Flipflopi: Circular economy design inspiration from a recycled plastic sailing dhow

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ABSTRACT

Flipflopi is an East African organisation with a mission to end single use plastic, driving this agenda using circular economy principles applied to the design and build of fully recycled plastic sailing dhows from their boatyard in Lamu Kenya. Flipflopi has achieved measurable global impact by showcasing the world's first ocean going recycled sailing boat, Ndogo, a 9 metre long, lateen rigged dhow which has sailed the East African coastline and across Lake Victoria. Flipflopi is now aiming to build a much larger ocean-going dhow, named Kubwa, which presents further technical challenges from a marine design perspective. To meet these challenges. Flipflopi are utilising a combination of generational heritage boatbuilding expertise in Lamu; specific design experience from building and sailing Ndogo; technological progress driven by other recycled plastic projects; and more formalised naval architecture and engineering design approaches. This paper introduces the context within which Flipflopi is centred, the links to circular economy design principles and the specific design challenges from working with recycled plastic as a boatbuilding material.

KEY WORDS

Plastic; Recycling; Circular Economy; Boatbuilding; Flipflopi.

INTRODUCTION

In this paper we consider a circular economy approach to the design, construction, and operation of marine craft through a broad overview of current achievements and challenges from Flipflopi, an organisation which has launched three sailing dhows made almost completely from recycled plastic waste and now plans to build a larger 24 metre ocean going sailing dhow. We also share some of the practical challenges and continuing design questions from using recycled plastic as a boat building material.

Flipflopi is an East African organisation, based in Lamu Kenya, with a stated mission to end single use plastic, ensure all other plastics are part of a circular economy and promote environmental solutions to the plastic waste crisis. The organisation is centred around the construction and operation of fully recycled sailing dhows. Flipflopi works with communities to "close the loop" on waste plastics, collecting and recycling waste to produce boats and products rooted in indigenous heritage. They also harness appropriate high technology techniques to meet the unique design demands from using recycled plastic as a construction material.

Flipflopi has demonstrated global impact from their campaigning work, perhaps most significantly by showcasing the world's first ocean going recycled sailing boat, Ndogo (small in Swahili), a 9 metre long, lateen rigged dhow with lines typical of Lamu heritage designs (Figure 1). Ndogo has completed several voyages around the East African coast and on Lake Victoria, which stretches across the borders of Kenya, Uganda, and Tanzania. These voyages aimed to promote messages to end plastic

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pollution, bring awareness to the issue, engage East Africans in alternative ways to use existing waste plastic and demand legislative action to ban single-use plastics. The impact is evidenced in several end of year organisation reports (Flipflopi 2021; 2022; 2023).

Since building Ndogo, Flipflopi have designed and built several smaller boats, including a canoe and a 7-metre taxi dhow that will carry passengers and light cargo within the Lamu archipelago. A training centre has been established at the Flipflopi boatyard, which has so far taught 30 people from the Kenyan Coast traditional boat building techniques in combination with circular economy practices.

A central ambition for Flipflopi is to launch a substantially bigger dhow, Kubwa (large, in Swahili), which will be about 24 metres long. The design of Kubwa aims to integrate the knowledge generated from Ndogo. There are also new challenges inherent in a larger and more complex boat.

This paper first introduces the context within which Flipflopi is centred – the plastic waste crisis that is especially problematic in LMIC settings such as East Africa. The principles of circular economy design are then introduced, starting from a broad overview and then focusing in on the open-loop recycling system followed by Flipflopi. The application of circular economy principles in other areas of marine design are briefly considered. The paper then focuses on the specific design principles and challenges from working with recycled plastic as a boatbuilding material: developing hull lines, structural design, material properties and joining techniques. The linked challenge of sustainable propulsion is also summarised.

Figure 1: A Flipflopi "closing the loop" poster with dhow Ndogo sailing in the Lamu archipelago (left), an impression of Kubwa sailing alongside Ndogo (right)

PLASTIC WASTE AND POLLUTION

Over 8 billion tonnes of virgin plastics have been produced up to 2021 (Geyer et al. 2017). Around 80% of this total has been discarded, demonstrating a loss of valuable resources and the origin of an environmental disaster (Bucknall 2020). The most visible consequence of this is the huge volume of plastic that ends up in the ocean, which has become a maritime crisis. Lau et al. (2020) shows that 78% of the plastic pollution problem could be solved by 2040 but only if all the possible reduction pathways are followed: that means reducing consumption, increasing reuse, improving waste collection and recycling, and accelerating innovation in the plastic value chain.

Plastic pollution strongly affects coastal communities and their natural environment. These communities, particularly in rural and lower economy regions, face sometimes overwhelming quantities of plastics on beaches and in fishing waters (Phelan et al. 2020). Negative consequences to the coastal environment include entanglement in plastic by megafauna, ingestion of plastic by fish, microplastic ingestion by invertebrates, ghost fishing by abandoned nets, algae growth in plastic debris, contaminated fisheries and reduced natural health of beaches littered with plastic (Thushari & Senevirathna 2020).

The focus of this paper is Amu Island, which is part of the Lamu Archipelago on the Kenyan coast with a population of around 30,000. The community generates about 14 tonnes of waste daily, of which about 2.5 tonnes is plastic waste (Moejes 2023a). The quantity of washed-up ocean plastic is not quantified, but by illustration a single community beach clean-up on a 10-km stretch of beach (see Figure 2) typically collects 35 to 40 tonnes of plastic waste (Scott Harden et al. 2020; Moejes 2023b). To exacerbate the problem, there is only one waste disposal site on Amu Island. This area has no separation facilities and waste is left to pile up, blow across the island into the ocean and in many instances is burnt openly.

A community survey in Lamu, completed as part of a plastic waste mapping study by Flipflopi in 2022, found that 98% of respondents viewed plastic waste as a problem. They also found significant interest in not only learning about the environment and pollution, but also taking part in innovative solutions, such as boat building with recycled plastic, as a practical way of tackling the growing plastic waste problem (Flipflopi 2022).

Figure 2: A beach cleanup on Shela beach, Amu Island (Flipflopi 2022)

CIRCULAR ECONOMY DESIGN PRINCIPLES

Definition

Circular economy is a model of production and consumption which centres on the reuse and recycling of materials. There are many definitions of circular economy and an extensive body of literature that discusses, applies and critiques the concept. We only provide a summary of some well-established circular economy definitions, for the purpose of contextualising the Flipflopi approach. We use circular economy from a practitioner-led perspective, and do not take a detailed theoretical position or critique of the concept in this paper.

Velenturf and Purnell (2021) summarise the circular economy as "a technology-focused concept that can generate economic gains while alleviating pressure on the environment". It involves "circularity of resource flow by preventing loss of material out of the system" (Bucknall 2020). It aims to make "better" use of resources, although "better" is sometimes difficult to define. For plastics this goes well beyond recycling, incorporating the pillars of sustainability – economic, social and environmental. In this way a product design incorporates life cycle aspects such as durability, reuse, repair, remanufacture alongside beneficial economic activity such as employment and enterprise, environmentally driven considerations of energy consumption and social considerations of ownership costs and community benefits.

The Ellen Macarthur Foundation, inspired by the founder's solo sailing circumnavigation of the globe, is a leading advocate of circular economy approaches. They base the circular economy on three principles driven by design (Macarthur 2019):

1. Eliminate waste and pollution
2. Circulate products and materials (at their highest value)
3. Regenerate nature

The Plastic Circular Economy

The plastic circular economy, shown in Figure 3, prevents linear economy waste such as landfill, incineration and environmental pollution. Circularity is enabled at several levels, including (Bucknall 2020):

- Reuse of plastic products for their original purpose, such as a reusable water bottle, or for new purposes, such as using a water bottle as a plant pot.
- Open-loop recycling, where the plastic is recycled into a new product or use, such as recycling water bottles into polyester clothing.
- Closed-loop recycling, where the plastic is recycled back to its original purpose, such as recycling used water bottles into new water bottles.

Open and closed loop recycling are typically characterised as remote industrial processes. Waste plastic is collected and removed from a community to a large-scale processing plant. It will then re-enter a different community economy as a raw material or a newly recycled product. Whilst this process may meet the "three principles" definition, there is less community engagement in the complete economic model. This misses opportunities to "better" the sustainability at a local level. For example, despite high awareness of recycling in the UK population, there continues to be pitifully low rates of acceptably separated plastic waste collection from the kerbside (Burgess et al. 2021).

Alternative circular models, such as that advocated by Precious Plastic (Spekkink et al. 2022), promote local engagement throughout the recycling-remanufacture process. This includes developing small scale recycling spaces to process plastic waste and demonstrating innovative manufacturing methods for recycled product designs that benefit the communities that collected the waste. Scott-Harden et al. (2022) discusses the design challenges of locally recycled products. Recycled material can be used to manufacture a diverse range of high precision, durable products where tolerances are high such as sunglass frames, plug sockets and jewellery. However, the processing of larger quantities of locally recycled plastic is often better suited to less refined large-scale structures such as furniture, window frames, bricks and fencing. Traditionally built dhows, and therefore many other wooden boat types, can be included in this category. With proper consideration of the material properties and consistency, boatbuilders can use recycled plastic lumber with established carpentry techniques in very much the same way as wood (Scott-Harden et al. 2022).

As will be shown, Flipflopi is an exemplar of a community centred approach to open loop recycling. The flow of plastic from waste to a new product is entirely within the community, and the products themselves contribute to and promote further recycling and awareness of the plastic pollution crisis. The success of Flipflopi suggests that alternative circular models hold an important and powerful role for building sustainability into the circular economy.

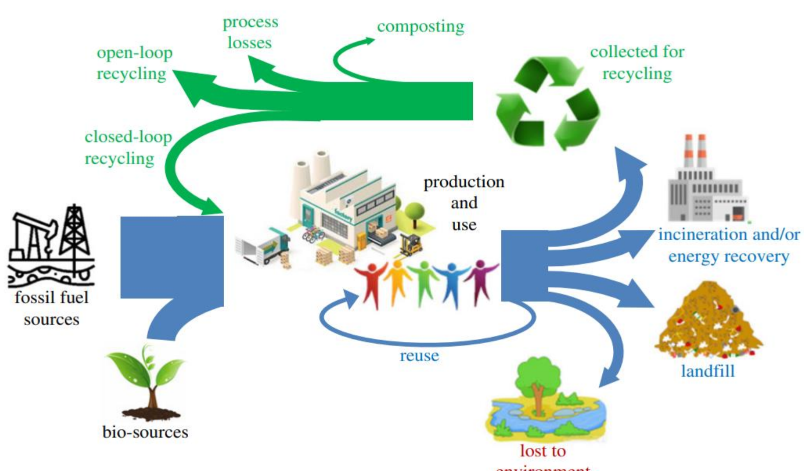


Figure 3: The lifecycle of plastics, including linear and circular economy principles (Bucknall 2020)

The Flipflopi Approach

Flipflopi uses an open-loop recycling system coupled to an alternative circular economy model to turn locally generated plastic waste into carpentry products for the community including dhows, furniture and decorative products. The system steps (Figure 4) are:

1. Household, small-scale industrial and washed-up plastic waste from the sea is gathered and macro sorted by people within the Lamu archipelago. At present only some plastic types can be recycled.
2. The waste is collected from various stations or brought to the Flipflopi boatyard on special collection days. It is weighed and a collection payment is made.
3. The waste is then further sorted into polymer type and colour. Some polymers, such as PET, are sent away to industrial recycling centres. Polymers that Flipflopi can effectively recycle, such as HDPE, continue through the recycling space.
4. The plastic is crushed into shreds, thoroughly washed, and then moulded or extruded into construction materials including planks, beams and special mouldings. New processes such as sheet pressing are being developed.
5. The construction materials are used in several carpentry and boatbuilding spaces within the yard, including a workshop for craft products and furniture, a skills training centre and the boatbuilding sheds.
6. Smaller carpentry products are commissioned and sold, mostly in the local community and often as high value items.
7. The dhows continue to be operated by Flipflopi as prototype demonstrators and are the focus of their broader campaign work to end single-use plastic. The smaller boats are also planned to be used for enterprise, such as passenger transport, and for plastic collection.
8. At end of life, the thermoplastics embodied in Flipflopi products can be looped back into the recycling process.

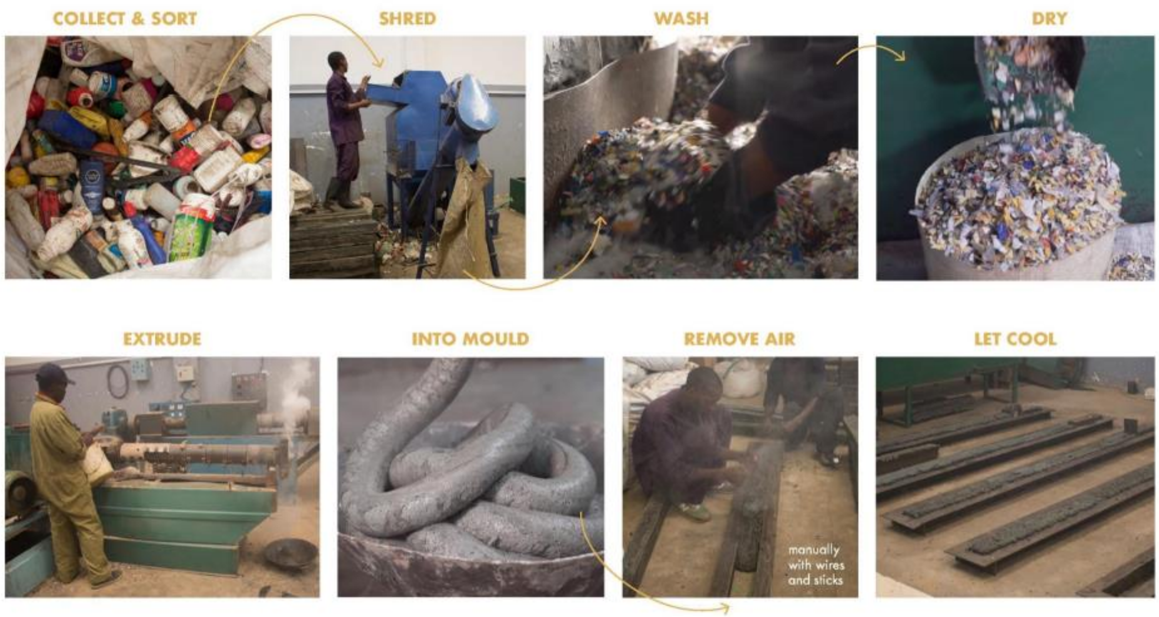


Figure 4: The Flipflopi recycling centre process, in this case showing a moulding technique to produce plastic lumber

Flipflopi operates a full systems approach to their organisation strategy, which they define as "the combination of education leading to behavioural change, innovation within the circular economy, and campaigning to influence legislative change to end single-use plastics" (Flipflopi 2022). This is applied through a strategy integrating education, innovation and influence. For example:

- Education is directly delivered via a heritage boatbuilding training centre, which piloted a 12-week vocational course in 2022. Broader educational programmes to change behaviour around plastic consumption is delivered via community-based partners and artivists across East Africa, with diverse contributions including storytelling, scientific research and projects to advance the role of women in waste management and boatbuilding.
- Innovation is driven broadly to include systems from recovery to upcycling and is applied directly to overcome the practical challenges of building larger boats such as Kubwa from recycled plastic, as outlined in the Design Challenges section of this paper.
- Influence is underpinned by the education and innovation activities, which provide a backdrop for Flipflopi to effectively lobby for regional consensus to ban unnecessary single use plastics in East Africa.

The Flipflopi approach meets the "three principles" of circular economy. The full systems approach creates added benefit to the design capabilities and philosophy that "betters" the overall sustainability of the process:

- Eliminate waste and pollution: Flipflopi now collects over 12 tonnes of plastic every month, has become the de-facto recovery and recycling centre for Lamu, and is now extending operations across the entire archipelago. About 30% of the collected plastic cannot be processed on site, and whilst the onward chain to larger recycling centres in Kenya is established it is not yet economical. Whilst this presents space and capacity challenges for the Flipflopi boatyard, it has also driven considerable design innovations to find new ways to use more of the waste plastic. For example, to investigate the use of polypropylene sacks, a common waste product from the food and construction sectors, to provide strength in sheet materials produced in a bespoke press machine. The envisaged outcome is large format sheets suitable for a new range of construction products such as stud walls and doors.

- Circulate products and materials (at their highest value): Flipflopi has proven that circulated plastic waste can be used to produce new products at high value. Apart from the dhows, the most notable high value product is the 'King's Throne' presented to the British monarch on a visit to Kenya in 2023 (Figure 5). However, the range of polymer types, quality, suitability for re-manufacture and subsequent consistency has challenged the design process. Whilst the plastic lumber can be worked in a similar way to wood, it does not have similar material properties. Flipflopi are now quantifying material behaviour by adapting established material testing methods and linking to formalised boat design codes (see Design Challenges section).
- Regenerate nature: Using recycled plastic as a building material potentially places less pressure on wood sourced from local forests. Flipflopi also contribute to regeneration of nature through their influence in better managing the local environment, for example by replanting mangroves, and campaigning for an end to single use plastic. The eco-design philosophy enables further innovation in additional benefits to other environmental issues. For example those hinging around the use of fossil fuels, including reducing carbon emissions from boats, building renewable energy capacity, improving local air quality, and preventing pollution from unburnt and spilled petrol. The potential of electric propulsion, discussed in the Design Challenges section, is an example of this added benefit.

Flipflopi also meets the three pillars of sustainability. An example is the impact on people engaged with the organisation in different ways. Flipflopi employs 30 people directly, 46% of whom are women, and has 9 skilled artisans on contract. The vocational course has trained 30 people in plastic carpentry techniques. The recycling process engages with over 700 local people, 50% of whom are women, from lower income communities. They collect waste and generate income from this, currently representing a cash injection of about $24,000 in direct payments to date. The employment and education activity therefore has economic benefit by promoting local enterprise. The high percentage employment of women promotes societal benefit, especially within a local maritime economy which is traditionally dominated by men. All the people involved in Flipflopi are engaged and contributing to the environmental benefit from recycling and reusing plastic waste.

Figure 5: High Value Recycled Plastic Products: the "Kings Throne" presented to King Charles III, November 2023 (left), a traditional Swahili chair (right). Left photo © British Embassy in Kenya

Circular Economy in Marine Design

Flipflopi is centred in heritage boatbuilding and maritime activities. It holds potential for direct application in many other coastal communities, particularly those where more traditional boat use is still prevalent. Whilst this constitutes a majority of the total marine craft across the globe, it is a small fraction of the total tonnage, which is dominated by large cargo vessels. What does the circular economy mean for this wider shipping industry and the marine design that underpins it?

Agarwala (2023) argues that the maritime industry continues to find it difficult to adopt full circular economy approaches to design. Aspects such as shipbreaking-reuse of materials (Rahman 2021) and decarbonization (Gilbert et al. 2014) can fulfil the "three principles" of circular economy, but currently suffer sustainability failings. For example, Dewan and Sibilia (2023) describe those exposed to toxic pollution from shipbreaking as suffering a form of structural violence in the maritime economy. Decarbonization, the most prominent current challenge for the maritime industry, suffers from "woefully insufficient progress in vessel designing with alternative fuels in mind, as well as in securing alternative fuel supply chains" (Tomos et al. 2024).

Despite the tiny-scale of Flipflopi within the global maritime industry, the project provides questions for marine design to more widely integrate full circular economy. For example, we briefly consider the two "grand challenges" for the marine industry summarised above: decarbonization and shipbreaking.

- Decarbonization: The media attention for Flipflopi demonstrates the social power of iconic boat design to capture public imagination and more crucially to promote engagement. Coastal communities across the world hold powerful cultural identity to maritime (Alegret & Carbonell 2014), from tangible activities like shipbuilding and fishing through to intangible feelings of ethos and identity. These communities also suffer some of the worst effects of climate change including erosion, extreme weather events and sea level rise. Can marine designers work better with coastal communities - the builders, users and witnesses of maritime activity - to better capture their imagination through iconic, locally centred ship designs, and through this engage community power to drive a more rapid change to decarbonization and zero emissions in the maritime industry?
- Shipbreaking: Flipflopi has made a real impact in their local community to reduce plastic pollution, whilst also inspiring action for zero plastic waste policy in Kenya and internationally. For example, Flipflopi and legal partners have drafted a Bill to ban unnecessary single use plastics across all seven countries in the East African Community (EAC). Over 16,000 people have signed a public petition and 22 legislators representing the EAC unanimously agreed to a regional approach to tackle plastic pollution. The Bill is now being considered for tabling at the East African Legislative Assembly. How can this impactful model – where the marine designers are also the campaigners - be transferred to improve the localised human and environmental costs associated with shipbreaking in countries such as Bangladesh, whilst highlighting the responsibility of the entire maritime sector to focus on stopping unsustainable scrapping practices?

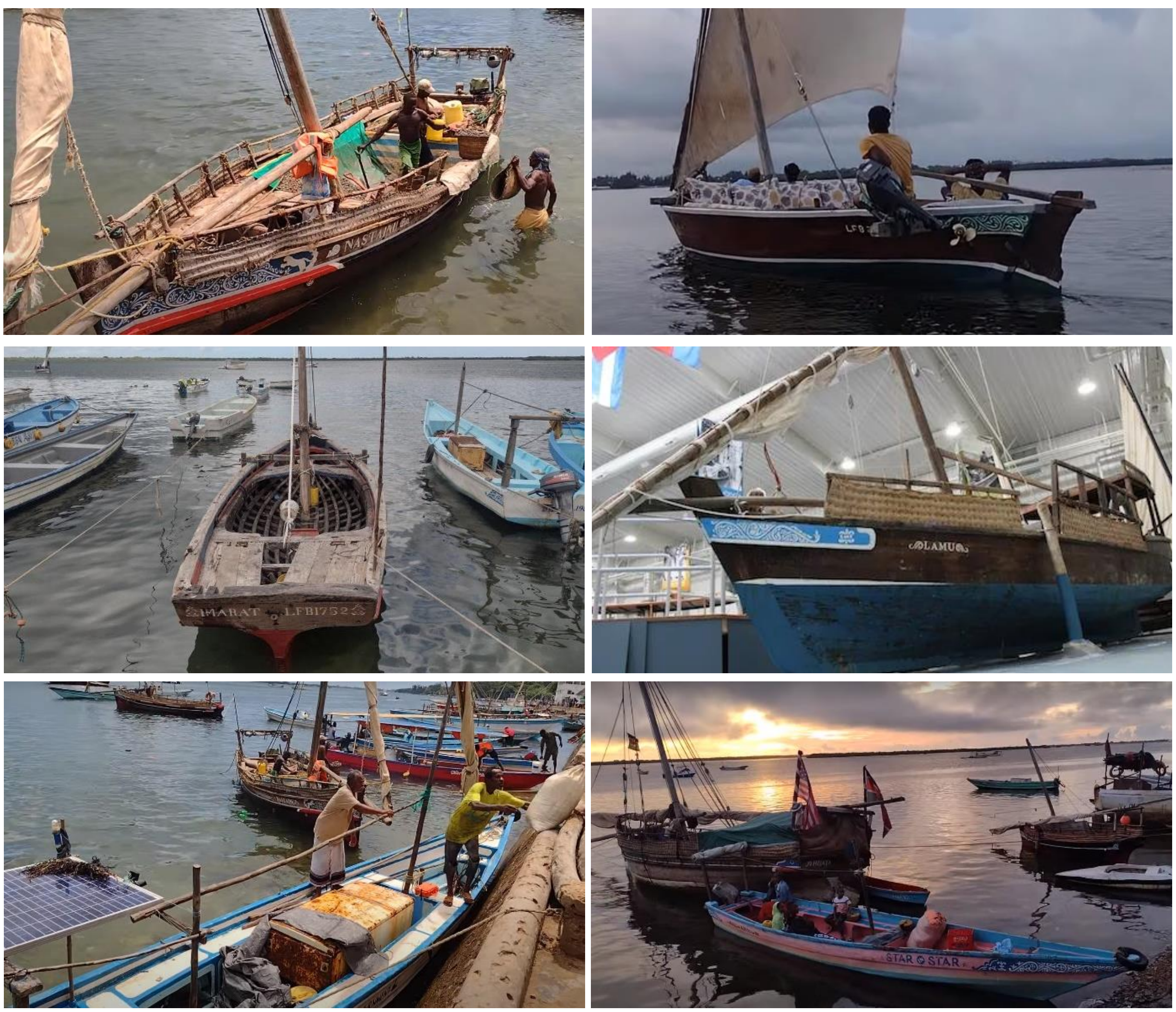


Figure 6: A wooden dhow offloading cargo (top left), a fibreglass Mozambique dhow on a tourist cruise (top right), a racing mashua (middle left), Ali Skanda's Lamu dhow in the International Small Craft Center, USA (middle right), a fibreglass dhow loading ice for a fishing trip (bottom left), a daily scheduled morning passenger dhow (bottom right)

DHOWS IN THE LAMU ARCHIPELAGO

Dhow Types, Construction Methods and Uses in Lamu

Boats and the maritime economy are woven into the fabric of Lamu's culture and daily life. This means there are many uses of boats including: local passenger transport within the archipelago; cargo transport from the mainland and between island villages; coastal goods transport stretching between Somalia and Tanzania; inshore and offshore fishing; a variety of tourist activities such as cruises, fishing, diving and expeditions; and a dynamic culture of competitive dhow racing.

Figure 7: Construction Methods. A new wooden build (top left), an older dhow, Utamaduni, prior to renewal (top right), fibreglass taxiboat moulds (bottom left), "Almas" – a fibreglass dhow under construction (bottom right)

Dhows with traditional aesthetics and construction arrangements are still prevalent, with examples shown in Figure 6. The Jahazi, with a standing bow stem and a flat transom, is the unique Lamu traditional design. The Jahazi is a recognized cultural icon, and is included in international heritage boat collections. The transom is notably different to the stereotypical boom stern of Arabic dhows. The shape is thought to give easier loading and added comfort. Increasingly popular, especially for tourism, are the wider beam Mozambique dhows. These may still be built from hardwood but are now increasingly using fibreglass which needs less skill to produce and reduces the challenges of boat maintenance.

Mashuas, also called taxi dhows, are the most common way of getting around the Lamu archipelago and are also used for fishing and cargo transport. These are slender flat bottom hulls 6-12 metres long and typically powered by a 15hp outboard. In recent years traditional wooden taxi dhows have been increasingly replaced by fibreglass boats.

There is an active boatbuilding, repair and maintenance industry concentrated in Lamu town and several other villages within the archipelago including Matandoni. Construction methods, also shown in Figure 7, include:

- New wooden "artisanal" construction of dhows. These are mostly for tourism;
- Renewal / refurbishment of existing wooden dhows, such as Utamaduni, a 20 metre dhow also pictured in Figure 15;
- Hand layup fibreglass construction of smaller boats using purpose built moulds, with a mashua shown in Figure 7;

- Fibreglass construction of larger boats, also using concrete and aggregates for keels and stems. These may use end of life wooden dhows as plugs, such as mashua Almas, pictured during construction in Figure 7.

The Flipflopi Fleet

Flipflopi have designed, constructed and launched three sailing dhows: Dau la Mwao (Canoe), a small mashua (Water Taxi) and the custom designed expedition mashua dhow Ndogo (see Figure 8 and Table 1).

Figure 8: Dau la Mwao / Canoe (left), Taxi (middle) and Ndogo (right) all sailing in the Lamu archipelago

Table 1: Main Particulars

	Dau la Mwao	Water Taxi	Dhow Ndogo	Dhow Kubwa
Length (m)	6	7.4	9	24
Beam (m)	1.4	2.4	4.0	7.5
Draft (m)	0.3	0.6	1.0	1.8
Approx. Displacement (tonnes)	0.7	1.1	7.25	115
Propulsion System	Sail	Sail and 15hp engine	Sail and 15hp engine	Sails and engine

Dhow Ndogo (Figure 9) was conceived in 2016 by Ben Morrison and Dipesh Pabari as a campaigning tool to spread the message about plastic waste. In Lamu they met master dhow fundi (boatbuilder) Ali Skanda who comes from a generational family of expert carpenters and boatbuilders. Ali accepted the challenge and construction started in 2016. Ndogo was conceived as a prototype to learn boat building methods using recycled plastic. The knowledge from this process was captured through different media resources including a boat building "toolkit" that can be downloaded from the Flipflopi website. All recycled plastic boat parts were first sourced from external recycling companies in Kenya before the in-house plastic recycling facility took over production later on, enabling a better control over quality. The keel, ribs and structural elements of Ndogo are all made from recycled HDPE (mostly found in jerry cans or other containers for liquids, like shampoo bottles). HDPE has favourable properties (buoyancy and flexibility) and is easily available to be collected in sorted and relatively clean form.

Figure 9: The elements of Ndogo – frames (left), planks (middle) and covering (right)

Dau la Mwao is a small canoe built entirely from HDPE recycled plastic by students on the first Flipflopi heritage boatbuilding course. The design follows a traditional fishing canoe (Figure 10) in shape and construction method, enabling the boatbuilders to use their traditional approach and maintain their boatbuilding heritage. The frames were extruded through custom moulds. The build then followed traditional techniques and was completed over a 6 week period. A complete build process is documented by Flipflopi in collaboration with Precious Plastic (Flipflopi 2023).

Figure 10: The basis fishing boat (left), placing the mataruma/ribs (centre), the completed canoe (right)

The Taxi dhow is the latest boat built by Flipflopi. It is a bespoke design sized for potential commercial use and to establish a market for recycled boats to compete with equivalent fibreglass designs now dominating in Lamu. The size is suitable for transporting goods and people across the archipelago, and also offering leisure and tourism trips. The build has also enabled Flipflopi to stress test new types of plastic lumber from the recycling centre, along with new construction and sealing techniques including plastic welding as shown in Figure 11.

Figure 11: Mould for a type of rib (left), welding planks (centre), view from transom showing welded transom (right)

The proposed large Jahazi dhow (Kubwa) will bring together the knowledge, techniques and experience gained from the previous boat builds. The size and subsequent design complexity of Kubwa presents new challenges, which are summarised in later sections of this paper.

DESIGN AND BUILD PRINCIPLES

The construction of the traditional dhows of Lamu are easily recognisable as similar to the wooden boat building techniques found in Europe and North America and would be described as carvel planking on sawn frames. However the procedure followed by the dhow builders is not the same as that usually followed elsewhere, being more akin to the method employed in clinker (called lapstrake in North America) boatbuilding. Once the keel, stem and transom have been set up, so defining the overall dimensions, temporary moulds are inserted to guide the shape of the planking. These moulds are continually adjusted by the builder who, using an experienced eye, continually makes minor adjustments to the shape. Once the planking is complete the frames are cut to shape and fastened inside the hull. The timber used has the required curve to the grain, however on larger dhows the entire frame has to be made in two parts (futtocks). These are simply butted together, without doubling pieces for continuity of the structure, however strength is maintained by moving the position of the butt joint in adjacent frames, with the frames themselves being closely spaced. For Ndogo the same traditional procedure was followed, but with plastic timber planks, and the curved plastic frames being made in individual custom steel moulds. This process is illustrated in Figure 12 and documented in the Flipflopi boatbuilding toolkit. While the wooden dhows are typically coated with antifouling paint externally, and with linseed oil and turpentine internally, the plastic dhow Ndogo was coated with the instantly recognisable pattern of recycled flip flop sheets.

From the description above the traditional dhows of Lamu are not 'designed' in the current sense of the word. The builder is responsible for the shape and scantlings, and this is based on inherited knowledge, experience, and several 'rules of thumb' to decide on scantlings. There is also an ongoing element of innovation as the builder responds to personal views of what would be an improvement, feedback from the operators of previous designs, and customer or market requirements. As a result, an evolution in the designs, or styles, can be observed in the multitude of dhows observable in Lamu harbour and the adjoining channels. Abandoned on the beaches can be seen old and decaying wooden vessels, with other similar solid working boats still working, their lateen sails furled while they offload cargos of coral stone bricks, timber, and sack of grain, or land fish at the town jetty. Alongside these are water taxis or small passenger ferries, with slender and sharp overhanging bows, driven by outboard motors. In amongst all these working boats are the latest evolution in the design of the traditional dhow: graceful sailing vessels with high aspect lateen rigs, and a finish that is of a similar standard to that found on many yachts. These are the tourist sailing dhows, taking guests to the reefs for snorkelling, or on sunset cruises in the channels of the estuary. The current peak of the evolution of this traditional craft is manifest in the design of racing dhows, developments in their shape, rig and construction material contributing to the success of this popular and highly competitive sport.

In this context the development of dhows whose shape echoes the traditional vessels in Lamu harbour, and whose construction is based on the heritage skills of the Lamu boatbuilders is in keeping with other influences on the evolution of these vessels. However as more ambitious vessels are planned the need for a more formalised approach to the refinement of the shape, and the scantlings of the structure, becomes increasingly important.

Figure 12: Design and construction process of Ndogo

DESIGN CHALLENGES

Flipflopi has encountered and overcome many design challenges since the first preliminary ideas were kindled for a recycled plastic boat building project in 2016. These range from very broad production challenges in the local recycling of plastic into structural materials, through to very specific challenges of a particularly difficult joint in the stern stem of the boat. Therefore, this section is not exhaustive, but instead focuses on five challenges which we have found to be important and specific to the design and construction of the dhow itself.

Hull Lines

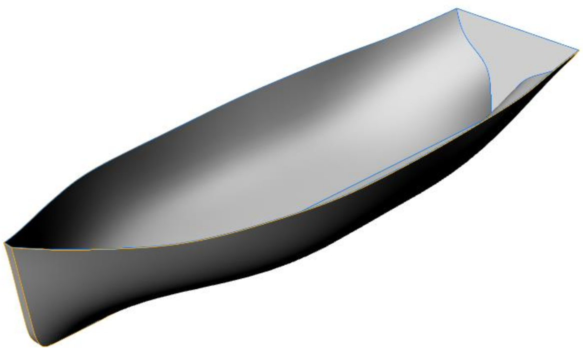
In a new dhow design following traditional methods, the hull lines are developed during planking from the fundi/boatbuilder's knowledge and experience of previous dhows. In other cases, such as Utamaduni pictured in Figures 7 and 13, older dhows are renewed to maintain their shape and characteristics whilst almost the entire structure is replaced.

This process is challenged when replacing wood with plastic, because there needs to be some prior knowledge of shape to efficiently form the frames, rather than selecting and shaping appropriate lumber. In addition, the change in material properties and subsequent scantling weight needs to be more properly considered.

To assist with this, marine design software including Rhino and Maxsurf have been introduced to the Flipflopi design process by bringing together a team including the boatbuilding fundis, naval architects and industrial designers. Working together, the team were able to transfer the traditional lines and design philosophy of the fundi into a digital model, with an example shown in Figure 14. This included measuring and digitising an existing dhow (Utamaduni) in Rhino and using this to conceptualise then fair the features for the new design in Maxsurf. The Maxsurf model was then used to give confidence with new features introduced by the fundi into the design, such as the unique rounded stern. This was checked in terms of buoyancy distribution, stability, and the shape of key hull lines known to influence resistance such as at the bilge diagonal. These efforts were effectively communicated back to the Flipflopi team through several webinars and online discussions. These were also incorporated into lectures for the heritage boatbuilding course.

The digital model also enabled a scale model of the dhow to be manufactured for towing tank and stability experiments at Newcastle University (Figure 15). A physical model provides a practical and effective way to communicate key naval architectural concepts to the Flipflopi team, including the methods to measure stability, the effects of free surface and the hydrodynamic performance.

Figure 13: The original ribs of Utamaduni in the Flipflopi boatyard (left) and the renewed structure (right)



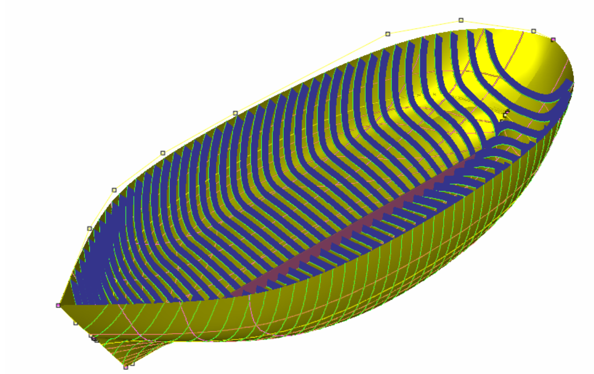


Figure 14: Rhino model of Utamaduni generated from a hull survey (left), Maxsurf model of an early iteration Kubwa design including ribs and keel for structural analysis (right)

Figure 15: A 1/16th 3D print model of Kubwa: preparation (left), inclining experiment (centre), resistance test (right)

Structural Design Principles

Traditional dhows are predominantly built from generational knowledge and expertise, which drives structural design principles including:

- The sizing of scantlings such as the keel, planking, frames, knees and brackets
- The sourcing of appropriate wood, locally and imported. Planks may be imported whilst frames are still sought locally and directly from the forest by the boatbuilder, selecting logs with the right shape for the curved frames.
- Joining methods include nailing, stitching and caulking.
- Dhows need to be heavy, to minimise the need for comparatively expensive ballast. Therefore, the scantlings are likely to be much larger than would be specified in a design driven by lightweighting.

We are unaware of any formal structural design guides, codes or calculations used for dhow construction. Provisions for traditional wood construction in design codes such as ISO12215 and Seafish, or empirical design approaches driven by the scantling number (Sn) such as by Gerr (2000) could probably be applied, but the success across generations of dhows sailing in Lamu probably precludes the need for this in typical wood construction projects.

Changing the material from hardwood to recycled plastic beams and planks must rely on the trusted knowledge of heritage designs. This is also essential for local acceptance of the design with factors including perceived seaworthiness, safety and aesthetics (Birmingham and Wibawa 2018). However, the significant change in material properties must be carefully investigated to ensure the boat remains stiff, strong and robust for a long sailing life.

For the smaller boats, including Ndogo, the Flipflopi team made incremental judgements on the structural design principles based on immediate observations of material quality and strength. This iterated with the production processes, with the eventual structure in Ndogo showing improvements during the build process. For example, the first laid planks were bought from external recycling suppliers, and were found to be poor for joining and strength. In response, the Flipflopi team developed better production processes and new equipment to produce their own higher quality planks. The relatively small scale of Ndogo also meant the structural spacing and sizing could mostly replicate equivalent wood.

The larger scale of Kubwa, with an envisaged length of 24 metres, further challenges the inherent structural design principles. The photo of the similar length Utamaduni in Figure 7 illustrates the typical magnitudes of wooden beams and planks in a large dhow. It is likely that stiffness, as much as strength, becomes critical for the equivalent recycled plastic structure. The boat will be ocean going, and needs to be prepared for significant wave loads. A judicious use of design codes is therefore being used, accounting for their limitations and boundaries when dealing with a completely different material. This is appropriate for some aspects, for example calculating maximum design hull pressures. But in other cases use of codes can be inappropriate and misleading, especially where they are bounded by material type (such as Seafish rules that are restricted to wooden construction).

This is an ongoing design challenge for Flipflopi. For example, ISO12215 can be applied to determine the hull pressure loading, which is independent of material type. ISO12215 provides an appropriate method to calculate bottom, side and deck design pressures (Nabi 2023). Using the provisional dimensions of Kubwa (Table 1), the calculated design pressures are shown in Table 2.

Table 2: Maximum Design Hull Pressures

	Value (kPa)
Bottom Pressure	50.3
Side Pressure	17.3
Deck Pressure	17.3

This enables first principles calculations to design and compare plastic scantlings as a replacement for wood. For example, the influence of frame spacing on the bending stress and deflection of different plank thicknesses under a design pressure of 50.3kPa is shown graphically in Figure 16. These provisional results indicate that doubling the plastic plank thickness compared to wood produces similar deflections under the design hull pressure loads whilst also keep bending stresses below typical strength limits for LDPE (note that these limits are literature values, and not necessarily equivalent to the actual strength of the recycled plastic planks).

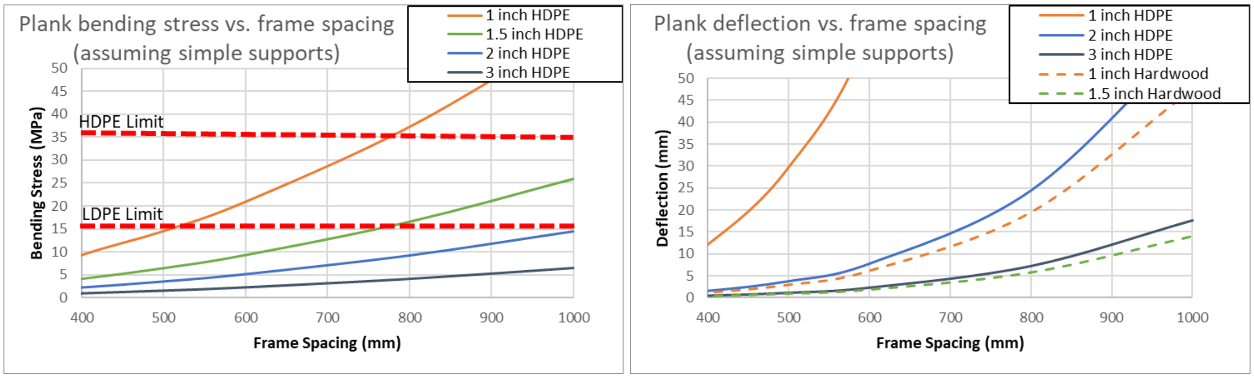


Figure 16: Provisional design charts to determine plank thickness as a function of frame spacing

Moulding, Welding, Bending and Laminating

The traditional construction of the dhows in Lamu required the need for large timber sections for the internal ribs and structural components. Flipflopi have developed low tech closed moulds which uses existing extrusion machinery to produce large complex forms that can then be used in the construction (Figure 17).

Figure 17: Large mould production using closed mould extrusion techniques

Traditionally sailing dhows in Lamu and from further afield have been secured together using rope, bolts, screws, and nails. Whilst these fixing methods are superb for use in wood, they present difficulties when applied to equivalent plastic joints. The flexibility and stress concentration around the screw causes them to easily become loosened cause stress concentration points within the plastic that can lead to cracking and failure. This led the team to identify plastic welding as a fabrication process, Figure 18 shows how the welded section removed the stress concentration that led to cracking and failure in the screwed section.

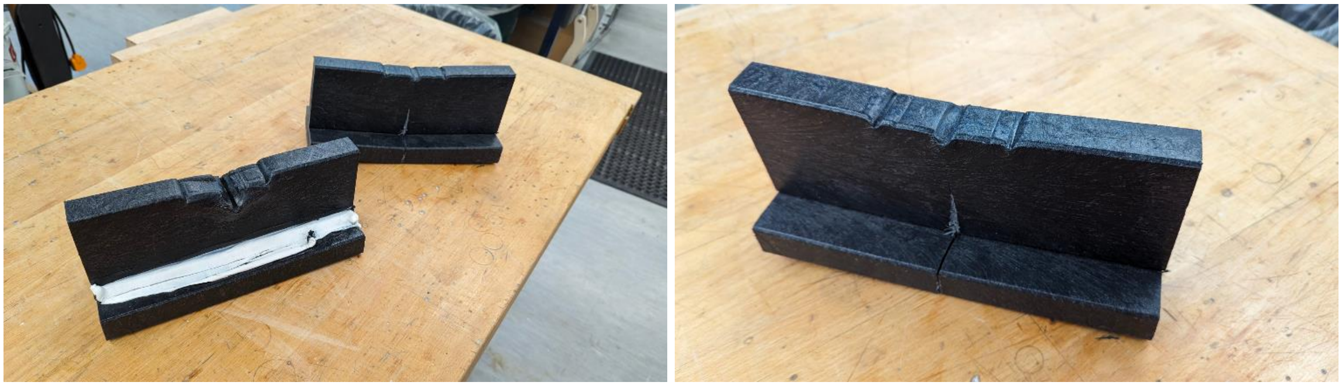


Figure 18: Testing of (left) screwed versus (right) welded sections of plastic lumber, the welded sections removed the stress concentration that led to cracking and failure.

Secondary uses (Figure 19) for the welding have yielded other benefits, welding the planks allows the vessels to be watertight, the HDPE planks do not expand when submerged in water so welding is used instead of the traditional methods of caulking. The production facility can also only produce planks successfully up to 4.80m long, to achieve longer profiles the welding can be utilised to join the planks together using the traditional scarf jointing methods already used in traditional timber construction.

Figure 19: Traditional timber scarf joint (left) and HDPE welding and scarf plank joining system (middle and right)

Figure 20 illustrates a further application for the welding process in the production of more complex shapes that are produced through post production heat bending and lamination of the planks into larger sections. The planks are re-heated using conventional steam bending used traditionally in timber fabrication, the sections can then be bent into their desired shape and then welded holding them together in their desired final shape.

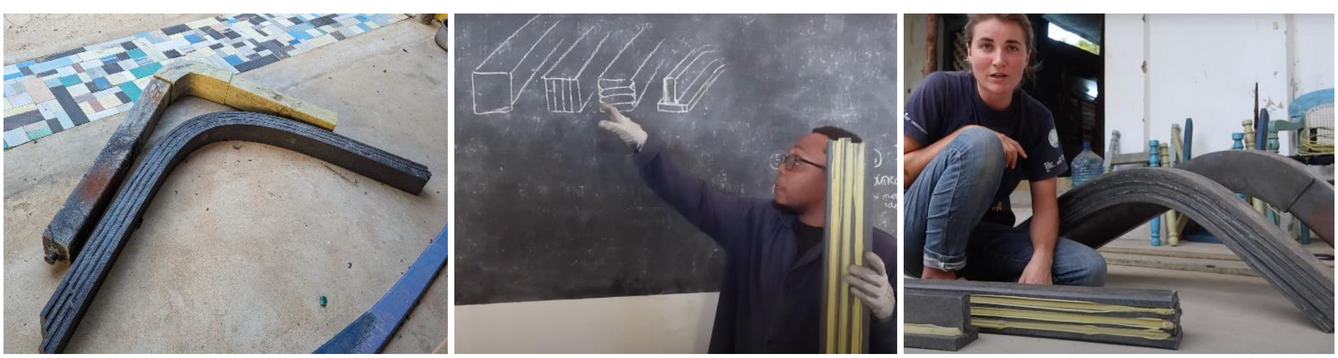


Figure 20: Heat bending and welding planks together creating laminated sections

Material Properties

Common polymer plastics have material properties less favourable to large boat construction when compared to wood, metals and polymer composites (the "big three" boat building materials). Creating construction materials from recycled plastics present additional challenges in terms of quality and consistency, initial materials produced was of low quality and with significant defects in the material, early testing in 2017 at Northumbria University, UK, yielded poor results. Applying plastic recycling techniques in a relatively low resourced setting furthers this challenge.

Figure 21: Materials bend testing (left) and materials (middle and right) May 2017.

Significant innovations in production methods have been developed to improve the material consistency, the principal influences on the material properties and structural behaviour of recycled plastic lumber include sorting appropriate plastics, washing, drying and applying a consistent production processes; appropriate use of moulds or extrusions; monolithic or laminated beam fabrications; the use of complex shapes; methods to bend beams into shapes; the colour; and joining and welding methods.

HDPE is the predominant polymer used in the Flipflopi recycling process. Typical material properties for virgin HDPE are 10-30MPa tensile strength and around 1000MPa modulus of elasticity. This means 10% the stiffness and 10-40% the strength of a typical hardwood (depending on the type, treatment and load direction of the wood). Flipflopi have completed several efforts to quantify material properties of recycled plastic using established research lab techniques. Figure 22 shows example results from 3-point bend tests on 4” x 1” planking samples conducted in Northumbria University, UK. These tests showed that the recycled HDPE maintained similar properties to equivalent virgin product, but only at this relatively small sample level, which didn’t fully account for the manufacturing and environmental variations inherent in the processes used at the Flipflopi recycling centre. It has also proven difficult to transfer samples appropriately from Lamu to test facilities within Kenya and internationally.

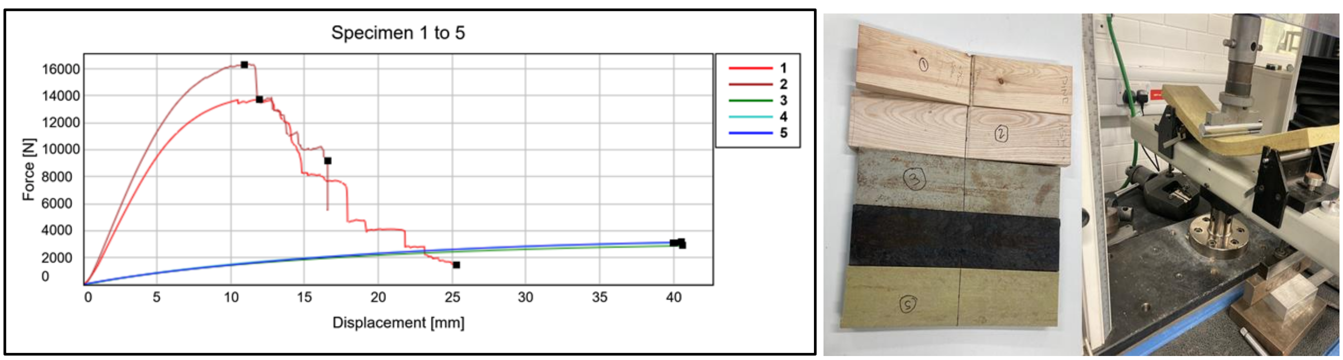


Figure 22: Bend test comparison results for Pine (1), Ash (2), White HDPE (3), Black HDPE (4) and Yellow HDPE (5)

To overcome these challenges an “on the ground” approach was required to test the structural properties of the recycled plastic in-situ and provide further confidence to the boat build. A bespoke 3-point bending test rig was therefore designed and fabricated at the boatyard as shown in Figure 23. This enables beams and planks about 1.45m long to be tested under 3-point bending. The test rig is manually operated and doesn’t require an electricity supply. The central load is applied via a hand-turned winch (meaning tests can continue with intermittent power supply) and deflections are measured using a dial indicator.

First results show reasonably linear load-deflection at relatively small loads (Figure 24). The tests are ongoing, so only provisional findings are reported here. These indicate that:

- The recycled plastic has a stiffness about 10% of locally available boatbuilding hardwood
- The Young’s modulus is about 800MPa, which is slightly lower than the reported values for new HDPE in literature but within acceptable boundaries.
- Tests are in relatively high temperatures, which has a greater detrimental effect on plastic than wood. Initial tests at lower temperatures, using ice packed around the test specimens, show slightly improved stiffness.

Figure 23: The 3-point structural test rig (left), a 4” x 4” HDPE laminated beam (right)

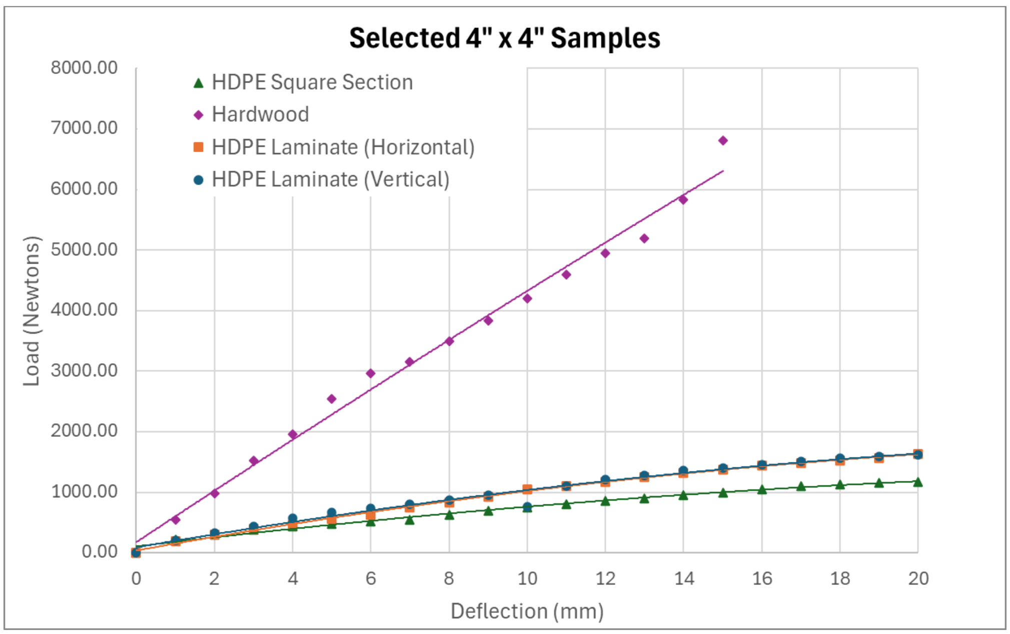


Figure 24: Selected Load-Deflection Test Results of 4” x 4” sections with different materials and constructions

Propulsion

Whilst the focus of Flipflopi is the use of recycled plastic as a construction material for boatbuilding and other carpentry products, the project opens up broader environmental and sustainability considerations. A specific and important challenge identified in the local Lamu maritime community is the cost, availability and distribution of fuel for inboard and outboard engines on almost all boats. Boat fuel in Lamu currently costs about 250 Kenyan Shilling ($1.50) per litre, the price of which has reportedly more than doubled within a year. This is putting significant pressure on local maritime activities, especially fishing and local transport. Added to this, distribution of fuel is via open poured jerrycans, outboard engines are often old and noisy, and there is notable pollution in waterways also used for swimming and agriculture. Examples of conventional outboard use are shown in Figure 25. This local challenge is likely repeated in many other LMIC coastal communities. This also intersects with the global challenge of fossil fuel use and the impacts of this on the climate emergency.

Flipflopi are addressing this challenge by trialling the use of a 6kW battery-electric outboard coupled to a solar panel charging system as a complete independent power system for their recycled plastic water taxi (Figure 26). The advantages of the water taxi as a use case for solar power is the size and arrangement of the boat, and the relatively short journeys. The 8kWh outboard battery provides sufficient power for an estimated 10 km at normal cruising speeds on a single charge. A canopy will be installed in the stern area of the boat to house 1-2kW of solar panels, which will be tested to determine whether the acquired charge power is sufficient to maintain 100% operability without resorting to mains charging.

Figure 25: Typical water taxi with 15hp Yamaha outboard and sun canopy (top left), jerrycan refilling of petrol from floating station (top right), fishing dhow with auxiliary sail used to save fuel (bottom left), A Lamu style and Mozambique style dhow on a sunset cruise with tourists – sail propulsion but outboards in reserve (bottom right)

Figure 26: The Flipflopi water taxi equipped with a 6kW battery-electric outboard

CONCLUSIONS

Flipflopi shows the synergistic power of imagination, passion, capability, creativity and practicality in a marine design context. The paper shows that novel marine design approaches, such as implementing a circular economy approach at a local scale, is effective in responding to global environmental crises such as plastic pollution. In the Flipflopi approach, waste has become a precious resource. It is collected, processed and remade into a valuable product that retains heritage whilst embedding innovative cutting-edge technologies. Whilst this process can be used for replacing timber in many applications, the iconic design of a traditional sailing dhow is a powerful tool that impacts on community, enterprise and engagement for environmental sustainability. Looking to the future, Flipflopi has plans to build a larger sailing dhow, which is hoped will circumnavigate the world taking the message of plastic pollution and local circular economy to coastal communities everywhere. Closer to home, the aspiration is to export this knowhow and technology to other communities in East Africa and eventually further afield.

CONTRIBUTION STATEMENT

Simon Benson: Conceptualization; investigation; visualisation; writing – original draft. **Ali Skanda:** conceptualization; methodology; project administration; supervision; writing – review and editing. **Hassan Shafi:** methodology; supervision. **Katharina Elleke:** conceptualization; methodology; visualisation; project administration; writing – review and editing. **Simon Scott-Harden:** methodology; writing – original draft; funding acquisition. **Nathan Smith:** writing – review and editing. **Richard Birmingham:** supervision; writing – review and editing. **Dipesh Pabari:** conceptualization; methodology; project administration; supervision; writing – review and editing; funding acquisition.

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People (Newcastle University): Aftab Nabi (structural calcs ISO12215), Georgia Richardson, Harry Syllantavos and Rebecca Stokes (summer 2021 model testing)

People (Northumbria University): Johnny Hayes, Phil Hackney and Simon Neville (production design, development and testing)

People (Flipflopi): The entire Flipflopi team and community (see https://www.theflipflopi.com/our-team)

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