MODULAR EXTRACTION TOOL FOR RIVERINE PLASTIC WASTE

DESIGN OF A PROOF-OF-PRINCIPLE PROTOTYPE

Joep van Stijn

TU Delft

THE OCEAN CLEANUP

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Author
Joep van Stijn

Supervisory team
Chair
Prof. Dr. Ir. Diehl, J.C.
Faculty of Industrial Design Engineering | TU Delft
Department of Sustainable Design Engineering

Mentor
Ir. Schermer, W.
Faculty of Industrial Design Engineering | TU Delft
Department of Human Centered Design

External mentor
van Eijk, J.
The Ocean Cleanup
Rivers - Data & Engineering

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PREFACE

I would like to extend my heartfelt appreciation to JC Diehl and Wim Schermer, my chair and mentor, for their unwavering support throughout this project. Their guidance allowed me to navigate this project independently while providing invaluable assistance when needed. Thank you for staying supportive and understanding throughout the project, while also posing critical questions that helped me zoom out and see the bigger picture.

I also want to express my gratitude to Jasper van Eijk, whose commitment and support added significant relevance and motivation to the project. Jasper's willingness to embrace mistakes and allow me to find my way is a part of the journey contributed to achieving the best results. It felt like you had my back, which is really nice to have if you are doing a long individual project.

The rest of The Ocean Cleanup, both inside and outside the office, also welcomed me warmly and treated me with kindness, creating a supportive atmosphere that significantly enriched my overall experience.

The successful development of the final prototype was made possible through the generous assistance and support of the PMB instructors at Industrial Design Engineering. I want to express my special thanks to Carlo, who devoted numerous personal days to keeping the workshop accessible and assisting me with my prototype. I appreciate the patience and guidance provided from everyone in the workshop whenever I sought advice on optimal fabrication methods. And thanks for letting me hijack half of the workshop for my enormous prototype.

I would also like to thank Scouting Nootdorp for lending me six large barrels, which played a crucial role in creating the walkable barrier for the final testing phase.

And, of course, last but not least, a heartfelt thanks to my friends and family for their emotional support and the moments of distraction they offered during demanding periods.

To everyone who contributed to this journey, I extend my sincere thanks. I hope you find this thesis an enjoyable read.

Warm regards,
Joep

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Problem statement

The Ocean Cleanup encounters challenges in new deployments with the mission to prevent riverine waste from entering the sea and harm the surrounding ecosystems due to inadequate existing waste extraction methods. This issue becomes more prominent when addressing entire river systems rather than individual rivers. For example, sites like Shoemaker Gully in Jamaica, hindered by natural obstacles like mangrove forests, require innovative solutions for direct-to-shore waste extraction. Beyond The Ocean Cleanup, local initiatives operate in areas where commercial solutions fall short, resorting to manual extraction or developing own tools due to worker health concerns. Introducing new designs capable of benefiting local cleanup organizations as well as The Ocean Cleanup can significantly impact the fight against riverine plastic pollution.

Goal

Develop a versatile, modular extraction tool to efficiently remove contained waste from water bodies directly to the shore, enhancing The Ocean Cleanup's deployment options and empowering local organizations to increase their impact. By creating a cost-effective, adaptable proof-of-principle prototype, a foundation will be established for further development of extraction tools for the selected use cases.

Imrovement to the current situation

- *Enhanced worker safety and operational efficiency.*
- *Expanded market potential through the modular design, offering versatile deployment options.*
- *Financially efficient design and operational approach, leading to sustained cost savings and greater accessibility for budget-constrained organizations.*
- *Minimal to no on-site construction needed for installation.*
- *Capacity to address numerous smaller streams, accumulating to a large impact.*
- *Streamlined, user-friendly design that minimizes training requirements.*

Modular plastic link belt for quick on-site repairs, minimizing downtime

User-friendly controls for easy operation, including speed and direction adjustments, and a **removable/ replaceable battery**, enhancing operational flexibility and safety.

Adjustable and interchangeable accessories like handles and eye-nuts for on-site customization.

Aluminium frame for strength, corrosion resistance, and weight

Adjustable and extendable legs to accommodate diverse deployment sites

Fenders for extra stability when the belt is partially submerged in water

Multiple wheels for effortless deployment and manoeuvring

Its **modular** design, exemplified by the semi-permanent stand, allows for flexibility in adapting to various site conditions and deployment approaches, ensuring suitability for specific situations.

INTRODUCTION

Plastic pollution is a pressing global issue, with significant environmental consequences. The Ocean Cleanup, a renowned organization dedicated to mitigating ocean and riverine plastic pollution, plays a pivotal role in addressing this global challenge. This thesis represents a collaborative effort between the University of Technology Delft and The Ocean Cleanup, uniting expertise and resources to develop innovative solutions for the extraction of plastic waste from polluted rivers.

Existing riverine waste extraction mechanisms are limited in number and effectiveness at several site specific characteristics, while the prevalence of polluted rivers is extensive. Consequently, there is an urgent need for the design and implementation of new mechanisms and tools in order to keep increasing the impact on this global environmental issue.

This thesis documents the journey from problem identification to the creation of a proof-of-principle prototype. It serves as a repository of insights gained throughout the process, shedding light on the research conducted to explore potential solutions and the iterative process of crafting a suitable solution.

The culmination of this endeavour is the creation of a final proof-of-principle prototype, a tangible manifestation of innovative problem-solving. This prototype is ready for real-world testing, providing a possibility to identify areas of improvement while simultaneously contributing positively to the ongoing battle against riverine plastic pollution.

Chapter one delves into the heart of the issue, contextualizing the problem, defining its parameters, and establishing the overarching objectives of this thesis. Chapter two embarks on an exploratory journey into the solution space, leveraging a combination of market analysis and field research to uncover design opportunities. Chapter three provides a concise visual overview of the evolutionary path traversed in the quest for the ideal solution, while chapter four presents the final design. Within this chapter, most important features are discussed, validating the expectations with a full-scale test, and ending with recommendations for further development.

Throughout this thesis, the following terminology is employed:

Extraction	The process of taking the waste out of the body of water, the next step can be anything as long as the waste is separated from the waterbody.
Offloading	The process of transporting the extracted waste to a site where it can be pro-cessed or loaded into trucks for further on land transportation.
Direct-to-shore	Extracting directly to an offloading site on the shore with one singe system.
Interception	The process of intercepting the floating riverine waste through concentration, containment, or entrapment.
Concentration	Redirecting the riverine waste to flow by a specific location.
Containment	Preventing the waste from flowing further downstream.
Entrapment	Completely entrapping the riverine waste, preventing it from flowingin the direction of the stream or any other direction.
Retention zone	The containment area of an intercepting intervention. A larger retention zone is capable of containing more waste before it passes the intervention and continues flowing downstream.
RORO bin	Roll-on-roll-off bin. Specific type of container that can attach to a specialized truck enabling the container to be released from the truck completely allowing the truck to drive away and pick it up later.
Big bag	A standardized bag often used in transportation of bulk material. These bags are made to fit on a pallet and contain straps to allow moving it with a forklift.

CHAPTER ONE

THE PROBLEM

1.1 CONTEXT

The Ocean Cleanup is a non-profit organisation that develops and deploys technologies to remove plastic pollution from the oceans and some of the most polluted rivers around the world. According to Meijer et al (2021), 1656 rivers are accountable for 80% of the global riverine plastic emissions. The Ocean Cleanup has established the River Team with the aim of reducing the influx of plastic waste into the ocean and safeguarding the adjacent ecosystems.

The Ocean Cleanup employs various containment and extraction technologies to address river pollution. Their current solution portfolio includes the Interceptor Classic, Interceptor Barrier, Interceptor Tender, and Interceptor Barricade (The Ocean Cleanup, 2023), as depicted in the figures below. Concise descriptions of how these four solutions operate and how they are applied can be found in Appendix 1. Additionally, detailed overviews of the Interceptor Barrier and Interceptor Barricade, among other in-water-waste interception technologies, can be found in Appendix 2.

The Interceptor Barrier serves as The Ocean Cleanup's primary method for containing pollution. It is used to direct the debris to the Interceptor Classic or contain it until the Interceptor Tender can extract it. While these extraction technologies are designed to transport the waste from the containment area to the offload site by water, which is suitable in some locations, there are instances where water-based extraction and transportation is impossible. For instance, consider the deployment site of The Interceptor Barricade, where the barrier is used to capture debris carried downstream during flash floods. This particular river frequently encounters prolonged dry periods between floods, rendering traditional water-based waste extraction impractical. As a result, the waste removal process relies on the use of a large excavator.


Figure 1: Interceptor Classic

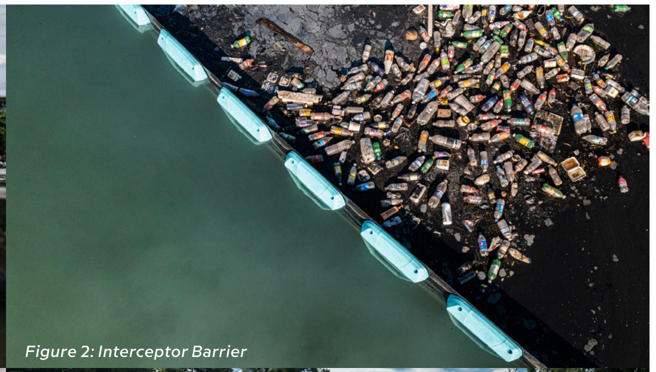


Figure 2: Interceptor Barrier


Figure 3: Interceptor Tender


Figure 4: Interceptor Barricade

The Ocean Cleanup's solution portfolio consists of two containment methods and two extraction methods. Both of the current extraction methods transport the waste to the offloading site via water, which presents unique challenges. One primary operational issue identified in current operations is the dependency on specific water levels for offloading. This can lead to an operational bottleneck and diminish the overall impact of the intervention. To enhance efficiency, a shift towards direct-to-shore offloading has been initiated, allowing the schedule to be primarily driven by the amount of contained waste.

Recognizing this gap in The Ocean Cleanup's portfolio, two projects were launched to develop direct-to-shore extraction technologies, with this thesis representing one of those projects.

1.2 PROBLEM DEFINITION

The Ocean Cleanup is increasingly facing scenarios where they can install barriers to prevent riverine waste from reaching the sea, but the challenge lies in the lack of suitable waste extraction methods. Even when considering third-party solutions, many sites lack a practical extraction mechanism. These sites become more apparent when cities or areas are addressed in a wholistic way, meaning that the focus is not only on one river, but the whole system.

For instance, consider Shoemaker Gully in Jamaica, where a mangrove forest near the sea entrance poses a challenge for the Interceptor Tender, hindering access as visualised in Figure 5.


Figure 5: Protected mangrove forest hindering access by Interceptor Tender

Introducing a modular solution capable of extracting and offloading waste directly onto the shore would introduce new possibilities as illustrated in Figure 6. There are a lot of specific situations for which there are no solutions available yet. To identify a category of deployment sites that strikes a balance between inclusivity and specificity, site characteristics are defined and selected on importance. In the market analysis, existing solutions are evaluated against these defined characteristics. More on this analysis can be found in Chapter 3.4.

Beyond The Ocean Cleanup's operations, several other organizations are also dedicated to addressing riverine plastic waste. Some of these organizations are local initiatives, such as Sungai Watch (Sungai Watch, 2023) and Chemolex (Chemolex Ltd, 2023). Notably, Chemolex operates in locations where there are no commercially available solutions. Initially, they relied on manual waste extraction, but due to a significant number of worker illnesses and injuries, they began constructing their own extraction tools (Chemolex, personal communication, May 12, 2023). Figures 7 and 8 showcase two of these innovative mechanisms.

If the new design could demonstrate its advantages for local cleanup organizations as well as for The Ocean Cleanup, it could potentially lead to a more substantial positive impact. In numerous scenarios, no extraction mechanisms are currently accessible, leaving manual extraction as the sole option. However, manual extraction is highly labour-intensive and perilous due to the handling of unpredictable, sharp, or otherwise hazardous waste, as illustrated in Figures 9 and 10. The water in which workers operate is frequently not only chemically contaminated but also harbours substantial quantities of pathogenic microorganisms that can contribute to the spread of waterborne diseases.

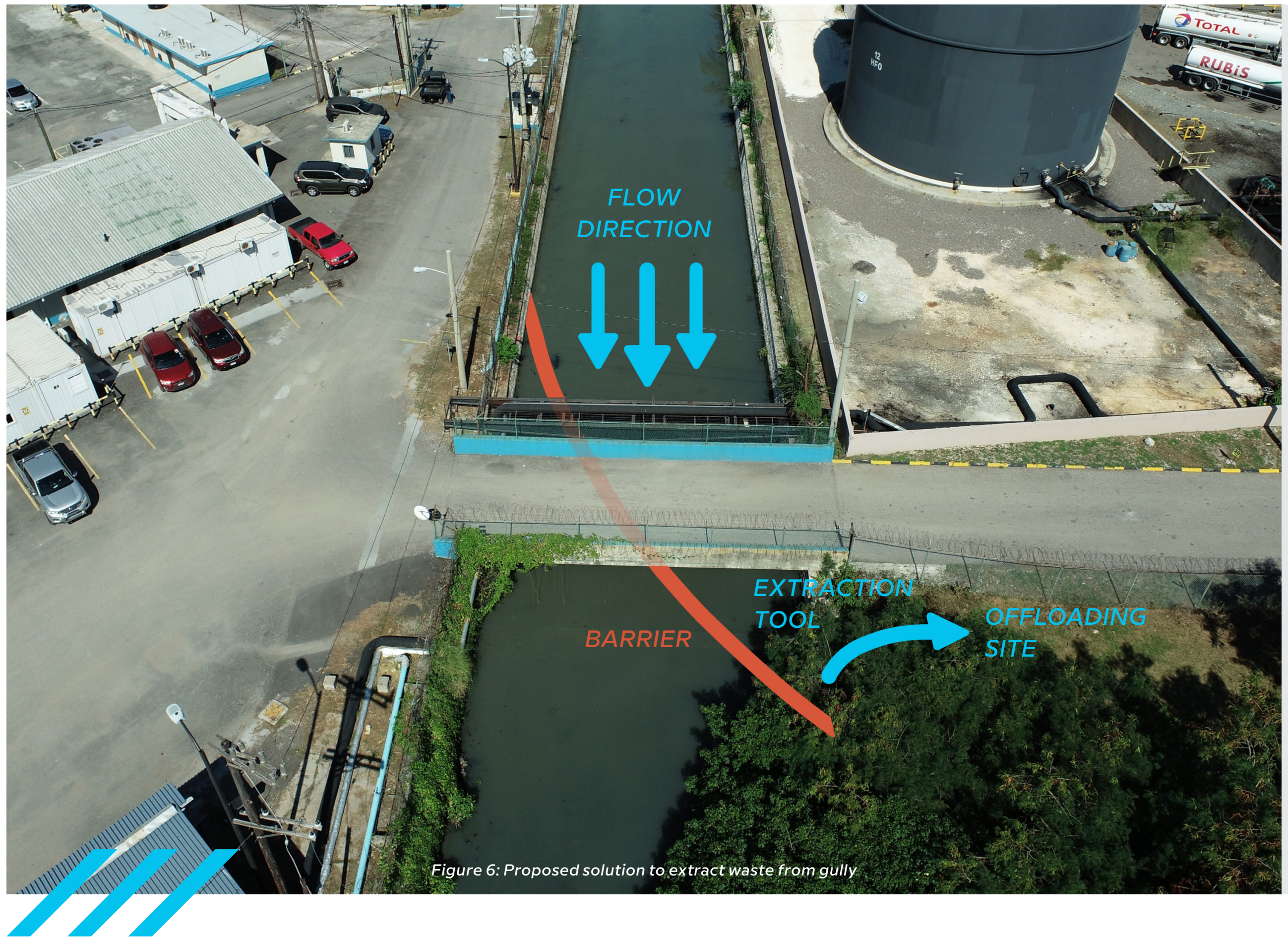


Figure 6: Proposed solution to extract waste from gully

1.3 DESIGN GOAL

The main goal of this thesis is to develop a modular and mobile extraction tool capable of efficiently removing contained waste from water bodies and transporting it to the shoreline. This solution aims to expand the range of potential deployment sites for The Ocean Cleanup while also enabling local organizations to increase their impact. The primary aim is to create a versatile and adaptable tool that considers cost-effectiveness, flexibility for various deployment strategies, and compatibility with diverse site-specific characteristics. By presenting a robust proof-of-principle design a foundation will be established for further iterative development, ranging from budget-conscious minimum viable products to specialized tools tailored for particularly challenging environmental or operational conditions.

Figure 7: Chemolex cleaning river with self-built mechanism

Figure 8: Chemolex cleaning river with self-built mechanism

Figure 9: Sungai Watch manual extraction

Figure 10: Plastic Fisher manual extraction

CHAPTER TWO

THE SOLUTION SPACE

2.1 DESIGN OPPORTUNITIES

Upon comparing existing solutions, it quickly becomes evident that there are limited commercially available direct-to-shore extraction mechanisms for river cleanup. To maximize collective impact, it's crucial to tailor a solution to address situations where current solutions fall short.

To identify these situations, site-specific characteristics were established based on real-world fieldwork experiences in Malaysia, complemented by insights from engineers within The River Team at The Ocean Cleanup. These characteristics are factors that can be used to differentiate between extraction sites. These factors may impact the characteristics of the water, the shoreline, the passing waste, and even the land use in the vicinity.

By selecting and clustering characteristics, the four main characteristics below were identified to have a large impact on the choice of extraction mechanism.

SITE SPECIFIC CHARACTERISTICS

- *Tidal/rainfall effects*
- *River bank inclination*
- *Total distance from the water to the offloading site*
- *Amount of waste*

The complete evaluation of site specific characteristics and selection of leading characteristics can be found in Appendix 4.

In Appendix 2 and 3, a selection of different technologies is compiled with a short explanation of the working mechanisms and use cases. Appendix 2 covers existing in-water-waste interception technologies, which have to be understood since extraction technologies work together with in-water-waste interception technologies. In Appendix 3, the existing direct to shore extraction technologies are addressed which are also used in the following comparison in order to identify design opportunities.

Riverbank inclination and distance

Upon evaluating the suitability of existing solutions in terms of riverbank inclination and distance to the offloading site, it became evident that there is a notable absence of commercially available options for shores with a shallow angle relative to the water's surface. As illustrated in Figure 11, this market gap is visually represented by the yellow area. Focusing the design on the central portion of this area, as indicated by the green zone, increases the likelihood of its usability or adaptability across a more extensive section of the yellow area. Additionally, if the design can accommodate steep shores or facilitate waste transport over longer distances, it holds the potential for a more substantial impact. However, this expansion should not compromise the design's suitability for sites characterized by shallow angles and short distances. The expansion into the yellow area will be explored in Chapter 3.4.

Insufficient data is available to determine the precise number of worldwide sites falling within this quadrant that would benefit from an extraction mechanism. However, experienced senior employees at The Ocean Cleanup state that due to the large amount of polluted rivers globally, there is an abundance of sites in every category that would benefit from an intervention (Personal communication, 2023). Therefore, as long as the chosen focus category isn't excessively specific or already addressed by existing riverine waste extraction solutions, it opens up opportunities to address sites that were previously inaccessible. The lower right quadrant in Figure 11 appears to exemplify one such opportunity. Additionally, as mentioned earlier in Chapter 1.2, Chemolex constructs their own devices to extract plastic waste at similar sites in Kenya, underscoring the demand for extraction mechanisms in this quadrant.

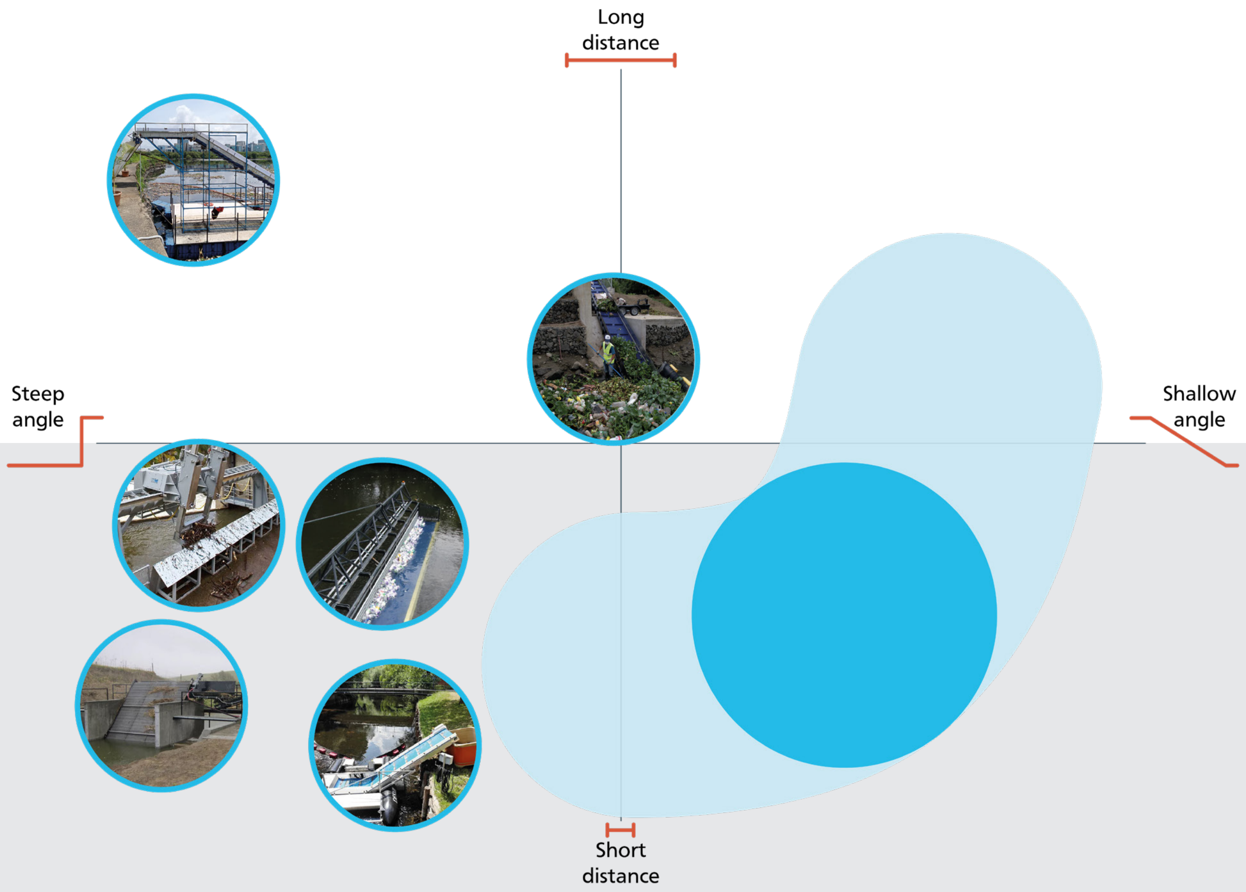


Figure 11: Existing commercially available direct-to-shore solutions plotted on matrix with distance and angle

Amount of waste and price

When assessing existing solutions based on their waste extraction capacity and cost, it becomes evident that all commercially available technologies possess the physical capability to extract substantial quantities of waste. The limiting factor is their operational efficiency. While these technologies can theoretically be used to extract smaller amounts of waste, their high cost renders them impractical for sites with lower waste volumes. An estimation of the amount of waste they can be used for based on the design and the probable operational efficiency is visualised in Figure 12.

To make these technologies more attractive for locations characterized by lower waste quantities per site or irregular waste flows, the key consideration is affordability. This consideration led to the concept of developing a mobile extraction technology capable of servicing multiple sites and therefore distributing the associated costs.

As mentioned in Appendix 4, not all site specific characteristics require alterations to the extraction technology's design. Some are highly influenced by operational changes, meaning that not only the site but also the use case needs to be taken into account to ensure a suitable fit.

Due to the limited number of existing use cases for direct-to-shore extraction of riverine waste, there is a shortage of scenarios available for analysis. Consequently, the process of selecting realistic scenarios involves examining both existing direct-to-shore and non-direct-to-shore operations, as well as gathering input from various stakeholders within The Ocean Cleanup, including project engineers, operations managers, waste managers, and others. For the finalized scenarios, please refer to Chapter 3.4.

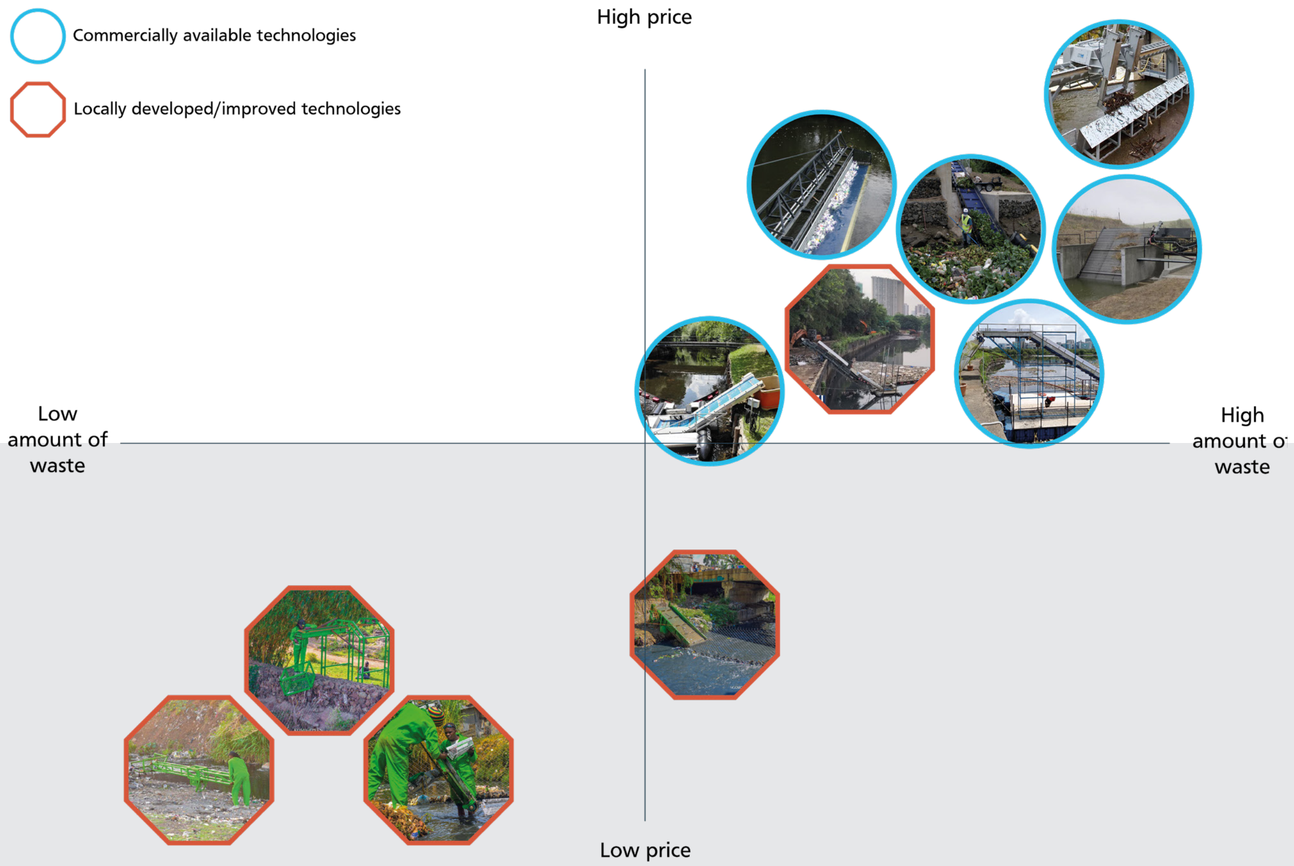
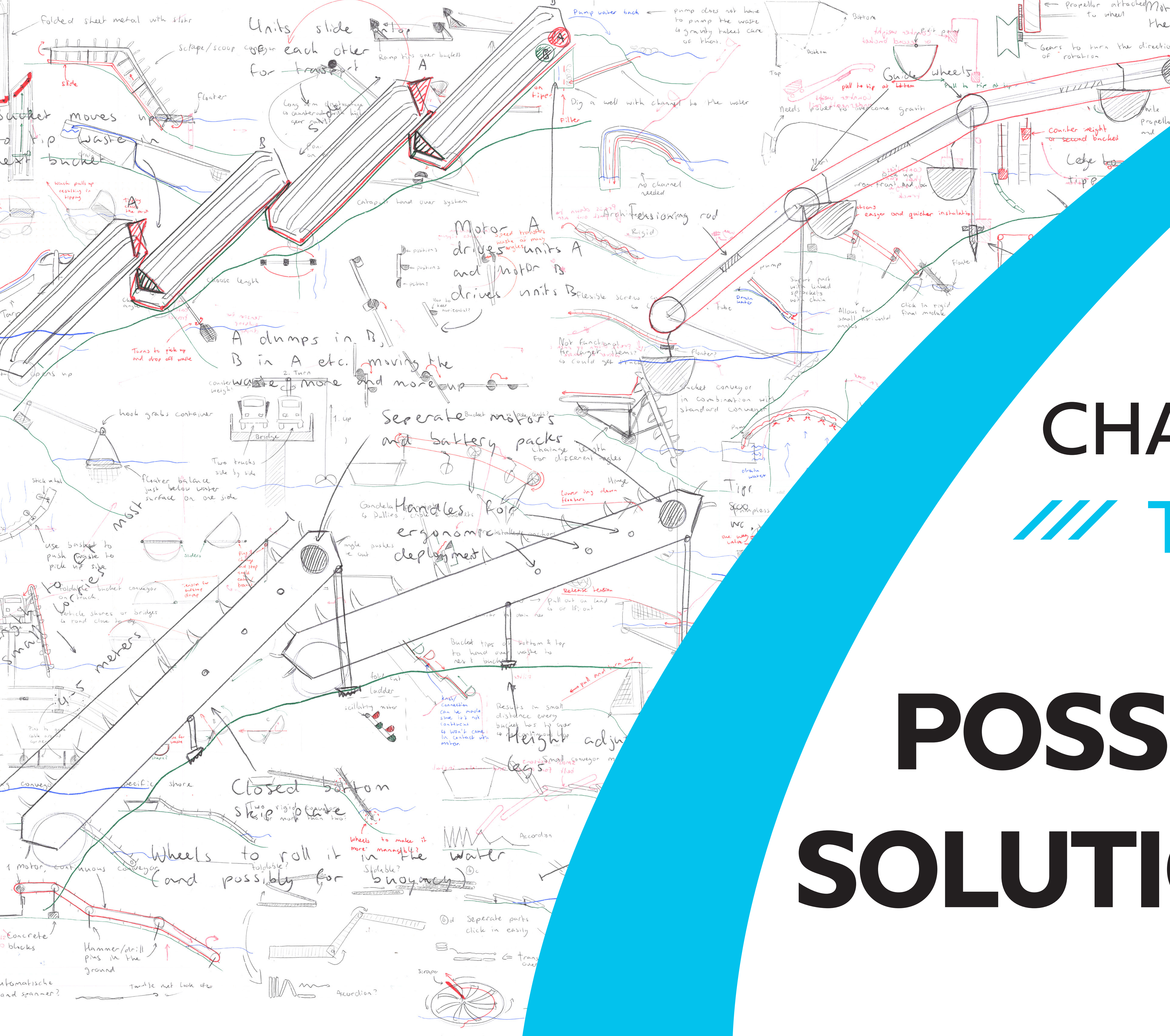


Figure 12: Existing commercially available direct-to-shore solutions plotted on matrix with distance and angle



CHAPTER

/// THREE

POSSIBLE SOLUTIONS

3.1 KEY DESIGN DRIVERS

For the selected design opportunity, essential design criteria were established to evaluate the most promising ideas. A survey involving 13 employees from The Ocean Cleanup was conducted in order to identify important selection criteria that were missed and score the criteria according to their importance with the intended use scenario in mind. This survey can be found in Appendix 8. Due to the diverse backgrounds and roles of the survey respondents, the outcomes varied and reflected the perspective of their rolls within The Ocean Cleanup. Instead of calculating an average score, the responses were individually analysed and considered from each respondent's viewpoint. This approach ultimately determined the final hierarchy of importance, as presented in Appendix 10. The final list comprised 34 criteria, with the most significant ones aligning with four key drivers, which also align with some of the main takeaways from conversations with (ex) Interceptor Classic operators in Malaysia. These main takeaways can be found in Appendix 7

Ease of transportation and deployment

Cost-effectiveness

Versatility

Increased safety and reduced workload

Ease of transportation and deployment

In order to fit the intended use case, the design should be mobile and easy to deploy. As the design turned out to be applicable for more use cases by including the possibility for a semi-mobile deployment, the mobility is decreased while the ease of deployment is increased. More on this diversification into different use cases and applicability for more site specific characters can be found in Chapter 3.4.

Cost-effectiveness

As mentioned in Appendix 3, existing riverine waste extraction mechanisms range from €40,000 up to hundreds of thousands of euros. However, in order to not only be interesting for The Ocean Cleanup but also for local organisations in low to middle income countries, the goal is to stay below €10,000 (Chemolex, personal communication, May 12, 2023).

By improving mobility and accommodating diverse site requirements, there is a higher likelihood that costs can be distributed across multiple deployments, thus reducing the investment threshold for an extraction mechanism. Conversely, for organizations with larger budgets, this approach can also decrease the volume of waste required to make extraction economically viable.

Versatility

By making the design suited for a wider range of deployment sites and operational strategies, it becomes more desirable for any organisation. The ability to customize the design to suit specific deployment sites or use cases ensures that the technology remains relevant and effective in addressing the varying challenges presented by different riverine environments.

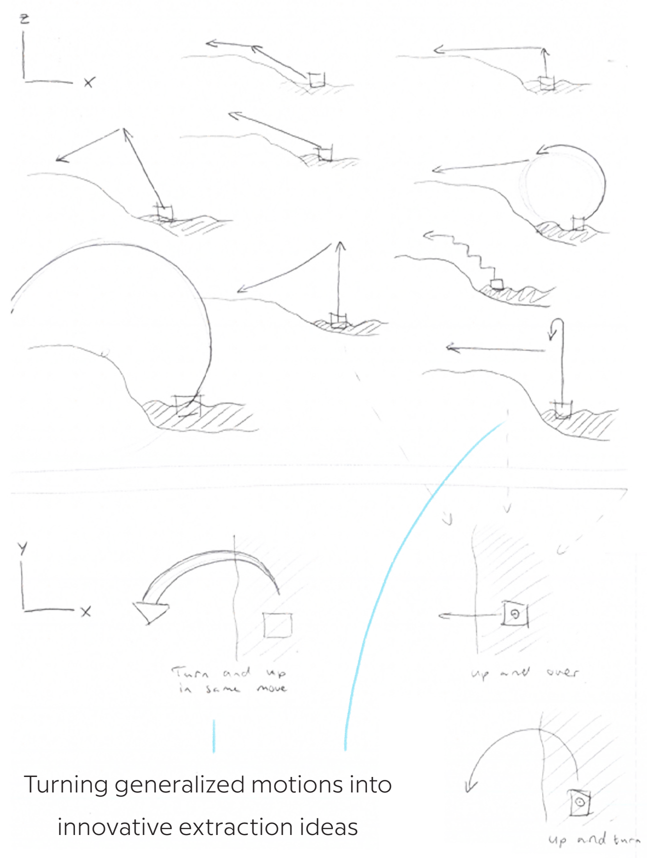
Increased safety and reduced workload

To be considered desirable, the design must offer enhancements over the current situation, as outlined in Chapter 1.2. For operations conducted by The Ocean Cleanup, there currently exists no solution tailored to this specific use case. However, prioritizing worker safety remains a fundamental requirement. For operations conducted by local organizations, the design should not only offer improved safety compared to manual extraction but also reduce the physical workload.

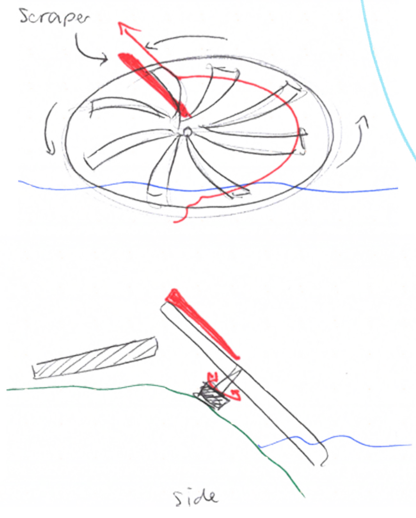
Enhancing safety involves minimizing or eliminating direct contact with polluted water, which, in turn, reduces the risk of contracting waterborne diseases. Furthermore, avoiding direct contact with the waste itself decreases the likelihood of contracting other illnesses or sustaining injuries, especially given the potential presence of sharp objects within the waste.
While the initial deployment of the tool may require physical exertion, the actual extraction process should entail little to no strenuous physical labour. This approach reduces the overall physical effort required, enabling a higher volume of waste to be extracted within a shorter timeframe.

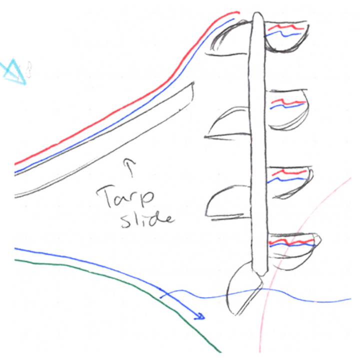
3.2 Ideation

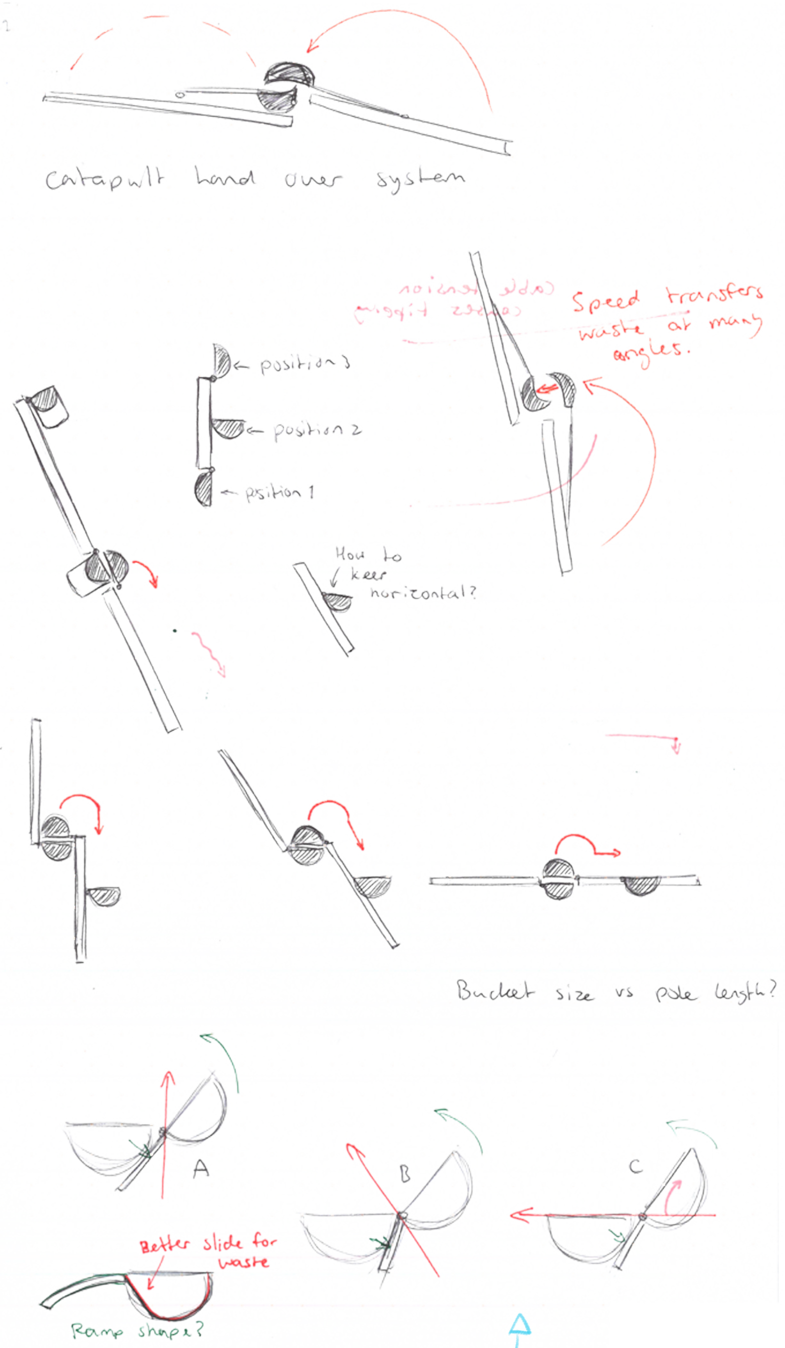
Using various ideation methods, a wide range of potential solution directions were explored. A visual representation of part of this process is presented on these two pages.



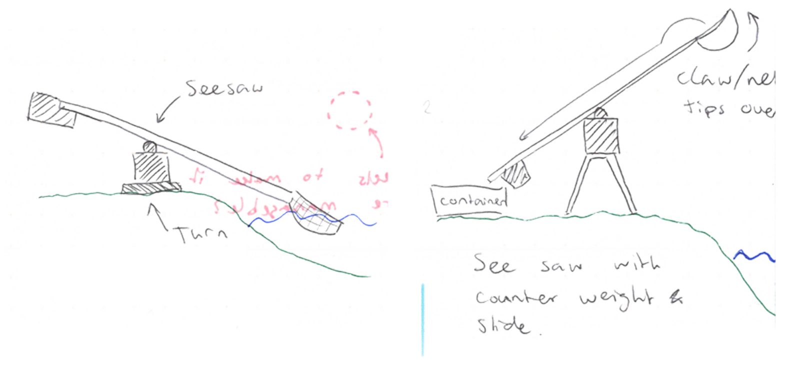
Turning generalized motions into innovative extraction ideas



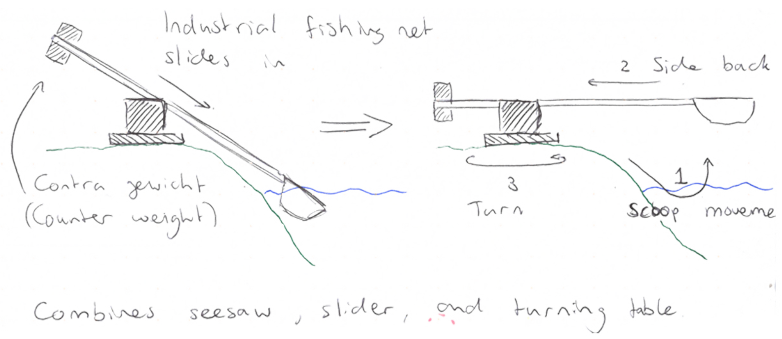


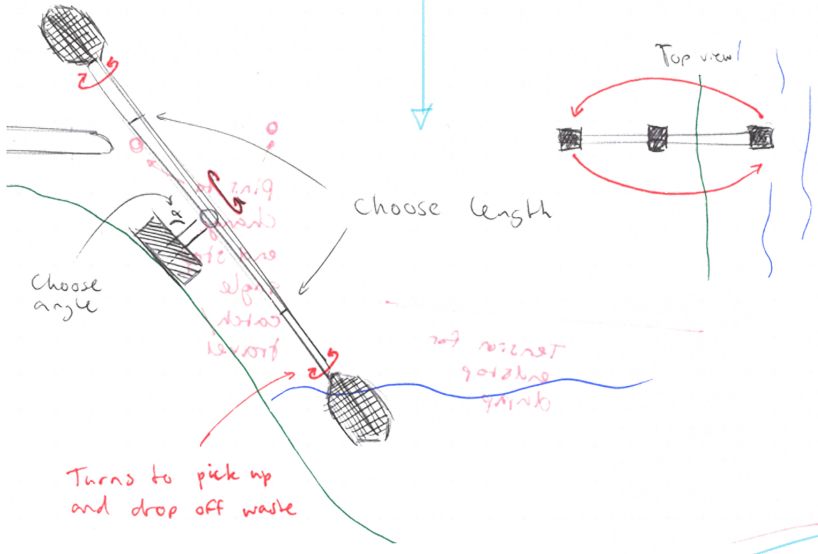


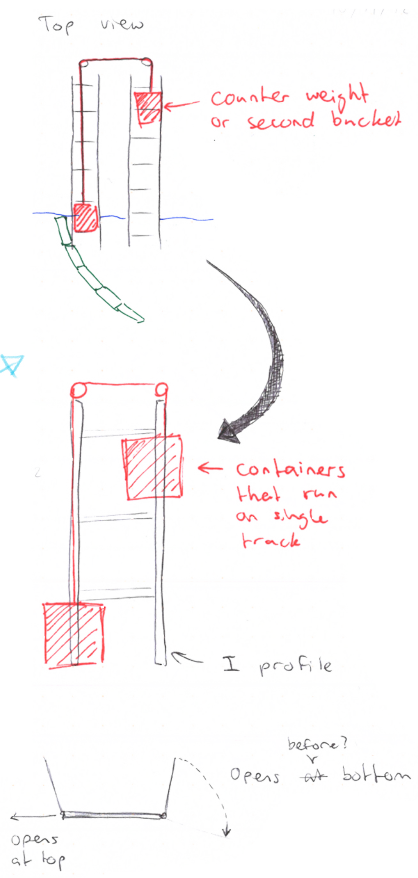
Exploring possible mechanisms



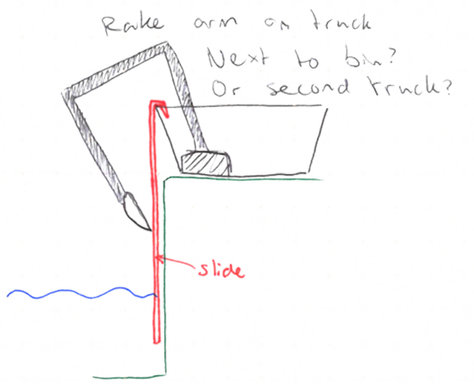
Iterative design process to develop more inovative ideas

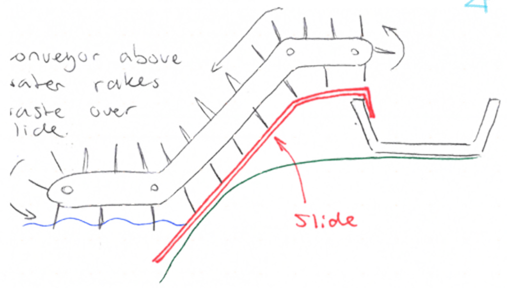






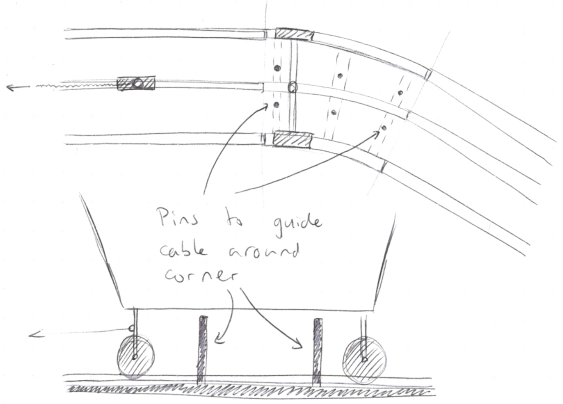
Exploring outside of original solution space for inspiration

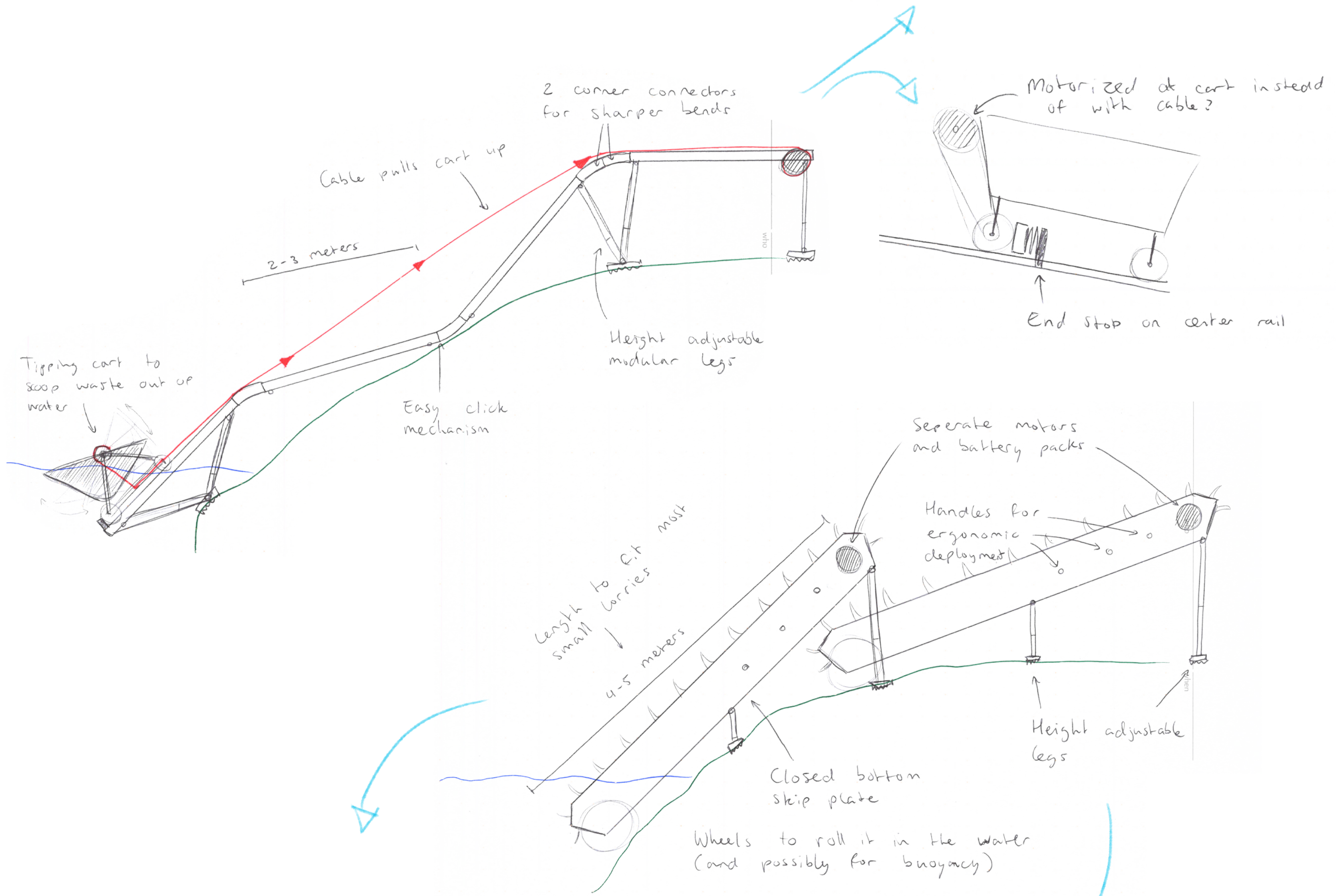


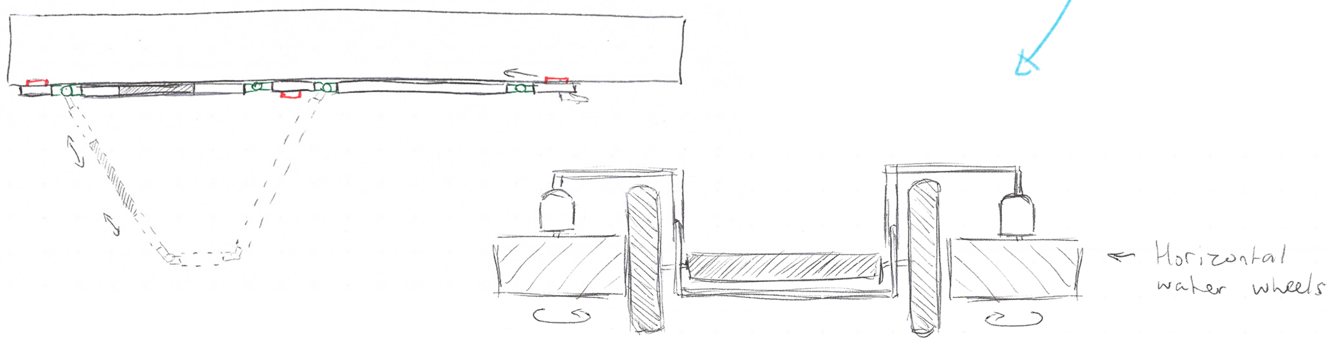


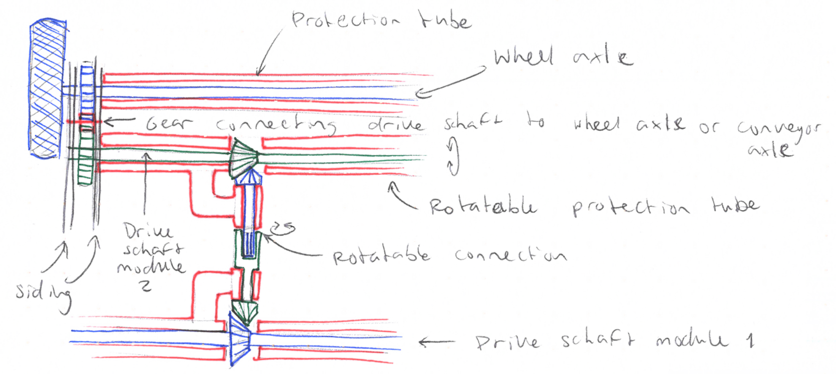
3.3 Conceptualization

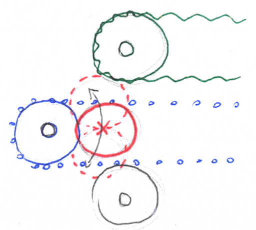
Utilizing a Multi-Criteria Analysis based on the 34 criteria mentioned in Chapter 3.1 and outlined in Appendix 10, the ideas with the highest potential were selected for further refinement. Some of these developments are illustrated on these pages.

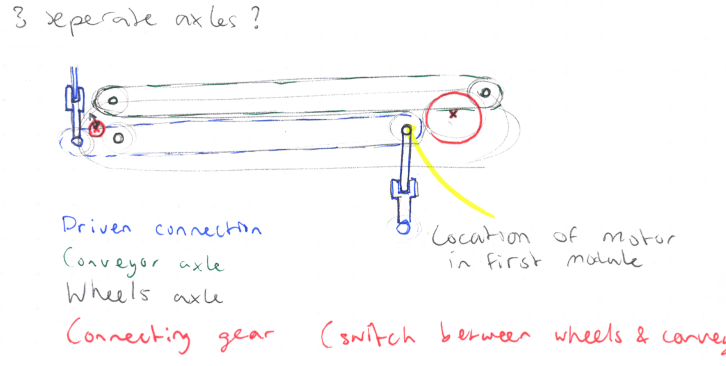


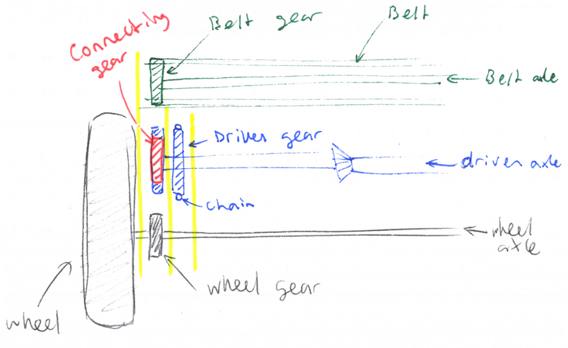


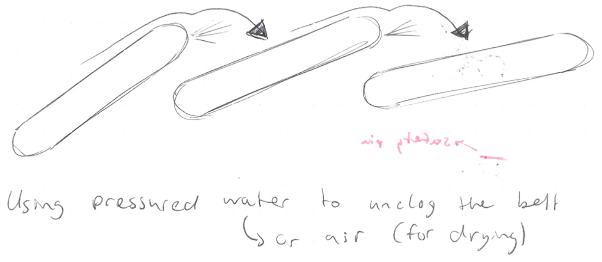


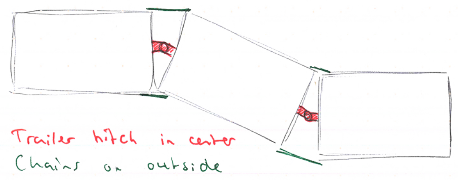


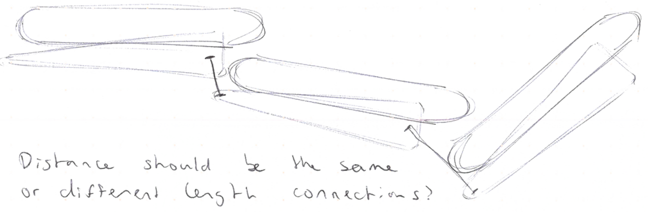


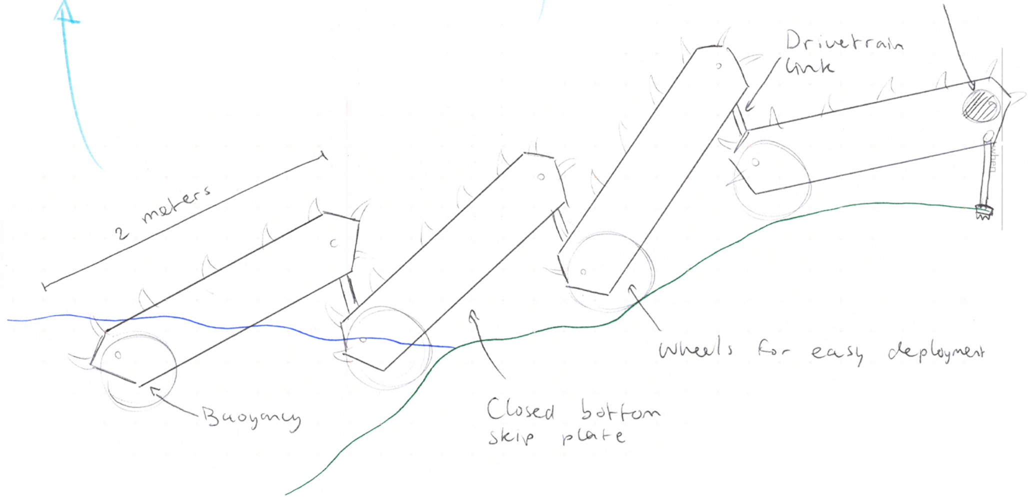












Rapid prototyping

Small scale prototypes were developed of the four best solutions in order to identify unexpected challenges before final selection. A few iterations of several rapid prototypes are showed on these pages.


Figure 13: Rapid prototype of hand over mechanism

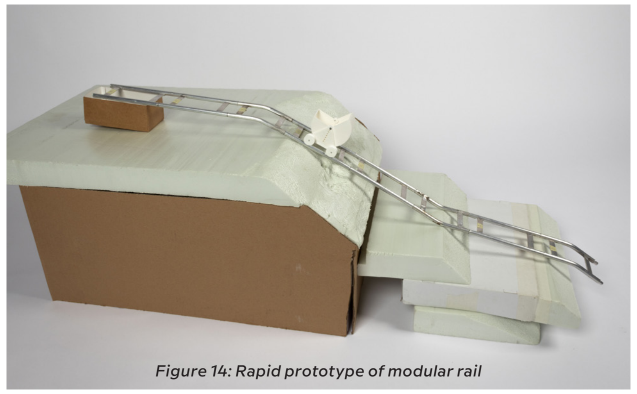


Figure 14: Rapid prototype of modular rail

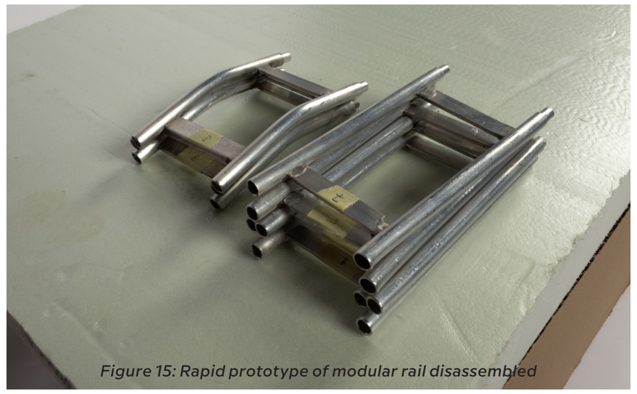


Figure 15: Rapid prototype of modular rail disassembled

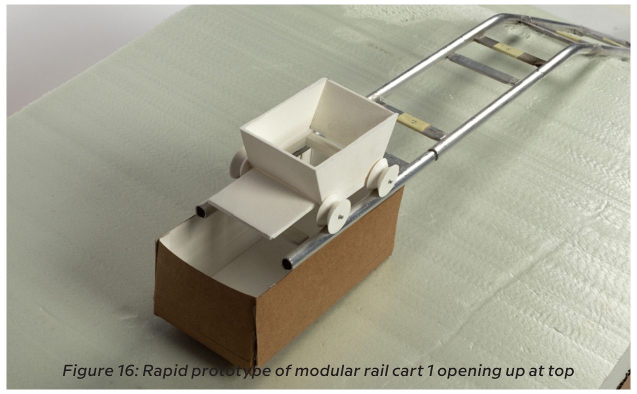


Figure 16: Rapid prototype of modular rail cart 1 opening up at top

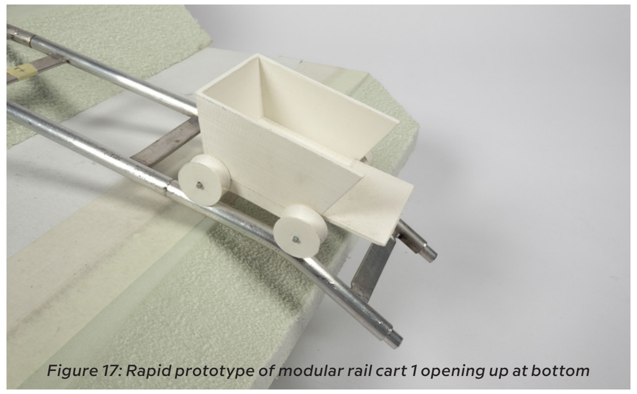


Figure 17: Rapid prototype of modular rail cart 1 opening up at bottom

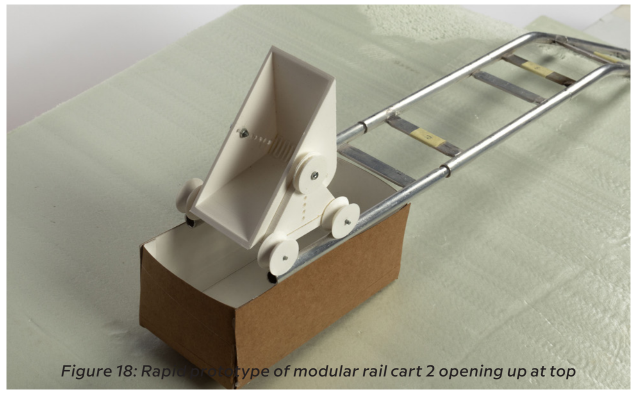


Figure 18: Rapid prototype of modular rail cart 2 opening up at top

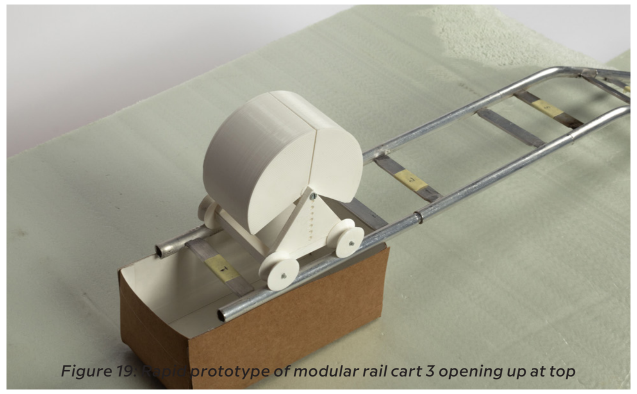


Figure 19: Rapid prototype of modular rail cart 3 opening up at top

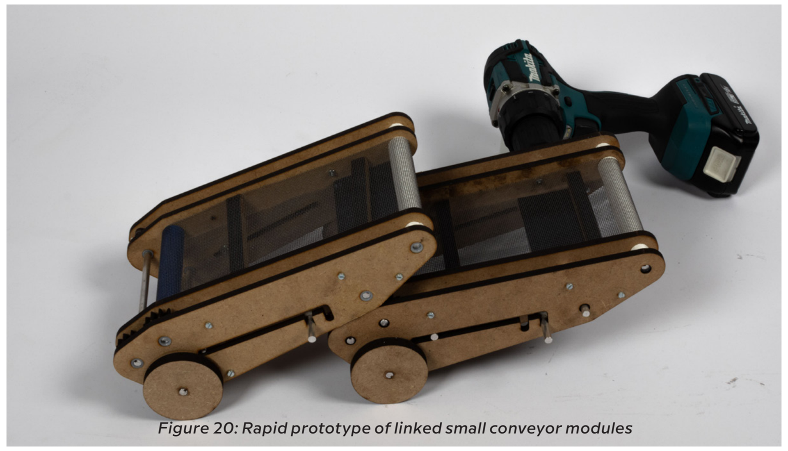


Figure 20: Rapid prototype of linked small conveyor modules

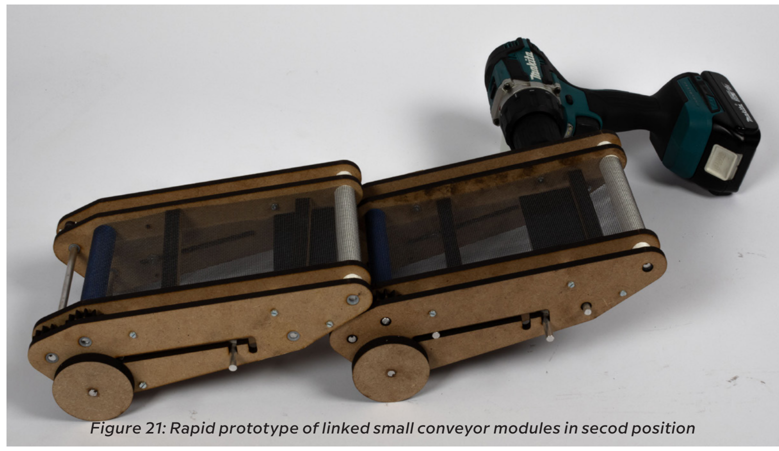


Figure 21: Rapid prototype of linked small conveyor modules in secod position

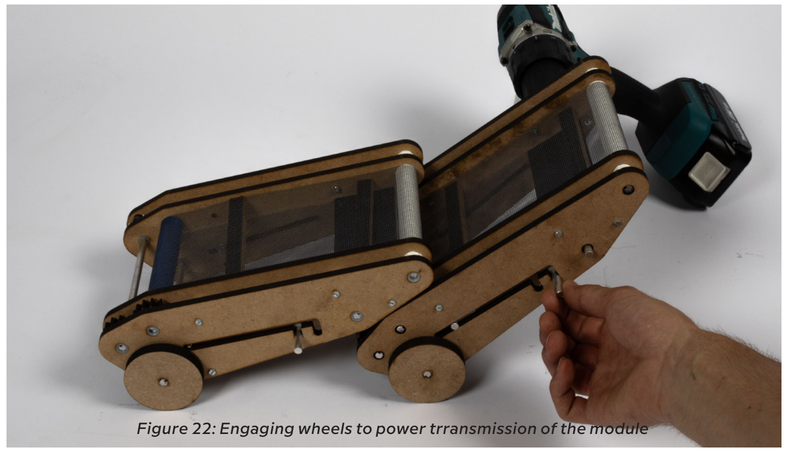


Figure 22: Engaging wheels to power trransmission of the module

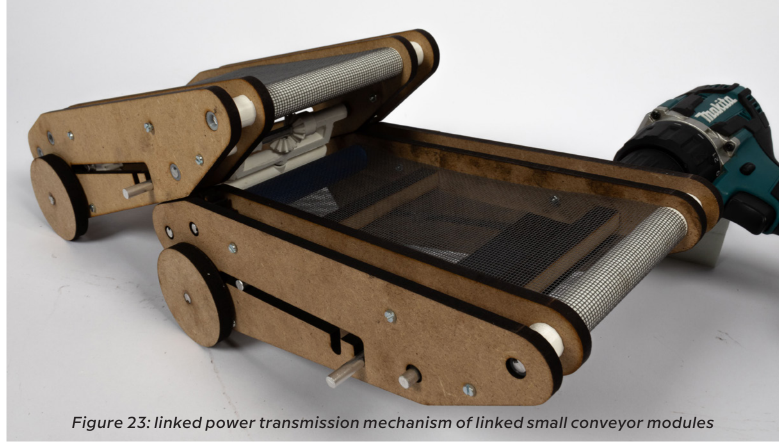


Figure 23: linked power transmission mechanism of linked small conveyor modules

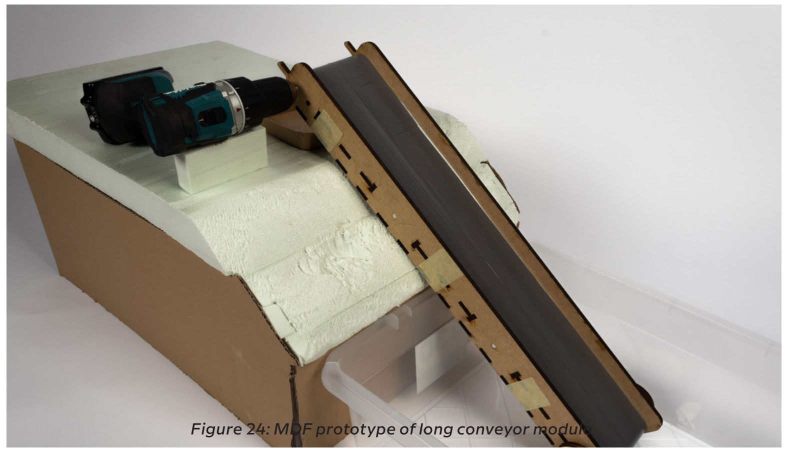


Figure 24: MDF prototype of long conveyor module

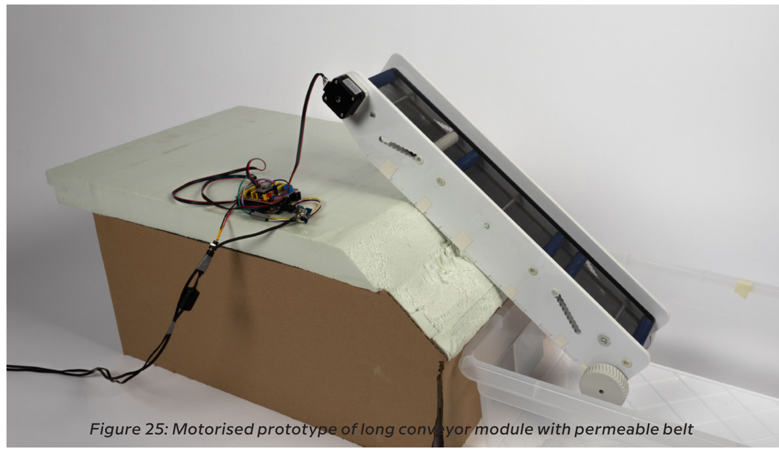


Figure 25: Motorised prototype of long conveyor module with permeable belt

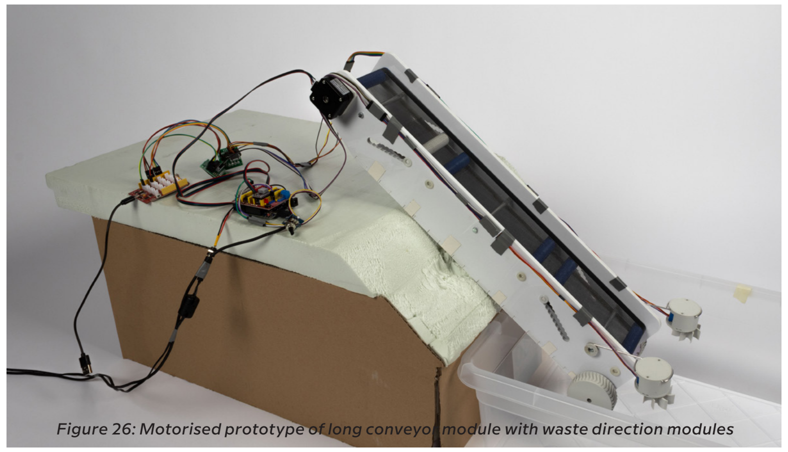


Figure 26: Motorised prototype of long conveyor module with waste direction modules

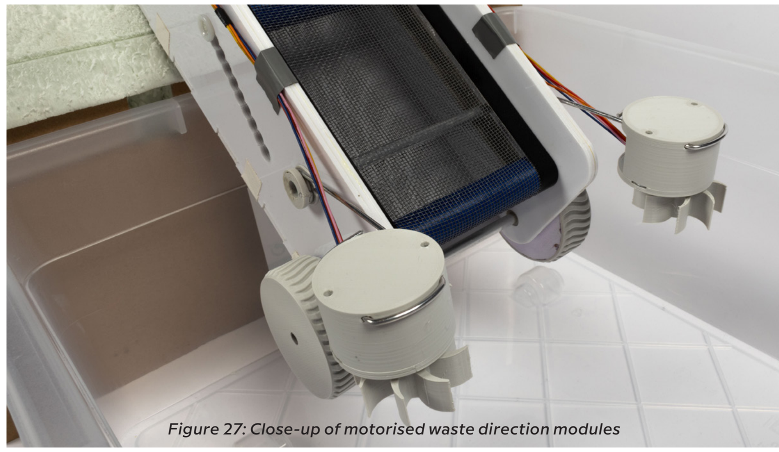


Figure 27: Close-up of motorised waste direction modules

3.4 CONCEPT SELECTION

The long conveyor modules were chosen as final concept. The decision was primarily guided by the following considerations, with the first four aligning with the key design drivers, while the last two were influenced by external input.

Continuous extraction
By choosing a solution that enables uninterrupted extraction, more waste can be removed within a given time frame. This not only improves operational efficiency for one deployment but also ensures that more sites can be serviced in a day, ultimately increasing the impact of the cleanup efforts.

Ease of deployment
The selected solution requires no on-site construction or assembly, reducing the time and resources required to make it operational. This ready-to-go aspect of the concept streamlines the deployment process and enhances overall efficiency.

Intuitiveness
A solution with a straightforward design, minimal moving parts, and clear operational principles enhances user comprehension. It reduces the risk of errors and accidents during deployment and operation, contributing to overall safety and efficiency during operation and maintenance.

Diversity of deployment options
A solution that can be modified or customized for different types of shores and use cases ensures that it can address a broader range of environmental challenges. The ability to make small modifications to the base model to suit specific site requirements without compromising on requirements for other sites enhances the concept's applicability and impact potential.

A more detailed explanation regarding the concept selection based on its diversity of deployment options is provided below in the section on use scenario refinement. This explanation not only facilitated the decision-making process but also outlined the final use cases.

Internal push from The Ocean Cleanup
During the project, it became evident that the Jamaica operations had unique requirements not met by existing solutions. This concept emerged as the best fit for this specific operation, offering an opportunity for field testing and direct real-world impact.

Confirmation from Chemolex
External validation from organizations like Chemolex provides valuable insights into the chosen concept's potential value. This confirmation reinforces the idea that the chosen solution can effectively address real-world challenges beyond the scope of The Ocean Cleanup's operations.
These factors collectively guided the selection of the long conveyor modules as the preferred solution direction.

Use scenario refinement

As mentioned on the left page, One of the reasons for selecting the final concept is its suitability for a wide range of sites and operational strategies. To compare the compatibility for different sites and identify concept specific opportunities, a scenario matrix was created with all the possible combinations of the most important variables of deployment. These variables were based on mobility, distance from the contained waste to the offloading site, angle of the shore, and container type. In the table below, these variables and their main options are visualised.

The definitions of the different distances, shore angles and container types are based on field research in Malaysia, where an analysis of ten tributaries was carried out. To ensure consistency, a survey was developed to collect identical data for all tributaries. The outcomes of this survey are documented in Appendix 6.

Regarding the mobility variable, initially, two categories were identified: mobile and permanent. Mobile referred to the concept of transporting the entire extraction mechanism from one deployment site to another, while permanent indicated that the extraction mechanism would be permanently deployed at one site. These two options seem to be irreconcilable within one design due to conflicting requirement. For instance, the heavy duty requirements for a flood proof design are contradicting the ones for a light and mobile design. Therefore, the project was directed towards focusing solely on mobile deployment.

However, for the long conveyor modules a new possibility was identified; semi-permanent deployment. In this scenario, the extraction mechanism remains situated at one site but can be taken out of the water to prevent damage from flooding. The design requirements for such a scenario do not directly conflict with those of mobile deployment. In fact, some of the requirements for mobile deployment offer distinct advantages for semi-permanent deployment. For instance, the final design can be stacked for transportability and is lightweight for easy deployment. The sliding mechanism can also be utilized to slide the extraction mechanism in and out of the water when combined with a fixed stand, with the low weight making this action more manageable. These functionalities are discussed in greater detail in Chapter 4.1. The complete scenario matrix for the final design can be found in Appendix 11.

Table 1: Deployment variables compination options

Mobility	Distance	Angle of the shore	Container type
Mobile	Short (<4m)	Shallow (10-50°)	RORO bin
Semi-permanent	Medium (4-8m)	Steep (50-90°)	Big bag
Permanent	Long (>8m)		Smaller bag/container

Final use scenarios

To summarise the final deployment options, the design can be used in two modes: mobile and semi-permanent.

Mobile

The mobile deployment allows for one or two modules to be taken from site to site. They are designed to fit on a flatbed truck with a bed length of 3 to 4 meters and can be deployed and operated with two people. Since there are only two workers needed to transport and operate the machines, the design allows for efficient and low cost operations. It can be used at sites with a steep shore if the distance to the offloading site is short (<4m). Longer distances require two modules which might become unwieldy and dangerous to deploy without a fixed stand on the shore. For natural sloping shores short and medium distances (≤8m) can be tackled by using up to two modules. In theory 3 or 4 could be stacked in order to deploy at sites with a large distance (>8m) from the contained waste to the offloading site. However, in this phase of riverine waste extraction, the consideration has to be made if the extra effort is worth it for each site. Similarly, the choice of container types for offloading and the volume of waste in each river must be considered. Thanks to its mobile and adaptable design, the extraction tool can accommodate various container types. The key question arises: is it practical to transport RORO bins using a second vehicle, or is it more sensible to employ big bags or alternative containers that can be transported on the same flatbed truck as the modules? This decision should also align with the amount of waste at the site. With mobile deployment, extraction can be scheduled on demand, allowing waste to accumulate behind a barrier for a specific duration before collection becomes necessary. This approach renders smaller rivers with lower daily waste volumes economically viable for cleanup efforts. In cases where the waste volume is substantial (>5000kg per day), a mobile strategy can still be employed, distributing the cost across multiple sites, such as four sites requiring daily extraction. However, when the waste must be extracted daily, and there is an adequate budget, the option of deploying multiple semi-permanent extraction mechanisms becomes feasible. A brief study on waste weight, volume, and site classification based on waste quantity can be referenced in Appendix 12 for more details.

Semi-permanent

In this scenario, only the operators need to travel from site to site with a flatbed, tip, or RORO truck to collect all the waste. The stable stand allows for safe deployment of two units on steep as well as natural shores. Similar to mobile deployment, distances longer than 8 meters could theoretically be covered with more modules. However, only the first two modules can realistically be tipped to the other side of the stand due to their total weight. If more modules are needed, it would be more practical to deploy them in a mobile fashion below or above the two semi-permanent modules. Again, each site should be carefully considered to determine the most suitable deployment strategy and whether this extraction method is the optimal solution. However, the design's versatility allows for unique strategies to be developed for specific situations or site combinations.

CHAPTER FOUR

THE FINAL SOLUTION

4.1 FINAL DESIGN & PROOF-OF-PRINCIPLE PROTOTYPE

Due to the fit with the Jamaica project, building a functional full scale prototype became more relevant. A budget of €4,000 is allocated for this prototype. In Jamaica, the intended use case is semi-permanent. However, the final design and prototype also includes adjustable legs to allow for mobile deployment.

Imrovement to the current situation

- *Enhanced worker safety and operational efficiency.*
- *Expanded market potential through the modular design, offering versatile deployment options.*
- *Financially efficient design and operational approach, leading to sustained cost savings and greater accessibility for budget-constrained organizations.*
- *Minimal to no on-site construction needed for installation.*
- *Capacity to address numerous smaller streams, accumulating to a large impact.*
- *Streamlined, user-friendly design that minimizes training requirements.*

Modular plastic link belt for quick on-site repairs, minimizing downtime

User-friendly controls for easy operation, including speed and direction adjustments, and a **removable/ replaceable battery**, enhancing operational flexibility and safety.

Adjustable and interchangeable accessories like handles and eye-nuts for on-site customization.

Aluminium frame for strength, corrosion resistance, and weight

Adjustable and extendable legs to accommodate diverse deployment sites

Fenders for extra stability when the belt is partially submerged in water

Multiple wheels for effortless deployment and manoeuvring

Its **modular** design, exemplified by the semi-permanent stand, allows for flexibility in adapting to various site conditions and deployment approaches, ensuring suitability for specific situations.

Frame construction

After evaluating various custom and off-the-shelf construction options based on criteria such as price, strength, and weight, a custom aluminium construction using extrusion profiles was selected for the proof of principle prototype. The material cost (excluding connectors) for the basic frame is approximately €450, compared to €250 for a frame made of square aluminium tubes. However, the construction profiles offer significant advantages in terms of flexibility. The ability to adjust the position of supports, handles, fenders, and incorporate personalized accessories is invaluable at this stage of development. Additionally, the availability of off-the-shelf components for connecting and articulating the profiles expedited the prototyping process. This eliminated the need to manufacture custom sliders or tracks in order to test the principle.

A comprehensive comparison of frame construction options can be found in Appendix 13.

In the current proof of principle prototype, all construction profiles are joined using corner brackets, screws, and sliding nuts to maintain flexibility for potential modifications during the design process. However, after the initial field testing phase, once any required changes have been implemented or if the design proves satisfactory as is, the current frame can be welded to enhance stiffness and ensure a longer lifespan.

Legs construction

Various leg designs were considered, taking different use cases into account. The challenge lay in striking a balance between stability and adaptability. The greater the adaptability of a support structure, the less stable it tends to be due to the added degrees of freedom. Rather than utilizing two straight legs, the design integrates two V-shapes on either side of the conveyor, connected with strategically placed cross bracing. This configuration ensures stability while preserving adjustability to accommodate uneven terrain or deployment at an angle in relation to the shoreline. By adjusting the positions of the two contact points of the V-shapes along the main structure, the angle of the V can be altered, and the ground contact point can be shifted forwards and backwards. One side of each V-shape is extendable to modify the leg height. These adjustable points offer versatility in accommodating a wide range of shapes for various situations, as illustrated in Figure 28.


Figure 28: Showcase of adjustable and extendable V-shape legs

To ensure a compact design during transportation, the legs can be folded into the frame and locked in place with a lock pin, as depicted in Figure 29. The hinge in the middle of each leg has been modified, as shown in Figure 30, to permit the two parts of the V to fold until they are parallel rather than up to a 90° angle. Folding in the direction of the frame beyond the colinear state offers no benefit. These middle hinges are also connected to a second pair of wheels, enhancing flexibility during transportation. More details on the wheels can be found in the sub-chapter on Interaction.

Belt

After desk research and a visit to a distributer of most types of belts, a modular plastic link belt is chosen for this design. A comparison of different belt types can be found in Appendix 14.

As Figure 31 illustrates, the plastic link belt consists of modular building blocks interconnected with rods to provide flexibility. The primary advantage of this belt type is its modular and repairable nature. A broken link can be relatively easily repaired on-site, minimizing downtime and long-term cost savings. For major maintenance tasks, the belt can be removed in a matter of minutes, providing complete access. Alternatively, in less extensive scenarios, the side panels can be removed, or minor adjustments can be made through the dedicated access hole located in one of the side panels, as illustrated in Figure 32.

Additionally, the belt's modular structure offers significant adaptability potential, allowing for the incorporation of modules with different textures, varying degrees of permeability, or alternative flight configurations.

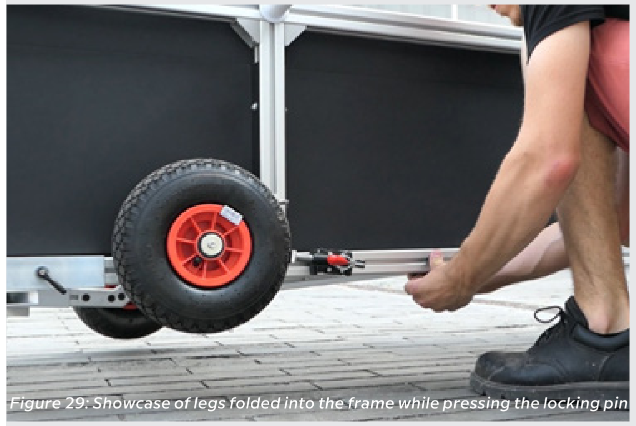


Figure 29: Showcase of legs folded into the frame while pressing the locking pin

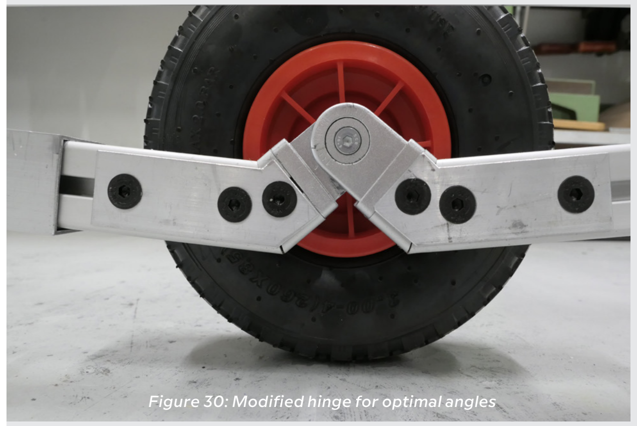


Figure 30: Modified hinge for optimal angles

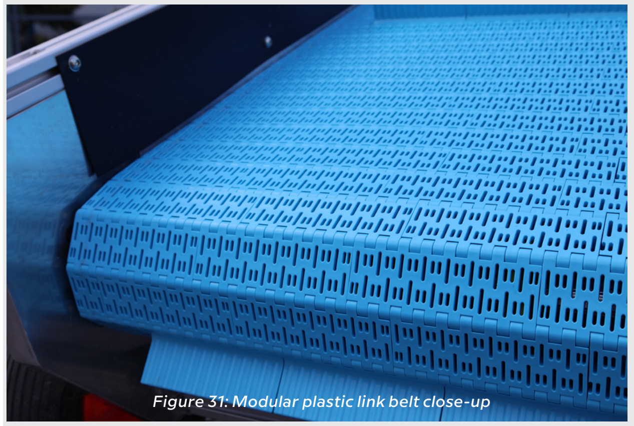


Figure 31: Modular plastic link belt close-up

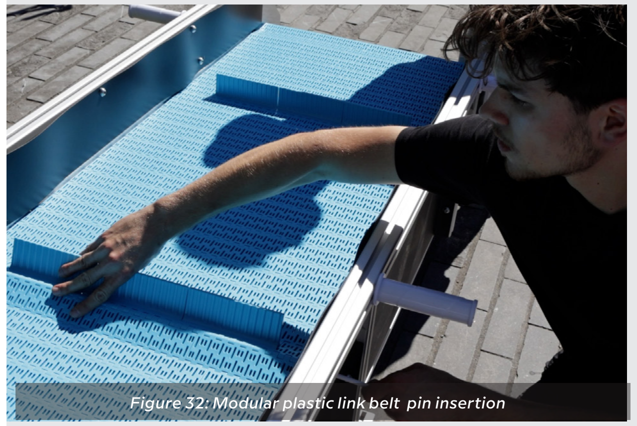


Figure 32: Modular plastic link belt pin insertion

Drive system

When considering weight and cost factors, a conventional belt might initially appear as the most suitable option for this application. Nevertheless, modular plastic link belts offer a significant advantage in terms of their drive system. Unlike conventional belts, which rely on friction between the belt and a drum for propulsion, modular plastic link belts are positively driven by sprockets that engage with the belt's modules, as can be seen in in Figure 33. Conventional belts tend to slip in wet environments or when improperly tensioned. Besides that, they can easily become misaligned when the axes are not perfectly aligned, when dirt accumulates between the belt and the drum, or when the load is unevenly distributed across the belt. In contrast, positively driven modular plastic link belts do not require tensioning to grip onto the sprockets. Additionally, they are less prone to misalignment because the sprockets restrict significant lateral movement, and the belt possesses lateral stiffness due to its construction.

For a more detailed comparison between different types of belts, see Appendix 14.

Since the belt does not have to be tensioned, the design does not need a dedicated tensioning system. Nonetheless, to minimize slack, the side plates to which the axes are attached can be adjusted along the aluminium profiles.

A motor and gearbox were selected based on three key requirements:
Torque: ≥80Nm
Power: ≥15.7W
Motor speed: 10-50RPM

These specifications were determined through calculations, which can be found in Appendix 15.

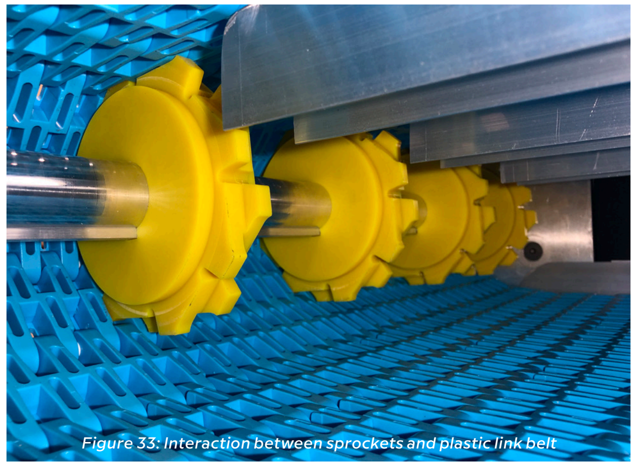


Figure 33: Interaction between sprockets and plastic link belt

To accommodate mobile applications, a 24 Volts DC motor was selected. Paired with a 24 Volts battery that can easily be connected and disconnected, this configuration enables flexible deployment. The battery can be recharged between deployments at the base of operations, powered by on-site solar panels, or replaced with a spare battery for immediate energy supply. Additionally, a 24 Volts motor can be connected to a generator or grid power with the appropriate transformer when necessary.

As illustrated in Figure 34, all electrical components are mounted one of the side panels. The motor is mounted directly to the axis with a custom mount, as shown in figure 35. Within the top box, you'll find the motor controller, which allows for the selection of direction and speed. The bottom box houses the battery. To facilitate maintenance or in the event of a malfunction, all components are equipped with waterproof wire connectors for easy disconnection.

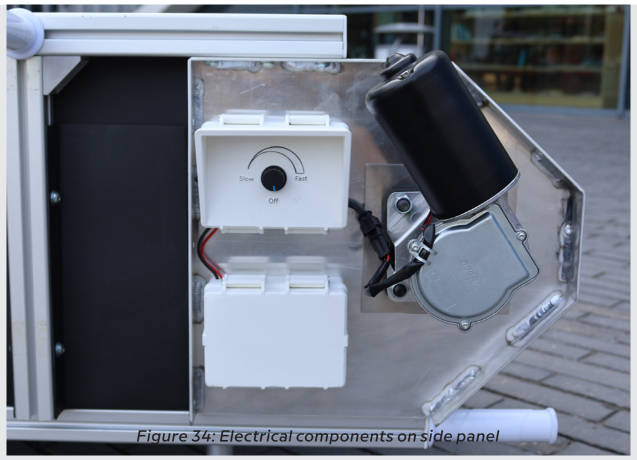


Figure 34: Electrical components on side panel

According to the spec sheet of the motor used in the proof-of-principle prototype, the nominal current is 5A. This means that for each hour of use it consumes 5Ah. While this estimation isn't perfect due to the higher starting current, it provides a good approximation. Depending on the intended use case, the battery capacity can be adjusted accordingly. For instance, with a 30Ah battery, the prototype can run for approximately 5 to 6 hours.

If the proof-of-principle prototype is tested further in real use cases as for example Jamaica, a deep cycle LiFePO4 battery is advised due to the ability to perform in higher temperatures and the lower risk of thermal runaway compared to for example LiCoO2 batteries (Jiang & Dahn, 2004).

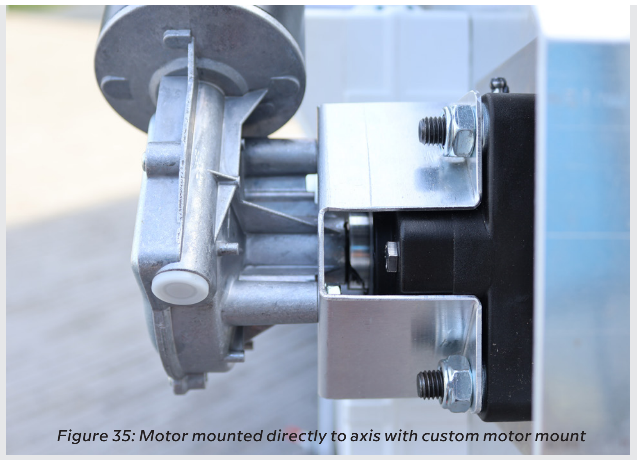


Figure 35: Motor mounted directly to axis with custom motor mount

Buoyancy

Initially, highly buoyant wheels were considered for flotation, but their practical placement posed challenges, especially to allow the bottom of the belt to be submerged effectively. To address this, less buoyant wheels were chosen, supplemented by inflatable fenders for additional buoyancy. Calculations were conducted to evaluate various options and materials, as detailed in Appendix 16. Ultimately, the design includes one wheelbarrow wheel and two inflatable fenders on each side, as shown in Figure 36, providing a total buoyancy force of around 734N, capable of supporting up to 75kg. This buoyancy should suffice to keep the extraction mechanism, along with the waste on top, afloat, especially considering that the module receives substantial support from the shore.


Figure 36: Two fenders and one wheel barrow wheel on each side

Versatility

Linking two or more conveyors together offers advantages for transportation and deployment. It enables multiple modules to be interconnected on the rear of a flatbed truck or trailer, allowing them to slide off separately or in tandem easily. During deployment, this feature facilitates the connection of two modules in a manner that enables waste to flow from one conveyor onto the next without the need for an extra set of legs.

To facilitate the seamless linking of two modules, a cavity is routed out bottom of the top stretcher, where the swivelling slider of the next module can be slid in, as visualised in Figures 37, 38, and 39. After stacking the modules on top of each other, a secondary set of sliders positioned on the inside of the wheels glides into the designated slots. Subsequently, the swivelling slider is securely locked in place using the locking handle, as showcased in Figures 40 and 41, effectively joining the two modules together.

The offset between the upper and lower stretchers permits the slider to pivot in both directions while remaining connected, as illustrated in Figure 41. This offset also enables the legs to fold in completely, as detailed in the subsection on leg construction.


Figure 37: Swivelling slider positioned above routed out cavity

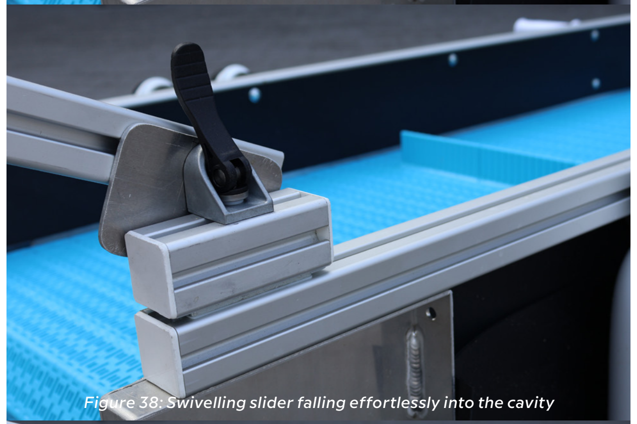


Figure 38: Swivelling slider falling effortlessly into the cavity

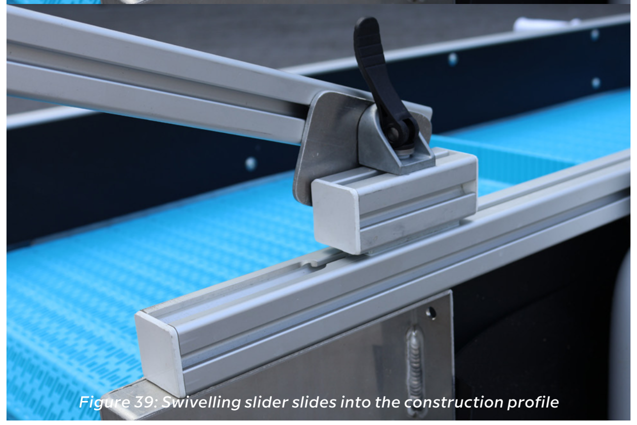


Figure 39: Swivelling slider slides into the construction profile

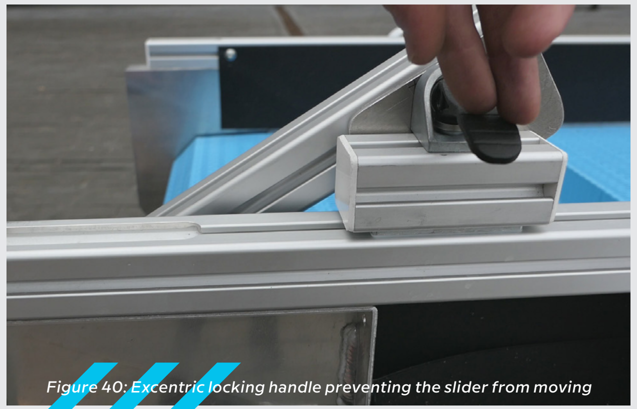


Figure 40: Excentric locking handle preventing the slider from moving

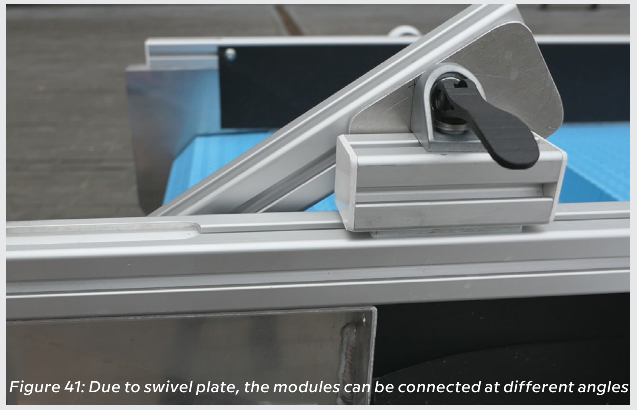


Figure 41: Due to swivel plate, the modules can be connected at different angles

Through the use of add-ons on top of the basic design, the tool's versatility for use in various sites and deployment scenarios is enhanced, as elaborated in Chapter 3.4, under the section on use scenario refinement. One of these add-ons is the stand for semi-permanent use as depicted in Figure 42 and 43. This stand enables the tool to be placed on dry land when not in use, protecting it from flood damage.

This stand utilizes the same sliding mechanism mentioned earlier but in reverse, facilitating the movement of the conveyor onto the shore. The stand features a platform with a hinge to which the conveyor is attached. This platform tilts over when the centre of gravity surpasses the tipping point. Consequently, the conveyor can be placed in two stable positions: one in the water (see Figure 42) and the other resting on the shore or on top of a RORO bin (see Figure 43).

In the illustrations below, the left side represents water, while the right side represents dry land.

The semi-permanent stand can be secured to the shore using a concrete foundation with studs. Alternatively, it can be anchored to a steel plate on which the RORO bin is positioned to prevent tipping. In cases where sites are relatively easy to navigate, a concrete slab can be directly attached to the stand before installation. Calculations have to be done for the specific site to ensure secure attachment.


Figure 42: Semi-permanent stand with module in deployed position


Figure 43: Semi-permanent stand with module in safe position on the shore

Due to the use of aluminium construction profiles, various add-ons, such as eye nuts as illustrated in Figure 44, can be attached at almost any point on the extraction mechanism. While the essential add-ons like handles and fenders are already integrated into the proof of principle prototype, additional add-ons can be designed for specific situations encountered during field testing.

Some examples of potentially useful add-ons that have not been developed in this thesis include anchor attachments for temporarily securing the mechanism to the ground with large pegs, a big bag support adaptor, or RORO bin connectors. Although the tool can already hook onto the edge of a RORO bin, adding support arms extending sideways to allow the conveyor to rest on top of the RORO bin in cases of semi-permanent deployment with the seesaw stand is a possibility.

The flexibility to introduce custom add-ons during field tests or even in the final deployment phase empowers operators to tailor the tool to their needs and encourages ongoing improvement.

Interaction

To ensure the operators' ease and comfort during deployment, efforts have been made to keep the weight as low as reasonably possible. Striking a balance between weight, functionality, and cost was crucial in design considerations. For instance, while a lighter belt type could have been selected, this choice might have compromised the design's durability. Therefore, a relatively lightweight version of the modular plastic link belt was chosen to ensure that weight was factored into the functional capabilities. If it turns out that the current belt is over-engineered, an even lighter plastic link belt can be considered for future use. These types of trade-offs and assessments were made for all design decisions.

To provide ergonomic and comfortable handling of the tool, multiple handles have been incorporated on the back and sides. These handles are adjustable, allowing operators to position them according to their preferences, as demonstrated in Figure 45. Furthermore, additional handles can be easily added in locations of the operator's choosing. Similar to other add-ons, these handles securely fit into the profile with a sliding nut and are secured in place with M8 nuts, ensuring they remain stable and do not come loose during use. These nuts won't be visible once the handle is placed on.


Figure 44: Eye nut with carabiner attached


Figure 45: Moving handle position

To facilitate the manoeuvrability of the extraction mechanism, two wheels are incorporated at the end, as depicted in Figure 48. These wheels, combined with the threaded handles into the stretchers' ends, enable the mechanism to be easily moved like a large wheelbarrow. However, given its length, it may be somewhat challenging to manoeuvre in tight spaces. To address this, smaller wheels are added to the foldable legs, as shown in Figure 48. When the legs are extended, these wheels create a pivot point in the middle of the device.

While these wheels enhance mobility, it is crucial that once deployed, the extraction mechanism remains stationary at the water's edge. Consequently, a linear toggle clamp, as illustrated in Figures 46 and 47, has been incorporated to ensure a reliable and secure lock when in the deployed position


Figure 46: Linear toggle clamp as wheel lock


Figure 47: Wheels in the locked position


Figure 48: Mobility with large wheels


Figure 49: Mobility with small wheels for manoeuvring tight spaces

Cost

The materials required for the basic model, comprising a fully functional conveyor with side panels, floaters, handles, and electronic components, amount to approximately €3,300. Notably, the plastic link belt with sprockets represents almost half of this cost (€1,413). While opting for a lighter-duty belt could reduce expenses, it's worth noting that this particular belt type is relatively costly per square meter compared to other off-the-shelf components and materials. Other individual items with relatively high costs include the aluminum profiles (€450), the motor (€403), and the waterproof bearings (€227).

Adding the extendable V-shaped legs increases the cost with €225 and a semi-permanent stand costs €230 in materials. Either of these options can be chosen, resulting in a total price of approximately €3,530 for an independently functional tool. If two modules are combined, one of them can be equipped with linkable sliders instead of legs or a stand, which adds around €70 to the overall cost.

The complete price breakdown can be found in Appendix 17.

Based on data from Salary Explorer (salaryexplorer.com), the average monthly salary for various production professions that may be required for the production of a replica of the current prototype in Kenya is approximately 45,500 KSh, equivalent to around €300. When considering Malaysian workers, the average monthly salary for these professions averages around 1,900 RM, roughly equivalent to €380. In contrast, the same professions in The Netherlands earn an average monthly salary of €1,800. A month of work per module would be an overestimation, however to account for other oversimplifications, this will be used. A complete extraction tool, including material and production costs, will range from €3,600 to €4,000 when produced in the country of intended use, while production in The Netherlands would increase the price range to €5,100 to €5,400, excluding shipping cost. Notably, these costs remain significantly below the initial target of €10,000 set in the key design drivers.

4.2 VALIDATION

Waste extraction

In the full-scale tests, the tool demonstrated its ability to extract waste from the water effectively. Since there was no water flow, the waste needed to be guided toward the conveyor belt as visualised in Figure 50. Once it reached the belt, the flight successfully grasped it and propelled it upward. In some cases, the waste required a slight nudge to begin its way up the belt. With the presence of water current, this task might be accomplished without human intervention. However, as the primary goal was not to entirely replace human labor but rather to enhance it, having a worker positioned on top of a walkable barrier during operations to ensure proper waste extraction is a reasonable approach.

Deployment

The prototype turned out to be slightly heavier than initially planned. Nevertheless, even with the additional weight, the deployment process remained relatively straightforward. The V-shaped legs automatically unfolded as the module was lifted, and with some minor enhancements to the lower hinges, deployment could become even smoother, resulting in effortless setup. During testing, deployment was conducted with three people for added caution, as shown in Figure 51. However, it appeared feasible with just two individuals.


Figure 50: Directing waste towards the belt with a long pole


Figure 51: Deployment of module at natural sloping shore

The semi-permanent base was tested on land rather than at the waterside to prevent potential tipping, as it couldn't be securely fastened to the ground for the test. Nonetheless, it proved easy to tip over to the other side of the stand. Attaching the module to the stand required three people but was significantly easier with 5 to 6 individuals. Since this assembly step is a one-time task, the additional workforce seems acceptable.

User interaction

Operating the prototype, including turning it on/off and adjusting speed, is highly intuitive and changing the battery is a straightforward process. Attaching the conveyor belt may require some effort and added knowledge but appears proportional to the frequency of this task. During testing, it took approximately 2 minutes to complete. This demonstrates how quickly and easily worn-out or broken parts of the belt can be replaced. The adjustable handles and eye nuts proved to be valuable assets during the testing.

Recommendations for possible prototype improvements identified during testing are discussed in the Recommendations.


Figure 52: Locking small wheels

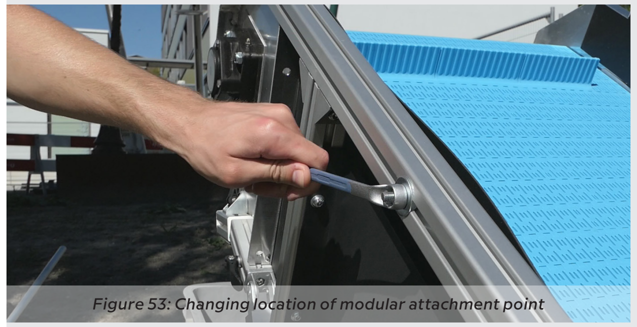


Figure 53: Changing location of modular attachment point

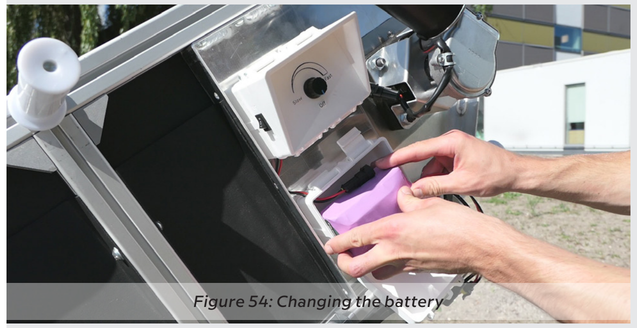


Figure 54: Changing the battery

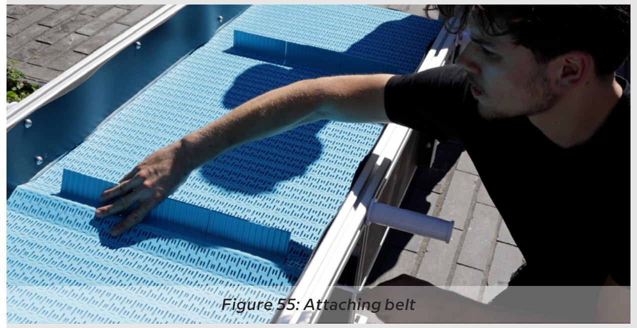


Figure 55: Attaching belt

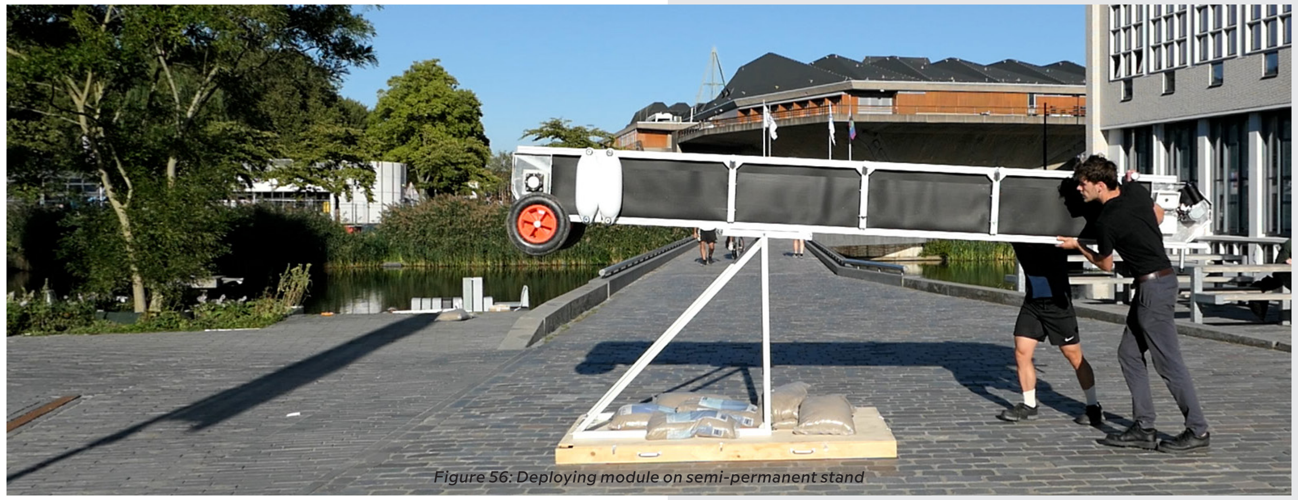


Figure 56: Deploying module on semi-permanent stand

4.3 CONCLUSIONS

The final design, developed through a comprehensive exploration of site characteristics, requirements and iterative design processes, addresses the critical issues outlined in the problem statement effectively. It expands the solution portfolio of The Ocean Cleanup and extends their reach of river cleanup efforts to sites that were previously challenging or inaccessible.

Additionally, the low cost and possibility to deploy at multiple sites, makes it also attractive for local cleanup initiatives. Increasing the health and safety of workers by minimizing contact with contaminated water and waste, while increasing the efficiency of the operations.

The final design exhibits a range of qualities that make it a desirable, viable, and feasible solution in the battle against riverine plastic pollution:

Desirability

Identified gap in the current solutions

The design is catered to site specific characteristics that limit the use of other commercially available solutions. Through conversations with The Ocean Cleanup and other cleanup organisations, the desirability for a solution in this market gap was confirmed.

Worker Safety

The design significantly reduces the risk of diseases and injuries for workers who would otherwise have to enter contaminated waters for cleanup operations.

Versatility

The tool's adaptability to diverse environmental conditions and deployment scenarios enhances its appeal, catering to the specific needs of various cleanup initiatives. Due to the modular nature of the design, the requirements for different site specific characteristics do not interfere, making it a well-fitting solution to several solution spaces.

Viability

Cost-Effectiveness

A detailed cost breakdown reveals that the tool can be manufactured at a reasonable cost. Its affordability, combined with the option to distribute costs across multiple deployment sites, positions it as a viable choice for organizations with budget constraints. Moreover, for organizations with larger budgets, it reduces the waste volume required to make extraction economical viable.

Real-World Testing

The full-scale testing validates its viability in real-world conditions. Test results confirm the deployment possibilities and its capability to effectively extract waste from water bodies, bolstering its viability as a practical solution. Further tests in Jamaica could add to these findings.

Feasibility

Production and material accessibility

Since a working proof-of-principle could be manufactured with basic manufacturing tools and off-the-shelf materials, there is a high likelihood that an optimized version can be manufactured on larger scale.

Ease of Use

The tool's user-friendly features, such as ease of deployment, intuitive controls, and quick component replacement, contribute to its feasibility. It can be operated with minimal training and expertise, making it accessible to a broader range of users.

4.4
RECOMMENDATIONS

The most urgent recommendation is to conduct an extensive field test of the proof-of-principle prototype in Jamaica. Prolonged testing will help unveil the prototype's strengths and identify areas for improvement. Additionally, investigating various use cases and operational scenarios will help validate or challenge the findings discussed in this thesis.

Several minor recommendations relate to the current proof-of-principle prototype. While it is deployable in its current state, some enhancements can be implemented either before deployment or on-site.

Depending on the selected use case for testing, consider using an alternative battery that allows for extended continuous operation. A LiFePO4 battery is most suitable for warm temperatures while staying relatively light weight.

After transportation, consider welding the aluminium profiles together to ensure a robust and torsion-resistant structure. This will also enhance the structure's longevity due to the materials used in fasteners. Replace any remaining fasteners with stainless steel versions.

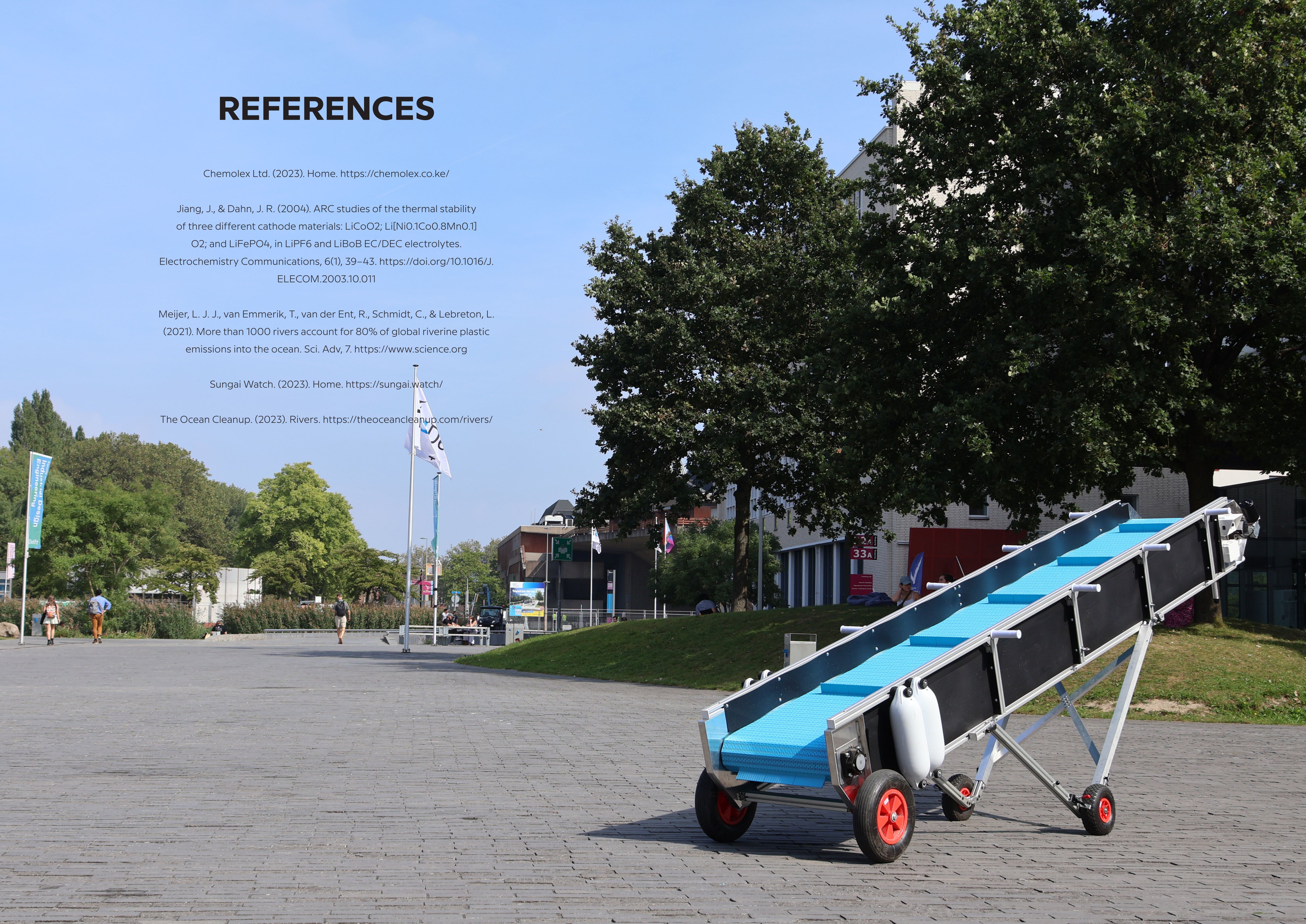
To reduce production costs for additional prototypes, some of the aluminium construction profiles can be replaced with square tubes. While the long stretchers should remain construction profiles for the sliders to function, square tubes can be used for cross-bracing and vertical supports. The flexibility of connection points can be mimicked by adding rivet nuts at various locations around the frame.

To increase the lifespan of the wheels, they could be equipped with stainless steel needle roller bearings. This same advice applies for the toggle clamps used as wheel locks.

The Recycled PE plates on the sides started expanding and buckling significantly when exposed to high temperatures. While this issue may not affect extraction effectiveness, it could potentially allow small waste to enter the inside of the belt mechanism and become entangled with the sprockets. Alternative materials or attachment methods could be explored to resolve this problem.

The hinges in the V-shaped legs appear to be too weak for prolonged use. They can be replaced with more robust hinges, which could also improve the connection to the smaller wheels. Especially if the profiles are welded instead of screwed together, the hollow design of the current hinges are not required anymore. They can be more massive, allowing for more resistance to torque and adding more surface area to tread the wheel connections in.

When testing mobile deployment, a new prototype with a lighter version of the plastic link belt can be considered, potentially saving around 20kg. Welding the frame can also reduce weight by 20kg by eliminating connectors. Replacing some construction profiles with square tubes, as mentioned earlier, can further reduce weight. Additionally, explore the possibility of revising the leg construction with lighter aluminium alloys to minimize overall weight, facilitating easier deployment. Lastly the handles are made out of solid aluminium rods while they can also be made with plugged tubes fitted with internal thread.



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MODULAR EXTRACTION TOOL FOR RIVERINE PLASTIC WASTE

DESIGN OF A PROOF-OF-PRINCIPLE PROTOTYPE

Master Thesis
MSc. Integrated Product Design
Faculty of Industrial Design Engineering
University of Technology Delft

Author
Joep van Stijn

Supervisory team
Chair
Prof. Dr. Ir. Diehl, J.C.
Faculty of Industrial Design Engineering | TU Delft
Department of Sustainable Design Engineering

Mentor
Ir. Schermer, W.
Faculty of Industrial Design Engineering | TU Delft
Department of Human Centered Design

External mentor
van Eijk, J.
The Ocean Cleanup
Rivers - Data & Engineering

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