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

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3.3 System Level Design

3.3.1 System Schematics

In this chapter, the system architecture of the pre-cleaning station is derived. Figure 7 illustrates the functional decomposition of the product, showcasing how all the functions and sub-functions interrelate within the product's boundaries. To identify distinct modules that comprise the product, a method of clustering for directly connected sub-functions was employed, leading to the clustered view in Figure 6. The modules are depicted using coloured boxes and are developed independently from one another. The modular approach not only facilitates the exchangeability of individual components or functions but also simplifies the process of incorporating redesign steps where needed. (Erixon, 1996; Kamrani & Salhieh, 2002).

In addition to the various functions of the system, material and energy flows are illustrated. The system receives water and contaminated plastic bottles as inputs, which undergo the cleaning process to be transformed into separated trash, wastewater, and clean plastic bottles as outputs. The energy needed for this transformation is generated manually through human force. As the energy is utilized in the cleaning process, it eventually dissipates into heat and kinetic energy within the wastewater stream, completing the material and energy flow cycle of the system.

The isolated modules are named in Figure 6. Each of them is assigned a different colour, that will be used in the following chapters for referencing to the corresponding module. Mainly, five distinct 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 and human force are introduced to perform the actual cleaning activity, effectively removing, and separating the contamination from the HDPE bottles.
- Water module: The water used for the cleaning process must be readily available, even in the event of potential tap water shortages. Additionally, the water is pressurized to ensure high cleaning efficiency while minimizing the overall water consumption.
- 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.

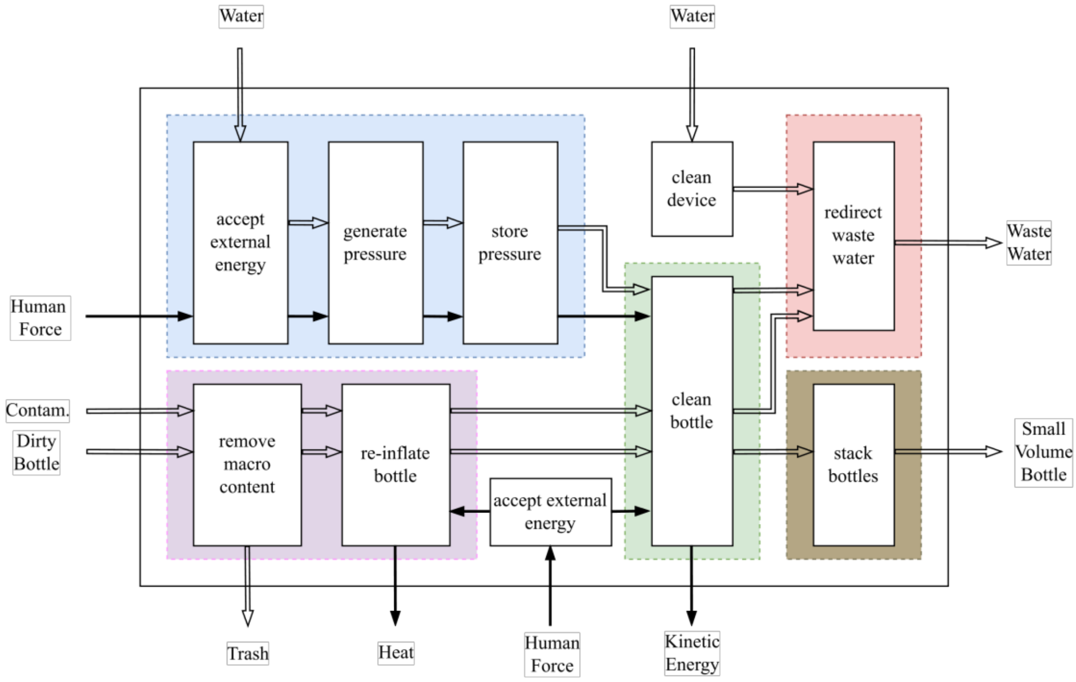

Figure 7: Functional decomposition of the pre-cleaning station. White arrows correspond to material flows, while black arrows correspond to energy flows.

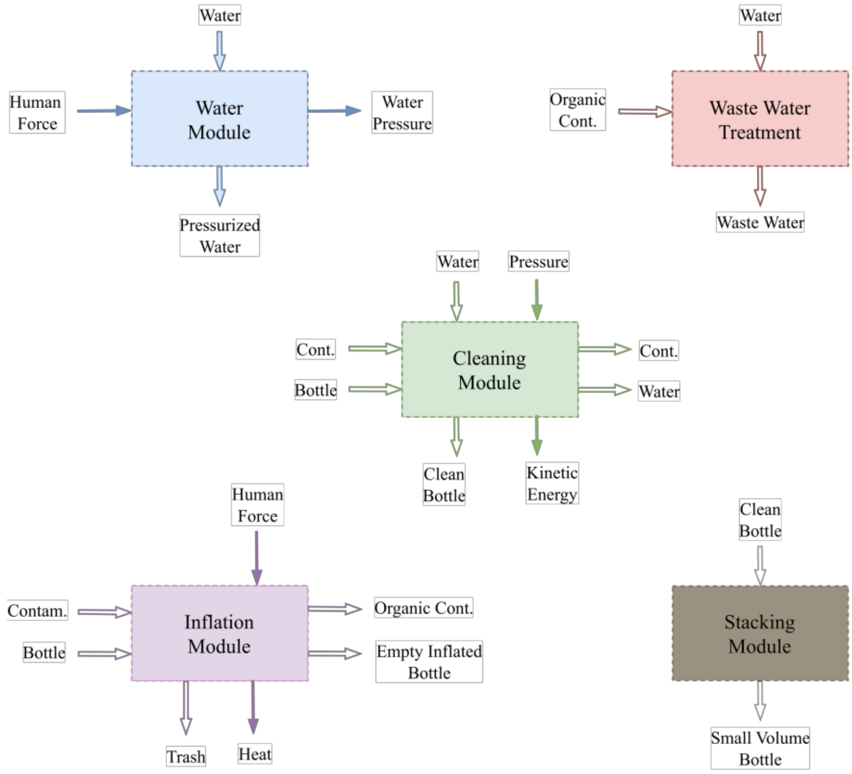

Figure 6: Clustered view of the system schematic. Five modules are identified and visualized with different colors.

3.3.2 Incidental Interactions

With the system architecture defined, it is crucial to focus on the interactions within the system to identify potential weaknesses. The use of the product introduces sources of errors that must be well-understood before proceeding with further development. The errors that may arise during the proper use of the product are represented by the incidental interaction graph, as depicted in Figure 8. Given that the system accepts external energy and partially stores it as pressure, various failure modes are presented and should be carefully considered.

Repeated use of the system may cause wear and tear on different components, particularly the inflation module and brushes, which are subjected to stress as bottles are inserted and moved forcefully. Next, the piping system, which contains various valves, is susceptible to clogging. Small particles present in non-filtered water could obstruct sensitive valves, affecting their proper functioning. High water pressure within the pipes may lead to leakage or even rupturing at weak points in the system. Further, since the main structure is built from metal, the water used for cleaning potentially introduces corrosion on unprotected metal parts. Finally, the workbench, to which all modules are attached, is exposed to stress from the use of the five modules. Depending on the location of the setup and the ground it stands on, this stress might result in structural instability, potentially causing the workbench to vibrate, collapse, or tip over.

Identifying these error sources before finalizing the design provides the opportunity to address potential weaknesses in the system and implement measures to prevent failures at an early stage of development.

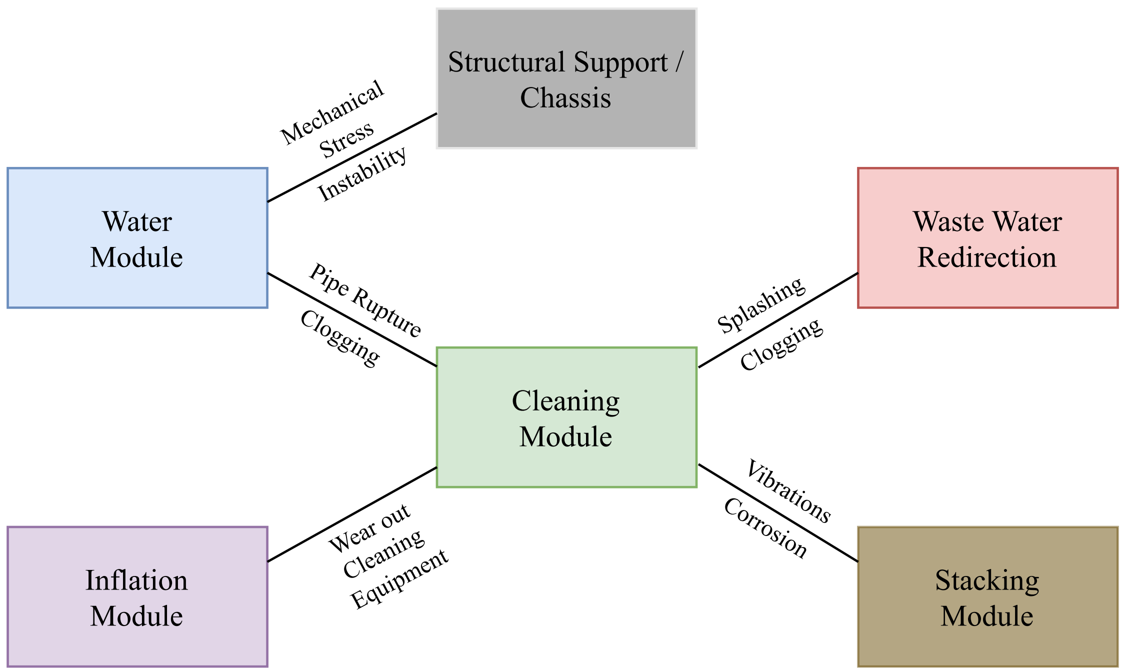

Figure 8: Incidental interaction graph of the identified modules.

3.3.3 Product Layout

Since Chibuku taverns and their storage rooms are constructed based on various blueprints, the specific location and available space for the pre-cleaning station can vary from one tavern to another. Possible arrangements are depicted in Figure 9, demonstrating the adaptability of the system to accommodate different spatial constraints and layouts.

The layout of the pre-cleaning station can vary based on the unique conditions of Chibuku taverns. However, the arrangements follow a consistent pattern to maintain a linear workflow from left to right or right to left, optimizing efficiency and user experience during the cleaning process. The list of layouts only shows a few options and is hence further extendable.

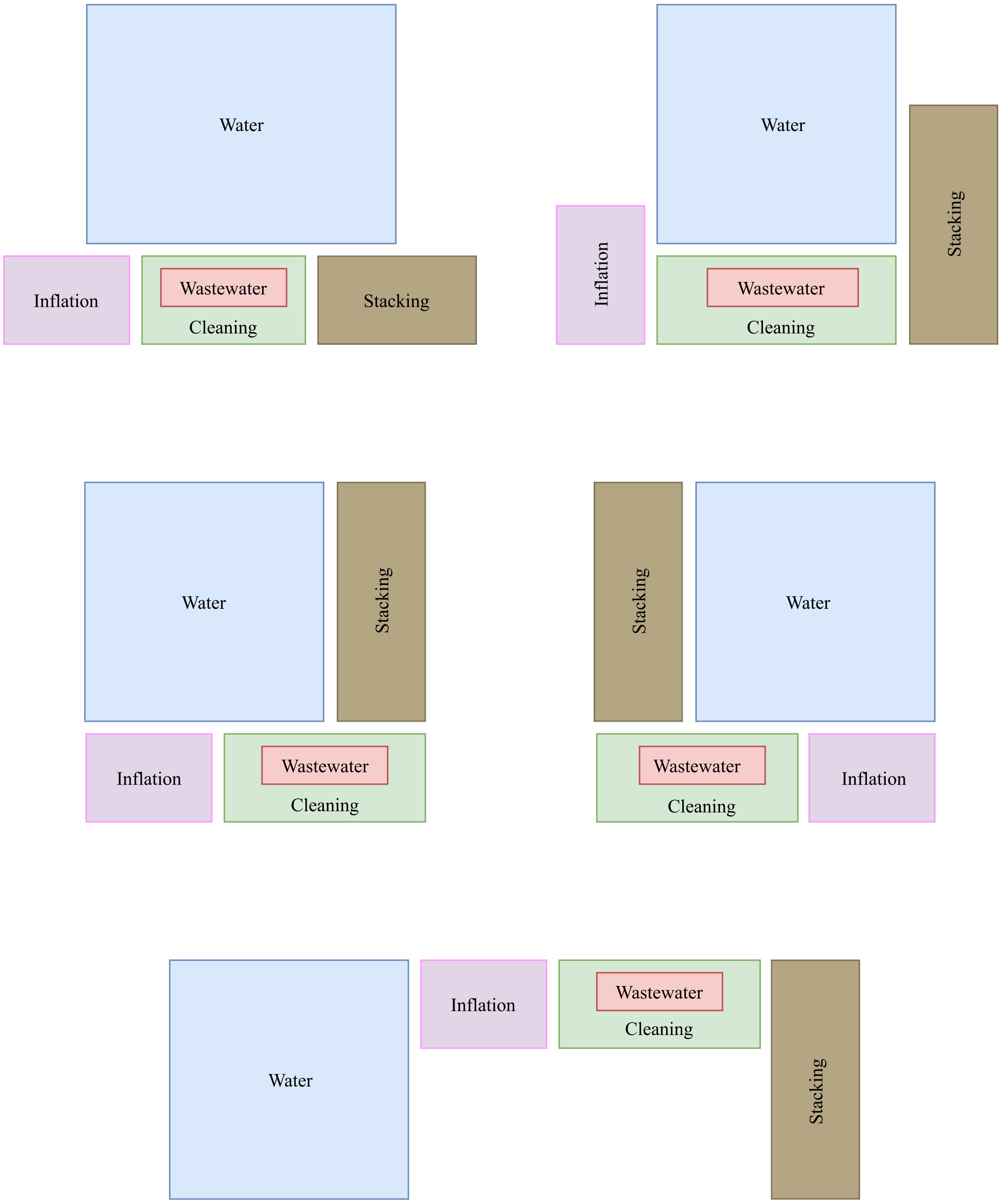

Figure 9: Different geometric layouts of the pre-cleaning station

3.4 Detailed Design

In this chapter, the detailed design of the pre-cleaning station is presented. The concepts selected in Chapter 2.1.2 have been translated into technical drawings and eventually transformed into 3D representations using CAD software. The figures below illustrate the individual modules as well as the complete assembly of all components.

3.4.1 Inflation Module

The realization of the inflation module is kept as simple as proposed within the selected concept and is presented in Figure 10a). The module consists of a round tube attached to a steel plate. The diameter of the tube is approximately 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.

3.4.2 Cleaning Module

The cleaning interface depicted in Figure 10b) consists of four primary components. Initially, the interior of the bottle undergoes a rinsing process facilitated by a glass rinser. This rinser incorporates an integrated spring mechanism, permitting water jets to ascend into the bottle upon placement of a bottle on the rinser's star-shaped platform and subsequent downward pressure.

Subsequently, the bottle is mounted onto the horizontally arranged brush. As the brush remains stationary, the bottle is rotated about its longitudinal axis and marginally inclined laterally to alter the primary contact regions between the brush and the bottle. The incorporation of a secondary brush allows for the simultaneous scrubbing of the bottle's exterior.

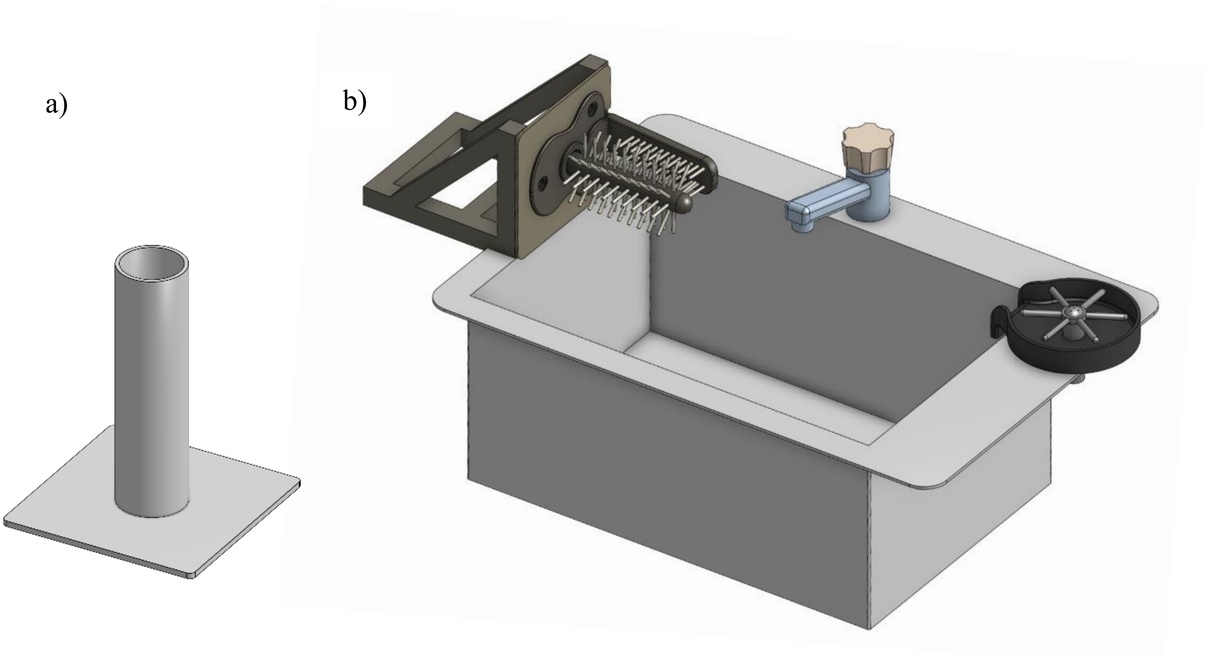

Figure 10: 3D-representation of modules: a) Inflation Module, b) Cleaning Module.

The previous steps 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, removing dust/ dirt on the outer surface of the bottle. The water utilized during this phase is gathered by the sink, which serves as a collection basin. This setup enables the efficient capture and subsequent redirection of wastewater to a predetermined location for appropriate disposal or treatment.

3.4.3 Water Module

The cleaning process described in this thesis utilizes pressurized water. Given the occasional shortage of tap water in the taverns, there is a need for an independent source of pressurized water. This ensures that the cleaning station can operate consistently, even in situations where tap water may be unavailable.

Figure 11 provides a schematic of the piping system, which includes the following components and processes:

1. **Manual Piston Pump**: A manual piston pump is used to pump water into the closed system.
2. **Dirt Filter**: The water first passes through a dirt filter to remove sand, dirt, and other particles. This filtering process is essential to protect sensitive valves downstream.
3. **One-Way Valve**: A one-way valve is used to maintain the generated pressure within the piping system while pumping by restricting upstream flow.
4. **Pressure Tank**: The filtered water enters a pressure tank, where the work introduced by the manual pump is converted into air pressure. When the water outlet (glass rinser/tap) is closed, the amount of air particles inside the pressure tank remains constant. As more water is pumped into the closed system, the air inside the pressure tank is compressed, exerting a certain force on the water. This pressure is utilized to operate the glass rinser and tap, even if they are located at a higher position than the pressure tank.
5. **Pressure Regulation**: The pre-cleaning setup is designed to work at 2.5 bars of pressure. To ensure worker safety, a pressure-limiting safety valve is included. The spring-loaded mechanism of the safety valve automatically opens if the water pressure inside the pipes exceeds 2.5 bars.
6. **Water access**: The water pressure can be accessed through the tap or the glass rinser by pushing the bottle onto a pressure-sensitive valve.

This design allows for the creation of sufficient pressure within the system to operate the glass rinser and tap without the need for a tall framework. It ensures a safe and reliable water supply for the cleaning station, even in areas with occasional tap water shortages.

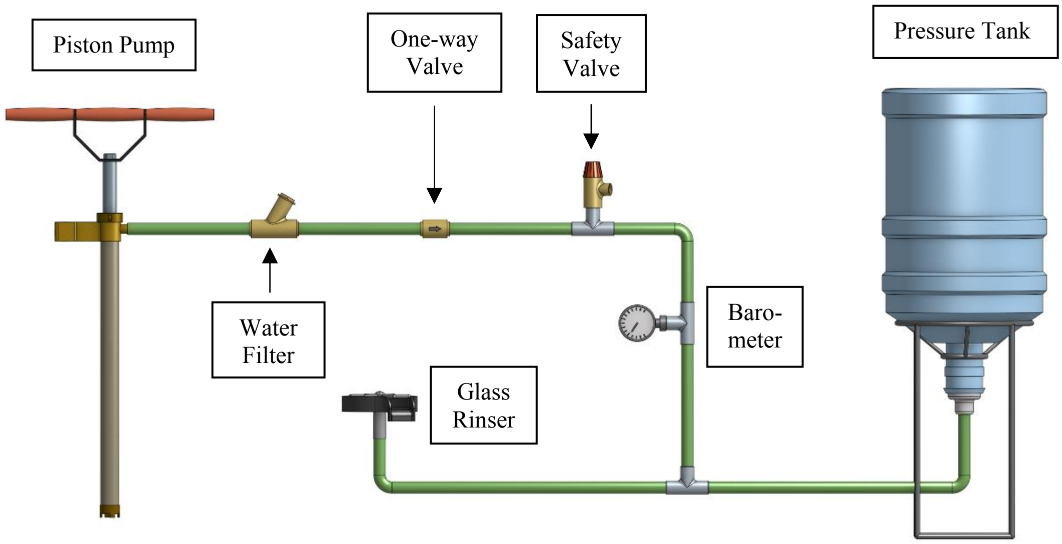

Figure 11: Schematic of the water module utilized to generate water pressure..

3.4.4 Stacking Module

The two concepts that received the highest rankings in the selection process outlined in Chapter 3.2.2 do not require additional equipment beyond the transport unit, which can be either a bag or a crate in case of uncrushed bottles. Therefore, the design presented in this chapter fo-cuses on the third-ranked concept.

In this approach, the bottles are cut using two blades arranged in a cross-like manner. This cutting method allows for the bending of the bottle walls outward while leaving the bottle opening intact. Figure 12a) illustrates the complete mechanism of the cutting tool, which includes an outer tube, inner tube, cutting interface, and a bottle adapter. Joints connect the outer tube with the inner tube, and manual force can be applied through a handle to operate the tool.

Figure 12b) depicts the rotating components of the module. The handle is manually oper-ated by pulling on the lever, and the applied force is then transmitted through the joints to produce a linear motion of the inner tube.

Figure 12c) provides a view of the inner tube and the cutting interface. The U-shaped tube serves as the sled for the cutting interface, allowing for linear movement within the outer tube. Movement along the short axes is restricted by the dimensions of the outer tube. The cutting interface comprises a plate with vertically attached blades. These blades are positioned with an inclination to improve the cutting properties of the sharp edges.

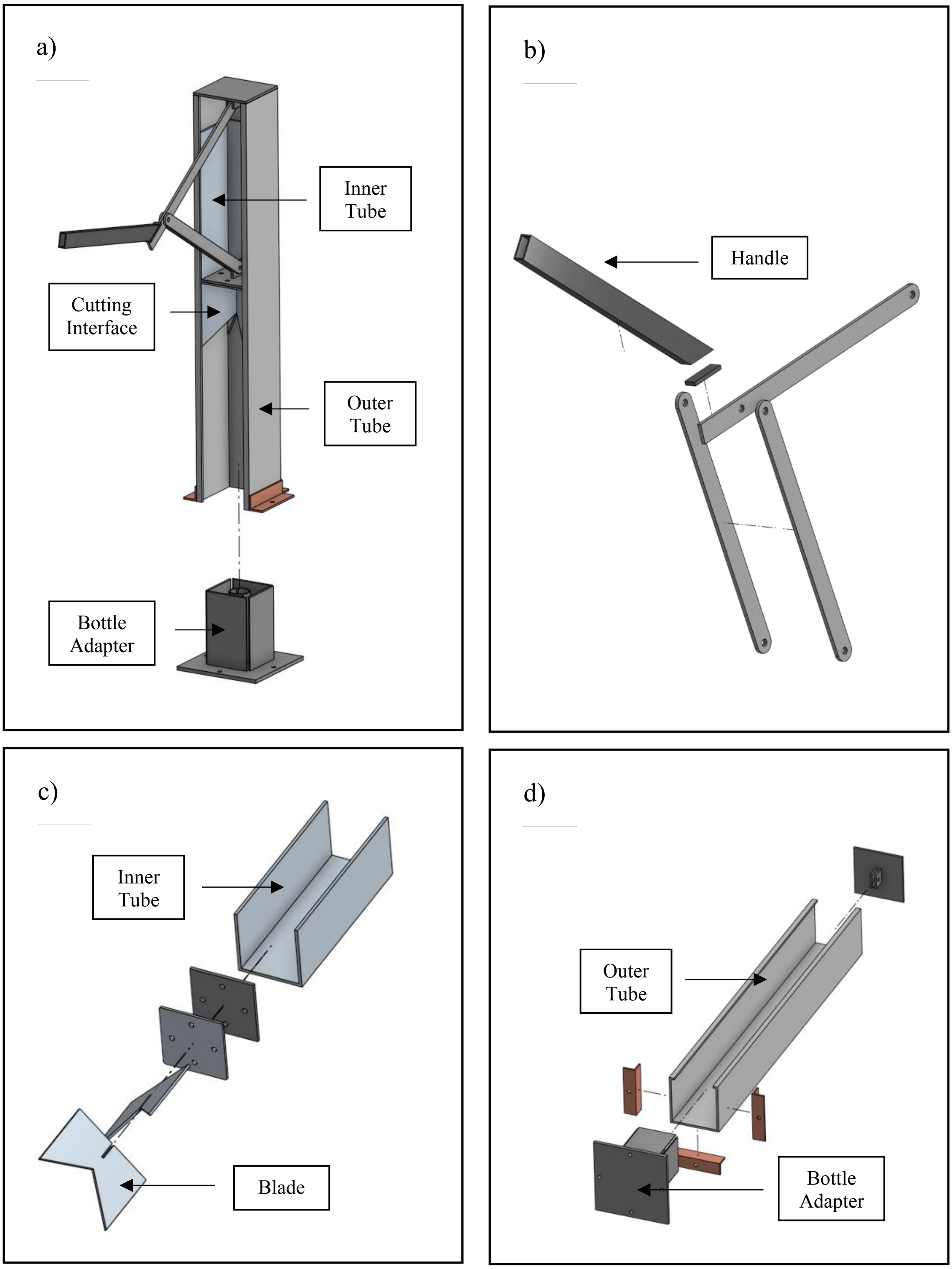

Figure 12: 3D- representation of the cutting module: a) Complete Assembly, b) Explosion view of the handle and joints, c) Explosion view of the inner tube with blades attached, d) Explosion view of the outer tube with the bottle adapter attached

Figure 12d) displays the guide tube of the cutting tool. The U-shaped metal tube that encases the inner tube ensures the linear movement of the sled. To prevent the cutting interface from potentially crushing a loose bottle placed underneath, a suitable counterpiece was designed in which the bottle can be placed upside down. The adapter walls help centering the bottle during the cutting process. Additionally, a metal tube with vertical cuts welded to the adapter creates counterpressure from underneath while pushing the blades through the bottom of the plastic bottle. These measures ensure a clean cut and shield the sharp edges from the user.

Following the bottle cutting process, a visual quality check can be performed to confirm the cleanliness of the bottle. If the bottle is clean, it can be placed on a pole for stacking. Since the bottle opening remains intact and the walls are folded outward, the efficiency of stacking is improved. To facilitate transportation, the poles can be loaded into the truck by sliding them into rails that are fixed on the ground and the sidewall of the truck, as depicted in Figure 13. This design prevents the poles from tipping over during transportation, ensuring safe and efficient transport of the bottles.

Figure 13: 3D-representation of the loading process. Bottles are stacked on the pole and slide into the rail

3.4.5 Wastewater Treatment

The wastewater module has not been fully developed at this stage. There are various potential solutions of different costs to address the issue of organically contaminated wastewater:

- **Sewage System:** One option could be connecting the wastewater to a sewage system if available and feasible.
- **Filling drum for second purpose:** Another possibility is to fill drums with the wastewater and use it e.g. for flushing of toilets or watering plants
- **French Drain:** Consideration could be given to using a French drain system to manage the wastewater, making use of the organic contaminants to nourish plants.
- **Water filtering:** Implementation of a water filtering system to purify the wastewater for reuse.

The selection of the most appropriate wastewater management solution would depend on the preferences and needs of the stakeholders involved in the project. Further discussions and evaluations with these stakeholders would be necessary to determine the best approach for dealing with the organically contaminated wastewater.

3.4.6 Complete Assembly

Figure 15 provides a comprehensive view of the complete assembly of the pre-cleaning station. The manual piston pump located on the far right is submerged into a basket of water (not shown in the figure) and is operated to generate the necessary water pressure for the cleaning process. The subsequent workflow progresses from left to right with the key steps being:

1. The bottles are re-shaped using the inflation module
2. The manual removal of the aluminum lid and the plastic label is performed.
3. The bottle is cleaned as described in Chapter 3.4.1
4. Once the bottle is clean, it undergoes cutting with the corresponding cutting tool.
5. Finally, the clean bottles are stacked on the empty pole for transportation.

This sequential process ensures that the bottles are properly prepared for transport and for the subsequent recycling activities in the facility.

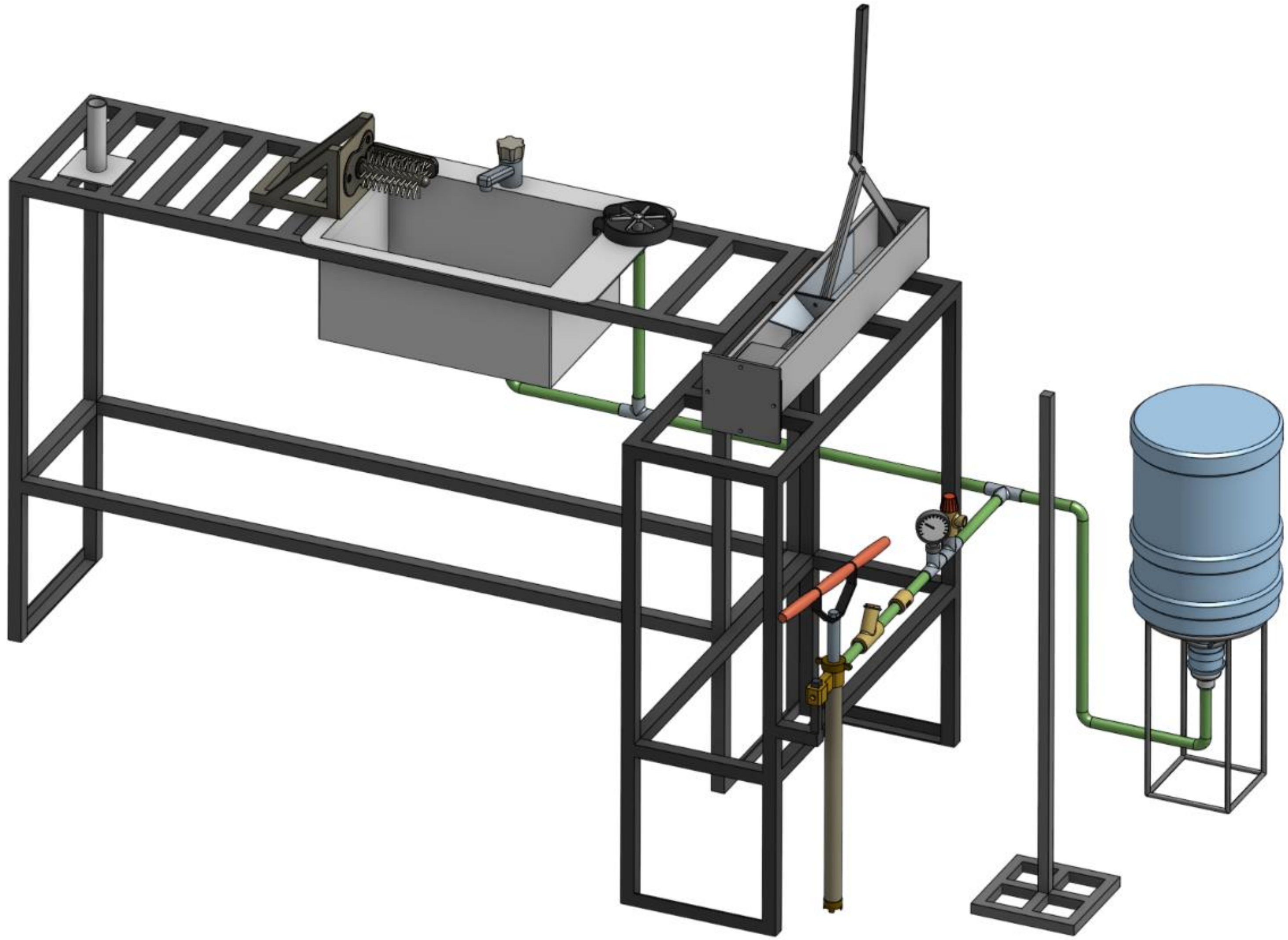

Figure 14: Complete assembly of the precleaning station before focus group discussion.

3.5 Design Verification

In this section, the focus group discussion results are presented, covering various categories of statements received from the tavern mamas. They include the tavern mama's affiliation with the upcoming pilot program for Super Maheu bottle-to-bottle recycling, comments on available infrastructure, their experience with cleaning and cutting bottles, and their ideas for a pre-cleaning station design without any prior bias. Additionally, their feedback on the pre-cleaning setup designed in this thesis is included. The main statements are summarized in Table 7 and Table 8. The summary of the transcribed focus group discussion is listed in Appendix A.3.

Table 7: Summarized user statements coming up in the focus group discussion (Part 1).

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.

Table 8: Summarized statements coming up in the focus group discussion (Part 2).

Category	User Feedback
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.
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 colours (blue and red) • The type of bottle should be displayed in proximity to the setup.

Besides crucial information about the local conditions such as infrastructure, safety of the equipment on site etc., the focus group discussion provided valuable insights into the design of the pre-cleaning station. While the tavern mamas expressed confidence in operating the designed cleaning station, they highlighted the need for optimizing the workflow. Additional storage options were suggested to maximize the use of available space on the workbench. This includes adding plates under the tables for storing dirty bottles and tools like knives for label removal. Vertically arranged pins were also introduced on the working surface to temporarily store bottles that have undergone specific steps, allowing for more efficient batch processing. As a result, the detailed design of the pre-cleaning station was adapted accordingly (see Figure 15).

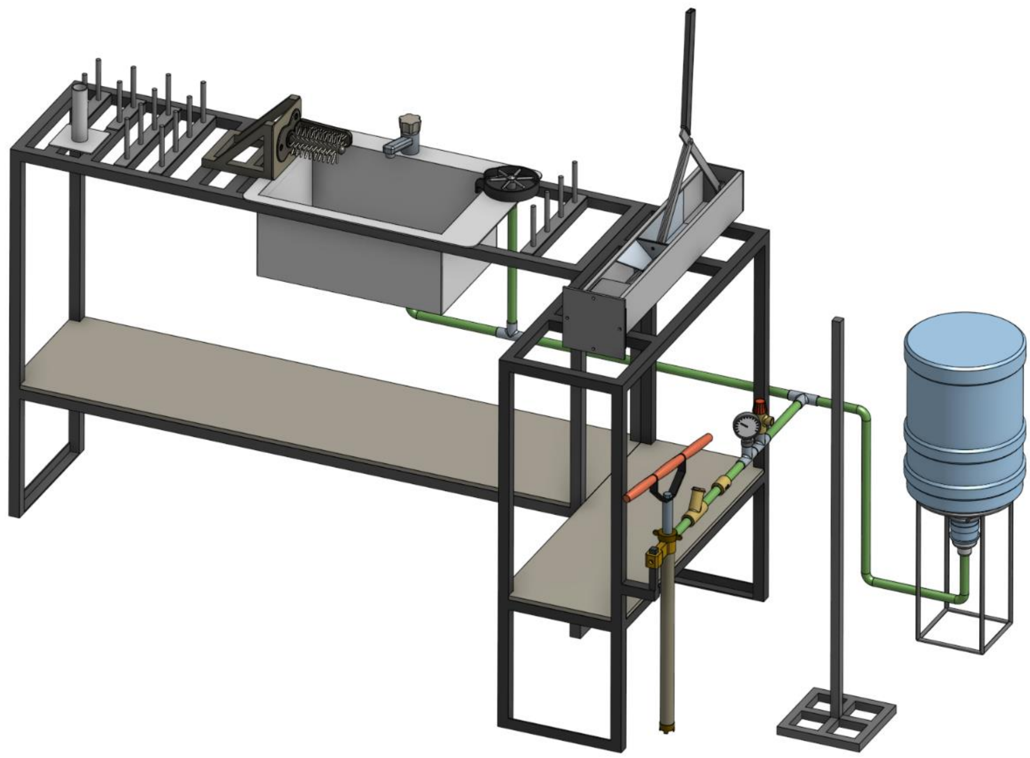

Figure 15: Complete assembly of the pre-cleaning station after focus group discussion.

3.6 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.

3.6.1 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. The materials used for the inflation and cutting module were either purchased from local steel suppliers or fabricated from free scrap metal available at Dynamo, Zurich. Processes such as cutting, drilling, welding, and assembling of these two modules was carried out at Dynamo. The total cost of the Swiss prototype was 560 CHF. This includes both the expenses for the materials utilized in the construction of the prototype and the costs associated with the use of the workspace at Dynamo.

1. **Inflation Module:**

The inflation prototype depicted in Figure 16. was built identical to the design previously presented in Figure 10a). In this phase of prototyping, one out of four Super Maheu bottles, available in this phase, was selected for testing the prototype. The testing involved subjecting the bottle to compression by stepping on with full body weight. To facilitate the reshaping process, the module's ground plate was securely fixed to the workbench using a pair of screw clamps. Several testing rounds were conducted to observe the functionality of the designed module, the operational effort, and the ease to clean the system. The module was able to re-shape the bottles reliably.

Figure 16: First inflation module prototype

The force exerted during this process did not result in any observable physical stress. Furthermore, the designed module was able to restore a bottle to its original shape within a matter of seconds.

2. Water module / Cleaning module:

Figure 17 illustrates the assembly of the water module, showcasing several key components. The manual hand pump is rigidly fixed in a position along a vertical beam, which is interconnected with a footrest. The pump is submerged into a water-filled bucket as part of the configuration. Additionally, the system incorporates a one-way valve and a barometer, with the safety valve yet to be integrated. To maintain intentional pressure control below 2.5 bar, the barometer's readings were monitored during the pumping process.

The pressure reservoir is constructed using a 20-liter plastic bottle made from copolyester, commonly employed in water dispensers. Remarkably, this plastic bottle exhibited no signs of plastic deformation within the pressure range of 0 to 2.5 bar, suggesting its viability as an economical solution for the intended application. Finally, this prototype included the incorporation of the glass rinser as main water outlet. To optimize cost-effectiveness, the setup was intentionally kept simple, and the construction of a dedicated workbench with a sink was deferred to a later stage.

Figure 17: First water module prototype. The glass rinser is connected as primary water outlet.

The water and cleaning modules were tested using the four available Super Maheu bottles, which were manually contaminated with a mixture of syrup and dirt to simulate the consistency and stickiness of organic contaminants. Cleaning procedures involved rinsing the bottles with water jets and subsequent manual brushing. Both the brush and the bottles were manipulated by hand during the cleaning process, which, imposed physical strain over time. In the final product iteration, this issue will be resolved by securely fastening the brush to the worktable.

The cleaning process appeared to be a highly effective method for removing the simulated contamination. In the subsequent phase of prototyping, a more comprehensive evaluation was carried out, involving a larger number of bottles and actual drink contaminants to further assess its effectiveness.

3. **Stacking Module:**

The fabrication and assembly of the cutting tool closely followed the specifications out-lined in the CAD-generated drawings and is depicted in Figure 18. The cutting mechanism fea-tured a single diagonally oriented blade. The bottle adapter effectively secured the bottles in place, ensuring stability during the cutting process. The blade executed the cutting process flawlessly. Given the single-blade configuration, the bottle was temporarily removed from the adapter after the first cut, rotated by 90 degrees, and then reinserted again. The second cut successfully

Figure 18: First prototype of the cutting module. The bottle adapter is re-moved from the guide rail.

achieved the desired cutting shape, preparing the bottle for stacking onto the pole. **F**igure 19 shows a Super Maheu bottle after cutting. One side was manually removed for better visibility.

Figure 19: Super Maheu bottle cut in a cross-shaped manner

3.6.2 Blantyre Prototype

The second prototyping phase took place in Blantyre and lasted for a duration of 5 weeks. Materials required for building the complete setup were sourced and acquired from local steel suppliers, hardware stores, and various markets in town. Only specific components such as the safety valve, brushes, glass rinser, and manual hand pump were reused from the Swiss prototype. The water and cleaning modules were assembled in a workshop at the Malawi University of Business and Applied Sciences (MUBAS) in Blantyre. The workbench, including the inflation module, sink, and stacking module, were manufactured either by specialized engineering companies or local steel workers found at local markets. Excluding the components that were reused from the first prototype, the cost of the Blantyre prototype amounted to 540 CHF. This expenditure covers the materials and the manufacturing costs encountered in the development of the prototype.

Figure 20 illustrates different steps in the manufacturing process, including the sealing of piping components with hemp fibers (see Figure 20a), the attachment of final reinforcements to the workbench by a welder (see Figure 20b), and the spray painting of the workbench with two layers to protect it from corrosion before adding the loose parts to the setup (see Figure 20c).

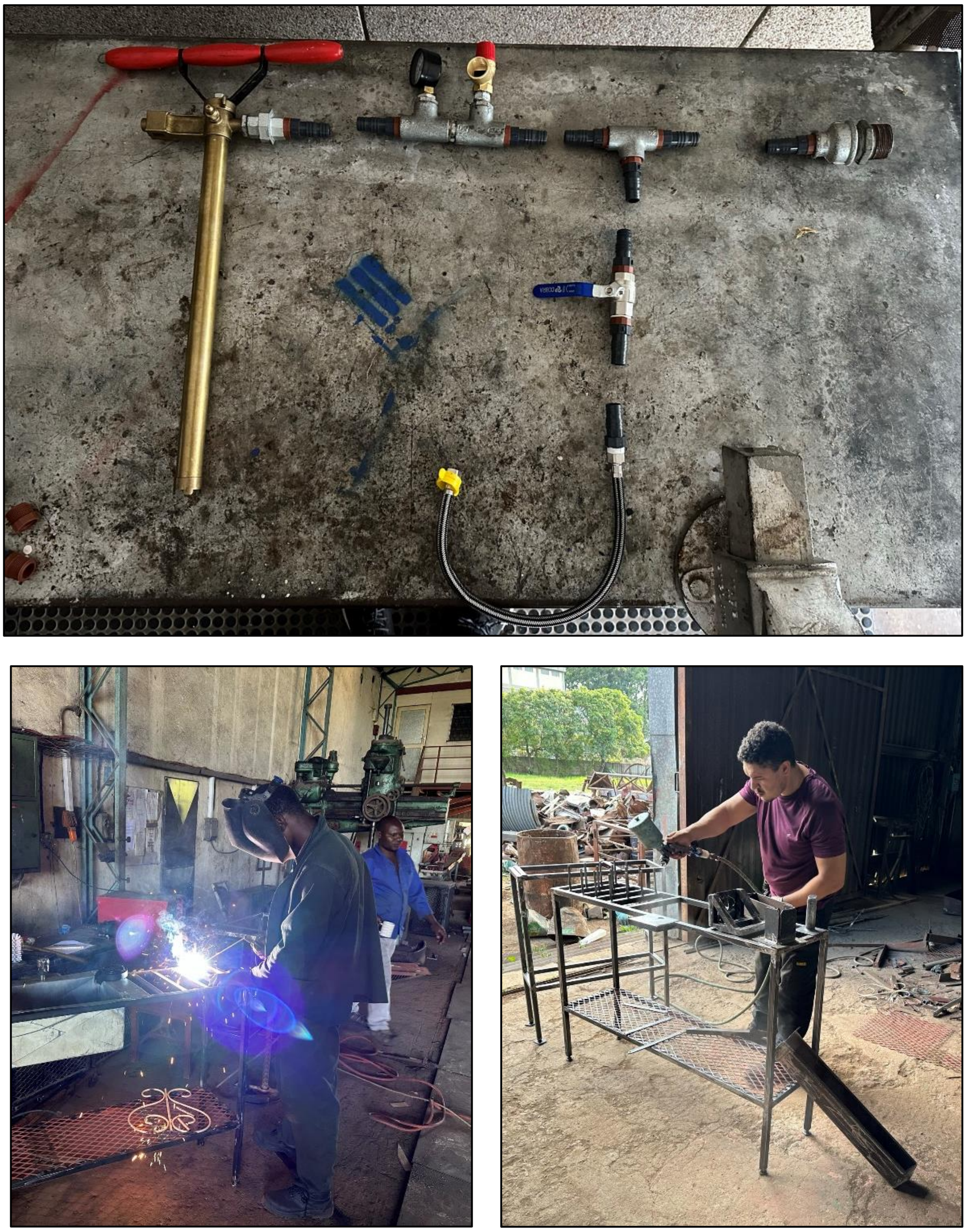

Figure 20: Different stages of manufacturing of the second prototype. a) Sealed components of the water module, b) Reinforcements being welded to the workbench, c) Spray painting of the workbench

Figure 21 shows the complete assembly of the pre-cleaning station. The water needed to operate the system is stored in a 50L drum that continuously fills the bucket underneath the piston pump. The pressure tank is located behind the drum. The tray underneath the sink serves a dual purpose: firstly, it captures wastewater which was directed into a bucket, and secondly, it acts as a storage space for dirty bottles that are prepared for cleaning.

Figure 21: Complete Assembly of the second prototype. All components are included in this prototype.

In Figure 22 a closer view on the main workbench is depicted. From left to right, the vertical tube of the inflation module, the sink with the cleaning interface and the pins for temporal bottle storage are visible.

After construction of the setup, the prototype was evaluated. The testing was conducted at the workshop, where the main workbench was assembled. The experimental procedure utilized a batch of 40 Super Maheu bottles as the test sample. At the time of these trials, there was no operational collection point for Super Maheu, necessitating the procurement of these samples from a local grocery outlet. The liquid contents of these bottles were distributed to students at the MUBAS campus. Following this distribution, the bottles, which retained residual beverage traces, were subjected to a drying period of three days in preparation for the testing phase. In the following paragraphs the test results of the different modules are presented:

Figure 22: Front view of the inflation and cleaning module as installed in the second prototype. The inflation module is located on the left, the storage pins on the right. The cleaning module in the middle includes: Brush, Sink, Tap, Rinser.

1. **Inflation Module:**

Since the bottles were bought in a store rather than obtained by street collection, none of the sample bottles had undergone initial crushing. Consequently, a subset of these samples was manually crushed underfoot and then subjected to re-inflation using the inflation module. This process mirrored observations made with the Swiss prototype, demonstrating that the module functioned both efficiently and reliably. However, a notable difference was the marginally increased diameter of the tube compared to the initial prototype. This variation posed challenges in the vertical placement and manoeuvring of the bottle on the tube. In subsequent iterations of the prototype, the diameter of the inflation module will be precisely dimensioned to ensure optimal functionality.

2. **Water Module:**

In the second prototype, the water module underwent different enhancements compared to its predecessor. Key developments included the integration of a safety valve, the addition of a secondary water outlet in the form of a tap, and the anchoring of the piston pump directly to the workbench, as opposed to its previous attachment to a footrest. During the initial phase of operation, any detected leakages were promptly sealed. This precautionary measure was taken prior to the generation of the main pressure within the system.

After the 5^{th} cycle of pumping water into the system up to 2 bars and releasing water until a pressure of 1.5 bars was achieved, pressurizing the pressure tank to 1.7 bars again leaded to permanent deformation of the 20L plastic bottle. The deformation incident resulted in the base of the bottle, typically concave (inwardly bent), being altered to a convex shape (bent outward). This phenomenon is not uncommon and has been previously documented for PET bottles (D'Agostino, 2019). Although bottle was still intact, the pressure level allowed for further testing was limited to 2 bars for safety reasons (including the cleaning experiment).

Currently, openly accessible results of a pressure test for 20L water dispenser bottles are unavailable. This might be due to the fact, that water dispensers usually are not operated under pressure but rather function with the static force of the water. An alternative realization of a plastic bottle pressure tank was explored by Manohar (2016). The author utilized 2L Pepsi bottles that were designed to contain pressurized carbonated beverages and are reported to burst at a pressure of around 11.4 bars. These bottles might offer a safer solution for the application as a pressure tank in the pre-cleaning station.

3. Cleaning Module:

The cleaning process starts with the removal of material contaminants. First, the plastic label was detached from the bottle. The label consists of a plastic sheet with imprints containing product information on it. A layer of adhesives is used to fix the label to the bottle. The label removal was tested with a peel angle of 90° and 180°. At an angle of 90° the removal process was noticeably straining after a handling several bottles. Expanding the peel angle to 180° was estimated much more convenient as less force was needed. This observation aligns with existing literature, which indicates that the critical force necessary for peeling at a 90° configuration is approximately double that required for a 180° angle. (Bartlett et al., 2023). Nonetheless, in both cases, the label could be peeled off with no adhesive residue sticking to the bottle.

The removal of the aluminium lid presented several challenges. The lid is composed of four distinct layers as described by (de Roiste, 1999). The top coating displays the product name and logo. Beneath this is the aluminium foil, serving as a barrier layer to shield the beverage from external influences. Following this is a plastic tie layer, functioning as the sealant. Adhesives are employed to bridge the aluminium and tie layers, as well as to secure the tie layer to the bottle. During the lid removal process, two primary issues were encountered. First, consumers open the beverages differently. Some gently remove most of the lid in one piece which allows to peel the complete lid off easily. Others puncture the lid, causing the aluminium to be torn into several fragments. This method often leads to the foil tearing along the rim of the opening during the removal of individual lid segments. Consequently, the residual aluminium adheres to the tie layer, posing significant difficulty in its complete removal. In both scenarios described, the primary challenge was not the aluminium itself, but rather the tie layer. After the lid removal, this layer was sticking to the bottles after removing the lid for most of the samples, introducing a material contaminant which could not be addressed by the cleaning setup. This specific issue is illustrated in Figure 23.

Figure 23: Empty Super Maheu bottle. Some aluminium foil and parts of the tie layer remained on the bottle rim.

In summary, the adhesive and the plastic label currently utilized in Super Maheu packaging are deemed appropriate for the subsequent recycling processes. The multilayer lid on the other hand is considered as problematic as it introduces material impurities for the subsequent recycling.

The last step of the cleaning process is the removal of organic contaminants. For testing, the sample bottles were separated into two groups. 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 24a) depicts the amount of water used to clean sets of five dry bottles. In Figure 24b) 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), making the process more resource efficient.

Figure 25a) and Figure 25b) 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.

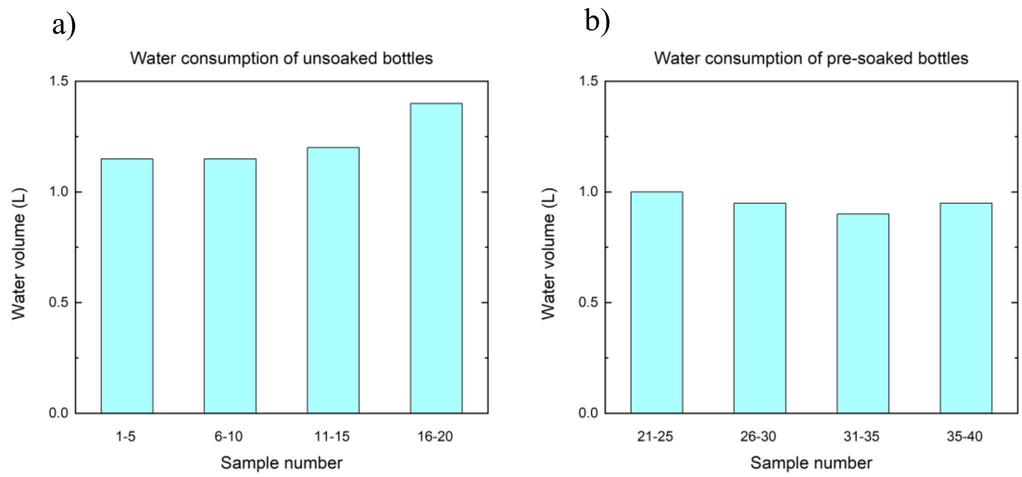

Figure 24: Water consumption of (a) unsoaked and (b) pre-soaked bottles.

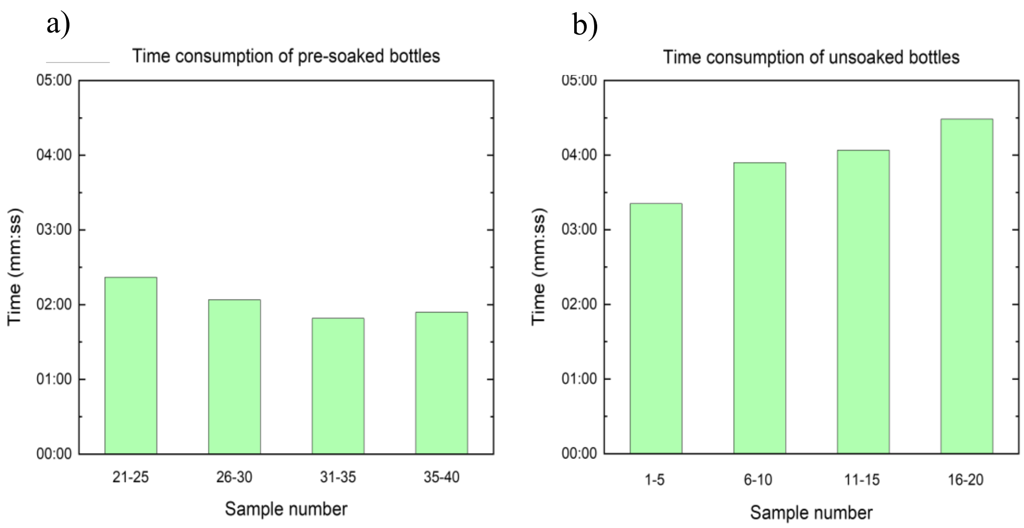

Figure 25: Time consumption of (a) unsoaked and (b) pre-soaked bottles.

Consequently, it is advisable to modify the cleaning process by incorporating a preliminary soaking step after the bottle reinflation. With this process, a water consumption rate of 0.2l per bottle with a cleaning time of 24 seconds per bottle can be achieved. The water used for this step does not need to be fresh, since the removal of contamination follows the soaking process.

4. **Stacking Module:**

Finally, the cutting tool built in Blantyre also showed some problems. In comparison to the first prototype, the blades were not able to penetrate the bottom of the bottle even when introducing 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 two. 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 little resistance to cutting manually.

3.7 Discussion

The design of the pre-cleaning station for HDPE bottles in low-income countries was realized through a methodical product development process. This structured approach facilitated a comprehensive analysis of the target user and the product environment. It also enabled the objective selection of the most viable concept for addressing the identified problem. The thorough documentation ensured that the design team, project board, and various stakeholders maintained a complete and clear understanding of the product's progress and specifications, enhancing the decision-making progress throughout all phases.

Through engaging discussions with WASTE advisors, Chibuku company, and the project board, essential insights were acquired, guaranteeing the design's compatibility with the low-resource environment. Additionally, a focus group session with the users of the pre-cleaning station provided inputs for design enhancement, addressing specific concerns and requirements highlighted by the participants.

The prototyping stage was carried out in two distinct phases, each offering valuable insights. The initial set of prototypes focused on evaluating the overall functionality of the designed modules, which were deemed apt for their intended functions. The subsequent phase of prototyping, conducted in Blantyre, revealed a number of issues. First, the pressure vessel, constructed from a 20L water dispenser bottle, exhibited signs of plastic deformation. This is a concerning issue in any pressurized system, as repeated cycles of deformation could further weaken the material, potentially leading to a catastrophic burst failure. To safeguard worker safety, it is imperative to incorporate a more robust pressure tank. One potential solution, as suggested by (Manohar, 2016), is to utilize plastic bottles specifically designed to withstand pressurized conditions. Alternatively, a steel pressure tank could be employed. This option might involve repurposing an old fire extinguisher or a gas tank. If stainless steel is not readily available, it would be advisable to apply a protective coating to the interior of the tank to prevent corrosion, thereby enhancing its longevity and safety.

After observation of the deformation in the pressure tank, the maximum cleaning pressure was limited to 2 bars. While visual assessment indicated that the bottles appeared clean at this pressure, the application of higher pressures could potentially yield better cleaning results in a shorter timeframe. This emphasizes the necessity for a more robust pressure tank capable of safely withstanding higher pressures.

Subsequently, the process for the removal of material contaminants was thoroughly examined. Although the label was easily peeled off, the multi-layer lid posed significant challenges. The remaining contaminants primarily consisted of adhesive residues from the seal, the tie layer, and potentially some remnants of aluminum. Therefore, further investigations are essential. These should either focus on identifying and developing processes capable of efficiently removing these specific contaminants or alternatively, consider a revision in the packaging process itself. Modifying the packaging method could potentially facilitate easier detachment of all components of the lid.

Finally, an alteration in the bottle's thickness was noted, leading to a malfunction in the stacking module. The existing cutting tool was unable to slice through the bottle as originally designed. Consequently, this necessitates a reconsideration of either the cutting pattern or the cutting process itself, to effectively transform the bottle into a state suitable for stacking. In addition to addressing the immediate issue with the cutting tool, it would be worthwhile to investigate the underlying cause of the increased bottom wall thickness. Understanding the reason for this enhancement is crucial to ensure that the production process is not using more plastic than necessary.

The pre-cleaning station developed for Super Maheu bottles presents a straightforward and effective method for cleaning used bottles. A key advantage of this station is its operational independence from electricity and running water, relying solely on sufficient water storage. The designed pre-cleaning station, with a production cost of 540 CHF, is appropriate for utilization in a low-resource context. However, expanding the project budget and loosening constraints to include resources like electricity – potentially sourced from photovoltaics and stored in batteries – could significantly enhance the station's efficiency, and overall user experience.

4 Conclusions and Recommendations

In this thesis, the implementation of a bottle collection and pre-cleaning station for HDPE bottles is investigated. This work is part of a PhD project conducted at the Chair of Global Health Engineering at ETH Zurich and aims to design and prototype a suitable solution to prepare dirty post-consumer bottles for mechanical recycling. The project develops a solution for a beverage company in Blantyre, Malawi, but the modular and simple design is intended to be translatable to other low-resource contexts.

The current work focuses on a maize drink in an HDPE bottle produced by Chibuku Products Ltd, but future work could be done to test the applicability of the solution for other drink or bottle types. The project benefits from access to a space at the Chibuku taverns, which are offered as a collection point for the Super Maheu bottles. These taverns are managed by tavern mamas who will act as one the main users of the pre-cleaning station.

A methodical development approach is selected for the desired setup and ensures user-centered design. This approach facilitates comprehensive documentation at all stages and acts as a portfolio for the decision-making process of the design team, project board and stakeholders. Various concepts addressing specific tasks within the pre-cleaning process are developed and the most suitable approach is objectively selected based on a numerical rating system. The chosen concepts are refined, embedded in the system architecture, and transformed into a detailed design using CAD software.

The detailed design comprises five different modules that were each developed independently. The inflation module re-shapes crushed bottles. A water module manually generates water pressure used in the subsequent steps of the cleaning process. The cleaning module consists of a stationary brush capable of brushing the inside and outside of a bottle simultaneously, a glass rinser propelling jets of water into the interior of the bottle, and a tap. Cleaned bottles are cut with a tool to enable efficient stacking for transport on a collection truck.

As the main users of the pre-cleaning station, the tavern mamas were interviewed in a focus group setting. They confirmed their affiliation with the project and were confident about the proposed design. New ideas discussed during the focus group discussion could be directly implemented in the present design.

The prototyping was conducted in two phases. A proof-of-concept prototype was built in Switzerland, providing initial findings that all modules were functional in the developed system. Further investigation was conducted on a second prototype at the study site in Blantyre to extensively test the design and investigate the interactions between the modules.

During this phase, various challenges were identified. The 20L plastic bottle used as a pressure vessel was not suitable for long-term use, as plastic deformation occurred below the operational pressure. As a result, the experimental pressure had to be set lower than planned. The effectiveness of the cleaning module was compromised due to the inability to achieve the desired water pressure, marginally reducing efficiency compared to the prototype developed in Switzerland. Additionally, the cutting tool faced difficulties in penetrating the locally purchased bottles. Between the design of the module and its implementation, the plastic thickness of the Super Maheu bottle base has increased by a factor of two. Finally, significant issues were encountered in the removal of the multi-layer lid from the bottles. A key challenge was the strong adherence of the tie layer to the bottle, frequently resulting in residual material attached to the bottle.

Based on the findings from the prototyping phase, several key revisions have been identified to enhance the system's functionality and safety:

- The current pressure vessel is prone to burst failure and should be replaced with a safer alternative. Options include re-using plastic bottles from carbonated beverages or employing standardized pressure tanks. These alternatives not only offer increased safety against burst failure but also have the potential to withstand higher pressures, thereby improving the overall efficiency of the cleaning process.
- A lab study could be done to determine the plastic purity needed for recycling. If needed, a suitable process to scrape away residual pieces of the lid could be developed. Alternatively, changes to the packaging process could be discussed with Chibuku Products to ensure easy removal of the lid.
- If the current increased material thickness of the bottles persists, the cutting tool will require a redesign. This redesign should explore alternative cutting patterns or different cutting methodologies to ensure efficient use of transport space.

The pre-cleaning setup was designed within budget and time constraints for a low-resource context without access to electricity. Future work could be done with an extended pilot of the proposed setup to ensure that cleaning efficiency and user experience are satisfactory. With the suggested revisions, the evaluated prototype can serve as a low-cost tool for the closed-loop recycling pilot in Blantyre with Chibuku Products.

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A Appendix

A.1 Needs-Metrics Matrix

Need No.	Need Catgory	Needs / Metric No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
		Metrics	Young Modulus of steel parts	Stability / Balance upon use cycle	Force needed to bring the system to fail	Amount of moving parts	Percentage of exposed corrosive parts	Corosity Resistance	Time needed to replace essential parts	Lifetime span of device	Windresistance / Inertia (windspeed without falling)	Displacement reached by one person upon pushing gently	Amount of loose parts (incl. Equipment)	Amount of fixation points of complete device to ground	Equipped material costs	Percentage of visible contamination after cleaning	Bottle specific volume	Adjustablilty to different bottles	Development Costs	Manufacturing Costs	Amount of imported parts	Costs of imported part	Time needed to treat one bottle	No. of steps needed to treat one bottle	Functionality ensured without electricity	Functionality ensured without running water	No. of people needed to operate the device	Mechanical Force required to operate the device	Height where mechanical input is applied	Time needed to clean the device	Time needed to remove the device from ist fixed location	Height of the device	Width / Length of the device	No. of harmful spots the user is exposed to	Level of accident protection	Exposure of waste to living organisms on the surface	Amount of water used to clean one bottle	Duration of contact between user and contamination per bottle	Level of self-explanation of the device	Clarity about the belonging of the device	Level of visual appealingness
1	Materials	The device withstands operational forces without failure	x	x	x																																				
2	Functionality	The device minimizes the amount of error sources				x																																			
3	Materials	The device is not susceptible to corrosion					x	x																																	
4	Useability	Damaged parts can be easily replaced							x																																
5	Functionality	The device is functional over many cycles								x																															
6	Stability	The device is sturdy enough to withstand strong wind and external pushes									x	x																													
7	Stability	The device is protected against theft											x	x	x																										
8	Functionality	Cleaned plastic bottles fulfill the standards of the recycling facility														x																									
9	Functionality	The clean plastic bottles use the transportation space efficiently															x																								
10	Functionality	The device is adaptable to different types of bottles																x																							
11	Costs	The development costs do not exceed the budget boundaries																	x																						
12	Costs	The overall production costs do not exceed the budget boundaries																		x																					
13	Costs	The device consists of only locally accessible material																			x	x																			
14	Useability	The device allows for quick cleaning of plastic bottles																					x	x																	
15	Functionality	The device can be operated with limited access to electricity																							x																
16	Functionality	The device can be operated with limited access to running water																								x															
17	Useability	The device can be used by a single person																									x														
18	Ergonomics	The device does not demand for specific strength requirements of the user																										x													
19	Ergonomics	The cleaning process is comfortable for an average sized person																											x												
20	Useability	Cleaning of the device is done quickly																												x											
21	Functionality	The device can be dismounted to be temporarily stored inside																													x	x									
22	Geometry	The device fits into the storage rooms of the taverns																															x								
23	Safety	Parts that could harm the user are designed properly to prevent accidents																																x	x						
24	Safety	The accumulated waste water and particles do not harm the environment																																		x					
25	Ecologics	The cleaning process uses low amounts of water																																			x				
26	Safety	The plastic bottles can be cleaned without contact between user and the contamination																																				x			
27	Aesthetics	The appearance of the device attracts the user to operate it in the planned manner																																					x		
28	Aesthetics	The design conveys the connection to Chibuku and the taverns																																						x	
29	Aesthetics	The design is visually appealing to workers, tavern clients and pedestrians																																							x

A.2 Target Product Specifications

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	Number 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	Wind resistance / 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 / m^3	> 250	300
16	Adjustability 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

A.3 Focus Group Discussion (Summary)

SECOND TAVERN VISIT

4th October 2023

The bellow report contains findings from first tavern meeting with tavern mamas as a focus group discussion

Registration of participants

Name	Selling point	Role
Veronica Awame	Chilobwe tavern	Chairperson
Rose Chimombo	Mbayani lower	Secretary
Irene Malata	Argentina Tavern	Chairlady
Jenifer Paulo	Ndirande Urban	Treasure
Esnarth Kadango	Limbe Tavern	Regional chair
Margret Mwase	Mbayani Upper	Vice Secretary
Agness Charles	Ndirande Lower	Vice Chairlady Ndirande Lower

The following table records responses from the discussion held

Explain the whole cleaning and storage process	Generally; cleaning materials are mostly sourced by the tavern mamas. Most of these tavern has tap water and where the pipe water isn't functioning they alternatively buy from nearby selling joints. Upon delivery the beer is stored in their storage facilities to be sold 3 or four days later as most customers prefer it like that. Before giving beer to customers mamas have to clean it first.
What are hygiene related issues and risks encountered before?	There have been cases in most of these taverns before where customers threatened to sue these sellers over allegations that they were selling beer below hygiene levels; i.e. customers complained about bottles having urine, petrol and even condoms stinks
Where do you get water? Beside here are there alternatives?	Every tavern has tap water for the majority of these taverns. In cases where tap water isn't functioning they purchase from nearby selling stations. .:these other taverns had piped water but now they are no longer functioning
What happens if there Is no piped water?	As earlier said most of these taverns have piped water**. Limbe tavern, lower mbayani tavern, ndirande upper and lower taverns,**

	argentina tavern have functioning taps. Alternatively the other taverns use drums and basins for cleaning.
How do you think a collection and pre-cleaning point could look like?	Majority of the responses holds that there should be 3 stations for this exercise; a station where all collected bottles should be put and further to that a sink that will be used for the actual cleaning of the bottles. Additionally, there should be the other part where cleaned bottles will be put after cleaning.

The below table accounts for responses the tavern mamas gave with regard to user needs.

How user friendly do you think the designs above might be?	Mamas from all selling joints view these designs very user friendly. They feel this is easy and not too involving since they will be only operating, having trained and the machine will do the rest.
What do you think about having cleaning station for bottles at a tavern? And possible issues that you think may come from it.	All tavern mamas present were delighted to hear such an innovative idea and they view this as a good development. The only possible issue the feel may come from it is that of vandalisation of such an innovation.
What are ways that we could prevent this new cleaning station from disrupting your tavern operations?	Here, majority of the mamas believe that this station needs to be placed near to their operating points for easy multitasking. They believe the remaining part is the issue of properly managing time but there won’t be any disruption of operations
What would be the best place for washing equipment for the super maheu bottles?	**Mbayani Lower tavern mama** would love to have the station in one of their storage rooms. The 8 by 5 meters room is probably their bigger store room and where the tap is placed hence the tavern mama hopes this fits for the initiative. Likewise, **Mbayani upper, Limbe, argentina, Ndirande upper and lower taverns** would love to have this station in one of their storages and mostly close to their selling side for easy multitasking of operations.
What should the collection point not look like? What to avoid within the looks (messy, ugly etc.)	Here the response of the majority is that the collection point should look familiar with their chibuku colours. And most importantly they should be well placed.
Does anyone working at the tavern have experience in using tools? How strong do you	All tavern mamas present have no experience in using the tools.

estimate you or any workers within your tavern rendering a helping hand during operating the machinery?	Also the majority of the mamas present believe the guards would love to help in operating the machinery but they would prefer to work alone in order to take a very good care of the property.
What ideas do you have to motivate people to collect and wash super maheu bottles here?	Here the response of the majority of mamas believe that money is the biggest motivation. They also suggest posters be posted to let people know about the bottle collection exercise
Any idea on how to make the equipment appealing?	All the mamas present hold that the equipment should have the colors their companies use.

The following table gives responses the tavern mamas gave on the issue of usability during the focus group discussions.

Have you ever had issues with cutting process i.e. the use of knives?	The common issue in all tavern mamas present is being cut by the knives used
What do you do to prevent injuries and ensure safety?	The common precaution the tavern mamas use is concentration when cutting the packets
How do you cut the bottles open?	Commonly there are two ways these tavern mamas cut the packets; they either use cellular in cases where a customer is drinking alone or round if two or three customers are drinking as a group
Have you ever seen a pressurized tank before? And who was using it?	Here most of the tavern mamas have seen the tanks before and some have eve used them. Mostly they have seen them in nearby areas and some used them during the days they were selling a certain beer brand (Jive) sometime back.
Is this brush design something you could see people using? How easy would it be for people to use to clean bottles?	The majority response was that they have never thought about it but they are all excited to see such a development edging towards their field. The tavern mamas feel having taught on how to operate them, they will find it easy and relieving to use to clean bottles.
How do imagine managing a collection point? Is there a time window where you could be available to oversee? Would people be interested in helping?	The tavern mamas present are excited with the imagination of managing the collection point. All tavern mamas present feel there will be enough time to oversee the whole collecting process. Another uniform response is that the guards will be willing to help

The last table below accounts for the additional logistical responses the tavern mamas gave during the focus group discussions.

How big Is the space that could be available on the site?	**Mbayani Lower** about 8 by 5 meters **Mbayani upper** about 5 by 4 meters **Limbe, ndirande upper and lower tavern, argentina and chilobwe** estimates atleast 6 by 5 meters spaces
Is there an outside tap water connection?	Only **chilobwe** and **ndirande upper** taverns had this facility but c**hilobwe'**s was vandalized and **ndirande upper** only remains with it. The other taverns have no such outside tap water connections.
Where does your wastewater go from the sink flow?	Some taverns have no such things. For **mbayani lower, limbe, ndirande upper** the wastewater go through the system and lead them to the manholes designed.
Where does the rainflow when it is heavily raining?	Some taverns like **limbe** the water spreads to some parts of the market. But for some taverns like **mbayani, ndirande** and **chilobwe** go down to the livers behind the taverns.
What is the safety of the taverns like throughout the day? Are there times when it is not safe around the taverns?	Here the common response was that there is security around the taverns though the measures and enforcements aren't tight.
When would be the highest danger of equipment being stolen and what do you do to prevent things from being stolen?	Here the answer is common in most of these taverns. There cannot be such cases since there are guards assigned to look after security of the taverns. Additionally, some taverns are located near police stations and this adds to the security of these places.
How much locked storage space do you have? How many rooms? Is there extra space to store some critical tools inside overnight?	All storages are always locked and big enough. For example; **Chilobwe**: They have 2 stores **Mbayani**: They have 4 rooms **Limbe:** They have 3 storage rooms **Ndirande lower and upper** have more than 3 store rooms. The store rooms are spacious and they have enough space for some critical tools.
Do you think there is space to store stacks of clean bottles until chibuku trucks collect them?	Here the common response is that there are spaces in all taverns to store stacks of clean bottles until trucks collect them.
How often do chibuku trucks come to your tavern?	Here there is a common response; chibuku trucks comes daily unless there is a fault somewhere.

ETH

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