



Design of an HDPE bottle collection and pre-cleaning system for recycling in Blantyre, Malawi

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I would not have made it without the help of many people.

If you want to thank someone in particular, this is the place. If not, the section can be removed.

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Abstract

The abstract should succinctly summarize the research gap, the methods you employed, your results, conclusions, and recommendations. Don’t use acronyms if possible and keep the language as general as possible.

Keep the abstract to a maximum of 500 words.

The abstract stays on its own page.

# Introduction

This thesis is part of a PhD project conducted at the Chair of Global Health Engineering at ETH Zurich. The PhD research aims to design, implement, and evaluate a closed-loop plastic bottle recycling scheme in low-income countries to efficiently, and effectively manage the flow of waste bottles from consumers into new drinking bottles. The work is carried out in collaboration with a plastic bottle manufacturer (Arkay Plastics), a local NGO (WASTE Advisers) as well as a Malawian beverage manufacturer (Chibuku Products).

## Global Plastic Waste

The generation of plastic waste is a rapidly growing process all over the world. Producing twice as much plastic waste in comparison to two decades ago (OECD, 2022), the world is faced with a major challenge to overcome the problem of mismanaged plastic waste. Almost half of the global plastic waste is generated in OECD (Organization for Economic Co-operation and Development) countries and is prone to regional differences. Inadequate collection and disposal of macroplastics as well as leakage of microplastics are a serious concern to our planet (OECD, 2022). Generally, plastics that served their purpose find their way into different channels: In 2015, 9% of the cumulative plastic waste was recycled, 12% was incinerated, and 79% was landfilled or disposed of in the natural environment (Ncube et al., 2021). Even today, plastics follow a linear approach (make, use, dispose) rather than a circular economy (design for use, recover, redesign) (C. A. Velis et al., 2022).

Openly disposed plastic material can have severe consequences on the well-being of the environment, animals, and humans. Plastic can clog sewers, provide breeding space for mosquitoes, entangle or choke animals, enter the human food chain, and much more. Plastic waste disposed in landfills or in the environment can travel far distances, being transported by wind, or washed away by heavy rain. The effects are enormous for living creatures. The waste in landfills further results in the generation of methane gas, a greenhouse gas causing global climate change (Ncube et al., 2021).

Globally, packaging contributes to almost 50% of the total weight of plastic waste (Geyer et al., 2017). This trend is due to the unique properties, high functionality, and low cost of plastic materials. Plastics allow for minimal material usage where the packaging material can account for less than 3% of the product weight. Among food packaging materials, a variety of thermoplastics have emerged including polypropylene (PP), polystyrene (PS), polyvinylchloride (PVC), high-/low-density polyethylene (HDPE/ LDPE), and polyethylene terephthalate (PET). Many of these are landfilled where they need centuries to degrade (Aarnio & Hämäläinen, 2008; Hu, 2014). The packaging industry has started their efforts to reduce waste disposed into the environment by including recyclable plastic in their designs. However, recycling has turned out to be difficult, time and budget consuming as the waste collected often consists of various plastic types that need to be sorted and separated first (Ncube et al., 2021).

## Plastic Recycling

Hahladakis & Iacovidou (2019) describe plastic recycling as the process of recovering and reprocessing waste plastic into secondary material that can be used to manufacture new components and products. Four types of plastic waste recycling can be identified:

1. primary recycling (re-extrusion)
2. secondary recycling (mechanical recycling)
3. tertiary recycling (chemical or feedstock recycling)
4. quaternary recycling (energy recovery)

The primary recycling is mostly used for pre-consumer plastic waste. Cuttings, trimmings, or faulty products/components can be re-extruded due to the high level of material homogeneity present. The secondary or mechanical recycling is well-established and widely known and serves as the main process focused on in this Thesis. In closed-loop mechanical recycling (‘upcycling’) the quality of the recovered material is equal or comparable to the original product. If the quality is inferior, (e.g. through erosion of the plastic properties), the material can be used in other applications (‘downcycling’). The latter process sequentially extends the lifetime several times before the material can no longer be used any further. The majority of post-consumer plastic waste enters a cascade recycling system while only a small portion is recycled in a closed loop.

Since mechanical recycling requires a rather strict polymer purity, a sorting process must take place in the beginning. Sorting can be done with help of automated machinery as well as manually, ensuring the purity of the recovered material. Mixed plastics such as labels made of PP on a bottle made of PET increases the difficulty of this step. The efficiency and effectiveness of the sorting process is largely determined by the personnel, the infrastructure, the space available, the selling price of the material, and the buyers (Hahladakis & Iacovidou, 2019).

In industrial-sized recycling plants, the plastic waste is then crushed into flakes and cleaned to remove food residues, pulp fibers as well as adhesives. The latest technology requires only a water volume of only 2-3 m3 per ton of material. After the washing, the material can undergo different separation processes ranging from sink/float techniques to air elutriation, thermal degradation of impurities, and laser sorting, etc. Next, the flakes undergo a drying process and are grinded to smaller sizes, if necessary. The plastic flakes can then be extruded, filtered, and sold (Hopewell et al., 2009).

## Plastic Collection in low-income countries

Although high income countries have generated more plastic waste per capita in comparison to low- and middle-income countries, the waste management systems in OECD countries are on their rise to tackle the massive plastic generation. This leaves low- and middle-income countries as the main source of mismanaged or inadequately disposed plastic waste (Ncube et al., 2021).

Around 3 billion people worldwide are estimated to lack access to municipal solid waste collection. Without any control over the accumulated amounts of inadequately disposed solid waste, the plastic pollution is even more difficult to stop. Although often left out of city operations by the government, informal waste pickers contribute to efficient and viable plastic recovery in low-income areas. These individuals’ work is even more relevant as solid waste is susceptible to leak into the environment where no municipal waste collection services are in place. Generally, most waste picking occurs at disposal sites, where the waste material density is high. Nonetheless, door-to-door collection has the potential of yielding more valuable waste and reducing physical contamination. Further, it could improve the work quality of the waste pickers (C. A. Velis et al., 2022).

According to C. Velis et al. (2013), the integration of the informal recycling sector into the cities’ solid waste management could improve the working conditions of the informal waste pickers. Furthermore, this would support the formalisation of the service provided by these waste experts, potentially leading to their own entrepreneurial ventures. Thus, the informal recycling sector has a lot of potential.

## Justification and Research Questions

The research site is located in Blantyre, Malawi. It is the second largest city in the country and has been home to 800,264 people as of 2018 (Kanyuka, 2018). Over 70% of the population is reported to live in rural areas (Mihai et al., 2022). As in most low-income countries, poor solid waste management is part of the daily lives of many inhabitants. These conditions have not yet significantly improved as a result of insufficient financing, capacity and institutional will. The lack of municipal waste collection leaves the residents in low-income areas on their own which leads to open dumping of solid waste on road sides and river banks. These circumstances harm the environment as well as the health of many people (Ndau & Tilley, 2018). The solid waste generation in Blantyre is around 275 to 280 tons per year of which plastics make up for 8% (average in low-income areas in Malawi). As less than half of the waste generated was collected, a huge portion of plastics ended up in the environment (Turpie et al., 2019).

Blantyre acts as the hub for Chibuku Super Maheu production in Malawi and is the location of WASTE Advisors, as well as a manufacturing facility of Arkay Plastics capable of reprocessing HDPE scrap. Chibuku Products distribute their alcoholic beverages via “Chibuku Taverns”, managed by “tavern mamas” who sell the brand’s beer in PET bottles. Another of their most popular beverages, Super Maheu, is sold at small shops and kiosks. It is served in HDPE bottles sealed with an aluminium lid. Although Super Maheu is not sold at the Chibuku Taverns, these locations are intended to serve as a drop-off collection site for Super Maheu HDPE bottles.

Because of the drink’s chunky composition, residual beverage contamination after consumption can be significant. This contamination increases the complexity and effort of the recycling process. For this reason, a suitable pre-cleaning process is desired before the plastic material enters the recycling facility. The Chibuku Taverns also allow for this pre-cleaning process.

This master’s thesis will focus on the design and prototyping of a suitable cleaning station to prepare the HDPE bottles as optimally as possible for the transport to the facility as well as the subsequent recycling processes. According to Dr. Paul Polak from International Development Enterprises, most designers worldwide primarily dedicate their efforts to creating products and services for the wealthiest 10% of the global population. A shift in design approaches is essential to extend innovation and accessibility to the remaining majority of the world (Energy Bulletin, 2007). For this reason, a user-centered design (UCD) approach is selected in this Thesis, ensuring that the product is tailored to the low-income context. The application of a UCD for a plastic cleaning station for rural areas is novel in this context. The research will thus address the following research questions:

Q1 What design of a pre-cleaning station for HDPE bottles is suitable to be implemented in a low-resource context?

Q2 To what extent does the design contribute to the accessibility and affordability of bottle pre-cleaning in low-income countries?

Q3 What are the users' experiences and satisfaction levels with the pre-cleaning station's design and functionality?

# Materials and Methods

## Product Development

The development of the plastic bottle pre-cleaning station is inspired by Prof. Dr. Shea’s lecture on “Product Development and Engineering Design” at ETH Zurich (Shea et al., 2022). The course is supplemented by the book “Product Design and Development” by Ulrich & Eppinger, (2016). The book provides a structured methodology for user-centered development activities. This results in a clear record-keeping of decisions throughout the complete process. This is beneficial for future referencing and for educating new Research & Development personnel. In addition, the structured approach acts as a checklist to ensure that all important issues are addressed. The proposed structure was adapted to the needs of this thesis, as recommended by Ulrich & Eppinger (2016), and is depicted in Figure XX.

### User & Product

The initial phase of the planning process involves the identification of the product user. The objective is to clarify the user's needs and the reasons behind them. This step also includes information about how the task is currently being solved, as well as where and when the task normally takes place. This knowledge serves to ensure a comprehensive understanding of user requirements, enabling user-centered product development. In the subsequent step, the mission statement is formulated. It serves as a summary of the fundamental aspects of product planning that the development team should adhere to throughout the entire process. The mission statement includes a brief description of the product, proposed benefits, and key business goals. Moreover, the identification of the target markets, along with other stakeholders, is carried out. Finally, in this section, also the primary assumptions and constraints that define the product's framework are specified. (picture)

Next, the user needs are gathered. This phase is a projection of what the product user actually needs. Unknown needs can be identified with help of interviews, focus groups or observation of a similar product that is already in use. (Lins Focus group) This allows the interaction between the developers and the use environment of the product. At this stage, needs have to be formulated independently from any specific product that might be developed. Once the needs are gathered, they are to be arranged in a hierarchy of primary and secondary needs, where primary needs are the most general needs while secondary needs further specify these general statements. Next, an importance level is assigned to each need statement resulting in an array of arranged needs. This helps prioritizing critically important over less desirable needs. To be able to provide more context to the collection of user needs, an Activity Diagram is created. It provides valuable information about the use and the life cycle of the product without prejudice on the actual design of the product. It contains all activities around the product from material purchase up to the end-of-life. Further, this step might shed light on aspects that have not been included in the user needs yet.

User needs are generally expressed by the subjective perception of the user. While such statements are helpful to establish a clear sense about the customer's expectations of a product, they provide little guidance about how to design and realize the product. For this reason, a set of measurable and clear specifications is elaborated by the design team. These specifications define *what* the products need to do rather than *how* the customer needs are addressed. Thus, the list of target specifications acts as one of the key information systems throughout the development process. The transition from user needs to product specifications is realized by the introduction of metrics. Metrics are measurable variables that show whether user need is successfully addressed or not. First, a suitable set of metrics needs to be prepared. One or more metrics are then assigned to each user need to verify that each need has its quantifiable units. Generally, this step is depicted in a need-metric matrix, where the relationship between needs and metrics is visualized. Last but not least, each metric is given a marginal and ideal value in the corresponding units. They act as the target values, allowing to objectively judge whether user need is fulfilled or not. These values are commonly set by research, industry standards or comparison with competitors. Where no suitable metrics are found, a justifiable subjective rating can be introduced. This set of information now acts as the target product specifications of the product and are normally listed in a table to maintain overview.

### Concept Development

With the specifications at hand, the concept generation phase can be initiated. In this work, Brainwriting (REF) is used as the main method for concept generation. This approach is largely based on the knowledge of the design team as the ideas for new concepts come from an internal search. The main requirements for successful brainwriting are:

* Suspend judgment: The presence of criticism during the concept generation phase has a negative impact on the quantity of ideas and restricts the creativity of each design team member. Thus, no judgment is allowed during this phase
* Generate a lot of ideas: The more ideas that are generated, the more exploration of the solution space is possible. All ideas are valuable, as they have the potential to stimulate even more concepts
* Welcome ideas that seem infeasible: Ideas that seem not realizable can often be improved by iterative approaches, or by inputs from other team members.
* Make plenty of sketches: Although text and verbal language can provide context to a topic, they are rather inefficient tools to perceive physical entities. Thus, sketches should be at hand throughout the whole concept generation phase. The quality of the sketch material is not critical, as long as it expresses the concept. (REF Yang, Cham)

As this work includes the contribution of a single individual only, the concept generation phase is carried out with the help of Design Heuristic Cards (Appendix). These cards are used to create new ideas based on existing concepts to further increase the quantity of ideas.

Once the concepts are generated, a selection of the most promising concepts for the product, or for sub-functions of the product needs to be carried out. The concept selection method in this work is built around decision matrices for evaluating each concept with a set of selection criteria. The criteria are mainly based on the user needs and product specifications elaborated in advance. The concepts are subsequently rated and given a score allowing to numerically compare the performance of each concept. The concept with the highest score is then chosen for further refinement, testing, or development.

### System-Level Design & Detailed Design

The subsequent phase in the development process contains the elaboration of the system architecture. This step is crucial because the product architecture has a profound impact for subsequent development activities as well as for the manufacturing. The result of this phase is a rough geometric layout of the product, descriptions of the major sub-systems, and a documentation of the interactions between the sub-systems. Once a variety of arrangements has been explored, the most promising is selected. The approximate layout is then specified more precisely, eventually leading to a detailed layout of the product with help of a CAD software.

## User feedback

The tavern mamas within the Chibuku taverns play an important role in the logistics of bottle collection processes, owing to their established trust with Chibuku management and their integral involvement in tavern operations and cultural practices. Consequently, the implementation of a focus group discussion methodology with the tavern mamas facilitates a comprehensive exploration of their perspectives and collective viewpoints (Nyumba et al., 2018). The utilization of focus groups as a forum for discussion enables participants to articulate their opinions in their native language, thereby revealing the degree of importance they assign to specific issues (Refsgaard & Magnussen, 2009).

The sample size was seven, including tavern mamas from different Chibuku taverns located in Blantyre. The main goal was to explore their ideas for the realization of a Super Maheu cleaning station, detailed information about the Chubuku taverns, and their opinions about the preliminary design presented in Chapter 3.4. Afterwards, the design was adapted and improved regarding issues that were brought up during the focus group discussion.

## Prototyping

The designs obtained at this stage of the development process were prototyped and tested in two phases. First, a proof-of-concept prototype was built in Switzerland. The materials and parts needed were purchased in a hardware store or ordered online. The manufacturing and assembly of all parts took place at Dynamo, a Youth Culture Center in Zurich providing working space and machinery for private use. Where no suitable raw material can be found, 3D printing was used allowing for fast production and testing of non-standardized parts. The prototype and its sub-functions were tested to verify the functionality of the design. The valuable insights gained from these tests were used to re-design iteratively. This further optimizes the performance of the product and enables observation of critical weaknesses of the system.

The second prototype was manufactured in Blantyre, Malawi. The goal was to test the complete system rather than the different modules independently. Further, a verification of the affordability and accessibility of the prototype with help of local resources could be conducted. Last but not least, the second prototype was presented to different stakeholders that contribute financially to the bottle-collection pilot.

# Results and Discussion

## User and Product

### User Identification

The identification of target users is crucial to a successful implementation of a new product. This not only allows to design the product based on the needs of the end user but also provides various stakeholders with valuable information. The definition of a target user acts as the base for the subsequent development process. Depicted in Table XX, two target users are presented. Informal recyclers as well as the Tavern Mamas will work with the product on site and act as the main users, interacting daily with the proposed design. For this reason, the design will be specifically adjusted with these parties in the focus.

### Mission Statement

The frame of the product development process is summarized in the mission statement (Table XX). It describes the legitimation of the product development and acts as the broader guideline throughout all phases. It contains a short definition of the product as well as the benefits arising from its development. Further, the target market as well as the complete set of stakeholders are identified. Assumptions and constraints that might restrict the design process at any point are introduced at this point to ensure that the development is elaborated in the suitable setting. The mission statement acts as the main information base for the product and is used to verify if the product development is on track through all times.

| **Questions** | **Target User 1** | **Target User 2** |
| --- | --- | --- |
| **Who is**  **the User?** | Jack, 45yo, Malawian informal recycler | Sbonisiwe, 54yo, Tavern Mama at Chibuku Taverns |
| **What do**  **they need?** | *A system that:*   * Opens the way to collect and sell used plastic * Yields an additional income source * Enables fast and easy cleaning of bottles | *A system that:*   * Is easy to maintain * Allows for efficient bottle storage * Keeps the taverns tidy |
| **Why do**  **they need it?** | * Opportunity to earn money * Indirect mediation with recycling facilities | * Reducing amount of plastic landing in the environment * Requested by Chibuku Tavern (main contractor) |
| **How is the task currently done?** | Unless a contractor has been found to buy plastic waste back (mostly PET), no plastic waste is being recovered | * Surroundings of the taverns are manually cleaned * Plastic waste is disposed through the household waste |
| **Where does it take place?** | *Bottle Cleaning:*   * On the tavern premises   *Bottle Collection*:   * In the neighborhood * Dumping hotspots * Communal bins | *Bottle Cleaning:*   * On the tavern premises   *Bottle Storage:*   * Valuable equipment and clean bottles stored inside * Temporal storage of plastic bottles around the tavern |
| **When does it**  **take place?** | * Daily operation of the cleaning station * For the duration of the whole cleaning process | * Daily operation of the cleaning station * Chibuku trucks drop-off beer and collect bottles daily |

*Table 1: Target User.*

*Table 2: Mission Statement.*

| **Product Opportunity Gap** | HDPE bottle collection and pre-cleaning station for low-income communities to reduce the water and energy consumption of the recycling process in the facility. |
| --- | --- |
| **Benefit Proposition** | * Reducing health risks to humans, animals and other living organisms * Saving limited raw materials * New job opportunities in the recycling sector,   especially when scaling up |
| **Key Business Goals** | Design and prototyping of a working system by the end of October 2023. Installation and user instructions at target area by the end of November 2023. |
| **Target Market** | * Beverage manufacturers * Plastic Manufacturers * Municipality * NGOs |
| **Assumptions &**  **Constraints** | * Limited access to running water / electricity * Equipment is secured but theft rate is high * Limited material availability * Development and Prototyping budget ~2000CHF * Target region: Low-income countries * Optimally operates with Super Maheu bottles |
| **Stakeholders** | * Beverage manufacturers * Plastic Manufacturers * Municipality * NGOs * Tavern Mamas * Informal recyclers * Transport contractor * Households |

### User Needs

The collection of user needs is crucial for the development of a user-centered product. This allows to address the desires and requests of a user before the design phase is initiated. Prior to this thesis, Lin Boynton has carried out a Focus Group Discussion where a set of Tavern Mamas participated. Their statements have been collected and transformed into a series of user needs. Further, discussions with WASTE Advisors and the project board were held to identify more user needs that were not yet addressed by the Focus Group.

Table XX depicts the 29 identified user needs. Primary user needs are specified in detail with several secondary needs that are ranked with an importance level ranging from 1-5. The ranking was based on the statements received. Repetitive and highlighted statements were ranked higher than rarely mentioned ones. Further, a special focus was put on safety during use, useability of the device, and budget boundaries. The final interpretation was performed by the author of this thesis.

### Activity Diagram

As mentioned in Chapter XX, an Activity Diagram is generated next. It summarizes the typical activities that arise around the product between its manufacturing and the end-of-life. In Figure XX, the expected activities of the HDPE pre-cleaning station are depicted. Since the device needs a material input (HDPE bottles) to function, the activity cycle for the bottles is added for further clarification. This leads to the interface between the device and the bottles in which the user is actively taking part. As depicted, a circular economy is desired for the HDPE bottles while the device itself is desirably repairable several times before it reaches its end-of-life.

*Table 3: User Needs.*

| **Need** | **No.** | **Rank** |
| --- | --- | --- |
| **The materials of the device endure the wear and tear of everyday use** |  |  |
| The device withstands operational forces without failure | 1 | \*\*\*\*\* |
| The device minimizes the amount of error sources | 2 | \*\*\*\* |
| The device is not susceptible to corrosion | 3 | \*\*\* |
| Damaged parts can be easily replaced | 4 | \*\*\*\*\* |
| The device is functional over many cycles | 5 | \*\*\*\* |
| The device withstands strong wind and external pushes | 6 | \*\* |
| The device is protected against theft | 7 | \* |
| **The device is functional** |  |  |
| Cleaned plastic bottles fulfill the standards of the recycling facility | 8 | \*\*\*\*\* |
| The clean plastic bottles use the transportation space efficiently | 9 | \*\*\* |
| The device is adaptable to different types of bottles | 10 | \* |
| **Costs are within limits** |  |  |
| The development costs do not exceed the budget boundaries | 11 | \*\*\*\*\* |
| The overall production costs do not exceed the budget boundaries | 12 | \*\*\*\* |
| The device consists of only locally accessible material | 13 | \*\*\* |
| **The device can be easily operated** |  |  |
| The device allows for quick cleaning of plastic bottles | 14 | \*\*\*\*\* |
| The device can be operated with limited access to electricity | 15 | \*\*\*\* |
| The device can be operated with limited access to running water | 16 | \*\*\*\* |
| The device can be used by a single person | 17 | \*\*\* |
| The device does not demand for specific strength requirements | 18 | \*\*\*\* |
| The cleaning process is comfortable for an average sized person | 19 | \*\* |
| **The device can be easily maintained** |  |  |
| Cleaning of the device is done quickly | 20 | \*\*\*\*\* |
| The device can be dismounted to be temporarily stored inside | 21 | \*\* |
| The device fits into the storage rooms of the taverns | 22 | \* |
| **The cleaning process does not endanger the user nor the environment** |  |  |
| Parts that could harm the user are designed properly to prevent accidents | 23 | \*\*\*\*\* |
| The accumulated waste water and particles do not harm the environment | 24 | \*\*\*\* |
| The cleaning process uses low amounts of water | 25 | \*\*\* |
| The cleaning process prevents contact between user and contamination | 26 | \* |
| **The system is aesthetically appealing** |  |  |
| The appearance of the device attracts the user to operate it correctly | 27 | \*\*\*\* |
| The design conveys the connection to Chibuku and the taverns | 28 | \*\*\* |
| The design is appealing to workers, tavern clients and pedestrians | 29 | \*\* |



### Need-Metrics Matrix

As explained in Chapter XX, an elaborated set of user needs is not suitable yet to be directly implemented in the product design. For this reason, a translation from user needs into measurable quantities has to be performed. This is generally done by identifying at least one metric to every user need generated. For the sake of visibility, the translation is carried out in a Need-Metrics Matrix. This allows to verify that each user need is addressed by a unit. Appendix XX depicts the Need-Metrics matrix where the rows contain the user needs, and the columns show the corresponding metrics.

### Target Product Specifications

Since the user needs have been successfully converted into measurable and thus, verifiable quantities, the units can be specified. While the Need-Metric matrix is suitable to observe the completeness of needs and metrics, it is not the most appropriate visualization for the subsequent design process. Thus, all the metrics identified are listed in a separate table. Next, marginal and ideal values are assigned to each metric. They have ideally been set by research, industry standards or comparison with competitors. Where a direct link to a physical entity was not possible, subjective units ranging from 1-5 have been introduced and were determined with help of the experience of the author. The target product specifications, depicted in Appendix XX, act as the main technical guidelines throughout the remaining development phases. Due to the iterative manner of a product development process, it is invaluable to be able to check whether the design always aligns with the fixed specifications.

## Concept Development

### Concept Generation

Brainwriting was the selected method for the generation of concepts. In this phase, the four requirements for successful brainwriting as described in Chapter XX were constantly kept in mind. To enhance the idea space for the large number of functions the device might offer, the tasks necessary to transform a dirty reject bottle into clean recyclables were categorized into three sub-systems. The concepts of each sub-system can be combined freely with concepts from another category, leading to an even higher number of possible end concepts. The concepts that appear in this Chapter have already undergone a first selection process, excluding concepts that are infeasible for the scope of this project. (accessibility electric etc)

Expecting the worst-case scenario, the collected bottles are dirty inside and outside, and potentially crushed in case the previous owner wanted to minimize the volume of the bottle after drinking. For this reason, the first subfunction focuses on the re-inflation of reject bottles. Exposing the complete surface is crucial for a successful cleaning process since hidden edges might not be reached by the cleaning interface. Possible solutions for this problem are visualized by the concepts a) - g) depicted in Figure X.

Concept XX.a) and b) both show air powered re-inflation. Instead of using manual power directly on the bottle, pressurized air is used to reshape the bottle evenly from the inside of the bottle. Several pumping cycles reduce the force needed in one movement. In concept a), an air-tight clamp is attached to the lid of the bottle and pressurized air can be pumped inside the bottle. In contrast, concept b) does not need a customized lid, as the air pressure is kept inside a flexible balloon. As soon as the ballon touches the inside wall of the bottle, it will start to push against the wall and reinflates the bottle. Once the original width is reached, the balloon’s shape is adapting to the shape of the bottle until full re-inflation is reached. In both cases, the air will need to be released before removing the bottle.

Concepts XXc) – g) on the other hand use mechanical force to inflate the bottle in its original shape. In concept c), a pull-string mechanism with a scissor joint can be used to build up mechanical pressure from the inside to the outside. Due to the translation of vertical into horizontal movement, the mechanism can easily fit into the opening of the bottle while expanding laterally as soon as the brackets are inserted. Concept d) shows an adapted version of a hose plier tool. Setting the joint nearby the opening of the bottle, the brackets and the handle can expand/shrink laterally without being hindered by the opening. The power is introduced by pressing on the handle of the tool. Another form of expansion mechanism is explored in concept e). A twisting movement on the handle leads to lateral expansion of the brackets through a gear system. The expansion block can be shifted up and down to re-inflate the bottle at different positions on the vertical axis. Concept f) works similarly as the hose pliers in concept d). Through the different arrangement of the lever, the tool is pressed down to rotate the brackets around the joint. Further, a spring is used to re-position the brackets upon release of the force to ensure easy removal of the bottle. This setup uses upper body strength rather than the hand muscles which might be more ergonomic considering repeated execution. Last but not least, concept g) introduces a re-inflation concept where in comparison to a) – f) not the tool but rather the bottle undergoes movement. Here, the plastic bottle is placed over a fixed round tube, pressed and wiggled over the tube into its original shape. No moving parts are present in this concept.

The second sub-system focusses on the actual cleaning of the bottle. The concepts depicted in Figure XX show different approaches of how to remove the organic contaminants as well as dirt that remain in/on the bottle after drinking and bottle disposal.

Concept XX.a) – d) cover different solutions for the mechanical removal of contaminants without the presence of water. The removal is introduced with help of the friction force between the bottle/contaminants and the solid cleaning surface. Concept a) introduces the cleaning with help of a brush or sponge with a handle. Further, narrow edges and the top rim of the bottle can be precisely cleaned with a smaller tool. In concept b), the bottle needs to be partially cut vertically in a cross-shaped manner before cleaning. This allows to bend the walls of the bottle outwards which exposes the inside of the bottle. Then, a scrapping tool with a sharp edge is moved over the inside walls of the bottles to scrap away the contaminants. Concept c) and d) stick to the need for cutting the bottle. In concept c) the bottom of the bottle is cut along 3 edges to create a pipe-like opening through the bottle. Next, a string with pieces of soft and abrasive brushes slides along the walls by being pulled through the bottle neck. Concept d) also makes use of the cross-shaped cut. The bottle is clamped between a spongy base plate and a bowl. By applying pressure onto the bowl as well as twisting the base plate, friction is created on the surface of the bottle. The last dry-cleaning approach is introduced by concept e). The bottle can be placed onto a set of brushes, which clean the inside and outside of the bottle simultaneously. Potentially, the brushes might be rotated around their vertical axes to remove the need of twisting the bottle itself.





The remaining concepts f) – h) show different processes for cleaning with water. Concept f) is the most basic approach, by simply rinsing the dirty bottle in a finite volume of water. This process includes filling the bottle, shaking it, and finally releasing the water. Concept g) makes use of a glass rinser. This tool allows to only release water when needed, preventing the unintentional loss of flowing water in a tap. By pushing on the moving plate, a pressure sensitive valve is opened to release narrow jets of water into the bottle. (Formel) Since the water jets move with higher speeds compared to a regular tap, the cleaning efficiency of the contact area is enhanced. Further, the rinsing of the non-contact areas through outflowing water is distributed more evenly. This approach has a need for pressurized water inlet. Concept h) combines the rinsing properties of water as well as friction through movement. The bottles need to be cut in a cross-like manner. Afterwards, they are stacked and placed onto a pole. The pole is now twisted around its center axis while being submerged in a water basin. While the contaminants are being softened by the water, the waves and bubbles introduced by the rotating bottle wings can carry away the contaminants.

The third sub-system explored aims to address the preparation of bottles for their transport. Since Chibuku trucks are collecting the clean bottles on their delivery tours to the Taverns, the empty HDPE bottles spatially compete with the delivered goods. Hence, reducing the space needed to move the plastic bottles is of high importance.

Concept XXa) depicts a stacking approach of cut bottles. The HDPE bottles are cut in a cross-like manner such that the sidewalls can be flapped out. This allows to place the bottles through their opening over a pole. The pole is easily movable and can be loaded and secured in the delivery truck. By stacking the bottles in this manner, the density of the packed stack can be increased because the internal volume no longer exists.

Concept b) introduces a shredder. This electrically or manually driven shredder convert the bottles into flakes that can be temporarily stored in a bucket or a bag throughout the transport to the recycling facility.

In concept c), the bottles are packed into a baler. This approach eliminates the need for cutting the bottles as they are crushed and pressed into a cuboid with heavy force. Finally, the bales can be tied to maintain their crushed volumes. The relatively dense bales are loaded into the trucks and might be stacked on top of each other.

In concept d), the bottles are crushed one by one either with help of a crushing tool or simply using the hands or feet. The bottles lose some of their volume and are placed in a bag to be collected.

Finally, concept e) renounces the need of any extra step after cleaning. The clean bottles are placed in a crate in their original shape and volume. This allows for quick counting of bottles received.

### Concept Selection

The selection of the most suitable concept for each sub-system (re-inflation, cleaning, transport preparation) is kept as objectively as possible by introducing decision matrices as explained in Chapter XX. The selection criteria are based on the user needs and their importance level, as discussed in Chapter XX. For this reason, some criteria weigh in to a higher extent than others. The first concepts of each sub-system (a) are taken as reference concept with a rating of 3 throughout all the categories. Following concepts are each rated in comparison to the reference.

The assessment of the re-inflation concepts is shown in Table XX. Clearly, concept g) is evaluated as the most promising candidate to proceed with. Its simplicity pushes down the capital and operational expenditures (CAPEX, OPEX). Having no moving parts or loaded pressure, the worker safety is insured without any special measures. The manual inflation by squeezing the bottle over a fixed pole only shows one deficit in comparison to the reference. Since the tool is fixed in position, the portability of the device decreases (relatively to the cleaning setup).

*Table 4: Concept Selection for Inflation.*

| **Concepts** |  | **1A** | | **1B** | | **1C** | | **1D** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | Weight  [%] | Rating | Score | Rating | Score | Rating | Score | Rating | Score |
| Worker Safety | 20 | 3 | 0.60 | 4 | 0.80 | 5 | 1.00 | 4 | 0.80 |
| OPEX | 15 | 3 | 0.45 | 1 | 0.15 | 2 | 0.30 | 5 | 0.75 |
| CAPEX | 12 | 3 | 0.36 | 4 | 0.48 | 2 | 0.24 | 4 | 0.48 |
| Ease of Use | 12 | 3 | 0.36 | 3 | 0.36 | 4 | 0.48 | 3 | 0.36 |
| Inflation Effort | 10 | 3 | 0.30 | 3 | 0.30 | 2 | 0.20 | 2 | 0.20 |
| Durability | 8 | 3 | 0.24 | 2 | 0.16 | 1 | 0.08 | 3 | 0.24 |
| Longevity | 8 | 3 | 0.24 | 4 | 0.32 | 2 | 0.16 | 2 | 0.16 |
| Cleaning Effort | 5 | 3 | 0.15 | 4 | 0.20 | 4 | 0.20 | 4 | 0.20 |
| Complexity | 5 | 3 | 0.15 | 3 | 0.15 | 2 | 0.10 | 4 | 0.20 |
| Portability | 5 | 3 | 0.15 | 3 | 0.15 | 4 | 0.20 | 5 | 0.25 |
|  | Total Score | 3.00 | | 3.07 | | 2.96 | | 3.64 | |
|  | Rank | 5 | | 4 | | 7 | | 2 | |
|  | Status | No | | No | | No | | No | |

*Table 5: Concept selection of inflation. (fortsetzung)*

| **Concepts** |  | **1E** | | **1F** | | **1G** | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | Weight  [%] | Rating | Score | Rating | Score | Rating | Score |
| Worker Safety | 20 | 3 | 0.60 | 5 | 1.00 | 5 | 1.00 |
| OPEX | 15 | 4 | 0.60 | 3 | 0.45 | 5 | 0.75 |
| CAPEX | 12 | 2 | 0.24 | 2 | 0.24 | 5 | 0.60 |
| Ease of Use | 12 | 4 | 0.48 | 4 | 0.48 | 4 | 0.48 |
| Inflation Effort | 10 | 3 | 0.30 | 4 | 0.40 | 3 | 0.30 |
| Durability | 8 | 2 | 0.16 | 3 | 0.24 | 4 | 0.32 |
| Longevity | 8 | 2 | 0.16 | 4 | 0.32 | 4 | 0.32 |
| Cleaning Effort | 5 | 1 | 0.05 | 5 | 0.25 | 3 | 0.15 |
| Complexity | 5 | 1 | 0.05 | 2 | 0.10 | 5 | 0.25 |
| Portability | 5 | 4 | 0.20 | 3 | 0.15 | 2 | 0.10 |
|  | Total Score | 2.84 | | 3.63 | | 4.27 | |
|  | Rank | 8 | | 3 | | 1 | |
|  | Status | No | | No | | Yes | |

The evaluation of the cleaning concepts is depicted in Table XX. The concept which got the highest score are e), f), g). Up to this point, waterless cleaning processes have been rated and ranked as competitors to washing with water. Evidently, a combination of both will yield an enhanced cleaning quality. For this reason, a mixed approach will be explored and investigated. Thus, combining the advantages of softening the organic contamination with water, as well as of mechanically removing the particles with friction. Again, the portability rating of these three concepts is worse than the reference as the tools proposed need to be fixed in position.

*Table 6: Concept Selection of Cleaning.*

| **Concepts** |  | **2A** | | **2B** | | **2C** | | **2D** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | Weight [%] | Rating | Score | Rating | Score | Rating | Score | Rating | Score |
| Worker Safety | 20 | 3 | 0.60 | 2 | 0.40 | 2 | 0.40 | 4 | 0.80 |
| OPEX | 15 | 3 | 0.45 | 5 | 0.75 | 1 | 0.15 | 2 | 0.30 |
| CAPEX | 12 | 3 | 0.36 | 3 | 0.36 | 3 | 0.36 | 2 | 0.24 |
| Ease of Use | 12 | 3 | 0.36 | 2 | 0.24 | 4 | 0.48 | 4 | 0.48 |
| Cleaning Effort (Bottle) | 10 | 3 | 0.30 | 2 | 0.20 | 2 | 0.20 | 4 | 0.40 |
| Durability | 8 | 3 | 0.24 | 5 | 0.40 | 2 | 0.16 | 4 | 0.32 |
| Longevity | 8 | 3 | 0.24 | 5 | 0.40 | 2 | 0.16 | 4 | 0.32 |
| Cleaning Effort (Equipment) | 5 | 3 | 0.15 | 4 | 0.20 | 3 | 0.15 | 1 | 0.05 |
| Complexity | 5 | 3 | 0.15 | 2 | 0.10 | 2 | 0.10 | 2 | 0.10 |
| Portability | 5 | 3 | 0.15 | 3 | 0.15 | 4 | 0.20 | 1 | 0.05 |
|  | Total Score | 3.00 | | 3.20 | | 2.36 | | 3.06 | |
|  | Rank | 6 | | 4 | | 7 | | 5 | |
|  | Status | No | | No | | No | | No | |

*Table 7: Concept Selection of Cleaning.*

| **Concepts** |  | **2E** | | **2F** | | **2G** | | **2H** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | Weight [%] | Rating | Score | Rating | Score | Rating | Score | Rating | Score |
| Worker Safety | 20 | 5 | 1.00 | 4 | 0.80 | 5 | 1.00 | 2 | 0.40 |
| OPEX | 15 | 2 | 0.30 | 1 | 0.15 | 5 | 0.75 | 1 | 0.15 |
| CAPEX | 12 | 4 | 0.48 | 5 | 0.60 | 4 | 0.48 | 2 | 0.24 |
| Ease of Use | 12 | 5 | 0.60 | 5 | 0.60 | 5 | 0.60 | 2 | 0.24 |
| Cleaning Effort (Bottle) | 10 | 4 | 0.40 | 1 | 0.10 | 3 | 0.30 | 1 | 0.10 |
| Durability | 8 | 2 | 0.16 | 4 | 0.32 | 4 | 0.32 | 3 | 0.24 |
| Longevity | 8 | 3 | 0.24 | 5 | 0.40 | 4 | 0.32 | 2 | 0.16 |
| Cleaning Effort (Equipment) | 5 | 3 | 0.15 | 5 | 0.25 | 4 | 0.20 | 4 | 0.20 |
| Complexity | 5 | 3 | 0.15 | 5 | 0.25 | 2 | 0.10 | 2 | 0.10 |
| Portability | 5 | 2 | 0.10 | 2 | 0.10 | 1 | 0.05 | 5 | 0.25 |
|  | Total Score | 3.58 | | 3.57 | | 4.12 | | 2.08 | |
|  | Rank | 2 | | 3 | | 1 | | 8 | |
|  | Status | Yes | | No | | Yes | | No | |

Last but not least, the concepts considering preparation of the bottles for transport are evaluated in Table XX. In contrast to the previous decision matrices, the category focusing on transport efficiency has been weighed higher than the OPEX and CAPEX of the product. The reason for this is the costs that arise from transportation, which do not appear in the expenditures of the device itself. Especially if the space in the truck is limited, minimization of the transport volume per bottle is crucial to avoid extra trips of the collection truck. Cutting the bottles and stacking them on a pole, crushing them manually, and packing them in crates uncrushed have received the highest scores. Once an assessment of the actual available transport space for collecting cleaned bottles in the Chibuku trucks has been made, the importance of the second category might be adjusted. Thus, concept a) has still been taken to the next phase of development since it not only reduces the transport space per bottle but also allows for quality control of the cleaning process. A cut bottle can be investigated on cleanliness from the inside and the outside, whereas a crushed bottle allows no option for an internal quality check. At least, bottles stored according to concept e) might be assessed by a glimpse through the opening.

*Table 8: Concept Selection of Cleaning.*

| **Concepts** |  | **3A** | | **3B** | | **3C** | | **3D** | | **3E** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Selection Criteria** | Weight [%] | Rating | Score | Rating | Score | Rating | Score | Rating | Score | Rating | Score |
| Worker Safety | 15 | 3 | 0.45 | 1 | 0.15 | 4 | 0.60 | 4 | 0.60 | 4 | 0.60 |
| Transport Space per bottle | 15 | 3 | 0.45 | 5 | 0.75 | 4 | 0.60 | 2 | 0.30 | 1 | 0.15 |
| OPEX | 12 | 3 | 0.36 | 2 | 0.24 | 2 | 0.24 | 2 | 0.24 | 3 | 0.36 |
| CAPEX | 12 | 3 | 0.36 | 1 | 0.12 | 1 | 0.12 | 5 | 0.60 | 1 | 0.12 |
| Ease of Use | 10 | 3 | 0.30 | 2 | 0.20 | 3 | 0.30 | 3 | 0.30 | 5 | 0.50 |
| Volume reduction effort | 8 | 3 | 0.24 | 1 | 0.08 | 1 | 0.08 | 3 | 0.24 | 4 | 0.32 |
| Durability | 8 | 3 | 0.24 | 3 | 0.24 | 3 | 0.24 | 3 | 0.24 | 3 | 0.24 |
| Longevity | 5 | 3 | 0.15 | 2 | 0.10 | 3 | 0.15 | 4 | 0.20 | 3 | 0.15 |
| Cleaning Effort (Equipment) | 5 | 3 | 0.15 | 2 | 0.10 | 4 | 0.20 | 5 | 0.25 | 4 | 0.20 |
| Complexity of the System | 5 | 3 | 0.15 | 1 | 0.05 | 2 | 0.10 | 5 | 0.25 | 5 | 0.25 |
| Portability | 5 | 3 | 0.15 | 3 | 0.15 | 2 | 0.10 | 5 | 0.25 | 5 | 0.25 |
|  | Total Score | 3.00 | | 2.18 | | 2.73 | | 3.47 | | 3.14 | |
|  | Rank | 3 | | 5 | | 4 | | 1 | | 2 | |
|  | Status | Yes | | No | | No | | Yes | | Yes | |

## System Level Design

### System Schematics

In this chapter, the system architecture of the pre-cleaning station is explored. Figure XX shows the functional decomposition of the product. The entirety of the functions and sub-functions is put into relation within the product boundaries. Clustering of directly connected sub-functions was used to determine unique modules that make up the product. The modules are visualized with help of colored boxes and are further developed independently of each other. This modularity enables exchangeability of single components/functions and simplifies the introduction of re-design steps where necessary. (Quelle Modularity). Framing/Chassis

Besides the various functions of the system, material and energy flows are depicted. Water, and contaminated plastic bottles enter the system and are transformed through the cleaning process into separated trash, wastewater, and clean plastic bottles. The energy required for this transformation is generated manually by human force. Eventually, the energy dissipates into heat and kinetic energy of the wastewater stream.

The isolated modules are named and analyzed in Figure XX. The colors used are identical as in the functional decomposition (Figure XX). Mainly, five modules were determined:

* Inflation module: Crushed bottles are put into their original shape to expose the entire surface of the bottle.
* Cleaning module: At this stage, the cleaning water as well as human force are introduced to perform the actual cleaning activity, removing, and separating the contamination from the HDPE bottle.
* Water module: The water used for the cleaning process needs to be available despite eventual tap water shortages. Further the water is pressurized to ensure high cleaning efficiency while reducing the amount of water used.
* Stacking module: Cleaned bottles are prepared for transport by reducing their stacking volume
* Wastewater treatment: The water exiting the cleaning process is mixed with organic contaminants. It is either redirected into sewage, collected for a secondary use, or recycled with help of a filtering / membrane system.

Further, material and energy flows are represented entering and exiting each module respectively.





### Incidental Interactions

Having defined the system architecture, a focus in their interaction is needed to identify weaknesses of the system. The use of the product introduces error sources that need to be well-known before further development. The errors that might occur through proper use of the product are represented by the Incidental Interaction graph depicted in Figure XX. Since the system accepts external energy and partially stores it as pressure, different failure modes are presented. First, repeated use might wear out different components over time. Especially the inflation module and the brushes are exposed to stress as the bottle is inserted and forcefully moved to achieve the desired function. Next, a piping system containing different valves is susceptible to clogging. Small particles present in non-filtered water might hinder sensible valves to work properly. Further, the water pressure within the pipes might lead to leakage or even rupturing at weak points. Since the main structure is built from metal, the water used for cleaning potentially introduces corrosion on unprotected parts. The workbench where all modules are attached to is also exposed to stress coming from the use of the five modules. Depending on the location of the setup and the ground it stands on, the stress might lead to structural instability which can result in collapsing or tipping over of the workbench. The identification of error sources before finalizing the design yields the option to address potential weaknesses of the system, and thus allows to implement failure preventing measures at an early stage.

Since the Chibuku taverns and hence, their storage rooms are built according to different blueprints, the designated location and available space of the pre-cleaning station vary from tavern to tavern. This imposes the need for flexible arrangements of the different modules. Possible arrangements are shown in Figure XX. 

### Product Layout

Depending on the local conditions of taverns designated for the pilot program, the most suitable layout can be chosen. Nonetheless, the arrangement shows a clear pattern. Since the steps of the cleaning process are carried out in a specific order (inflation, cleaning, stacking), the modules are arranged equally to ensure a linear workflow from left to right or right to left. This results in a more efficient workflow and a more comfortable user experience. The list of layouts only shows a few options and is hence further extendable.



## Detailed Design

In the last step of the design process, the detailed design of the pre-cleaning station is presented. The concepts selected in chapter XX have been transformed into technical drawings and eventually led to 3D-representation with help of a CAD software. The figures below depict the different modules separately as well as the complete assembly of all components.

### Inflation Module:

The realization of the inflation module is kept as simple as proposed within the selected concept. The module consists of a round tube welded to a steel plate. The diameter of the tube is about 1cm smaller than the bottle opening to ensure quick and reliable mounting of the bottle. The steel plate is welded to or screwed into the surface below the module. This allows for controlled movement of the bottle during re-inflation.

### Cleaning Module:

The cleaning interface consists of mainly four components. First, the bottle is rinsed on the inside with help of the glass rinser. A spring that is built into the rinser closes a valve when no bottle is placed on top. If a bottle is placed onto the star-shaped surface and pressed down, the valve is open and allows water to flow into the bottle. Due to the water pressure withing the piping system, and the narrow openings at the rinser outlet, jets of water shoot up into the bottle. They rinse the entire inside of the bottle and removes contamination at the contact points between the jets and the bottle.

Next, the bottle is mounted onto the horizontally placed brush. Since the brush is fixed in position, the bottle is rotated around the long axis and slightly tilted to the sides to shift the main contact points between the brush and the bottle. Due to the presence of a second brush, the outside of the bottle can be brushed simultaneously.

Step 1 and 2 are repeated until the inside of the bottle is considered clean by visual inspection. Subsequently, the outside of the bottle is rinsed with help of the tap installed on the sink. This removes dust/ dirt on the outer surface of the bottle.

The water used during this process is captured by a sink. The sink allows to collect and redirect the wastewater to the desired location.

### Water Module:

The cleaning process presented in this thesis makes use of pressurized water. Since the tap water in the taverns is on shortage occasionally, an independent source of pressurized water is desired. This allows to always operate the cleaning station despite the potential absence of tap water. Figure XX depicts the schematic of the piping system. A manual piston pump is used to pump water into the closed system. First, the water passes the pump into a dirt filter. Since the tap water available in Blantyre might contain sand, dirt and other particles, filtering is crucial to protect the sensible valves that follow the filtering process. Next, the filtered water passes through a one-way valve ensuring to maintain the generated pressure within the piping system while pumping. The water that enters the system is transported into a pressure tank. The work introduced by the manual pump is converted into air pressure. If the water outlet (glass rinser / tap) is closed, the amount of air particles within the pressure tank is constant. By inserting more and more water into the closed system, the air inside of the pressure tank is compressed, pushing with a certain force on the water. This pressure is used to operate the glass rinser and the tap even if they are located at a higher position than the pressure tank itself. Due to the static force of water, the water module presented eliminates the need for building a 25m tall framework, leading to the same amount of pressure according to FORMULA.

At every moment during pumping, the generated pressure can be read off a Barometer. The pre-cleaning setup is designed to work at a pressure of 2.5 bar. For safety reasons, a valve limiting the pressure is added. The spring-loaded mechanism of the safety valve opens automatically once the water pressure inside the pipes exceeds 2.5 bars.

Finally, the water pressure can be accessed through the tap or the glass rinser by pushing the bottle onto the pressure sensitive valve.

### Stacking Module:

The two concepts that were ranked highest in the selection have no need for further equipment besides the transport unit. This can either be a bag or a crate in case of the uncrushed bottles. Thus, the design approach shown in this chapter focusses on the third ranked concept. In this approach, the bottles are cut with two blades arranged in a cross-like manner. This allows to bend the walls of the bottles outwards while leaving the bottle opening intact. Figure XXa) shows the complete mechanism of the cutting tool. It consists of an outer tube, inner tube, a cutting interface, and a bottle adapter. A set of joints connects the outer with the inner tube, while the manual force can be introduced through a handle.

Figure XXb) depicts the rotating parts of the module. The handle is moved by hand by pulling on the lever. The applied force is translated through the joints into a linear motion of the inner tube.

Figure XXc) shows the inner tube as well as the cutting interface. The U-shaped tube acts as the sled for the cutting interface. It can be moved linearly through the outer tube. Movement along the short axes are prohibited by the dimensions of the outer tube. The cutting interface consist of a plate and vertically attached blades. The blades are positioned with an inclination to enhance the cutting properties of the sharp edge.

Figure XXd) shows the guide tube of the cutting tool. The U-shaped metal tube that encompasses the inner tube ensures linear movement of the sled. Since the cutting interface might crush a loose bottle placed underneath, a suitable counter piece was designed. The bottle is placed into the bottle stand depicted in Figure XX. Due to the walls of the stand the bottle is centered throughout the cutting process. Further, the metal tube with 90° cuts builds up counter pressure while pushing the blades through the bottom of the plastic bottle. These measures ensure a clean cut as well as shielding the sharp edges from the user while most of the force is introduced.

After cutting of the bottle, a visual quality check can be carried out to verify the cleanliness of the bottle. If the bottle is clean, it can be put on a vertical pole for stacking. Since the bottle opening is intact and the walls flapped out, the stacking efficiency is increased. Further, the poles can be loaded into the truck by sliding them into rails fixed on the ground and the sidewall of the truck, as shown in Figure XX. This prevents the poles from tipping over during the transportation. 

The wastewater module has not been further developed yet. Different solutions at different costs are possible to deal with the organically contaminated wastewater.

* Sewage possible?
* Fill in drum -> toilet flushing
* French drain, what if inside?
* Water filtering -> reuse?

The selection of what the wastewater is used for is pending within the groups of stakeholders.

Figure XX depicts the complete assembly of the pre-cleaning station. The manual pump is inserted into a basket of water (not shown in Figure XX). The piston pump, attached on the very right, is used to build up the water pressure needed for the cleaning. The cleaning workflow is kept from left to right. First, a basket with dirty bottles is placed on the tray underneath the sink. From there, the bottles can be picked out, and reshaped with help of the inflation module. The pins next to the inflation module act as a temporary storage of reinflated bottles. As soon as all spots are taken, the removal of the aluminum lid and the multilayer plastic label is carried out. Next, the actual cleaning process of the bottles is initiated. Washed bottles are again temporarily stored on the bolts to the right of the sink. Last but not least, the bottles are cut with the cutting tool and placed on the empty pole.



## Design Verification

Focus Group Discussion

In this section, the output of the focus group discussion is presented. The complete transcript can be found in Appendix XX.

Comment the two tables, say what has actually be implemented / changed in my design.

| **Category** | **User Feedback** |
| --- | --- |
| **Project** | * The tavern mamas are eager to start the pilot phase of collecting and pre-cleaning Super Maheu bottles. Managing these collection point needs to be monetarily beneficial. * The Super Maheu collection program needs to be made visible to the people. Advertising helps to make people aware of the program. * The tavern mamas are willing to take over the cleaning themselves. Nonetheless, they still must serve customers and would be happy to get suitable support. |
| **Infrastructure** | * Despite the installation of taps, they frequently experience water shortages in the pipes. The absence of running water can persist for up to three days. * The taverns are equipped with drums, acting as a temporal storage of water in case of a shortage. * Not every tavern is connected to a sewage system. Heavy rain causes some taverns to be flooded, lacking a suitable drainage system. * Every tavern is equipped with storage rooms, providing space for the storage of both cleaned and dirty bottles without any spatial constraints. |
| **User Experience** | * Daily, tavern mamas clean the bear bottles they serve to customers with a bucket of water and a towel. * Opening the beer generally is carried out with a knife. Thus, tavern mamas are experienced to use a knife to cut a bottle. |

| **Category** | **User Feedback** |
| --- | --- |
| **Design Ideas** | Before the elaborated design was shown to the tavern mamas, their unbiased ideas about what they need for cleaning the bottles were collected:   * The setup should be like a table with a sink to perform the cleaning * The setup needs to have storage space for dirty and clean bottles * The space below the cleaning station can be used as additional storage * The cleaning station must be located inside. First, the tap is located inside the storage room. Second, the tavern mamas agreed that equipment will be damaged by customers under the influence of alcohol. * The cleaning station should be placed near the existing sinks. |
|  |  |
| **User Feedback** | Afterwards their opinions about the elaborated design were discussed:   * The design is viewed as user friendly. They are happy to get trained on operating the setup. * They fear the cleaning station to be damaged if left outside. * The cleaning station should be painted in Chibuku colors (blue and red) * The type of bottle should be displayed in proximity to the setup |

## Prototyping

The prototyping of the designed pre-washing station is presented in this chapter. Before the product can be manufactured and installed in Blantyre, a functional verification of the design is necessary.

### Switzerland Prototype

For this reason, low-cost prototypes investigating the functionality and useability of the modules (excluding the wastewater module) were built and tested in Switzerland. The materials for the cleaning module and water module were purchased and ordered mainly from local stores. Some parts were imported, where no suitable alternative was found in Switzerland. The materials used for the inflation and cutting module were either purchased from local suppliers or fabricated from free scrap metal available at Dynamo. Cutting, drilling, welding, and assembling of these two modules was carried out at Dynamo, Zurich. (REF)

Inflation Module:

The inflation prototype depicted in Figure XX was kept identical to the design previously presented in Figure XX. Upon assembly, the prototype was tested with 1 of 4 Super Maheu bottles available in this phase of prototyping. The bottle was crushed by stepping on it with full body weight For re-shaping, the ground plate of the module was fixed to the workbench with help of two screw clamps. Several testing rounds were conducted to observe the effectiveness of the designed module, the effort needed, and the ease to clean the system. The module was able to re-shape the bottles reliably. The force required for the process did not yield any signs of physical strain. Further, the process was carried out quickly. In a few seconds a bottle can be given its original shape with help of the designed module.

BILD Inflation-module

Water module / Cleaning module:

Figure XX shows the assembly of the water module. The following components are visible: The manual hand pump is fixed in height to a vertical beam connected to a footrest. The pump was immersed into a bucket filled with water. Next, the one-way valve as well as the barometer are connected to the system. The safety valve is not yet introduced to the system. If the barometer is observed during pumping, the pressure could be intentionally kept below 2.5 bar. The pressure tank was realized with help of a 20L plastic bottle (type of plastic) normally used in water dispensers. In the pressure range from 0 - 2.5 bar the bottle showed no sign of plastic deformation, potentially making it a suitable low-cost solution for the desired use case. Last but not least, the glass rinser is connected. The setup was kept simple to prevent unnecessary costs. Thus, a work bench with a sink was not built at this stage. The module was tested with the 4 bottles available by manually contaminating them, using syrup mixed with some dirt to mimic the consistency and stickiness of the organic contamination. For the cleaning, the bottle was rinsed with the water jets and subsequently brushed. Both the brush, depicted in Figure XX, and the bottle were grabbed and moved by hand during the cleaning which introduced some physical strain over time. In the final product, the brush will be fixed to the worktable which eliminates this problem.

Stacking Module:

The cutting tool was fabricated and assembled according to the drawings elaborated in CAD. The cutting interface consisted of one diagonally oriented blade. The bottles fit well into the bottle stand as was kept in position. The blade cut the bottle without any problems. Since there was only one blade, the bottle was removed from the stand, twisted by 90° and re-inserted. The second cut led to the desired cutting shape, preparing the bottle for stacking on the pole.

Bild Cutting Module

COSTS

### Blantyre Prototype

The second prototyping phase was carried out in Blantyre for five weeks. The materials needed to build the complete setup were searched and acquired from local steel suppliers, hardware stores or different markets in town. Only the safety valve, the brushes, the glass rinser and the manual hand pump were re-used from the Swiss prototype. The water and cleaning modules were assembled in a workshop at MUBAS University (REF) in Blantyre. The workbench including the inflation module, sink, and the stacking module was manufactured either by different engineering companies, specializing on manufacturing of steel components, or by steel workers found at local markets.

Figure XX shows the complete assembly of the pre-cleaning station. Once the setup has been built, it was tested to determine the water consumption and the time used for cleaning the bottles.

For this experiment, 40 bottles of Super Maheu were bought, emptied, and dried for 3 days before going through the cleaning process. The first half of the samples were cleaned starting from their dry state. The remaining bottles were soaked in a finite water volume of 4L for one minute before the cleaning process was initiated. Figure XXa) depicts the water used to clean sets of five dry bottles. In Figure XXb) the water consumption of sets of five pre-soaked bottles is visualized. The water consumption per bottle could be reduced by 23% when pre-soaking the bottles first. The soaking loosens the contamination and hence, reduces the amount of cleaning repetitions (rinsing, brushing) leading to a smaller water consumption.

Figure XX a) and b) compare the time needed to clean a set of 5 bottles for dry and pre-soaked bottles. The cleaning time is drastically reduced (almost 50%) by pre-soaking the bottles in water first. As a result, the cleaning process was adapted by introducing a pre-soak step after reinflation. With this process, a water consumption of 0.2dl per bottle with a cleaning time of 24 seconds per bottle was achieved. The water used for this step does not need to be fresh, since the removal of contamination follows the soaking.

After the 5th cycle of pumping water into the system as soon as the pressure dropped below 1.5 bar, pressurizing the pressure tank to 1.7 bars leaded to permanent deformation of the 20L plastic bottle. The bottle was still intact, but the pressure for further testing was limited to 2 bars for safety reasons. In comparison to the Swiss prototype, the plastic bottle purchased in Blantyre was made from PET. (material stiffness etc.?). This needs to be further investigated to always ensure safe operation of the cleaning station.

Finally, the cutting tool built in Blantyre also showed some problems. The blades were not able to penetrate the bottom of the bottle even when putting the maximum manual force on the lever. The tool was designed to work with the bottles available in Switzerland. Comparing them with the newly acquired ones shows that the thickness of the bottom layer has increased by a factor of 4. Even though different geometries and cutting angles of the cutting interface were investigated, the bottom of the bottles could not be cut. Even manual cutting with a sharp knife was energy and time consuming while the bottles, available in the design phase, showed almost no resistance to cutting manually.

Costs





# Conclusions and Recommendations

# Bibliography

Aarnio, T., & Hämäläinen, A. (2008). Challenges in packaging waste management in the fast food industry. *Resources, Conservation and Recycling*, *52*(4), 612–621. https://doi.org/10.1016/j.resconrec.2007.08.002

Energy Bulletin. (2007, June 9). *Design for the other 90%*. Resilience. https://www.resilience.org/stories/2007-06-10/design-other-90/

Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20–32. https://doi.org/10.1111/2041-210X.12860

Refsgaard, K., & Magnussen, K. (2009). Household behaviour and attitudes with respect to recycling food waste – experiences from focus groups. *Journal of Environmental Management*, *90*(2), 760–771. https://doi.org/10.1016/j.jenvman.2008.01.018

Shea, K., Stanković, T., & Tilley, E. (2022). *Product Development and Engineering Design*.

Ulrich, K. T., & Eppinger, S. D. (2016). *Product design and development* (Sixth edition). McGraw-Hill Education.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782. https://doi.org/10.1126/sciadv.1700782

Hahladakis, J. N., & Iacovidou, E. (2019). An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling. *Journal of Hazardous Materials*, *380*, 120887. https://doi.org/10.1016/j.jhazmat.2019.120887

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311

Hu, B. (2014). Biopolymer-Based Lightweight Materials for Packaging Applications. In *ACS Symposium Series* (Vol. 1175, pp. 239–255). https://doi.org/10.1021/bk-2014-1175.ch013

Kanyuka, M. (2018). *Malawi Population and Housing Census* [Census]. Malawi National Statistics Office. http://www.nsomalawi.mw/index.php?option=com\_content&view=article&id=226&Itemid=6

Mihai, F.-C., Gündoğdu, S., Markley, L. A., Olivelli, A., Khan, F. R., Gwinnett, C., Gutberlet, J., Reyna-Bensusan, N., Llanquileo-Melgarejo, P., Meidiana, C., Elagroudy, S., Ishchenko, V., Penney, S., Lenkiewicz, Z., & Molinos-Senante, M. (2022). Plastic Pollution, Waste Management Issues, and Circular Economy Opportunities in Rural Communities. *Sustainability*, *14*(1), Article 1. https://doi.org/10.3390/su14010020

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2021). An Overview of Plastic Waste Generation and Management in Food Packaging Industries. *Recycling*, *6*(1), Article 1. https://doi.org/10.3390/recycling6010012

Ndau, H., & Tilley, E. (2018). Willingness to Pay for Improved Household Solid Waste Collection in Blantyre, Malawi. *Economies*, *6*(4), Article 4. https://doi.org/10.3390/economies6040054

OECD. (2022). *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*. Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/environment/global-plastics-outlook\_de747aef-en

Turpie, J., Letley, G., Ng’oma, Y., & Moore, K. (2019). *The Case for Banning Single-Use Plastics in Malawi* (AEC/1836/1; p. 64). UNDP. https://www.lilongwewildlife.org/wp-content/uploads/The-Case-for-Banning-Single-Use-Plastics-Report-in-Malawi.pdf

Ulrich, K. T., & Eppinger, S. D. (2016). *Product design and development* (Sixth edition). McGraw-Hill Education.

Velis, C. A., Hardesty, B. D., Cottom, J. W., & Wilcox, C. (2022). Enabling the informal recycling sector to prevent plastic pollution and deliver an inclusive circular economy. *Environmental Science & Policy*, *138*, 20–25. https://doi.org/10.1016/j.envsci.2022.09.008

Velis, C., Wilson, D., Rocca, O., Smith, S., Mavropoulos, A., & Cheeseman, C. R. (2013). An analytical framework and tool ('InteRa’) for integrating the informal recycling sector in waste and resource management systems in developing countries. *Waste Management & Research*, *30*, 43–66. https://doi.org/10.1177/0734242X12454934

# Appendix

| No. | Metric | Units | Marginal | Ideal |
| --- | --- | --- | --- | --- |
| 1 | Young Modulus of steel parts | Pa | > 180 | ~ 200 |
| 2 | Stability / Balance upon use cycle | Subj. | > 3 | 5 |
| 3 | Force needed to bring the system to fail | N | > 250 | 400 |
| 4 | Amount of parts exposed to stress | # | < 8 | 4 |
| 5 | Percentage of corrosive parts | % | < 10 | 0 |
| 6 | Corosity Resistance | mm/year | < 0.5 | 0 |
| 7 | Time needed to replace essential parts | min | < 30 | 20 |
| 8 | Lifetime span of device | years | > 2 | 4 |
| 9 | Windresistance / Inertia (windspeed without falling) | m/s | > 20 | 25 |
| 10 | Displacement reached upon pushing gently | cm | < 5 | 0 |
| 11 | No. of loose parts (incl. equipment) | # | < 4 | 0 |
| 12 | No. of fixation points of complete device to ground | # | > 4 | 8 |
| 13 | Equipped material costs | CHF | < 150 | 100 |
| 14 | Percentage of visible contamination after cleaning | % | < 20 | 5 |
| 15 | Bottle specific volume | units / | > 250 | 300 |
| 16 | Adjustablilty to different bottles | Subj. | > 2 | 5 |
| 17 | Development Costs | CHF | < 2500 | 2000 |
| 18 | Manufacturing Costs | CHF | < 800 | 500 |
| 19 | Amount of imported parts | # | < 4 | 0 |
| 20 | Costs of imported part | CHF | < 500 | 200 |
| 21 | Time needed to treat one bottle | s | < 45 | 30 |
| 22 | No. of steps needed to treat one bottle | # | < 8 | 5 |
| 23 | Functionality ensured without electricity | Subj. | > 3 | 5 |
| 24 | Functionality ensured without running water | Subj. | > 3 | 5 |
| 25 | No. of people needed to operate the device | # | < 3 | 1 |
| 26 | Mechanical Force required to operate the device | N | <150 | 80 |
| 27 | Height where mechanical input is applied | cm | < 140 | < 120 |
| 28 | Time needed to clean the device | min | < 10 | 5 |
| 29 | Time needed to move the device from fixed location | min | < 10 | 5 |
| 30 | Height of the device | m | < 3 | < 2 |
| 31 | Width / Length of the device | m | < 3 | < 2 |
| 32 | No. of harmful spots the user is exposed to | # | < 3 | 0 |
| 33 | Level of accident protection | Subj. | > 3 | 5 |
| 34 | Exposure of waste to living organisms on the surface | Subj. | > 3 | 5 |
| 35 | Amount of water used to clean one bottle | L | > 0.2 | < 0.1 |
| 36 | Contact duration between user and contamination | s / bottle | > 15 | 6 |
| 37 | Level of self-explanation of the device | Subj. | > 3 | 5 |
| 38 | Clarity about the belonging of the device | Subj. | > 3 | 5 |
| 39 | Level of visual appealingness | Subj. | > 3 | 5 |