards (approximate length 127 mm x 25 mm; 5 in x 1 in) and a rectangle was formed by gluing two lumber boards and two strips of 3/8 in plywood (11 ft by 5 in) together. In this approach, the lumber on the upper and lower side of the beam supports the bending load, while the plywood on the vertical sides acts as shear web.

To obtain knot-free lumber for the beams, pre-selected lumber\(^9\) from a local supplier (see A.10) was cut (sliced lengthwise) using a table saw to strips approximately 1 x 1 in. All knots were cut out of the individual strips and those that were shorter than the required length for a beam were scarf cut using a self-made fixture for the table saw (see A.10 items b, c, and d). The strips were then glued together with thickened epoxy resin to a 5 in wide board (see A.11). It is important to ensure that all wood strips are leveled to form a plane board and an even surface. After the epoxy is fully cured, the boards are planed from both sides and coated with thickened (but still viscose) epoxy on one side. This is the first layer of rot protection for the inside surface of the wood planks.

Plywood with the following dimensions were cut: 5 in strips of 3/8 in. Scarfing was required to create strips of 11 ft by 5 in out of 8 ft plywood sheets. The bevels were made with a planer (see A.12). When the scarfs were glued together, it was important to ensure that all components were level (a long ruler was used to confirm that all parts were level).

\(^9\)Rope hinges are long known and have been used by Wharram for decades on many catamaran rudder designs. They are sometimes used for hatches as well.

\(^{10}\)Chosen by strait grain, few knots and moisture content.
To prepare for the beam, the plywood was glassed with 6 oz fiberglass cloth on one side and flow-coated with epoxy to create a thick rot protection layer (the glassed side serves as the inside surface of the beam).

Before the beam was glued together, the glassed side of the plywood strips were ground (angle grinder, 40 grid). Epoxy glue was then spread onto the two smaller sides of the lumber boards and all four parts were placed as shown in figure A.9. It was important to orient the materials so that the glassed surfaces of the plywood and the coated surfaces of the lumber faced the inside of the beam. All pieces were then clamped together until the glue cured (see A.13).

In the process described in this section, it is important to ensure that the lumber and plywood are carefully aligned. To save time and reduce waste, excess glue can be collected and recycled for parallel projects. The glued beam is then ground and planed (if needed), and the edges are rounded; a router with a bull-eye bit is helpful at this stage (see A.127d). To protect the outside of the beam from rot, it should be glassed and flow-coated twice (see A.14).

3.1.5. HarryProa

The HarryProa mini cargo ferry design is a drua-styled shunting proa with buoyant windward hulls. Unlike traditional Marshallese canoes, both HarryProa hulls are flat bottomed with a rectangular cross section; a bidirectional leeboard is used to reduce leeway. The box-shaped hulls are comparably easy to build (i.e., they easily incorporate a plywood sheet’s rectangular shape) and allow a high degree of displacement for a shallow draft. The HarryProa uses a traditional Marshallese steering oar and canoe sail. Cargo can be stored on top of the hulls, as well as on the center platform.

For a detailed explanation of the HarryProa’s construction, see the comprehensive plans prepared by Rob Denney from HarryProa (see A.7). Corresponding workshop pictures the can be found in A.2.2.

3.1.6. WAM Catamaran

The WAM Catamaran Design

The WAM Catamaran was designed in close collaboration with WAM by a non-Marshallese boat-building expert, who served as a project consultant. The catamaran was based on
a 2018 early design study (see A.8). The design was used as a prototype for the comprehensive three-month training program at WAM in order to (a) enhance the program’s trainee’s understanding the catamaran’s benefits as a low emission\textsuperscript{11} lagoon craft for cargo and passenger transport, and (2) increase the trainee’s boat-building capabilities with contemporary materials by participating in the catamaran’s construction.

The WAM Catamaran, which is a variation on the traditional Marshallese outrigger canoe, has been modified to carry more payload than the traditional canoe. Instead of a small outrigger float (\textit{kubaak}), a second main hull is attached to the crossbeams to form a double canoe. The hull shape, construction philosophy, and rig/sail are directly derived from Marshallese canoe-building. For easier sailing maneuverability, the WAM Catamaran tacks (i.e., turns around like a car), instead of shunts (i.e., the sailing method used by traditional Marshallese canoes).

To simplify its plywood construction, the WAM Catamaran was designed to be built using \textit{stitch and glue} technology. The stitch and glue technique is an easy and expedient way to build boats from plywood that can be adapted to traditional Marshallese canoe construction in the future (see 3.1.3). This construction approach relies on the superior strength of epoxy as glue and flexible rope lashings. No metal fasteners (such as screws or nails) are required. Epoxy (in combination with fiberglass cloth) is used to encapsulate all wooden parts from water to prevent rot (see 3.1.3).

Hinges (for rudders and hatchs), beam-hull connections, and the rigging are made by rope lashings (see A.8). The keels are protected by lashed-on keel shoes (\textit{erer}) made from local hardwood (see A.95 items e and f).

The rig is based on the traditional Marshallese canoe. The main difference is the second mast (i.e., both masts form an A with the sail in between); all other changes are minimal.\textsuperscript{12} The WAM Catamaran’s platform (hulls and beams) and rig were developed using scale models from 1.2 mm birch plywood. The use scale models (as opposed to full scaled boats) made it easier for workshop trainees to repeat processes to understand the catamaran’s overall design (i.e., technical equipment, drawings, and computer skills were not required).

\textsuperscript{11}In fact it’s a no-emission craft.

\textsuperscript{12}In fact, it is possible to use traditional canoe sails from the right size without any changes.
### WAM 20 Prototype Main Dimensions

<table>
<thead>
<tr>
<th>Building method</th>
<th>Ply/Glass/Epoxy, Stitch and Glue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall:</td>
<td>6.00 m / 20 ft</td>
</tr>
<tr>
<td>Waterline length:</td>
<td>5.00 m / 16.4 ft</td>
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<tr>
<td>Beam overall:</td>
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</tr>
<tr>
<td>Beam hull:</td>
<td>1.00 m / 3 ft</td>
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<tr>
<td>Weight:</td>
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<tr>
<td>Max. Loading capacity:</td>
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<tr>
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<tr>
<td>Beam hull CWL:</td>
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<tr>
<td>Beam hull max. capacity:</td>
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<tr>
<td>Draft empty:</td>
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<tr>
<td>Draft CWL:</td>
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<tr>
<td>Draft Max. capacity:</td>
<td>0.60 m / 23.6 in</td>
</tr>
<tr>
<td>Sail area:</td>
<td>15 sqm / 170 sqft</td>
</tr>
</tbody>
</table>

### Measuring System

In keeping with the Marshallese canoe-building tradition, the WAM Catamaran was designed without any technical drawings or numeric measurements and units. Instead, the catamaran’s designing and lofting was done using string, and all dimensions were developed in relation to the hull’s length. This unusual approach has advantages when compared to the Western approach using technical drawings, plans, and static measurements:

- The main dimensions are not static measurements, but rather are flexible within certain ranges. This allows the measurements to be adapted to the dimensions of the materials available on site (in the workshop this meant to the standard size of available plywood sheets).

- It is easier to scale the design up and down because every dimension is a fraction of the overall length (i.e., when changing the overall length, the ratios remain constant).

- By using string for lofting, no numbers and units are involved in the entire construction process; therefore, there is no confusion with unit differentiations (i.e., imperial vs. metric systems).
The entire construction requires knowing different relationship between a few key
dimensions; therefore, the system can be easily memorized and adapted to build-
ing canoes between 20 ft and 30 ft. This contrasts with the Western approach to
boat-building which necessitates the creation of additional plans and drawings when
changing dimensions.\footnote{\textit{It should also be considered that (1) plans (hard and soft copies) can get easily lost and or damaged
in the marine environment of RMI overtime, and (2) reading plans requires a special skillset.}}

The relational measurement system for the WAM Catamaran is akin to the traditional
pandanus leaf technique for designing dugout canoe hulls (as documented by Alessio\cite{Alessio});
however, the system was slightly modified to accommodate working with plywood hulls.
As part of the design process, 1:12 (one foot in real size is one inch in model size) scale
models from 1.2 mm birch plywood were built to confirm and optimize the dimensions
and bulkhead positions before cutting full-size plywood.
Whenever Marshallese names seem applicable in the following, they were used according
to the notation of Alessio.

Building the WAM Catamaran began with determining the canoe’s main dimensions
based on supplies available. Standard plywood sheets (4 ft by 8 ft) were used and deter-
mined the canoe’s finished dimensions:

According to the list of requirements, the hulls were proposed to be 2.5 sheets (which
was 20 ft long; see figure\ref{A.28}). The width of the entire platform (and therefore the
length of each cross beam) was determined to be 11 ft, which is 1.5 sheets (12 ft), minus
one foot for the overlap of a scarf. The total length of the canoe served as a reference
for determining the other component’s dimensions, which were proportional to the total
length. A string of the total hull length (2.5 ply sheets) was prepared as a master tool for
lofting (see red line in figure\ref{A.28}). In the next step, the 2.5 plywood sheets were joined
(butt-joint, glass tape on the outside and plywood doubler on the inside) and placed flat
on the ground for lofting. The height of the catamaran hulls was set to 1/6 of the hull
length (which is approximately 3.3 ft or 1 m,) taking into account wind resistance, free
board, and internal volume. The exact hull height was determined by folding the master
string into six parallel lines, 1/6 of the hull length (see figure\ref{A.29}). A line (referred to
as baseline) was marked 1/6 from the top edge of the plywood sheet (blue line in\ref{A.29}).
The plywood was now separated in 8 rectangular parts by 7 vertical section lines as shown
green in figure\ref{A.30}. With the station lines marked, the bow and stern measurements

were determined as fractions of the total hull length, using the master string. This step established the hull shape, i.e., a measurement was taken 1/8 of the hull length down the maan jorjor line (see figure A.31). In case of the WAM Catamaran, the bow and stern were designed to be symmetric, (both 1/8 of the hull length down the maan jorjor line). For future designs, an unsymmetrical shape (i.e., different lengths for bow and stern) are possible and recommended.

The keel line was developed as a round spline by bending a PVC pipe around the intersection of the maan jorjor with the bow line and mejaaanj with baseline (see figure A.32). As an alternative to the round keel is the easier-to-build straight keel, which is created using simple straight lines between the intersection of maan jorjor/bow line, malmal/baseline and mejaaanj/baseline (see figure A.33).

The shape of the first hull side sheet was cut out after this step and used as pattern for the following three sheets; therefore, repeating the entire measuring process was not necessary.

The size and positions of the bulkheads were measured using the master string as shown in section A.34, A.35 and A.36. The center bulkhead was the only bulkhead manufactured using the master string before the hull sides were joined by wire stitching and spread for the first time. All other bulkheads and support frames were fitted into the already opened hull shell.

No other conditional measurements were applied to the parts and components; therefore, future builders need only to memorize the process described above. All other parts were designed to fit into the measured parts and please the builder’s eye.

**Hulls**

As with most stitch and glue hulls, the building of the WAM Catamaran hulls started with the plywood flat side panels. For this very first prototype, the desired hull length was 20 ft. To achieve this 20 ft length, 2.5 plywood sheets (8 ft x 4 ft) were joined together, with a small part in the center, to form one side of a hull. A scarf was not needed to join the plywood sheets; they were butt-joined and doubled up with a plywood strip from the inside (see A.37). The outside seam was closed and reinforced with fiberglass tape. The inside doubler ended approximately one hand-width above the future keel line to allow the plywood sheets to lie flat on the keel lumber. With 2.5 plywood sheets, or 20 ft, as the master dimension, all other dimensions were determined using a string, according to the traditional custom, the length would determine whether the hull is going to become a jekad, mwijitbok or one of the designs in between.
to Marshallese relational measuring system described in 3.1.6 and A.38. Following this technique, an outline was cut and the shear stringer was glued on the top of the side panels (see A.39 and A.40 for the entire process).

The shear stringer were made from knot free scarfed lumber as described in 3.1.2 and 3.1.3.

The center bulkhead was then constructed according to the measurement rules and by ensuring its fit to the side sheet (see A.36 and A.41). The width of the future keel lumber (1.5 in were used in the workshop) had to be taken into account (see A.36) as well as some cut-outs for the shear stringer. The inside cutout (to be used to open up the cabin interior) was not subject to the relation rules and could be determined by the builder’s preference. However, a minimum of three finger-widths (approx. 2.5 in) should be left to each side to create a strong bulkhead. The cut-out was made as round as possible for strength (see A.41 c and d) and wide enough to allow a sufficient bunk board width (the width of the lower edge of the cut-out); a recommended approximation is 1/14 of the hull length.

In the next step, the keel lumber (solid piece of Douglas fir, 1 in wide and 2 in high), the bow lumber (same size), and the skeg (glued from three sheets of ply to 1 in thickness and tapered to the trailing edge) were prepared (see A.42). For the keel, lumber with a natural crown (slightly bent shape) was picked. To create the round spline shape of the hull sides, the lumber was shaped and left under tension to pre-bend for approximately 2 days.

The size of the plywood parts for the skeg was not determined by any measurement rules and was left to the builder’s discretion; however, one recommended approach was to place a sheet of cardboard under the rear part of the side sheet and draw the preferred skeg shape. Advice on how the skeg should be shaped can be found in 3.1.6. The bow lumber was cut to the length of the bow edge of the side sheets.

In a final preparation step prior to the stitching process, a bevel was machined to the keel and stern edges of the side sheets at the inside of the bow (see A.43). The bevel is important in allowing a smooth transition from the keel plywood and to reduce the tension in the seams during the spreading of the hull sheets.

To create the final hull shape, two side panels were placed flat on the ground on top of each other (with keel, bow, and stern in between) and stitched together with copper wire on keel, bow, and stern (see A.44 and A.45). In the next step the entire assembly was placed shear up and keel down in prepared cradles, the center bulkhead nearby to

15Stripped out from off-cut wires from the Home Depot.
By gently pulling the side panels apart in the middle, the hull opened and the center bulkhead could slide in (i.e., the design allowed for self-locking on the shear stringer, with no clamps or other fasteners required), see figure A.46.

By taking dimensions directly from the hull shell, the other bulkheads were manufactured and mounted simultaneously into the hull (see figure A.47). To later fit the bunk boards, all horizontal edges of the bulkheads were leveled (see figure A.46a). All horizontal edges on bunk level are equipped with 1x1 in lumber to allow the bunk boards to rest on a larger surface (see figure A.47b). Bow and stern were equipped with diagonal stiffeners (see figure A.48).

Before the parts were glued in place with epoxy fillets\textsuperscript{16} (see 3.1.3), a string was held tautly from bow to stern to assess if there was any twisting of the hull or angle in the skeg (see A.47d). This dimensional check underscores the importance of ensuring that the skeg is aligned with the hull’s center line before any fillets are applied. Thickened epoxy resin was applied to the keel joint, bulkheads, and hull shell connections (see A.49 and A.50). The thickness of the epoxy mixture was critical, especially since flour was used. The viscosity needed to be relatively thick because a runny mixture would exude from the vertical fillet leaving a weak joint.

Parallel to the construction of the hull, the parts that served as the beam cleats were prepared. Beam cleats are hooks, which are mounted on each side of the hull to take the beam lashings. The full force between beams and hulls is transferred by the cleats into the hull shell\textsuperscript{17}. To distribute this load, the hull shell was reinforced by plywood doublers (squares that approximately measured two by two hands or 8 x 8 in) from in- and outside (see A.51). The inside doubler touched the cabin bulkheads and the shear stringer; beveled edges for a smooth transition and easy glassing were mandatory. The cleats themselves were made from laminated plywood as shown in A.52. The prepared hooks were glued to the outside of the hull and centered outside of the doubler. In positioning the piece, it was important to remember that the beam would need to sit on the deck one finger-width apart from the cabin bulkhead. To eliminate the risk of the plywood hooks peeling off the hull (plywood is easily split along the plies), the cleats were further reinforced by hardwood pins (see A.53). Holes for the pins (at least 3/4 in) were drilled into the cleats.

\textsuperscript{16}Due to the high price and limited availability of colloidal silica and microballoons, baking flour was used to thicken the epoxy for glue and fillets. The flour worked well and proved to be strong in tests but added additional weight to the boats. Furthermore, using flour required training in order to create a mixture which was not too runny and suitable for vertical fillets.

\textsuperscript{17}The cleats are important structural parts, their construction must carried out carefully. A failure of a cleat on the water could lead to a dangerous loss of structural integrity of the catamaran.
through the cleat base in the hull (see A.53 b). The holes were not drilled all the way through, the inside remained closed (the drill was stopped 1/8 ” before it broke through the inside doubler). After pins of the right size were made from hardwood (see A.53 c), the holes were filled 1/3 with slightly thickened resin. By inserting the wooden pins and squeezing out most of the resin, a safe and strong bond was achieved (see A.53 d-f). To optimize the bonding strength of the applied resin, the hulls were flipped onto their side, and the pins on top were glued to prevent resin runoff. Hardwood pins were used in place of conventional bolts to secure the plywood layers.

The next construction step focused on the bunk-board support stringers, which were glued inside the hull; they needed to be positioned along the lower edges of the bulkhead cut-outs. The bunk-boards acted as an internal deck (roughly at the waterline) and created a 10 ft long internal cargo hold with flat, removable floorboards. The support stringers were be made from maximum-sized 1 x 1 in lumber or two strips of 3/8 in plywood. The support stringers were glued onto the round hull shell using copper wire (see A.54). The bunk-boards were cut from 3/8 in plywood with dimensions taken directly from the hull as shown in A.55.

In the next step, the hulls were prepared for the deck panels and the cabin roof. The top edges of all bulkheads were equipped with glued-on 1 x 1 in lumber to increase the bonding surface for a strong joint with the deck and the cabin roof (see A.56 item a). The shear and the bulkhead tops were ground to allow a smooth fit of the deck panels (see A.56 item b). A smooth fit with small gaps is important for a strong bond. Before the hulls were permanently sealed off by decks and cabin roofs, the entire interior (especially fore and aft compartments) was sealed by three layers of epoxy resin (see A.57). The epoxy was applied wet-in-wet with one hour of curing time between the individual layers to allow for a chemical bond that did not require sanding (see 3.1.2 for more information about wet-in-wet). The epoxy was carefully applied to every corner, gap, and overhang ensuring that no bare wood remained. The importance of rot prevention cannot be overemphasized (see 3.1.3); rot prevention was stressed again at this point in the construction process. It is most convenient to flip the hulls right/left on the floor for the application of the epoxy resin.

To prepare for closing the hulls, deck and roof panels were made from 3/8 in plywood, and the cabin side panels were made from 1/4 in plywood. The dimensions of the decks were directly derived from the hulls by placing plywood sheets on top of them at the desired position and marking the outline of the shear with a finger-width offset (see A.58). The cabin roof was a simple rectangular cut bent over the center bulkhead down to the cabin
bulkheads and temporary held in place by clamps (see A.59 items a and b). The cabin side panels were cut according to the shape of the roof panel and the hulls shear (see A.59 items b, c, and d). The deck panels were glassed from the inside as reinforcement and for rot protection (see A.60 items a and b). The cabin sides and roof were coated with three layers of epoxy (wet-in-wet) from inside for the same reason (see A.60 item c).

After the above steps were followed, the decks were sanded on the inside and glued to the upper side of the hull shear using thickened epoxy, clamps, and weight (see A.61).

Unfortunately, this approach was not appropriate: With the decks in place, it was impossible to place clamps on the cabin roof as shown in A.59. In the future, it is strongly recommended to glue the cabin roof and the cabin sides on first, followed by the decks. During the workshop, this problem was solved by using screws, hot melted glue and ropes to keep the cabin roof and the side sheets in place until the glue cured (see A.62 and A.63).

After the cabin roof glue cured, the cut-out for the main hatch was marked and cut with a jigsaw (see A.64 item a and b). To bond the cabin sides permanently in place, fillets between the side panels, the roof, and the shear were applied from the inside (see A.64 items c and d). In preparation for the external application of fiberglass, all edges of the cabin and the shear were rounded and filled with thickened resin as needed (see A.65).

The recommended tools at this stage were a router (see A.127 item d) for the main job and a sander for the final task of ensuring surfaces were smooth.

For external reinforcement and rot prevention, the entire deck and cabin surface was glassed with 6 oz fiberglass cloth. The fiberglass cloth was rolled over deck and cabin roof and cut to the size of the hull with a 3 in offset to allow for overlapping to reinforce the edges (see A.66). The epoxy resin was then applied directly on top of the fiberglass cloth until it became clear (see A.67). The overlap for the edges was wet out by folding it up on the rinsed deck. One hour after the glasing process, another layer of epoxy was applied wet-in-wet (i.e., a flow-coat) to reinforce the rot-resistant epoxy layer (see A.68). After the final epoxy layer cured, the deck and cabin were sanded in preparation for painting.

With the entire structure finished and the top glassed, the hulls were turned upside down and the copper wires were carefully removed with a pincer. The rectangular lumber of the bow was shaped round and streamlined (see figure A.69 a, b and c). All gaps in the transition from hull to keel, and all holes from wires, were filled with thickened epoxy (see A.69 items d and e). An eyelet was glued into each bow for the forestay and anchor.

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\(^{18}\)Works only with insulated wires. It is not problem if wires stay inside the hull. The outside can be smoothed with a grinder.
attachment (see A.69 item f). The eyelets were made from 1 in PVC pipe covered with an 1/8 in layer of fiberglass cloth.

The hulls were then tipped onto one side, leaving an almost horizontal surface for glassing the sides. The hull’s glassing process was analogous to the glassing of deck and cabin (see A.70). With both sides glassed, each hull was further reinforced on the keel, bow, and skeg with seven layers of 6 oz fiberglass cloth to protect against ground contact (see A.71). The bow eyelets were reinforced by fiberglass to spread the load of rig and anchor (see A.72). The bottom of each hull was sanded after the final epoxy layer (i.e., flow-coated) cured in preparation for painting.

As additional reinforcement against the rough underwater and beach terrain in the Marshall Islands, the WAM Catamaran hulls were equipped with traditional lashed-on hardwood keel shoes (errer) to protect the hulls from coral (see A.73). The attachment holes for the keel shoes had been drilled and filled with epoxy to seal the wood; these holes were now drilled again to allow for lashing.19

Like the keel shoes, the mast steps for the A-frame rig (see 3.1.6) were carved from local hardwood (see A.74). The mast steps were placed outside each hull above the second bulkhead (counted from the bow) and glued in place with epoxy (see A.74 item f). The position of the bulkhead was determined by tapping on the deck and using the reverberant sound to determine the supported (bulkhead underneath) and unsupported (no bulkhead underneath) areas of the deck. At this stage, eight hardwood blocks of the same size were cut as support for the cross beams (see A.75 item a). The blocks were glued to beams, right in front of the cabin bulkheads and above the beam cleats (see A.75 items b and c). The blocks served as a necessary spacer between the deck and beams (see A.75 items d and e). Contact between the deck and beams would otherwise create a gap which makes it difficult to prevent water from entering; this, in turn, creates a moist environment in which rot thrives. After coating the mast bases and the beam blocks with epoxy (three times), they were sanded in preparation for painting.

The cutout of the hatch opening was reinforced with 1 x 2 in lumber (see A.76 items a and b). The short pieces (bow and stern) were glued to the cabin roof. The long lumber pieces in the hatch were glued so that they touch the cabin roof in a butt-joint manner. The entire frame was glued and reinforced, inside and outside, by fillets. The hatch cover was made from 3/8 in plywood and lumber with the same cross section as the hatch frames (see A.76 items c and d). The longer lumber pieces were manipulated to fit the bent shape of the cabin roof. The hatch cover’s front plywood extended approximately 2 in beyond

19Very careful from both sides with a small drill bit to avoid cutting wood.
the front lumber to accommodate the holes for the rope hinge (see \ref{3.1.3}). The holes were pre-drilled, filled with epoxy, and drilled again. To determine the position for the hinge counterpart (hinge plates), the hatch cover was placed on top of the hatch frame (see \ref{A.76} item e). The hinge plates were pre-manufactured (drilled, filled, and drilled again) and glued in place (see \ref{A.77}).

Once everything was sanded, the hulls were cleaned with fresh water to remove any dust and debris in preparation for painting. Painting was necessary because epoxy, in general, has limited UV-light (sunlight) stability. Two coats of exterior house paint were applied (see \ref{A.78}).

**Beams**

The bare beams of the WAM Catamaran were constructed as described in \ref{3.1.4}. The following features were added to incorporate the beams into WAM Catamaran’s design:

- End blocks on the top to keep the beam lashing from slipping off (see figure \ref{A.79}a)
- Alignment blocks on the bottom for faster assembly and to prevent a sideways motion of the beams (see figure \ref{A.79}c). The alignment blocks were positioned to line up with the beam mount blocks on the deck of the hulls (see \ref{3.1.6})
- Backstay cleats (rear beam only) (see figure \ref{A.79}a and b)

**Rudder System**

The WAM Catamaran is equipped with a twin rudder system (one rudder on each hull), which is used on most catamarans. Each rudder is permanently mounted to the skeg of the hull’s canoe stern by rope hinges (see \ref{3.1.3}). The skeg protects the rudder from touching ground (therefore the skeg needs to extend one inch beyond the rudder) when dry docking or beaching (see \ref{A.80}).

For the workshop, the size of the skeg was determined by the builder without following any particular rules (see \ref{A.81} item a); however, the following dimensions were kept in mind shaping the skeg: The trailing edge of the skeg, where the rudder is lashed on, needed to be more vertically positioned (compared to the stern) to allow a horizontal tiller motion. The top of the skeg needed to be cut flush with the deck and extend a minimum of three

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\footnote{Decoration and blocking sunlight are the only purpose of the paint. Any exterior paint is suitable, water-based products are favored for their environment friendliness, easy tool cleaning and fast curing.}
finger-widths (approximately 2 in) past the stern’s trailing edge. Another three finger-
width extension was needed inside the hull along the full length of the stern to allow a
proper bond inside. The transition from keel to skeg needed to be smooth to prevent rope
or seaweed from getting caught. The maximum draft of the skeg was determined to be
slightly above the deepest point of the keel to protect the rudder.

The skeg was glued from three sheets of plywood (two 3/8 in and one 1/4 in between) to
1 in thickness (because the keel lumber was 1 in wide) and tapered on the trailing edge
down to 6/8 in (i.e., the thickness of two 3/8 in sheets, see 3.1.6 for the early stage of the
catamaran hull construction and additional information). Once the shape of the skeg was
determined, two skegs (one for each hull) were prepared using the same pattern (see A.81
item b).

As described in 3.1.6 the skeg was stitched in between the side panels and integrated in
the hull shell (see figure A.82).  21

The rudder was measured and shaped in the same way as the skeg (i.e., without specific
pre-determined measurements). The rudder was cut so that it extended above the deck
by approximately 3 in with enough space to mount a tiller. The rudders were glued from
two 3/8 in plywood pieces to match the thickness of the tapered edge of the skeg. The
trailing edge of the rudder was then tapered to create an airfoil shape (see A.83 items a
and b), and the leading edge was rounded using a router (see A.83 item c). Four sets
of lashing holes for the rope hinges (nine holes for each set) were pre-drilled (twice the size
of the required diameter) in the skeg and rudder (see A.84). All lashing holes were filled
with epoxy resin (see A.85 items a, b, and c) and re-drilled (smaller size) to accommodate
the lashing rope (see A.85 item d). After the rudders were lashed to the skeg, they were
tested to ensure they functioned as intended (see A.86). After this test, the rudders were
glassed, epoxy-coated, and prepared for painting.

The twin rudders operate using tillers and are connected by a cross-bar. Taking the
Ackermann criterion 22 into account, the tillers were designed with a round shape, pointing
toward the inside. This resulted in creating a tiller cross-bar that was substantially shorter

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21 It is recommended to round the trailing edge of the skeg with a router at this point. It further saves
time to pre-drill and fill the rope hinge lashing holes before the skeg is permanently integrated into
the hull shell. Unfortunately, this was not done in the workshop.

22 Ackermann steering geometry is a geometric arrangement of linkages in the steering of a car or other
vehicle designed to solve the problem of wheels on the inside and outside of a turn needing to trace
out circles of different radii. The intention of Ackermann geometry is to avoid the need for tires to
slip sideways when following the path around a curve. This can be directly translated into a twin
rudder arrangement of a catamaran: The rudder on the inside of a turn needs a larger angle of attack
compared to the rudder on the outside. This is achieved by making the linkage between the tillers
(tiller crossbar) substantially shorter than the width of the hull center-lines.
than the width of the hull center-lines which, according to Ackermann, allows for steering with reduced drag and more maneuverability.

Figure A.87 item a) shows the finished tiller with the round Ackermann shape on top. The tillers were made in a simple mold on a flat table (see A.87 item b). The straight raw parts were manipulated into round shapes using clamps; once the round shaping was achieved, the piece was glued to permanently maintain the shape (see A.87 items c and d). Additional pressure was applied to the lumber blocks to ensure a secure bond (see A.87 items e and f). After the glue cured, the clamps were removed and the tiller was rounded (using an angle grinder and sander), and base reinforcement plywood prepared (see A.88 items a, b, and c). Once prepared, the base reinforcement plywood was glued to the tiller (see A.88 item d). The tiller was then equipped with a tapered mount for the top of the rudder, which allowed for a fast and tool-free assembly. At the front, the pre-drilled holes for the tiller crossbar were filled with epoxy (see A.88 items e and f). The tiller crossbar was made from 1 x 1 in lumber, which was somewhat longer than required to have room for rudder adjustments (see 3.1.6).

**Rig and Sail**

To reduce costs and building time, a traditional Marshallese oceanic lateen sail was selected to power the WAM Catamaran. Normally used on shunting canoes, the rig required some modification to fit on a tacking catamaran: The traditional Marshallese sail is raised between an A-frame shaped mast setup (each hull’s mast leans towards the other and is lashed together on the top, see A.97 and A.98). The masts were made from solid lumber with a thickness of 3 in (tapered to 2 in on each end). The apex connection (see A.90), the attachments for the stays (see A.91), and the halyard cleats (see A.92) were lashed on. The geometry of the rig was confirmed by an indoor test prior to the catamaran’s launch (see A.93). The masts were supported by two fore- and back stays. The backstays were designed as running backstays (attached by the cleats on the rear beam, see A.79) to allow the boom to open wide for downwind sailing. The forward tip of the sail (where upper and lower boom meet each other) was tied between the bows with a strong rope (see A.97 b).

See A.94 for a general overview about the initial setup after the launch.

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23 For the first sea trials an existing tarpaulin sail from an 18 ft korkor was used. Changes were not required, canoe and WAM cat sails are compatible.
Assembly

After 35 days of construction, the catamaran’s parts were painted and assembled, and the catamaran was prepared for its launch. First, the rudders were lashed on (see A.95 items a-d for the lashing process and 3.1.3 for general information about the technique). Next, the keel shoes were attached (see A.95 items e and f). The hulls were then carried out of the workshop and placed on cradles in front of the slipway (see A.96 item a). The beams were placed at their desired position on top of the beam blocks and lashed on with 18 tight loops (see A.96 item b). The trampoline from strong tuna fishnet was tied as tautly as possible in the rectangular space between the beams and the hulls. The A-mast was lashed onto the mast steps and raised with the fore- and backstays attached. The catamaran was then pushed into the lagoon and paddled on a beach, sail, hatch covers and tillers were mounted there. See A.97 and A.98 for a general overview of the initial setup.

3.1.7. Ailuk Catamaran

History and Background Information

United Nation Development Programme/Food and Agriculture Organization (UNDP/FAO) undertook several global artisanal boat-building projects between 1982 and 1989. In the Pacific, building on the work of Jim Brown in Tuvalu, FAO (O. Gulbrandsen) produced designs for ten different vessels, from a one-person paddling canoe to a 11 m transport trimaran. This initiative resulted in an experimental fleet of more than 350 artisanal fishing vessels built in eight Pacific Island Countries (PICs), many of which were either pure-sail or sail-assisted designs. The uptake of the sail-powered vessels, however, was minimal and did not survive beyond the officially funded project. The vessel designs were exemplary, have been well recorded, and are still available for use.

In 2004, WAM took one of these designs, the KIR 5A (drawings made by Gulbrandsen in 1991 for FAO, see A.6), and modified the long wooden outrigger design to a shorter fiberglass catamaran. The construction was ordered by the local government of Ailuk, at a cost of 20,000 USD, to supplement the traditional canoes for lagoon transportation. The hulls were made from molded solid fiberglass (the mold is still available at WAM) and connected by wooden beams, which were lashed in a Hawai’ian style. After launching

24It should be noted that the WAM Catamaran was built parallel to the HarryProa cargo proa, and the paint required five days to cure for both boats. Therefore, three weeks is sufficient for constructing only the WAM Catamaran for a skilled boat-builder and trainees.
and conducting sea trials around Majuro, the Ailuk Catamaran was sailed to Ailuk atoll. Unfortunately, the construction process, aside from a few pictures (see A.99 and A.100), was undocumented.

The Ailuk Catamaran’s construction characteristics and features include:

- Catamaran with symmetric flat bottom hulls with daggerboards
- Hulls built from glass fiber in a mold, beams shaped from solid lumber
- Rig, beams, rudders etc. made by lumber
- Hulls resistant against rot; superstructure not
- Beam joints made by rope lashings
- Use of Hawai’ian style lateen sail
  - Mast and spares made by timber
  - Limited upwind capability

The Ailuk Catamaran’s operation characteristics and features:

- Shallow draft (flatbottom); retractable daggerboards
- Decent payload and stable platform
- Very heavy, difficult to handle on the beach

<table>
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<th>Ailuk Catamaran Data</th>
<th></th>
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<td>Building Method:</td>
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<tr>
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<tr>
<td>Loading capacity:</td>
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</tr>
<tr>
<td>Sail area:</td>
<td>18.00 sqm (estimated)</td>
</tr>
</tbody>
</table>
**Inspection and Refit Plan**

The Ailuk Catamaran was inspected during a field trip to Ailuk in July 2018. Unfortunately, the vessel was in poor condition, i.e., all wooden parts (e.g., beams and the platform) had rotted and were beyond repair (see A.101). However, the parts which had been sheltered from the elements (e.g., mast, sail, rudder) survived. A decision was made to return the fiberglass hulls (which had sustained moderate damage) to WAM and rebuild the catamaran there.

The hulls of the catamaran were surprisingly heavy; it took 12 men to slide one hull down the beach. It was estimated that each hull weighed approximately 400 kg (800 lbs). It is possible that the catamaran’s weight and handling difficulty on land impacted how frequently it was used. The people of Ailuk reported that the catamaran had a slow sailing speed, especially upwind. This observation is in accordance with the Ailuk Catamaran’s ratio of sail area and displacement.

The hulls were so heavy that a truck and a crane were necessary to move them (see A.102). It was decided to rebuild the Ailuk Catamaran by substantially different methods, implementing all workshop key techniques as outlined in section A.1.

**Hulls**

Due to the lack of any documentation of the Ailuk Catamaran’s construction process, it was unclear how the design was carried out and which parts were salvageable. Fortunately, a member of the WAM team was a trainee during the Ailuk Catamaran’s hull construction in 2004 and was able to provide some information on the catamaran’s original construction, which aided in its rebuilding.

As a first step, both hull’s deck and the lashing beams (heavy beams on top of the deck of each hull to lash the cross beams to) were removed to gain access to the inside (see A.103 and A.104). The deck, once made from plywood and glassed over from outside, was heavily rotted. The likely main reason for this excessive rot was the lack of any rot prevention measures (a) on the inside (i.e., the sealing of wood against moisture using epoxy coat.) and (b) by connecting all compartments (even the inaccessible ones) by small drain holes near the bilge.  

The lashing beams were originally made from laminated plywood and then covered by fiberglass and glued to the shear. Due to the use of unsealed screws to hold the lashing

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25 Usually, the ventilation of closed compartments is key in rot prevention. In this case, the ventilation was insufficient, and the drain holes aided in spreading rainwater to all compartments resulting in condensation and permanent moisture.
beams in place temporary for the gluing and glassing, the plywood inside got wet and eventually composted (see A.104). Unfortunately, the deck’s bare plywood was glued and screwed down (without any rot prevention measures taken) onto the wooden shear stringer and the bulkhead tops with a rubber sealant, before it was glassed over from outside. Although the bulkheads and shear stringer were glassed very well at all sides, the top (where the deck had been secured with rubber sealant) was untreated. Both, the shear stringer and all bulkheads, were saturated with water and beyond repair (see A.105). Based on these findings, the decision was made to strip everything out of the hulls, keeping only the solid fiberglass hull shells for the Ailuk Catamaran’s rebuild.

The process of cutting out the bulkheads was difficult and laborious work, involving heavy tools like chisels, axes, and grinders (see A.106 items a and b). Due to an uneven, stained, and rough surface, the entire hull shell had to be ground from in- and outside (see A.106 items c and d). The result was an almost-new fiberglass shell, similar to its original state when it was unmolded in 2004. It was estimated that approximately 200 kg (400 lbs) was removed from each hull during this refurbishing process.

Considering the rigidity of the bare refurbished fiberglass shell (3/8 in thick walls) without any additional stiffeners, it is likely that the original construction was far heavier than necessary. Being attentive to the craft’s final weight, the following construction decisions were made: (1) the rebuild included two bulkheads in each hull (see A.107, the number of beams was reduced from 5 to 2), and (2) only 1 x 1 in shear stringers were used as stiffeners (see A.108). The deck was made from 3/8 in plywood (glassed from the inside), supported by cross-stringers from 1 x 1 in lumber every 2 ft and affixed with epoxy and no screws (see A.109).

To seal and further reinforce the deck, it was glassed from the outside with a 6 oz fiberglass cloth. The shear was rounded with a router and reinforced with fiberglass tape (see A.110). The hulls were finished by gluing on the beam cleats (see A.111) and the beam blocks using the process described in section 3.1.6; the next steps included sanding and painting (see A.112). The hull’s center was made accessible using a large hatch, leaving the sealed fore and aft compartments to contribute towards the boat’s reserve buoyancy (see A.112 item c).

### Beams

The beams were rebuild from scratch using the same method a described in 3.1.4
Rudder

The Ailuk Catamaran was equipped with a twin rudder system as described in section 3.1.6. In contrast to the WAM Catamaran, these rudders were not mounted on skegs to maintain flat underwater body for easy beaching and shallow draft; instead, the rudders were mounted into rudder heads with the option to kick them up (see A.113).

Leeboards

As a flat-bottom design, the original Ailuk Catamaran was equipped with retractable leeboards. The old leeboards were not in existence; therefore, new ones were made from three layers of 3/8 in plywood. The new leeboard’s airfoil shape was created using a planer, grinder, and sander (see A.114). The leeboards were mounted retractably on the outside of each hull.

Rig and Sail

The Ailuk Catamaran rebuild utilized the same A-frame mast setup as the WAM Catamaran, i.e., a Marshallese oceanic lateen sail (see 3.1.6).

3.2. Commissioning and Sea Trials

3.2.1. HarryProa

The HarryProa was first launched on the February 19, 2020, after 23 days of construction. She was not 100% finished at the first couple of launches (e.g. not painted) to make adjustments and modifications easier. The HarryProa’s inaugural sail was successful, although the swinging leeboard was quickly converted to a fixed retractable one. The shunting line, added to the otherwise unchanged Marshallese rig, was not as functional as expected and was eventually removed. By adding mast and sail steps, the rig was fully converted into a stile, which is traditionally used on Tipnols. Figures of the first test sails can be found in A.115 and A.115.

During the short test sails on the lagoon, the HarryProa prototype proved to be a fast and well-pointing sailing vessel. Compared to the WAM Catamaran, the HarryProa pointed slightly higher upwind and sailed faster on all courses.\footnote{Unfortunately, no data was collected due to a malfunction of the GPS tracker. To a certain level, the speed difference can be explained by the larger sail of the proa (60% bigger than the catamaran sail).} The HarryProa’s maneuverabil-
ity was somewhat slower than what Western sailors are used to from tacking; however, this experience was not problematic for individuals familiar with traditional Marshallese canoe sailing.

In examining the HarryProa’s advantages, the platform is relatively spacious (a slat deck was mounted between the beams), and its buoyant hulls can accommodate numerous passengers. The HarryProa is also well-suited for fishing due to vessel’s speed and the uncovered open platform, which provides adequate space for fishing gear.

Unfortunately, the HarryProa’s design does not include any dry cargo holds; therefore, the vessel might not be suitable for transporting copra and other dry goods.

For the first long-range sea trial, the uninhabited Bok Island, located on one of the furthest northern reefs of the Majuro atoll (20 nm air line from WAM), was picked as the destination to simulate travel between islets of a remote outer island atoll.

Following features of the HarryProa were modified prior to the sea trial:

- The apex of the sail was mounted in dipakeak (sail steps of traditional canoes).
- A lashed-on deck was created from slats between the main beams.
- An Ailuk-style rudder was mounted on the stern of the leeward hull.

The voyage from WAM to Bok was reported as smooth sailing and without difficulty (see A.117 items a and b). On the return voyage, the HarryProa encountered rough swells (especially at the reef channel) and strong winds of 28 knots (see A.117 items c and d)\textsuperscript{27}. The HarryProa handled the conditions well and made landfall at WAM without any issues. All modifications were deemed valuable and will be implemented in future designs.

### 3.2.2. WAM Catamaran

#### Maiden Sail and Short Lagoon Trips

The WAM Catamaran was first launched on March 9, 2020, after 35 days of construction. From the onset, the catamaran was easy to handle and smoothly performed its first tacks. Individuals who sailed the catamaran reported feeling safe and comfortable handling the vessel. The WAM Catamaran was very balanced on all points under the day’s weather

\textsuperscript{27}Unfortunately, no other than the two sails used were available to test.

\textsuperscript{27}These conditions are not very common for the Marshall Islands and are not what the prototypes (HarryProa and WAM Catamaran) were designed for. There has even been a rough seas warning from the weather station, and it was recommended that no small crafts sailing.
conditions. The twin rudder system proved to be easy and effortless to use. The WAM Catamaran has a spacious cabin to transport dry cargo dry and provides a place for the crew to relax or take shelter from the elements. Although, it remains to be verified, approximately six bags of copra could fit in each hull (i.e., 12 bags total) and be transported without being exposed to moisture.

For most of the people involved in this project, the WAM Catamaran was the first tacking boat they had ever sailed. Despite that, the handling proved to be easy so that even individuals without sailing experience could sail the WAM Catamaran within a few minutes. Maneuvers (tack and jibe) were done almost instantaneously using one hand and did not require the crew to change positions or move parts of the rig.

Because of the hardwood keel shoes, the WAM Catamaran could be beached (and even sailed directly on the beach) without risk of scratching the hull’s keels. This feature is especially important for on- and off-loading of cargo and passengers.

With a draft of 47 cm (18.5 in) empty and 60 cm (24 in) full (800 kg or 1800 lbs), the draft is significantly lower compared to those of most Tipnols (2-3 ft). The lower draft and the keel shoes make the WAM Catamaran especially suitable for operating in shallow lagoons. The A-mast, combined with the traditional Marshallese sail, provides uncomplicated handling and reliable performance that is cost-effective. The forces in the system are relatively low. Unlike conventional catamarans with the mast step located in the front beam’s center, the A-mast does not contribute compression and bending moments on the platform structure. Instead, the mast setup transfers loads from the sail directly to the hulls. By using traditional spilling lines, the sail can be depowered if needed. On the beach, the spilling lines work as lazy jacks, catching the sail cloth and booms. The running backstays are uncomplicated to operate. Upwind, it is not necessary to adjust them; downwind, the leeward stay is eased somewhat to open the sail further. However, if the sail is opened all the way, then the cloth hits the leeward mast, and the sail shape is deformed. This is an unfortunate drawback with an A-mast setup. Fortunately, the sea trials demonstrated that this constraint did not affect the craft’s performance; the vessel was able to sail downwind with modest speed. The upwind performance of the WAM Catamaran is not extraordinary, but adequate for everyday use. Tacking angles of 110° are possible.

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28 It should be noted that shunting canoes are the common design in Micronesia; tacking sailboats are relatively unfamiliar in the region.

29 It should be noted that the WAM Catamaran with a waterline of only 5 m carries 8 people and more while using the sail of an 18 ft canoe made from polytarp. It is doubtful that a much better performance than right now would be possible under the given constrains.

42
Pictures of the launch can be found in the appendix under A.3.2.

**First Long Range Trial**

After numerous short sailing trips around Majuro’s Delap-Uliga-Djarrit area, extensive sea trials of more than 20 nm were conducted.

The first long-range trial was a sail from WAM (Delap) to Laura beach (20 nm estimation, as shown in A.121 items a and b). The sail from Delap to Laura, which occurred in a deep reach of 15 - 18 kn trade winds, was smooth with no complications. The WAM Catamaran averaged 6.1 kn (with runs faster than 9 kn) and dropped the anchor at Laura beach after 3 h and 25 min (see A.121 item c).

The sail from Laura back to WAM (Delap) was an uncomfortable upwind beat against wind and steep chop. Although the catamaran performed well, it was observed that the crew would benefit from more specialized sailing training in maintaining the vessel’s optimum upwind angle. Unfortunately, the wind died half-way on the return trip, and the assistance of a motorized pace boat was used for 3 nm to ensure a landfall in daylight (no lights or navigation equipment were carried on board of the catamaran). Despite the long-range trial’s challenges, 13 Pacific mackerels were caught while sailing (see figure A.121 d).

The sailing trial showed that a slimmer and/or longer hull would significantly improve the vessel’s upwind ability in steep chop. Despite the challenges and unfavorable conditions (i.e., tacking upwind in high steep wind swell with lots of pitching), the WAM Catamaran successfully met its design goals. Both trips were documented in a video that is accessible on the WAM facebook page or under [https://youtu.be/MgKCwoP5RmE](https://youtu.be/MgKCwoP5RmE).

**Lagoon Fishing**

The under-floor compartments were used to carry fishing gear as well as freshly caught fish (i.e., when filled with water). The WAM Catamaran proved to be well-suited for lagoon and reef fishing. A fishing trip with eight individuals on board was made in 20-25 kn of wind.

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30 The upwind behavior of the WAM Catamaran is substantially different compared to a traditional canoe (i.e., there is no risk of getting caught aback).

31 Under-floor compartments provide storage for items that are often left on the deck and can hinder crew movement or lead to accidents (i.e., the risk of injury from fishing gear, such as hooks, is minimized).
Polar Data Trial

It was proposed by the project’s implementation guideline to measure the performance of all three prototypes in different wind speeds and course angles to visualize and compare the results as polar plots. Unfortunately, the GPS tracker broke down after the first set of data was collected on the WAM Catamaran in 8 kn of wind. Although further investigations with appropriate measurement equipment are required, the data obtained (see A.124) looks very promising and confirms the positive experiences of the test crews.

Second Long Range Trial

The second long-range sea trial was the first long distance sail by a WAM Marshallese-only crew without any involvement of foreign sailing experts. The unsettled Bok Island, one of the furthermost northern islets of the Majuro atoll (20 nm air line from WAM), was picked as destination to simulate real remote outer island conditions.

For this long-range trial, the following features of the WAM Catamaran were modified prior to the sail:

- The apex of the sail was mounted in dipakeak (sail steps of traditional canoes) on a rigid bow cross-beam (see figure A.123 a and b).
- A trampoline net was installed between the new bow beam and the former fore-beam (see figure A.123 e).
- A lashed-on deck was created from slats between the main beams (see figure A.123 c, d and e).
- Toe rails were placed on each bow and stern (see figure A.123 f).

The voyage from WAM to Bok was reported as smooth and with no complications. During the return voyage, the WAM Catamaran encountered rough swells (especially at the reef channel) and strong winds of 28 knots. These conditions are not very common for the Marshall Islands and are not what the prototypes (HarryProa and WAM Catamaran) were designed for. There has even been a rough seas warning from the weather station, and it was recommended that no small crafts sailing. 

This long-range trial provided valuable information on the catamaran’s capabilities and

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32 These features were initially planned for the design but postponed to expedite sailing the catamaran.
33 These conditions are not very common for the Marshall Islands and are not what the prototypes (HarryProa and WAM Catamaran) were designed for. There has even been a rough seas warning from the weather station, and it was recommended that no small crafts sailing.
Figure 3.1.: The polar plot above shows the performance of the WAM Catamaran as measured under real conditions on the Majuro lagoon in 7.5 knots of wind. Due to the limited number of possible measurements, the constant fluctuation of the wind speed, and deviations in the measuring equipment, the data was heavily smoothed to obtain the plotted result.
limitations. It was reported that the rudders lost grip and the hulls slipped to leeward. These reported experiences were likely due to broaches\footnote{Very common on racing monohulls in overpowered downwind sailing.} caused by an over-powered sail and steep waves (a smaller sail would have been helpful). All modifications proved to be worthwhile and will be implemented in future designs.

### 3.2.3. Ailuk Ferry

At the time this report was written, the Ailuk ferry, unfortunately, was not yet relaunched.
4. Evaluation and Recommendation for Future Workshops

4.1. Evaluation according to LoR

Prior to the design of the prototypes (WAM Catamaran and HarryProa), a detailed List of Requirements (LoR) was published in mid-2018 as the result of six months of fieldwork by a sailboat building expert (see A.9.1 for the original LoR). The LoR specified clear requirements and priorities for potential low-emission lagoon crafts in the RMI. Each new prototype was designed to meet the 2018 requirements as close as possible. For an initial validation, the designs were rated in 2018 based on (1) the blueprints and assumptions about each vessel’s characteristics according to the LoR, and (2) the priorities of each requirement (see A.10.1 for results). Each requirement was rated according to the overall design goal. The priority of each requirement was measured using a scale of 1-5, with 1 representing ‘low priority, nice to have’ and 5 denoting ‘high priority, must have’. Existing designs and future design options can be rated by multiplying the priority number and the grade of fulfillment. The fulfillment of a requirement was rated on a scale of 0-5, with 0 representing ‘no fulfillment’ and 5 denoting ‘100% fulfillment’. The overall suitability of each requirement calculated by multiplying the priority rating by fulfillment rating. The calculated suitability rating number allows for comparing different designs and supports evidence-based decision-making.

The validation process was repeated after the WAM Catamaran and the HarryProa prototype were finished and tested in April 2020. Questionnaires (see A.133) were administered to all persons involved (WAM staff, trainees, GIZ advisers, local sailors, and external consultants). The questionnaire focused on the fulfillment of the requirements on the LoR. Respondents were asked to rate the WAM Catamaran compared to the HarryProa prototype on scale from 1 to 5 (using the rating system described above). The questionnaires were completed anonymously. From the results, an average value was calculated for each requirement of the two prototypes (see A.134). In the same manner as the pre-workshop evaluation (described above), the average value of fulfillment for each requirement was multiplied by the corresponding priority. The final results (see A.135 and A.136) differed when compared to the outcomes from the 2018 pre-evaluation. Although both designs performed extraordinarily well, with high overall scores, the WAM Catamaran was rated

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1 Two requirements were added compared to the original LoR due to new gained insights, see A.9.2
as slightly more suitable for the tasks intended by the LoR. This outcome should be further investigated given that long-range sea trials and subsequent improvements were not complete at the time of the survey.

4.2. Lessons Learned

In general, the methodological approach of the training proved to be effective and appropriate for the goals of the program. The biggest limitation impacting the program’s efficiency was the English-Marshallese language barrier\(^2\). Using English-only was not sufficient as the main teaching language for the workshop. To enhance the comprehension of training concepts and processes, Marshallese staff should play a leading role in future training. Furthermore, that the extent that it is possible, non-Marshallese advisers should complete basic Marshallese language training before conducting fieldwork.

Resin plays an extremely important role in the vessel constructions; therefore, it was very important that trainees be given a comprehensive introduction into epoxy resins and their use in boat-building. The resin used in the WAM workshop allowed a pot life of 20 minutes only\(^3\). This short pot life of the resin used in the WAM workshop did not allow for mistakes and created a somewhat ‘rushed’ teaching-learning experience. For future workshops, it is recommended that the slowest available resin (at least 1-hour pot life at 30 °C (86 °F)) be procured. Due to the limited availability and high prices of suitable resin in the RMI, it is advisable, from an economic point of view, to import larger amounts of resin (shipping time should be considered when placing orders originating in other countries).

Due to supply constraints on island, baking flour was used, instead of colloidal silica and micro balloons, to mix epoxy glue and putty for fillets. Despite its higher density and lower thickening effect, compared to micro balloons, flour proved to be a suitable adaption to the local conditions in RMI.

The strength of the flour joints and fillets were, among other samples like sandwich constructions, demonstrated to the trainees by break tests. These tests were particularly interesting to the trainees and assisted in creating a baseline understanding of epoxy’s important role in boat-building.

\(^2\)Theory lessons were rather ineffective in English only.

\(^3\)It should be noted that the curing speed of epoxy resins get usually designed for an ambient temperature of 20 °C (68 °F). A temperature increase of 10 °C (18 °F) results in a 50% reduced pot life (i.e., the time available to work with it).
An unexpected challenge was the procurement of untreated lumber on island. The availability of untreated lumber was very limited (most of the lumber in stock was heavily treated), and most of warehouse stockpiles were damp and rotten. For future boat-building projects, it is important to gather suitable lumber early on. To ensure optimal lumber is used, it is recommended that lumber with straight grain and minimal knots be selected then stored in dry conditions for two or more weeks.

The long-distance sea trials showed that, under certain conditions (low wind and high/steep swell), the WAM Catamaran tends to pitch. This is not a critical problem and does not affect the WAM Catamaran’s suitability for its intended purpose. However, it is recommended that the final version of the WAM Catamaran should be stretched to 24 ft (three sheets of plywood instead of two and a half) to gain waterline length and improve the catamaran’s overall performance (especially upwind in choppy conditions). The HarryProa proved to be a fast-sailing canoe, appropriate for use as a fishing vessel (i.e., the Marshallese test crew rated it favorably for fishing). As the sea trials showed, the HarryProa is less suitable for copra cargo transport, for which dryness is a critical requirement. A future HarryProa version should include internal dry cargo holds to allow for better cargo transport of copra and other dry goods.

The importance of adequate keel protection cannot be overemphasized. RMI’s beaches and reefs are rough and can easily destroy the hull’s bottom protective layer of fiberglass and epoxy. The WAM Catamaran’s keel shoes (lashed on sacrificial pieces from hard wood under the keel) solved this problem and provided adequate hull protection.

4.3. Recommendation for Future Workshops

Transitioning to Low Carbon Sea Transport will be a gradual process in the RMI. Therefore, an approach should be taken that identifies key steps and acknowledges movement towards the ultimate LCST goal. Identifying the key steps should be done carefully: too big a step or too many steps at once risks overwhelming the project setup and long-term sustainability.

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4Treated lumber can not be used for epoxy bonds.
5Not a big surprise after all, taking into account the short waterline.
6The idea for the keel shoes were derived from traditional canoes (erer).
7This means boat sizes as well as general ambitions.
For WAM, as well as for LCST, the 2020 prototype workshop was an important step forward. The sea trials in the second half of 2020 will consolidate the achievements of the workshop and prepare WAM for the next step. It is recommended that a second workshop be implemented with following changes (to improve upon the first workshop):

- Construct a slightly bigger lagoon vessel (35 ft) based the results of the sea trials. A vessel up to 35 ft could be maintained and operated by WAM independently without overwhelming the NGO’s resources over the long term. A mix of 20 to 35 ft vessels seems to be a good choice for reliable service inside the lagoons.

- Utilize Marshallese leadership for the second workshop, i.e., WAM staff should prepare and lead the workshop. A non-Marshallese consultant may can serve as an adviser and as an assistant capacity.

The procurement of materials for a second workshop should be optimized from an economically point of view. The importing of epoxy resin offers a significant cost-savings potential.

For professional documentation of the boat-building process, WAM should be provided with a waterproof camera and film equipment.

Finally, regarding human resources, to supplement the need for both English and Marshallese fluency, foreign staff who serve in an advisory capacity should receive basic Marshallese language training in advance of conducting fieldwork in RMI. Future workshops would benefit from a more bilingual approach that reflects both English and Marshallese.
A. Appendix

A.1. Construction Techniques

Figure A.1.: Scarf joint (side view). The long bevels increase the bonding surface and, therefore, the strength of the connection. [02]

Figure A.2.: Cross section of a T-joint with a high-density and a low-density fillet of the same strength. Note that the low-density fillet needs a much larger radius to match the high-density fillet’s strength. [02]
Figure A.3.: The application of fillets in three steps.\[02\]
Figure A.4.: Schematic of a stitch-and-glue joint cross section.
Figure A.5.: Breaking test of a fillet sample.
Figure A.6.: Broken fillet sample. If break occurs outside and fillet remains clean and smooth, then the bond exceeds the material’s strength, i.e., fillet size and density is appropriate.
Figure A.7.: Demonstration of fiberglass’s strength. The right plywood strip (broken) is untreated 3/8 in marine plywood. The left sample strip (bent) is a plywood strip of the same dimensions that is covered with a 6 oz fiberglass cloth layer on each side. The glassed sample on the left can carry twice the load of the right sample before the plywood in between the fiberglass layers collapses.
Figure A.8.: Functional model of a hinge lashing.
A.2. Figures Construction

A.2.1. Beams

Figure A.9.: Rectangular and hollow cross section of a beam. The lumber is positioned on the top and bottom to absorb the bending loads, while the vertical plywood works as shear web.
(a) Stockpile of hand picked lumber. Air circulation in between the lumbers is important to prevent rot and reduce the moisture content.

(b) Table-saw with self made jig for scarf cuts.

(c) Cutting scarfs.

(d) Puzzling full length battens by using the scarf connections.

Figure A.10.: Preparation of the beam lumber.
(a) Spreading epoxy glue on the lumber strips.  

(b) Gluing the lumber strips together to form a beam plank. Clamps keep everything in place.

Figure A.11.: Preparation of the beam lumber.
(a) Cutting scarf bevels on plywood strips for beams by using a planer.

(b) Scarf bevels planed half way through. Every line of the steps should be parallel for a good result.

(c) Three scarf joints waiting for glue. Clamps or something heavy is sufficient to keep them in place until the epoxy is cured. Wax paper is used to separate both joints from each other.

Figure A.12.: Scarf joints of the beam plywood.
(a) Ply and lumber clamped to form a beam. Wood clamps are perfect for making beams and help to align everything.

(b) Ply and lumber clamped to form a beam. Wood clamps are perfect for making beams and help to align everything.

Figure A.13.: Beam lumber and plywood are glued.

(a) Beam gets glassed with a 3 ft wide piece of 6 oz glass cloth.

(b) Beam after flow coat with epoxy resin.

Figure A.14.: Beams are glassed and finished.
A.2.2. HarryProa

Hulls

(a) Full size plywood panels were cut lengthwise and the bow curve is marked on the halve sheets.

(b) A second halve sheet is used as spline ruler.

(c) A second halve sheet is used as spline ruler.

(d) The first bow part is cut. The off-cut is used as template for all following parts to ensure that all are identical.

Figure A.15.: Bow curve.
(a) Glass fiber cloth is applied on one side of the panel.

(b) Glass fiber cloth is applied on one side of the panel.

(c) The glass fiber is laminated with epoxy resin.

(d) All joints are reinforced by an extra layer of glass cloth and clamped down for better alignment.

Figure A.16.: Joining the panels (in this case the bottom panel of the windward hull. The process is the same for all panels.).
(a) Chine stringer and bottom bulkhead doublers are cut to size and glued on the bottom panel (same process for windward and leeward hull).

(b) Chine stringer and bottom bulkhead doublers are cut to size and glued on the bottom panel (same process for windward and leeward hull).

Figure A.17.: Assembly 1: Chine stringer and bottom bulkhead doublers.
(a) Pre-cut bulkheads are glued to the bottom doublers.

(b) Pre-cut bulkheads are glued to the bottom doublers.

Figure A.18.: Assembly 2: Bulkheads doublers glued on the bottom panel.

(a) Mid-height stringer are glued around the bulkheads.

(b) Gunwhale stringer are glued around the bulkheads.

Figure A.19.: Assembly 3: Mid-height and gunwhale stringer are glued around the bulkheads.
Figure A.20.: Assembly 4: Side panels (pre-glassed) are glued to the bulkheads. The hull was flipped on one side to avoid vertical fillets.
(a) Cockpit floor glued in.

(b) Deck panels glued on.

Figure A.21.: Assembly 5 and 6: Cockpit floor and deck panels are glued on.
(a) Bows reinforced by lumber.
(b) Chines sealed by thickened resin.
(c) Chines sealed by thickened resin.
(d) Chines glassed over with a tape.
(e) Hulls glassed outside.
(f) Cockpit glassed.

Figure A.22.: Assembly 6: Chines sealed and hulls glassed.
Figure A.23.: Tapers were made (slightly different to the method suggested in the plans) from lumber.
Figure A.24.: Beam attachments.
Leeboard

(a) Laminated plank of lumber.
(b) The rough shape is carved by a planer . . .
(c) . . . followed by an angle grinder.
(d)
(e) Finished shape before sanding.

Figure A.25.: Leeboard shape (1 of 2).
(a) Finished shape after sanding.

(b) The changing profile (flat to curved and vice versa) is clearly visible here.

(c) Ogival airfoil section.

(d) Leeboard glassed and flow-coated.

Figure A.26.: Leeboard shape (2 of 2).
(a) Bulkhead box for the leeboard attachment.  
(b) Bulkhead box for the leeboard attachment.  
(c) Leeboard case from glass fiber tow.  
(d) Leeboard case from glass fiber tow.

Figure A.27.: Leeboard box and case.
A.2.3. WAM Catamaran

Measuring

Figure A.28.: Length of the WAM cat hull (20 ft) derived from the plywood size.

Figure A.29.: Height of the WAM cat hull set to 1/6 of the total length by folding the master string.
Figure A.30.: 7 stations dividing the plywood in 8 sections are marked on the plywood. The Marshallese names of the corresponding part of the traditional method are given in green according to \[03\].

Figure A.31.: Establishment of the bow and stern shape (yellow). In case of the WAM cat bow and stern were symmetric, measuring 1/8 of the hull length down the \textit{maan jorjor} line. For future designs unsymmetrical shapes (different lengths for bow and stern) are possible.
Figure A.32.: The keel line was developed as a round spline by bending a PVC pipe around the intersection of *maan jorjor* with bow line and *mejaanij* with baseline.

Figure A.33.: An alternative to the round keel is the easier to build strait keel. It is developed by simple strait lines between the intersection of *maan jorjor* /bow line, *malmal*/baseline and *mejaanij*/baseline.
Figure A.34.: The positions of the purple full sized bulkheads are measured and marked by using the master string.

Figure A.35.: Main bulkheads are denoted in purple; support bulkheads and stiffeners are denoted in grey. The size of the cutouts for the cabin interior is made according to the builder’s preference. A minimum frame width of 2.5 in is required. Corners should be cut with a large radius (min. 3 in).
Figure A.36.: The center bulkhead (number 4) is measured by using the master string. All other bulkheads are fit to the height of the hull side panel at their particular position and the spline shape of the shear after the stitched hull sides are spread. The height of bulkhead 3 is calculated from the center bulkhead 4 (green). The width of the keel plank must be taken into account when the bulkheads are lofted.
Hulls

(a) 2 and 1/2 sheets of plywood are placed flat on the ground. Design model and Master string (as long as the 2.5 ply sheets) in the center.

(b) The ply sheets are joined by glued on doublers. Water bottles are used as weight to keep everything in place.

(c) The ply sheets are ready for lofting. The long white PVC pipe is used as spline batten. The shear stringer (including scarfs) is already prepared on the right.

Figure A.37.: Preparation of the hull side sheet for lofting.
Figure A.38.: Preparation of the master string. It is folded to the required fraction, i.e.,
$1/2$, $1/3$, $1/4$, $1/6$, $1/8$ and so on.
(a) Station lines are marked on the plywood.

(b) The straight edge of an off cut plywood sheet is used as long ruler.

(c) Bow line is marked as measured by the master string.

(d) The keel line is splined using a PVC pipe.

Figure A.39.: Lofting process of the hull side sheet.
(a) The side sheet is cut out using a jigsaw.

(b) Side sheet ready to glue the shear stringer on.

(c) Shear stringer glued and clamped on the pre cut side panel.

(d) Shear stringer glued and clamped on the pre cut side panel.

Figure A.40.: Lofting process of the hull side sheet.
Figure A.41.: Lofting process of the center bulkhead.
(a) The skeg is glued together from plywood to the same thickness as the keel lumber. It is designed to support the rudder as vertical as possible. It should not draft deeper than the keel to keep the rudder protected in case of ground contact.

(b) The keel is made from a solid piece of lumber (can be scarfed if necessary). It is pre-bent for a couple of days to make it easier to assemble. Lumber with a natural crown (lumber which comes already bent) is perfect for this job.

(c) Skeg, bow and keel getting fit to each other.

(d) Skeg, bow and keel getting fit to each other.

Figure A.42.: Preparation of keel lumber, bow and skeg
(a) The hull side sheets get a bevel at the edges which will be joint to the keel, bow and skeg. The bevel is important to allow a smooth fit and reduce the tension in the stitch seams when the hull is spread.

(b) An angle grinder is a fast tool to manufacture the bevel.

Figure A.43.: Preparing the side sheets for stitching.
(a) Holes (slightly bigger than the already prepared copper wires, approx. one hand width apart of each other) are drilled through both hull sides.

(b) Keel, bow and skeg are clamped in between the side panels.

Figure A.44.: Assembling process.
(a) Keel lumber and holes for the copper wire stitch.

(b) Keel stitch.

(c) Stitch of the skeg.

(d) Hull sides, skeg, keel and bow are stitched together. Clamps are not necessary anymore. The cradles are already prepared (right) to support the hull shell in its upright position.

Figure A.45.: Stitching process.
(a) The stitched hull sides are lifted vertically and placed in the cradles.

(b) Ready to spread the hull. The prepared center bulkhead is ready to grab.

(c) The shear is gently pulled apart to open the hull shell. The center bulkhead is carefully pushed inside. The shear stringers should snap into the cut-outs of the bulkhead and lock in place.

(d) The center bulkhead is locked in place. Gaps between hull and bulkhead should be minimal.

Figure A.46.: Spreading of the hull shell.
(a) After the center bulkhead is mounted successfully, the bunk board support triangles (bulkhead 3.5) are cut and shaped. They should fit right on the edge of the butt join doublers and allow the bunk boards to sit even on them. The batten in the picture is used to level the upper edges of the three bulkheads.

(b) All horizontal edges on bunk level are equipped with 1x1 " lumber to allow the bunk boards to rest on a larger surface.

(c) All bulkheads are tinkered to the size of the actual hull. Goal is to give the shear a continuous and symmetric spline shape.

(d) All bulkheads are mounted without any gaps between their edges and the hull shell. A string tightened from bow to stern indicates whether the hull is twisted or not.

Figure A.47.: Preparing and assembling the bulkheads.
(a) Diagonal stiffener (symmetric in bow and stern). The exact measurements are from little importance as long as it connects keel lumber and bow bulkhead top in a diagonal manner.

(b) Diagonal stiffener (symmetric in bow and stern). The exact measurements are from little importance as long as it connects keel lumber and bow bulkhead top in a diagonal manner.

Figure A.48.: Diagonal stiffeners.

(a) Application of a fillet to the join of the center bulkhead and the hull side. The tool is easy made by a stick of lumber for the handle and a round plastic piece (cut from a lid i. e.g.).

(b) The 'thickness' of the epoxy mixture is critical, especially if flour is used. A runny mixture will run of a vertical fillet leaving a weak joint.

Figure A.49.: Application of fillets.
(a) Keel fillet under construction.

(b) Tools with long handles might be helpful for the deep keel fillet.

(c) Application of the keel fillet.

Figure A.50.: Application of fillets.
(a) Reinforcement for the beam cleats in front and astern of the cabin bulkheads.

(b) Out- and inside doublet as reinforcement for the beam cleats.

Figure A.51.: Reinforcement for the beam cleats.
(a) Basic components for the beam cleats, both laminated from two 3/8 " plywood pieces.

(b) Cleat base and hook glued together.

(c) Cleat base and hook glued together.

(d) Manufacturing steps of the beam cleat.

(e) Manufacturing steps of the beam cleat.

(f) Manufacturing steps of the beam cleat.

Figure A.52.: Manufacturing process of the beam cleats.
(a) Beam cleat glued outside on the reinforcement doublet on the hull.

(b) Holes (at least 3/4 \") are drilled into the cleats through the cleat base in the hull. Attention, the holes are not drilled all the way through! The inside mast remain closed! The drill is stopped 1/8 \" before it brakes through on the inside. A mark on the drill bit indicates the maximum depth.

(c) Hardwood pins fit for the holes.

(d) The holes are halve filled with slightly thickened resin (like thick syrup). The pins are pressed into the holes squeezing out most of the resin.

(e) The process lined out in d) ensures enough resin along the pin and a proper bond.

(f) After the glue is cured the pins are trimmed and sanded.

Figure A.53.: Bonding and reinforcement of the beam cleats to the hull.
(a) Measuring the individual lengths for the support stringers and marking their position on the hull.

(b) Leveling the bunk-boards with a straight batten.

(c) The bunk-board support stringers are glued in by using copper wire to temporarily fix them on the bent hull.

Figure A.54.: Gluing the bunk-board support stringers into the hull.
(a) The shape of each bunk-board is different. A large sheet of paper is used to get the dimensions right from the hull.

(b) The paper is pressed into the hull the same way as the bunk-board will go in later. A second pair of hands is helpful to keep everything tight while the outline is marked.

(c) Finished bunk-boards in the hull. The finger hole makes it easy to lift the boards and gain access to the bilge.

(d) Finished bunk-boards in the hull. The finger hole makes it easy to lift the boards and gain access to the bilge.

Figure A.55.: Manufacturing of the bunk-boards.
(a) The top edges of all bulkheads are equipped with glued on 1x1 in lumber to increase the bonding surface for a strong joint with the deck and the cabin roof.

(b) The shear and the bulkhead tops are ground to allow a smooth fit of the deck panels. A smooth fit is important for a strong bond.

Figure A.56.: Preparation of the hulls for the deck and the cabin roof.
(a) Application of epoxy inside the hull.

(b) It is very important to cover every bit of bare wood with epoxy to keep the hull rot free.

(c) The accessibility proved to be best with the hulls flipped on one side.

(d) Both hulls are treated parallel to each other with three layers wet in wet. The organization requires some preparation and planning of the crew to finish the job in time.

Figure A.57.: Application of three layers epoxy as rot prevention inside the hulls.
(a) The size of each deck panel is derived directly from the hull by placing it at the desired position and drawing a line around the outline.

(b) Preparation of all four deck panels.

(c) Cutting a deck panel to size.

(d) All four deck panels cut to size.

(e) Perfectly aligned deck panel, ready for glassing the internal surface.

Figure A.58.: Preparation of the deck sheets.
(a) The cabin roof is cut to the width of the bulkhead tops and placed at its desired position.

(b) Fixed by clamps, the side panels are cut according to the shape of the roof and the shear.

(c) Cabin sides and roof cut to the right dimensions and placed temporary at the desired positions.

(d) Cabin sides and roof cut to the right dimensions and placed temporary at the desired positions.

Figure A.59.: Preparation of the cabin roof and cabin side panels.
(a) The deck panels are glassed frome the inside as reinforcement and for rot protection.

(b) The deck panels are glassed frome the inside as reinforcement and for rot protection.

(c) Cabin sides and roof are coated with 3 layers of epoxy (wet-in-wet) as rot prevention.

Figure A.60.: Glassing and epoxy treatment as rot prevention measure of the decks, cabin roof and cabin side panels.
(a) The deck panels are glued on the shear and the bulkheads with thickened epoxy. Clamps and weights are used to temporary hold it in place. It is important to use enough glue (it should squeeze out a little bit everywhere) to create a strong bond without any gaps.

(b) The deck panels are glued on the shear and the bulkheads with thickened epoxy. Clamps and weights are used to temporary hold it in place. It is important to use enough glue (it should squeeze out a little bit everywhere) to create a strong bond without any gaps.

(c) Fillet between deck and cabin bulkhead.

Figure A.61.: Deck panels glued on the hulls.
(a) The cabin roof is sanded at the bonding surfaces and wet with resin.

(b) Plenty glue is spread on the bulkhead tops for a strong bond without any gaps. The glue is supposed to squeeze out as an indicator of a good joint.

(c) The roof is placed on top of the bulkheads.

(d) The roof is bent down to its intended shape and fixed temporary by screws (not recommended for a repetition!).

(e) The screws should be avoided by gluing on the deck panels last and using clamps to hold the roof down on the cabin bulkheads.

(f) Scooping of squeezed out glue.

Figure A.62.: Cabin roof panels glued on the hulls.
(a) Cabin sides sanded at the bonding surface.

(b) Hulls prepared with glue and resin.

(c) The cabin sides are held in place by hot melt glue from outside. In the next step they will be fixed by fillets from inside permanently.

Figure A.63.: Cabin sides glued on the hulls.
(a) Cut-out for the hatch is marked on the roof.

(b) Hatch is cut into the roof after the clue has cured.

(c) Fillets between the side panels, the roof and the shear are made from inside.

(d) Finished internal fillets.

Figure A.64.: Hatch opening and fillets of the cabin roof and sides.
(a) All edges are rounded and filled with thickened resin (if needed). A router (see A.127 d) for the main part of the job is very helpful in addition to a sander for final smoothness.

(b) All edges are rounded and filled with thickened resin (if needed). A router (see A.127 d) for the main part of the job is very helpful in addition to a sander for final smoothness.

(c) The entire deck and cabin surface is sanded in preparation for glassing.

(d) The entire deck and cabin surface is sanded in preparation for glassing.

Figure A.65.: Preparation of the exterior shear and cabin edges.
(a) Glass fiber cloth (6 oz) is rolled over deck and cabin roof. It is cut to the size of the hull with an offset of 3 in to reinforce the edges by overlapping.

(b) Glass fiber cloth (6 oz) is rolled over deck and cabin roof. It is cut to the size of the hull with an offset of 3 in to reinforce the edges by overlapping.

(c) Additional glass cloth is prepared for the cabin sides.

Figure A.66.: Preparation of the glassing of the cabin and the deck.
(a) The epoxy resin is applied directly on top of the glass cloth until it becomes clear (wet out). The overlap for the edges is wet out by folding it up on the already wet deck.

(b) The wet overlap is than folded back...

(c) ...and formed into place by hand.

(d) Finished deck laminate. No white spots (air) left, the glass cloth is everywhere attached to the plywood.

(e) Finished deck laminate. No white spots (air) left, the glass cloth is everywhere attached to the plywood.

(f) The deck laminate overlaps all the way up to the cabin roof.

Figure A.67.: Glassing of the cabin and the deck.
(a) One hour after glassing another layer is applied wet-in-wet (so called flow-coat) to beef up the rot resistant epoxy layer.

(b) The flow coat is clearly visible by the absence of any fiber structure of the glass cloth. The surface is shiny.

(c) Application of the flow-coat.

(d) Shiny flow-coat in the right and fiber structure of the glass cloth laminate in the left.

Figure A.68.: Application of a flow-coat on the cabin and the deck.
(a) Hull turned upside down and wires removed.

(b) The bow lumber is shaped round and streamlined.

(c) The keel lumber is rounded but still rectangular.

(d) All gaps in the transition from hull to keel are filled with thickened epoxy.

(e) All gaps in the transition from hull to keel and all holes from wires are filled with thickened epoxy.

(f) An eyelet is glued into each bow as fore-stay and anchor attachment. The eyelets were made from 1 in PVC pipe covered by 1/8 in layer of glass fiber cloth.

Figure A.69.: Preparation of the bottom for glassing.
Transitioning to Low Carbon Sea Transport

(a) Hulls turned on one side to work on a horizontal surface.

(b) Glass fiber cloth is rolled over the hull side.

(c) Glass fiber cloth wet out with epoxy resin.

(d) Glass fiber cloth is cut to size (3 in overlap at keel and bow).

(e) Glass fiber cloth is cut to size (3 in overlap at keel and bow).

(f) First side glassed. Second side is analogous.

Figure A.70.: Glassing of the hull bottom.
(a) Keel, bow and skeg are covered by 7 Layers of 6 oz cloth as reinforcement in case of ground contact.

(b) Keel, bow and skeg are covered by 7 Layers of 6 oz cloth as reinforcement in case of ground contact.

(c) Keel, bow and skeg are covered by 7 Layers of 6 oz cloth as reinforcement in case of ground contact.

(d) Keel, bow and skeg are covered by 7 Layers of 6 oz cloth as reinforcement in case of ground contact.

Figure A.71.: Reinforcement of keel, bow and skeg.

(a) The bow eyelet is reinforced with glass fiber tow. A sheet of wax paper is used to smooth the surface.

(b) The star shape (to spread he load on a bigger surface) of the glass tows is clearly visible after sanding.

Figure A.72.: Reinforcement of the bow eyelet.
(a) Shaping of the keel-shoes from local hardwood according to the shape of the keel.

(b) Finished keel-shoes.

Figure A.73.: Manufacturing of the keel-shoes (Marshallese: erer).
(a) The mast bases are carved from massive local hardwood.

(b) The mast bases are carved from massive local hardwood.

(c) The mast are lashed to the bases, therefore a lashing hole is provided.

(d) A second hole (not in the picture) serves as drainage to avoid water getting trapped in the mast bases.

(e) Both holes are sealed by epoxy from inside.

(f) Firs side glassed. Second side is analogous.

Figure A.74.: Manufacturing and mounting of the mast steps.
(a) 8 hardwood blocks of the same size are cut as support for the cross-beams.

(b) The blocks are glued at the position of the beams, right in front of the cabin bulkheads and above the beam cleats.

(c) The blocks should not touch the cabin bulkheads to allow water to drain.

(d) The blocks serve as spacer between deck and beams.

(e) Direct contact between deck and beams would create an undefined gap which would be difficult to maintain and always wet.

Figure A.75.: Manufacturing and mounting of the beam support blocks.
(a) The hatch frame is made from 1x2 in lumber. The short pieces (bow and stern) are glued on top of the cabin roof, the long ones in the hatch opening (touching the cabin roof in a butt-join manner. 

(b) The hatch frame is further reinforced with small fillets.

(c) The hatch cover is made from 3/8 in plywood and lumber of the same cross section as the hatch frame. The long lumbers are ground to fit the bent shape of the cabin roof.

(d) The front of the hatch cover plywood extends approx. 2 in beyond the front lumber to take the holes for the rope hinge (see 3.1.3). The holes are pre-drilled, filled with epoxy and drilled again.

(e) The hatch cover is placed on top of the hatch frame to determine the position for the hinge plates.

Figure A.76.: Manufacturing of hatch frame and hatch cover.
(a) Hinge plate. Pre-manufactured and glued on the cabin roof by fillets.

(b) Hinge plates matching up with the hinge holes of the hatch cover.

(c) Hinge plate matching up with the hinge holes of the hatch cover.

Figure A.77.: Mounting of the hatch cover hinge plates.
(a) Painting equipment: regular exterior house paint, brushes and big rollers.

(b) Brushes are used for detail work only.

(c) The main surface is covered by the rollers.

(d) The main surface is covered by the rollers.

Figure A.78.: Painting the hulls.
Beams

(a) Backstay cleat from hard wood (rear beam only) and end block. (b) Backstay cleat from hard wood (rear beam only).
(c) Alignment blocks on the bottom of the beam. The contact area of beam and hull is reinforced with additional glass.

Figure A.79.: Modifications of the bare beams for the WAM Catamaran.
Rudder System

Figure A.80.: The WAM catamaran on the dry during low tide. The rudders do not touch the ground and are protected by the skeg.
(a) Determination of the skeg’s dimensions by placing a plywood sheet underneath the hull side panel.

(b) The first skeg plywood is used as pattern to cut 6 pieces (3 for each hull).

(c) Each skeg is glued from two 3/8 in and one 1/4 in plies.

Figure A.81.: Construction of the skeg.
(a) The skeg is stitched into the hull. (b) The skeg is stitched into the hull.

(c) Hull shell with skeg at the stern.

Figure A.82.: Integration of the skeg into the hull.
(a) The rudder is glued from 2 pieces of 3/8 in plywood and tapered at the trailing edge to 1/8 in to create an airfoil shape.

(b) The job is fast finished by using an angle grinder. The parallel lines of the individual veneer layers of the plywood give a good visual feedback of the shape.

(c) The leading edge is rounded by using a router (see A.127 d).

Figure A.83.: Manufacturing of the rudder blade.
(a) Four sets of nine holes for the hinge lashing are pre-drilled with twice the diameter of what would be required for the lashing rope.

(b) The sets of holes are copied to the skeg.

Figure A.84.: Pre-drilling of the lashing holes.
(a) The pre-drilled holes in the skeg and the rudder are filled with unthickened epoxy resin.

(b) The bottom of the holes is closed by ducktape (red) and further sealed by a stick clamped underneath.

(c) Filled holes. The plywood absorbs the resin, the holes need a couple of refills.

(d) After the resin in the holes has cured they are re-drilled carefully without cutting into the wood to the required diameter.

Figure A.85.: Filling and re-drilling the lashing holes.
(a) The rudder is lashed to the skeg to check if everything is working as intended.

(b) Rudder lashing, see 3.1.3 for further information.

(c) Glassed rudders.

(d) Rudders sanded and prepared for painting.

Figure A.86.: Test assembly of the rudder and further preparation for painting.
(a) Finished tiller (on top) and explosion of all parts (below).

(b) The tiller are made in a mould on a flat table.

(c) The strait raw parts are forced into the round shape by clamps.

(d) Resin and glue is spread. A wax paper keeps the tiller from sticking to the table.

(e) All parts are forced into shape by clamps to allow the glue to cure.

(f) Tiller un-moulded, clamps at the lumber parts still on.

Figure A.87.: Manufacturing process of the tiller (1 of 3).
(a) Clamps removed.

(b) Tiller rounded (by angle grinder and sander) and base reinforcement prepared.

(c) Base reinforcement plywood.

(d) Base reinforcement plywood glued on and tiller coated with epoxy. The base slot is tapered to fit the top of the rudders.

(e) Pre-drilled holes for the tiller crossbar lashing are filled with epoxy.

(f) Pre-drilled holes for the tiller crossbar lashing are filled with epoxy.

Figure A.88.: Manufacturing process of the tiller (2 of 3).
(a) Tiller painted.  
(b) Tiller crossbar.

Figure A.89.: Manufacturing process of the tiller (3 of 3).

Rig and Sail

(a) Recess for the lashing.  
(b) Tight lashing in a figure-eight motion.

(c) Lashing finished and locked.  
(d) Finished mast head lashing with halyard block.

Figure A.90.: Masthead lashing.
Figure A.91.: Lashing as for- and backstay attachment.
(a) Preparing the cleat from hardwood.

(b) Lashed on cleat at the mast.

Figure A.92.: Halyard and spilling line cleats.

(a)

(b)

Figure A.93.: Indoor test of the rig.
Figure A.94.: Rig and sail setup after launch.
Assembly

(a) Rudder hinge lashing.  
(b) Rudder hinge lashing.  
(c) Rudder hinge lashing.  
(d) Rudder hinge lashing.  
(e) Lashing of the keel-shoe.  
(f) Lashing of the keel-shoe.  

Figure A.95.: Lashing of rudder and keel-shoe.
(a) First hull placed in cradles in front of the slip way.

(b) Each beam Lashing is done by 18 loops of fishnet twine rope.

Figure A.96.: Lashing of beams and hulls.

(a) Rudder and tiller setup.

(b) Bow line and mount of the sail.

(c) A-mast setup.

(d) Running backstays on the rear beam.

Figure A.97.: Final setup (1 of 2).
(a) Spilling lines attached to the lower boom.

(b)

(c) The anchor line is attached to each bow by a V-shape bridle.

(d)

Figure A.98.: Final setup (2 of 2).
A.2.4. Ailuk Ferry

History and Background Information

(a) Ailuk cat after launch.  
(b) Maiden sail with WAM Director Denis Alessio.

(c) Ailuk cat moored in front of MIR.

Figure A.99.: Launch of the Ailuk catamaran in 2004.
(a) Glassing of the deck structure.  
(b) Spray-painting the hull.  
(c) Refit on Ailuk in 2011.

Figure A.100.: Construction of the Ailuk cat at WAM in 2004 and refit on Ailuk in 2011.
Inspection and Refit Plan

Figure A.101.: Ailuk catamaran inspected during a GIZ field trip in July 2018.

Figure A.102.: Handling of the Ailuk catamaran hulls at WAM.
Hulls

(a) Cutting of the deck with angle grinders.  
(b) Bow deck removed.

(c) Rotten shear stringer.  
(d) Rotten shear stringer.

Figure A.103.: Removing the deck to gain access to the inside of the hulls.
(a) Cutting out the lashing beams.

(b) The wooden lashing beams were simply screwed in place and glassed over. The screws were rot starter.

(c) Composted plywood in a glass fiber shell, that once was a lashing beam.

(d) Composted plywood in a glass fiber shell, that once was a lashing beam.

Figure A.104.: Removing the lashing beams.
(a) Unsealed shear and bulkhead top.

(b) All bulkheads were rotten, starting from the unsealed top edge.

(c) Screws as rot starter in the shear.

(d) Removing all rotten parts.

Figure A.105.: Rotten shear and bulkheads.
(a) Bulkheads are removed by chisel and axes.

(b) Bulkheads are removed by chisel and axes.

(c) The inside of the hulls is grind out.

(d) The inside of the hulls is grind out.

Figure A.106.: Removing of shear stringer and bulkheads.
Figure A.107.: New bulkheads glued into the hull shell.

Figure A.108.: New shear stringer glued into the hull shell.
Figure A.109.: Cross stringer as deck support are glued in.

Figure A.110.: Inside doublets on each side of the bulkheads as reinforcement for the beam cleats.
Figure A.111.: Deck is glued on the hulls.
(a)

(b)

(c) Big hatches for the center compartment. Bow and stern compartments are not accessible for reserve buoyancy.

(d)

Figure A.112.: Painted and finished hulls.
Rudder

(a) Plywood part for a rope hinge is glued to the stern.

(b) The rudder itself is mounted in a rudder head which allows it to be lifted in shallow waters.

(c) Kick-up rudder with tiller mounted on the back of the Ailuk ferry.

(d) Rudder painted.

Figure A.113.: Ailuk catamaran kick up rudder.
Leeboards

(a) Leeboard with airfoil shape.  
(b) The cut-out is a measure to reduce the leeboard’s weight and makes it easier to carry it around (handle).  
(c)  
(d) Leeboard painted.  

Figure A.114.: Ailuk catamaran leeboards.
A.3. Commissioning and Sea Trials

A.3.1. HarryProa

(a) Preparation of the Harryproa on the slipway.

(b) Preparation of the Harryproa on the slipway.

(c) First launch of the HarryProa prototype.

(d) Last preparations at the nearby beach.

(e) Hoisting the sail and slowly sailing over the reef shallow.

(f) HarryProa on a reach.

Figure A.115.: Launch and maiden sail of the HarryProa Mini Cargo Ferry.
Figure A.116.: Second test sail of the HarryProa Mini Cargo Ferry.
Figure A.117.: First long range test sail to Bok Island (20 nm) of the HarryProa Mini Cargo Ferry.
A.3.2. WAM Catamaran

Maiden Sail and Short Lagoon Trips

(a) WAM catamaran floating just after she touched the water for the first time.

(b) Hoisting the sail and slowly sailing over the reef shallow.

(c) Hoisting the sail and slowly sailing over the reef shallow.

(d) Hoisting the sail and slowly sailing over the reef shallow.

(e) Drone shot of the WAM catamaran sailing.

(f) WAM catamaran and HarryProa moored on the beach close to WAM.

Figure A.118.: Launch and maiden sail of the WAM catamaran.
Figure A.119.: Maiden sail of the WAM catamaran.
Figure A.120.: Short lagoon trip with WAM staff.
First Long Range Trial

(a) Planned course Delap to Laura (reach).
(b) Planned course Laura to Delap (upwind).
(c) WAM catamaran at Laura beach.
(d) Fish caught on the trip from Laura to Delap.

Figure A.121.: First long range test sail from Delap to Laura and back (20 nm air line each trip).
Second Long Range Trial

(a) Preparing the WAM cat for the sail to Bok Island.

(b) Windy and choppy conditions on the Majuro lagoon.

(c) Windy and choppy conditions on the Majuro lagoon.

(d) Windy and choppy conditions on the Majuro lagoon.

(e) Windy and choppy conditions on the Majuro lagoon.

(f) WAM catamaran at Bok Island.

Figure A.122.: Second long range test sail from Delap to Bok and back (20 nm air line each trip).
Figure A.123.: Modifications of the WAM Catamaran for the second long range sea trial.
A.4. Materials

Figure A.124.: Breaking test for an epoxy joint. The epoxy itself and its adhesion to the wood should be stronger than the wood and therefore result in the wood splitting right next to the joint.
A.5. Tools

A.5.1. Figures Tools

Figure A.125.: All tools used during the three month training.
Figure A.126.: Detail figures of tools used during the workshop.
(a) Power cords and connector strips.

(b) High pressure cleaner (was only used to clean the Ailik ferry hulls. Is not really necessary).

(c) Recipro saw (not really necessary).

(d) Router with bull eye bit.

(e) Jigsaw.

(f) Handsaw (only one on display as example).

Figure A.127.: Detail figures of tools used during the workshop.
(a) Cord(less) driller and drill bits)  
(b) Electric planer.
(c) F-clamps (various sizes 40+ pieces).
(d) C-clamps (various sizes 15+ pieces).
(e) DIY pipe clamps (30 pieces).
(f) Locking clamps (15 pieces).

Figure A.128.: Detail figures of tools used during the workshop.
(a) DIY wood clamps (20 pieces, used for beams only).

(b) DIY wood clamp.

(c) Tablesaw.

(d) Chopsaw.

Figure A.129.: Detail figures of tools used during the workshop.
A.6. KIR 5A Original Drawing
A.7. HarryProa Mini Cargo Ferry Plans

Hulls

The hulls are identical, except the leeward hull has an extra panel of ply in the middle.
If possible purchase 12 sheets of 6mm 1/4" plywood cut in half lengthwise. If not, cut them.
Mark a centreline down all sheets.
Cut the bow shape, using one of the half sheets as a guide. The guide piece is held on the corner of the bow piece and bent into a fair curve, ending on the centreline. It will not be the end of the bow piece.
Cut the curve and smooth it if necessary.
Use the curve to cut 5 other bow shapes, then use one of the cut pieces as a pattern for the opposite side. Ensure all are identical.
Apply a liberal coat of epoxy to the end grain and allow it to soak in. Before it cures, apply high density filler/glue mix and run it down with a shaped spatula, leaving a rounded edge. It does not have to be very accurate as the glass will help it conform. Apply a layer of 2"/50mm wide tape over this, then the rest of the laminate as per the instructions. The more glassing that is done wet on tacky, the better.
JOINING THE PANELS

Lay the sheets on a flat surface and ensure the centre lines align. The sides are 3 pieces of parallel sided ply. The deck and bottom are 2 bow pieces with a parallel sided piece between them.
Glass the panels and add one layer of 200mm/8" fibreglass over the joins.
Cut the doublers from 20mm-3/4” pieces of clear timber. 2 stringer widths shorter than the width of the bottom panel. ie if the panel is 2’ wide, the doubler will be 1’10 and a half inches long.

Router/round one edge. This edge is not glued. Rounding it makes it easier to apply epoxy.

Glue one over each ply joint. 4 between the ply joins (these will all be the same length) and 2 down on between the ply joint and the ends.

Ensure that they are at right angles to the centreline.

When cured, wrap a stringer (20mm-3/4” pieces of clear timber) around the edge of the ply. The doublers should ensure that it is flush with the edge.

Mark the location of a doubler on the stringers.

Repeat for the other side.

Trim the ends so the ends butt together.

Repeat for 2 more sets of stringers, ensuring they are marked.

Router/round 2 edges of the centre stringer and one edge of the chine and gunwhale stringers.

Glue the chine strings in place, including the ends.
ASSEMBLY 2

Cut 6 half height bulkheads from a half sheet of ply. These are the cockpit bulkheads.
Cut 2 full height bulkheads from a half sheet of ply. These are the cockpit end bulkheads.
Cut 2 full height bulkheads from a half sheet of ply and trim them to the width of the hull at the doubler locations. These are the end bulkheads.

All bulkheads have 20mm-3/4” cut outs in each corner for the stringers. These are 20mm-3/4” cut outs on the edges at the same height as the half height bulkheads. The easiest way to cut these is to stack the bulkheads together, clamp them and make all the cuts at the same time.

Glue the bulkheads to the doublers and the stringers. Ensure they are vertical (not glued right angle pieces of ply to the opposite side to the doublers) and that the centres align.

Cut 6 half height bulkheads from a half sheet of ply. These are the cockpit bulkheads.
Cut 2 full height bulkheads from a half sheet of ply. These are the cockpit end bulkheads.
Cut 2 full height bulkheads from a half sheet of ply and trim them to the width of the hull at the doubler locations. These are the end bulkheads.

All bulkheads have 20mm-3/4” cut outs in each corner for the stringers. These are 20mm-3/4” cut outs on the edges at the same height as the half height bulkheads. The easiest way to cut these is to stack the bulkheads together, clamp them and make all the cuts at the same time.

Glue the bulkheads to the doublers and the stringers. Ensure they are vertical (not glued right angle pieces of ply to the opposite side to the doublers) and that the centres align.
Glue the mid height stringer and gunwhale stringers to the bulkheads, ensuring the locating marks align.
Glue the ends ensuring they are vertical from ahead and from the side.
Apply 3 coats of epoxy to all uncoated timber and ply, except where bonding will occur.
Sand the side panels where they will contact the stringers and bulkheads, then glue them in place, glass side inboard.

Use the straight edge of the side panels to ensure the bottom panel is flat. The bottom edges align with the top edge of the bottom panel. They do not overlap.

Fillet the sides to the bulkheads with 10mm-3/8” diameter fillets. None of these will ever be seen, so do not waste time making them perfect.

Bond doublers to the tops of the bulkheads and half way up the cockpit end bulkheads.
Fit the cockpit floor and walk on it. If it is too springy, add a stringer down the middle, rebated into the cockpit bulkheads.
Glue the cockpit floor in place.
Fillet the cockpit to the sides and end bulkheads and glass the cockpit, ideally before the fillets cure so they can be smoothed.

All ply joins have an extra layer of glass, 100mm/4" wide.

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**HARPYRDA**

**Mini Cargo Ferry**

**Hulls**

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All dimensions in millimetres.
Fit the decks and walk on them. If they are too springy, add a stringer down the middle, rebated into the bulkheads.
Glue the deck in place.
The top edges of the ply align with the bottom edge of the deck panel. They do not overlap.

Use peel ply on all glassed surfaces. Or apply 2 more resin coats. Or apply a thickened filler coat. The latter 2 will require sanding pre painting, gluing or glassing. Remove the peel ply to get a paint/ready ready surface.

Flip the hull upside down and sand off any dirt or lumps of resin. Apply resin to the exposed edges of ply, then filler.
Glass the bottom and at least 100mm/4" of the topsides before the filler cures, resulting in a smooth radius and no exposed end grain.
Stop the glass 1-2"/20-50mm short of the bow.

Turn the hull on its side and glass, extending the glass to the middle of the bottom of the hull and at least 100mm/4" onto the deck.
Repeat for the other side.

Turn the hull upright and glass the decks, extending at least 100mm/4" down the sides.
Fill and round the bows and apply 3 layers of glass extending at least 2"/50mm over the already glassed areas. Stop the glass 1-2"/20-50mm short of the top and bottom.
Cut 3 circles of glass 1-2"/20-50mm larger than the area to be glassed.
Wet these out and smooth them in place by hand over the corners.
Cut 5 pieces of full length 10mm-3/8” ply 125mm/5” wide. These will be the sides.

Cut one length into 4 equal lengths. Butt join these to the other pieces and fibreglass one side, plus 2 layers of fibreglass (1 x 200mm/8”, 1 x 150mm/6”) on the join.

Glue 4 pieces of 3m/10’ long, 25 x 25/1” x 1” clear timber together side by side. Any joins are 8:1 scarfed and scarffs should not be adjacent to each other.

Glass one side of each panel. These are for the top and bottom.

Glass the ply sides to the timber pieces, ensuring it is all straight and true. Glassed surfaces are internal.

Rout/grind rounds on the edges and glass with one layer of glass, plus 2 extras on the ply joins. Apply multiple coats of resin to the beam ends.
Hot melt glue a 25mm/1” thick piece of timber on 2 adjacent faces of each beam. These should be the width of the hull plus 50mm/2” from each end.

Apply a 50mm/2” wide x 25mm/1” lump of filler against the inboard faces and a 50mm/2” wide x 6mm-1/4” thick lump on the ends.

Lay plastic taped pieces of ply on the bog and gently apply pressure until the ply is resting on the timber and the end of the beam.

When cured, remove the ply and the timber, round the edges and clean up the bog, resulting in a tapered surface on 2 faces of each of the beam ends. Cover these with plastic tape.
Set up the hulls, ensure a beam length apart.
Mark the inboard gunwhale of each hull at the midpoint.
Lay the beams on the hulls with the taper on the timber face on top. Align the hulls so each beam touches all 4 gunwhales.
Mark the widthwise centreline on 1.5 sheets of ply and clamp them to the beams so the beams are parallel and the length of a sheet of ply apart.
Move the beams/ply assembly until the centrelines align with the hull centreline.
Move the hulls so there is 25mm/1" of beam extending past each gunwhale. Recheck the hulls are level and the centrelines aligned.
Cut 100 lengths 1m/40" long 200 gsm/6 oz or 30 lengths of 600 gsm/18 oz glass tow per attachment point.
Sand the hulls where the tow will be laid.
Check everything.
Wet out the tows and wrap them over the beams and down onto the hulls. Half inside, half outside. Spread them as evenly as possible under the beams.
Apply a layer of glass over them.
When cured, remove the tape from the bottom of the beam and apply tape to the hull under the beam.
Glass a full width L shape to the bottom of the beam with at least 6 layers of glass.
Then fill the corner and apply another 6. This stops the beam becoming wedged in place.
When cured, use clamps or a hammer glass a piece of ply or timber over the beam and before you hit it to loosen the beam, then slide the hull clear. Remove the tape.
Leeboard
**LEEBOARD**

Edge glue 12 pieces of 1.5m/5’ long 50 x 25 timber together.

Draw a line 600mm/24” from one end (the top).

Plane/round one side of the top to an ogive shape (section of a circle).

Smooth and fair is more important than the actual shape. Repeat for the other side of the board and line.

Merge the ogives at the 600mm/24” line.

Shape the bottom to a semi circle and glass the board, especially the end grain. The edges should be sharp. Either glass them or fill them after.

---

25x50mm timber
Install 2 bulkheads in the middle of the lee hull cockpit. The distance between them is the same as the width of the daggerboard. Glue a lid on the bulkheads.
Cut 12mm-1/2" wide x 25mm/1" long slots in the hull side at cockpit floor level abutting the bulkheads. Repeat into the gunwhale.

Cut and cover with plastic 2 pieces of wood spacers 25mm/1" wide and the width of the leeboard wide. Round the ends.
Hot melt glue flanges on the spacers. Hot melt glue these spacers between the slots.

Wet cut 100 lengths 1m/40" long 200 gsm or 30 lengths of 600 gsm/18 oz glass tow and wrap half of them from one bulkhead/floor, through the slot, along the flanged spacer, through the other slot and onto the bulkhead/floor. Spread them as evenly as possible.

Apply bog to the glass on the flanged spacer, and place a piece of 6mm thick timber/ply with rounded ends between the flanges. Apply the other half of the tow.

When cured, remove the flanged spacer.

Using the case as a guide, build up the leeboard to square section at the top and where it passes through the bottom of the case.

LEEBOARD CASE

These plans are licensed not sold. They remain the property of Harryproa and are to be used for one boat only. They are not to be copied or used for unauthorized purposes.

www.harryproa.com
harryproa@gmail.com

All dimensions in millimetres.
Mast and Boom Step

Apply plastic tape to a squash, golf or exercise ball. Build a 4 sided box on a piece of 10mm-3/8" ply. The height of the box equals half the diameter of the ball, the inside box measurements = the ball diameter.

Cut circles of glass and mould them against the ball, part fill the box with bog and place the ball in it. When cured, remove the ball, round all edges, fillet the box to the ply and apply 3 layers of glass. Glue and glass the step to the hull.
A.8. WAM Catamaran Study Plan (2018)

WAM 6.5 - Sustainable Lagoon Craft
Prototype

—Study Plan—

Alson J. Kelen
Henrik Richter-Alten
This document intend do give a brief overview on the WAM 6.5 prototype design option, chosen for the TLCSeaT lagoon shipping project part. Further information, data and background knowledge may be found in the latest version of the TLCSeaT lagoon shipping project report.
WAM 6.5 Design Goals

After intense research and design work in close collaboration with Waan Aelōn in Majel (WAM), the University of the South Pacific (USP) and Hochschule Emden-Leer, University of Applied Science (HEL) a comprehensive List of Requirements for lagoon crafts in RMI was developed:

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<thead>
<tr>
<th>Number</th>
<th>Requirement:</th>
<th>Priority</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Length of waterline, m</td>
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<td>1.2</td>
<td>Loading capacity - 1500kg</td>
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<tr>
<td>1.3</td>
<td>Empty weight - 400kg</td>
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<td>1.4</td>
<td>Use of local materials (timber) whenever possible and sustainable construction at WAM</td>
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<tr>
<td>1.5</td>
<td>Consideration of Marshall’s traditions</td>
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<td>2.1</td>
<td>No special Marshallese skills/knowledge needed</td>
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<tr>
<td>2.2</td>
<td>Use of rope lashing (traditional) instead of conventional hardware</td>
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<tr>
<td>2.3</td>
<td>No need for power tools</td>
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<tr>
<td>2.4</td>
<td>A simple roofed space must be sufficient for all construction work, maintenance work</td>
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</tr>
<tr>
<td>3.1</td>
<td>All basic repairs must be possible on board with local resources</td>
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<tr>
<td>3.2</td>
<td>No use of Teflon fastenings</td>
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<td>3.3</td>
<td>Easy to beach</td>
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<td>3.4</td>
<td>A simple roofed space must be sufficient for all maintenance work</td>
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<td>3.5</td>
<td>Service life must be protected from aging influences (at least 20 years)</td>
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<td>4.1</td>
<td>Main propulsion by solar power</td>
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<td>Easy handling on the water in all conditions</td>
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<td>4.3</td>
<td>Singlehand sailing</td>
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<td>4.4</td>
<td>Fast and easy maneuver (tack, jibe)</td>
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<td>4.5</td>
<td>Easy to beach</td>
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<td>4.6</td>
<td>Easy loading and unloading of freight</td>
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<td>4.7</td>
<td>Sufficient speed performance</td>
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<tr>
<td>4.8</td>
<td>Sufficient speed for everyday use</td>
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<td>4.9</td>
<td>Seaworthiness for occasional inter island trips</td>
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<td>4.10</td>
<td>Economical reasonable (price)</td>
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<td>5.1</td>
<td>Overall appearance with reserve buoyancy</td>
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<td>5.2</td>
<td>Crash compartments in bow and stern</td>
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<tr>
<td>5.3</td>
<td>Singlehand sailing possible</td>
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<tr>
<td>5.4</td>
<td>Capacity for short offshore distances</td>
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</table>

WAM 6.5 Key Features

- Combination of 2 traditional canoe hulls to a catamaran
- Concept proofed by similar designs since decades
- Made by plywood and local timber, reinforced and preserved with glassfiber/epoxy
WAM 6.5 - Sustainable Lagoon Craft Prototype

- Minimized use of expensive and non sustainable materials
- Strong and durable construction

• Natural waste reduction by degradation at end of lifetime
  - The thin epoxy surface degrades by UV radiation and abrasion. The internal timber gets exposed and the craft breaks down within decades. No special treatment is required.

• Decent payload and stable platform
• Spacious cargo hold for rapid handling of copra bags
• Sliding hatch opens access to cooler for efficient fishing
• Light enough to handle on the beach by small crew
• Average sailing performance
• Prepared for electric auxiliary propulsion
• Different sizes possible
• Easy made locally and maintained on outerislands
WAM 6.5 Main Dimensions

<table>
<thead>
<tr>
<th>WAM 6.5 Prototype Main Dimensions</th>
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</thead>
<tbody>
<tr>
<td>Building method:</td>
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<tr>
<td>Length overall:</td>
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<td>Waterline length:</td>
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<td>Beam overall:</td>
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<td>Beam hull CWL:</td>
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<td>Beam hull max. capacity:</td>
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<td>Draft CWL:</td>
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<tr>
<td>Draft Max. capacity:</td>
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<tr>
<td>Sail area:</td>
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</table>

WAM 6.5 Options

Rudder System

Lashed Twin Rudders

- Lashed to the stern, no metal involved
- Inexpensive and easy to maintain
- Protected from grounding by a skeg
- Effortless helm
Steering Oar

- Traditional steering oar mounted on rear beam
- Cheap and fast without any fittings
- Offers option for bow-thruster like support of tacking (especially in combination with the traditional sail)
WAM 6.5 - Sustainable Lagoon Craft Prototype

Rigging

Wing Sail

WAM 6.5 with wingsail and twin rudder option
WAM 6.5 - Sustainable Lagoon Craft Prototype

WAM 6.5 with wingsail and twin rudder option

- Decent performance
- Easy to operate
- Dacron cloth and precise lofting required
- Sewing machine required
- Strong mast and reinforced main beam required
Traditional Sail

WAM 6.5 with traditional sail and twin rudder option
WAM 6.5 with traditional sail and twin rudder option

- Very fast, simple and inexpensive to build
- Minimized rigging loads
- Smaller sail area compared to the wingsail option
- Difficult to tack (the use of the steering oar option is recommended)
WAM 6.5 catamaran platform with wing sail and twin rudder option.

- High aspect gaff sail with mast pocket, 1 boom
- Twin rudder option
- Coral safe keel shoe

WAM 6.5 - sustainable lagoon craft prototype

LoA: 6.5m, CWL: 6m
Dpl: 1.5t
Scale: 1:50

A. Kelen, H. Richter-Alten
Majuro, 2018
WAM 6.5 category boat with wing sail and twin rudder option.

LoA: 6.5m, CWL: 6m
Dpl: 1.5t

A. Kelen, H. Richter-Alten
Majuro, 2018
WAM 6.5 - sustainable lagoon craft prototype
LoA: 6,5m, CWL: 6m
Dpl: 1.5t
Scale: 1:50
A. Kelen, H. Richter-Alten
Majuro, 2018

WAM 6.5 catamaran platform with traditional sail and steering oar option.
WAM 6.5 catamaran platform with traditional sail and steering oar option

WAM 6.5 - sustainable lagoon craft prototype

LoA: 6,5m, CWL: 6m
Dpl: 1,5t
Scale: 1:20

A. Kelen, H. Richter-Alten
Majuro, 2018
A.9. List of Requirements

A.9.1. 2018 Version

<table>
<thead>
<tr>
<th>Number</th>
<th>Requirement</th>
<th>Priority</th>
<th>Comment</th>
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<tbody>
<tr>
<td>1.1</td>
<td>Length of service time</td>
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<tr>
<td>1.2</td>
<td>毛重 / sailing weight</td>
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</tr>
<tr>
<td>1.3</td>
<td>sailing capacity</td>
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</tr>
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<td>1.4</td>
<td>Weight / tonning</td>
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<td>Consideration of Marshallese traditions</td>
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<td>No special Marshallese skills needed</td>
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<td>2.1.2</td>
<td>Use of local materials (timber)</td>
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<tr>
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<td>All local repair may be feasible</td>
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<tr>
<td>2.3</td>
<td>No use of heavy lifting</td>
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<td>Easy to beach</td>
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<td>Maintenance</td>
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<td>All local repair may be feasible</td>
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</tr>
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</tr>
<tr>
<td>4.1</td>
<td>Main propulsion by wind power</td>
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<tr>
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<td>Easy handling on the water in all conditions</td>
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<tr>
<td>4.3</td>
<td>Depth / depth of draft</td>
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<td>Easy to beach</td>
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<td>4.5</td>
<td>Safety / stability</td>
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Figure A.130.: List of Requirements as prepared in 2018.
A.9.2. 2020 updated Version

Figure A.131.: Updated List of Requirements from 2020.

A.10. Design Evaluation

A.10.1. 2018 Evaluation

The following tables show the rating of a traditional Marshallese Tipnol outrigger canoe and the proposed options 1 (Ailuk Ferry), 2 (WAM Catamaran) and 3 (HarryProa) according to the List of Requirements (LoR) (calculated as explained in 4.1) based on assumptions and expectations prior to the prototype construction in 2018:
<table>
<thead>
<tr>
<th>Design option 1: Ailuk Catamaran</th>
<th>Traditional marshallese canoe (tipnoi)</th>
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<table>
<thead>
<tr>
<th>Design option 2: WAM Catamaran</th>
<th>Design option 3: Mini Cargo Prow</th>
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Figure A.132.: Comparison of the rating of the LCST prototype design options acc. to the List of Requirements as addition to traditional canoes. The Tipnol and the „Perfect Design“ (highest possible number) are shown as reference.
A.10.2. 2020 Evaluation

![Questionnaire](image)

Figure A.133.: Questionnaire as handed out to all involved persons for feedback.
## Requirement: Comment

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<thead>
<tr>
<th>Trainee</th>
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<th>Average</th>
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### 1.1 Length of waterline: 6m

- 5 5 5 5 3 5 5 2 5 4
- Average: 4.4

### 1.2 Loading capacity: ~1000kg

- 5 4 5 5 5 5 3 5 2 4
- Average: 4.6

### 1.3 Empty weight: <600kg

- 5 5 5 5 3 4 5 3 5 4
- Average: 4.7

### 1.4 Green technology
- no fossil fuel
- sustainable materials
- sustainable construction at WAM
- sustainable maintenance on outer islands

- 4 5 5 5 5 4 4 4 4 2
- Average: 4.2

### 1.5 Consideration of Marshallese traditions

- 4 3 5 4 5 5 5 4 3 3
- Average: 4.2

### 2.1 No special Marshallese canoe skills/knowledge needed

- 5 4 4 3 5 5 5 2 4 5
- Average: 4.2

### 2.2 Use of local materials (timber) whenever possible and sustainable (replantation), reduced use of plastic

- 4 5 4 4 5 5 5 3 4 0
- Average: 3.9

### 2.3 Use of rope lashings (traditional) instead of conventional hardware

- 4 1 1 1 5 5 5 5 5 3
- Average: 3.4

### 2.4 No need for power tools

- 3 2 1 3 5 3 5 4 3 2
- Average: 3.1

### 2.5 A simple roofed space must be sufficient for all construction works

- 4 5 5 5 5 5 1 5 3 3
- Average: 4.1

### 3.1 All basic repairs must be possible on outer islands with local resources

- 4 3 3 5 5 5 5 3 4 3
- Average: 4.0

### 3.2 No use of metal fastenings

- 5 5 5 5 5 5 5 5 5 5
- Average: 5.0

### 3.3 Easy to beach

- 5 4 5 3 5 5 5 2 5 4
- Average: 4.3

### 3.4 A simple roofed space must be sufficient for all maintenance works

- 4 5 5 5 5 5 4 5 4 3
- Average: 4.5

### 3.5 All components should be protected from aging influences (20 years service life)

- 3 5 5 5 5 5 5 2 4 0
- Average: 3.9

### 4.1 Main propulsion by wind power

- 5 5 4 5 5 5 5 5 5 5
- Average: 4.9

### 4.2 Easy handling on the water in all conditions

- 4 3 2 2 2 5 1 3 5 4
- Average: 3.1

### 4.3 Singlehand sailing

- 4 3 3 2 1 4 1 2 3 5
- Average: 2.8

### 4.4 Fast and easy maneuvers (tack, jibe)

- 4 4 2 2 2 5 5 3 3,5 4
- Average: 3.5

### 4.5 Easy to beach

- 5 3 5 3 5 5 5 2 5 5
- Average: 4.3

### 4.6 Easy loading and unloading of freight

- 5 3 5 3 5 5 2 4 3 5
- Average: 4.0

### 4.7 Sufficient upwind performance

- 5 4 5 5 5 5 1 4 3 5
- Average: 4.2

### 4.8 Sufficient speed for every day use

- 5 4 5 5 5 4 3 5 4 5
- Average: 4.5

### 4.9 Seaworthy for occasionally inter island trips

- 5 5 5 4 4 5 4 2 3 5
- Average: 4.2

### 4.10 Economical reasonable (price)

- 4 5 4 5 5 2 4 4 4 4
- Average: 4.1

### 4.11 Suitable for fishing

- 4 5 5 4 5 4 4 4 5 4
- Average: 4.4

### 4.12 Suitable for copra transport (dry cargo hold)

- 4 3 1 3 3 1 1 5 5
- Average: 2.6

### 5.1 Sealed compartments with reserve buoyancy

- 4 1 2 4 4 3 1 5 5 5
- Average: 3.4

### 5.2 Crash compartments in bow and stern

- 4 1 2 4 4 1 2 5 5 5
- Average: 3.3

### 5.3 Singlehand sailing possible

- 4 3 3 2 1 3 5 2 3 5
- Average: 3.1

### 5.4 Capability for short offshore distances

- 5 5 2 3 4 5 1 3 4 5
- Average: 3.7

### 5.5 Safety

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<th>3</th>
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Figure A.134.: Anonymous data collected from the questionnaires.
Figure A.135.: Calculated rating for WAM Catamaran (option 2) and HarryProa (option 3).
Figure A.136.: Overview on the results of the 2020 prototype rating.
Bibliography


[03] Alessio, Waan Aelon Kein Reports 1-9, 1989-97, Majuro