Washing solution in the aftermath of natural disaster

Final Masters Project Technical Report

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Project Abstract

This project presents a solution for washing clothes in areas affected by natural disasters where access to power and water are limited or non-existent. A modular washing machine kit is proposed where the user would be able to turn a basin into a washing machine. The first module is a washing drum with a manual agitator and a second module is a filtering system to allow the water to be re-used and allow for the use of different types of surface water. The User Centred Design Methodology by IDEO.org and Jugaad Innovations were used as the basis for design believing that they would frame the design to ensure that they would meet the user requirements established. The resulting process is an efficient way of cleaning clothes with the least amount of water possible and utilizing the materials available to users.

To ensure that the function is executed properly the user should place the drum inside a basin, possibly a bin and fill it with clothes, detergent. If the water is not from the governmental pipeline, as in was obtained from lakes, rivers or the sea. The filter should be placed on top of the drum and later enough water to cover the clothing should be added. They should then agitate the water for 10 minutes ensuring that every article of clothing is circulated within the drum. After the 10 minutes, the inner drum should be lifted and placed on the drum attachments to drain the water and later placed on the floor next to the basin. The basin should be emptied, if the water was not from the pipeline this should be done into the bucket used to collect the water. Then, the drum should be placed in the basin with the filter again, the water should be added from the bucket and the clothes should be agitated once again for another 5 minutes. This rinsing process should be repeated at least once, until all the detergent has been removed from the clothes, before completing the wash to ensure that the clothes are properly cleaned. Once the second rinse cycle is completed the water should be drained and the clothes can be wrung and hung on a cord to dry. This process protects the clothes from the damage they would be subjected to when being washed by hand as it avoids excessive friction and it sanitizes the clothes quickly and effectively.

Objectives

The intent of this product is to facilitate the washing process in areas affected by natural disasters such as hurricanes.

General Objectives

- Provide a solution for washing clothes when there is a lack of power from the power grid and water.

Specific Objectives

- Provide an off the grid solution for washing clothes in disaster struck areas.
- Provide a low-cost way to wash clothes.
- Provide an efficient alternative to washing clothes with a washboard or by rubbing them together.
- Deliver a mobile, or portable solution.
- Utilize items readily available to users.

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I would like to thank my advisors and mentors for guiding me through this process, helping me learn about new topics and allowing me to grow as an engineer and designer. Your advice and support were instrumental in ensuring the success of this project.

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Introduction

On September 20th, 2017, the island of Puerto Rico was devastated by hurricane Maria, and thousands of people were left without power and water for weeks. Weeks earlier, Texas was destroyed by Irina, years previous New Orleans had Katrina and Florida had Harvey. These natural disasters are a common occurrence in these areas and have become a part of their history and culture. Houses are designed to withstand stronger winds; cyclonic patterns are analyzed from the moment they form, hurricane season is marked in every calendar, and people begin to prepare for a hurricane, weeks in advance. While people try to prepare as best they can, the actual impact of a hurricane can never be properly estimated, the government's attempt to prepare for the aftermath but predicting the impact of the hurricane and the problems that the public will face is nearly impossible. In cases like Katrina, Irma, Harvey and Maria people may be without power or water for days, weeks and even months. This lack of power and water affects the daily life of all who live in those areas, from cooking, and cleaning, to being able to get around their communities, some people can't even get out of their homes for the first weeks.

One of the issues faced by people is the difficulty with washing clothes. In these situations, many companies like Tide have created movements like *Loads of Hope* where they take a bus with a generator and washing machines to disaster-affected areas and allow people to wash clothes. The main objective of this project was to design a comfortable way to wash clothes in these disaster-affected areas, therefore eliminating the need for movements such as this. Through iterative design, a modular washing kit was created in which one module would be composed of a washing machine that could be operated manually. A second module would be a filter that would allow the user to purify and recycle the water necessary for washing. Some of the features of this product include a reduction in water consumption and the ability to be operated with objects easily accessed by the users.

Problem Statement

The first of June marks the beginning of hurricane season and with it a period where people who live in the tropics are constantly preparing for a natural disaster. When these hurricanes make landfall, they leave in their wake destroyed homes, neighbourhoods, businesses, and a weakened infrastructure. It is after the storm that the real work begins, the fallen infrastructure leaves thousands of people without power and water for days or even months, many times people can't even leave their homes. The recovery process can be arduous and exhausting, people are generally focused on restoring their houses, businesses and communities. This work requires a lot of effort and can be very exhausting physically, mentally and emotionally, after a long day the feeling of being clean is a small pleasure that is can be a privilege.

An important aspect in feeling clean is having clean clothes, with limited resources (power, water, time) cleaning clothes can be an issue. Washing clothes by hand require a lot of water which can be hard to come by, it takes a lot of time and effort, resources that people in these conditions do not have to waste. In the past people have solved this issue by using washboards and buckets, going to rivers and lakes or connecting a washing machine to a generator which wastes a lot of resources, not just energy but also water.

Design Process

The IDEO.org Human Centred Design Handbook was used as the basis for the initial design process, in which the first step is to frame the design brief. In this initial challenge, the designer attempted to fully understand the problem at hand and to postulate a design challenge that would lead to a solution. The main challenge at this stage was avoiding being too specific, if the challenge was framed improperly it would lead to one specific solution that may not necessarily be the optimum option. Therefore, the brief had to be stated properly to be open to various possibilities and limit the designer's bias. A design question was proposed: How might people wash their clothes when they have limited resources? Based on this question, the impact of the design brief was envisioned as allowing users to wash their clothes after a natural disaster. Ideally, they would be able to do this with limited effort and as efficiently as possible. Some possible solutions would be the use of renewable energy to power a washing machine, the use of kinetic energy, the collection of rainwater, or atmospheric water generation. All these ideas were evaluated separately and they, in turn, led to further research into other possible solutions such as the use of nylon beads. One of the most important constraints for the resulting product would be the need for it to be cost-effective and easy to use. Because the underlying problem is the country's debilitated infrastructure, it was important that the designer work with the resources that would inherently be available to the user. The use of solar power although studied proved to be unsuccessful due to the inefficiency of solar panels, although the technology is improving, and in a few years, they may become a viable option, the options available today would require a very large solar panel to power the washer and it would not meet the design criteria.

Inspiration was also taken form Jugaad Innovations in the hope that this would provide a cost-effective and innovative basis for the design process. Jugaad is an innovative method that is based on three principles: frugality, flexibility and inclusivity. Meaning that a Jugaad design must reduce cost as much as possible, a solution must be versatile enough to be able to be used in different ways and it must be available to most of the population, focusing especially on those in extreme situations. This methodology allowed the designer to think from the perspective of low-income communities and opened the design to a new market. Although primary users would be those in developed countries where natural disasters are common a secondary user group would be developing countries where the power grid is unreliable like Pakistan, India and Bangladesh.

Some of the initial concepts for this project included a solar-powered washing machine, which would essentially be a smaller version of the product that is found in most homes but powered by sustainable energy source to not require a connection to the governmental power grid. Another idea, was to create an alternative power source and water source for the existing washing machine, therefore converting it into a usable product during this time of emergency. Other ideas included the generation of water and electricity to power an existing washing machine and creating an impeller that could turn a basin into a washing machine. A list of requirements was compiled and used to evaluate the methods currently used to wash clothes, these were studied and used to establish possible design concepts (figure 1).

Methods	Benefits		Disadvantages			
Top-loading	Easy Seal	More comfortable	More resources	Size		
Front-loading	Smaller	Efficient	Seal			
Board	Manual		Time	Resources	Drying	
Rocks	Manual		Time	Resources	Drying	Bad for the environment
Beads	Less Water	Less Detergent	Specific Process	Cleaning the beads		

Figure. 1 Washing methods

While the initial concept was to create a washing machine that could be operated without the need for a generator, further research into this concept proved that this idea would not meet the user requirements. Additionally, detailed research into the aftermath of past natural disasters revealed that many of the people in these situations have added solar panels and generator to their homes, to power the most important appliances.

Consequently, a decision matrix (figure 2) was created to evaluate all concepts and the final concept was selected. In this decision matrix, each decision criteria or requirement was given an importance rating from one through five, one being the lowest importance and 5 being the highest importance. The different ideas were evaluated on whether they met the criteria, -1 for not meeting the criteria, 0 for meeting the criteria and 1 for exceeding expectations.

	Criteria							
	Cost	**Portability**	**Size**	**Energy use**	**Water**	**Effort**	**Load capacity**	
Ideas	5	4	4	5	5	3	3	**Total**
Solar washing machine	-1	0	0	0	-1	1	0	-7
Energy and water generation	-1	-1	-1	-1	-1	1	1	-17
Kit	1	1	1	0	1	0	0	18
Washing Beads	-1	-1	-1	-1	1	1	1	-7
Impeller	1	1	1	0	0	1	0	16

Figure. 2 Decision matrix

The concept selected was the creation of a kit that would turn a basin into a washing machine, this would be a modular product that would consist of a washing drum, and a filter to ensure that the water used does not damage the clothing. This filter would also allow the user to re-use the water making this kit maximize the resources available. Although the concept of an impeller that would agitate the water within any basin to allow for washing resulted as a viable option as well, the kit was selected due to its ability to operate without power. The impeller would require a motor which in turn would restrict the design. The washing kit, on the other hand, allowed for more exploration in the design process and expansion into more complex concepts.

To better understand the user and further evaluate the viability of the concept selected interviews were conducted. The results of which proved that the intrinsic issues with washing clothes were the amount of water, time and effort it required. Later, a business model canvas was developed, shown in figure 3 to display the proposed business plan for this product in the existing market. Created by Alexander Osterwalder a business model canvas is a strategic management and entrepreneurial tool, used to describe, design, challenge, invent, and pivot a business model. The idea behind it is to present all the primary components of a business venture or entrepreneurial idea. This canvas was used to visualize the marketability of the selected concept, it is divided into 9 sections which include the key partners necessary to ensure the success of the product. The value proposition, which is the value presented behind this idea, the concept's unique selling point. The cost structure and customer segments or description of possible users. It also displays the customer relationships which details the way that this business will contact its customers. Furthermore, the key resources display the resources required for the success of the business venture. The key partners segment represents the companies and associates that will be needed. In this canvas the different business decisions taken to ensure the feasibility of the product and guarantee its success.

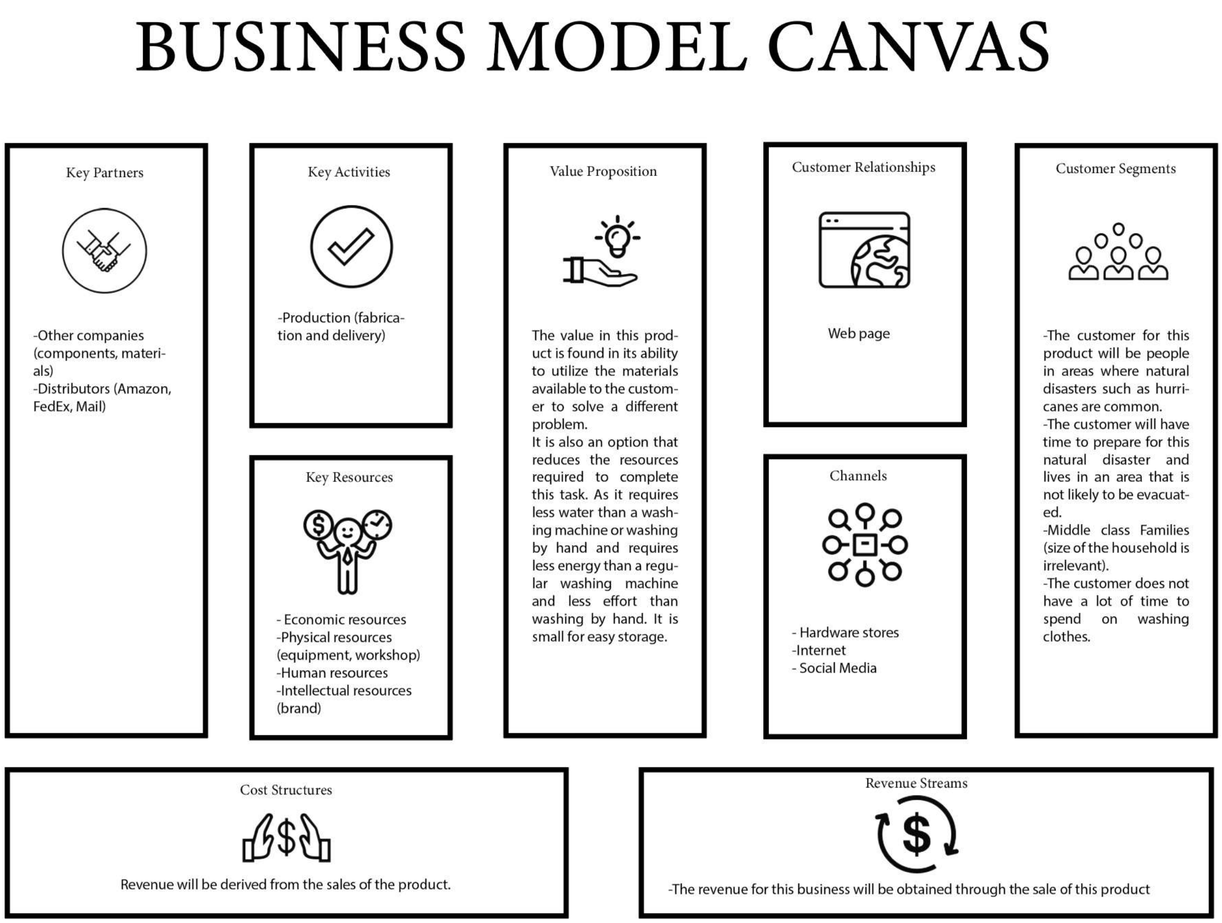


Figure. 3 Business Model Canvas

In the business model displayed above the user is defined as people in developed countries that normally have access to power and water but have been cut off from these due to a natural disaster such as a hurricane. Upon a detailed study of the potential customers and the uses and applications for this product it became apparent that a secondary market existed. Because the unique selling point of this product lies in its ability to utilize the materials already available to the customer, this product could be used in developing countries such as Pakistan, Bangladesh and India. Although these markets are not the intended users during the design further research can be executed to accommodate these users.

Technical Development

There were many technical aspects to be evaluated in the development of this concept each module had to be evaluated to ensure their proper function not only individually but also in conjunction with the other modules. The materials to be used were also studied extensively, as well as the filter that would clean the water to protect the clothes and allow for it to be re-used. This was a primary feature of the design because it contributed greatly to the efficiency of the wash by reducing the amount of water required and the versatility of the product as it allowed it to provide a proper wash with different types of water. The technical development of the final concept was envisioned in modules focusing on the different parts in the process of washing clothes.

The first step in the technical development of this product was the study and evaluation of existing products in the market displayed in appendix S1. The designer had to research and understand how a washing machine cleans clothes to be able to recreate this effect in a different way. In a modern washing machine, there are two drums, an inner drum which has holes to allow the water to move freely and an outer drum used to contain the water and protect the electrical components of the washer. The inner drum rotates, and the friction caused by the clothes rubbing against each other removes the soil from the clothes. In earlier versions of this product, there was an agitator that generated the movement, but this piece has been eliminated in recent years because it reduces the amount of space available for the clothes. This agitator was generally found in Top-Loading washers, in Front-Loading washers it was more common to find an impeller which also helped circulate the water, but the friction was generally caused by the rotation of the drum itself. Because it is on a horizontal axis, it requires less water and space to wash, making it the more efficient option.

These features and benefits were taken into consideration during the design process (fig 1) and were evaluated as possible options for the design. The primary reason behind selecting a Top loading concept was the seal, a Front-Loading washer requires a tighter seal to ensure that the water does not escape the intended area. Although the literature suggests that the difference in efficiency is significantly in favour of the Front-Loading washer the need for a good seal was an extremely important factor in this selection.

Filter

Since people may have obtained their water from lakes, waterfalls, the beach or rivers not just the main water line, a filter is essential. This filter ensures the protection of the clothing, by eliminating any microorganisms that may stain the clothing. The possible pathogens that exist in surface water were studied to determine how the water should be purified. This research was executed considering that the water would be used for washing and not drinking, therefore, the pathogens that would need to be evaluated and eliminated are those that can be absorbed through the skin. For the initial research, an interview with Dr Zhugen Yang of the University of Glasgow was conducted in which he advised the designer to first identify the pathogens of interest, and if necessary develop a sensor for them and then establish a way of eliminating them. The research revealed that the only pathogen capable of entering the body through the skin is the Leptospira bacteria. This bacterium causes an illness called Leptospirosis which can cause influenza-like symptoms and in some cases Weill's disease. It is generally contracted when the bodily fluids of an infected animal come in contact with a human's damaged skin. "Pathogenic leptospires are fragile little bacteria and die when exposed to chemicals and conditions that many other bacteria and viruses will happily live with. In terms of chemicals, there are two main reasons for lethality – compounds that attack the bacterial envelope, and compounds that damage the internal chemical processes that the bacterium needs to survive. Detergents, alkalis and soaps damage the envelope's outer layer (which is made of a compound called lipopolysaccharide or LPS), while acids and heavy metals generally attack the inner elements and cell metabolism" (leptospirosis.org, 2018). Therefore, this pathogen would be eliminated with the detergent used in the wash and there would be no need for advanced sensors in the product since no pathogens need to be monitored.

Consequently, the primary concern for the water would be the microorganisms and sediment that may be in it capable of staining and damaging the clothing. Interviews were conducted with various water researchers at the University of Glasgow, these experts suggested letting the water settle before filtering it to allow the bigger pieces of sediment to settle at the bottom of the basin or bucket used to collect the water. They also suggested the use of egg cartons as inexpensive water filters or muslin cloths to eliminate the bigger contaminants in the water and Granular

Activated Carbon (GAC) to eliminate any discolouration in the water. These solutions were tested with coloured water to evaluate their effectiveness. The egg cartons were not a feasible idea as they absorbed a large portion of the water tested and later lost structure and strength, although they did not lose their shape they lost all strength and became extremely malleable. If used in the final concept they would become a disposable part of the product and for this reason, they did not meet the design criteria. As they would force the user to purchase filters constantly requiring further investment, more time and possibly other resources. The muslin cloth was effective in capturing the bigger contaminants and absorbed a minimal amount of water which made it a possible solution in conjunction with another filtering element. It would need to be accompanied by another filtering element because although it captured the big pieces (any rocks or sediment) it did not discolour the water. Finally, Granular Activated Carbon (GAC) was observed to reduce the colouring of the water. According to Katsigiannis et al., 2015, "Activated Carbon's ability to absorb a large number of chemical substances and to be regenerated has made the process of absorption on Activated Carbon one of the most effective and economically feasible processes for water and wastewater treatment." In their research, they concluded that activated carbon in the form of GAC columns can provide for effective removal of target compounds during water treatment. To further research the effectiveness of GAC on sediment contaminated water a small sample of this compound was used to filter ink-stained water. When the coloured water came in contact with the GAC, the water did lose some of the colour but not completely, thus sand was included to help eliminate the colouration in the water.

The filter designed would be comprised of three layers, the first layer would be a muslin cloth used to capture big contaminants, this would be followed by a layer of sand, and later a layer of GAC would capture any microorganisms left in the water. This filter would be placed above the basin to utilize gravity as the main force behind the filtration, the water would be poured into the basin and would consequently be filtered before coming in contact with the clothing. Later, after the initial wash cycle, the user must lift the inner drum to remove the clothing from the basin and then empty said basin into a bucket and repeat the initial process of placing the clothes in the basin and filtering that water. This system will allow the user to reduce their water consumption to 22L making this washer extremely efficient. Taking into account that a standard washer requires a minimum of 50L to wash and rinse a full load, this would equate a reduction of 28L or 56%.

Agitator

To generate movement in the water an agitator was designed, an iterative process was used to develop this agitator. Various models were created and tested to determine both the most comfortable option and the most effective option. One of the proposed agitators is mainly comprised of a disk with eight holes, 4 with 20.00mm of diameter and 4 with 10.00 mm of diameter, figure 4. These holes allow the agitator to move freely between the clothes and generate the friction necessary to clean them, they also allow the water to circulate freely throughout the wash. This agitator is manually operated and moved up and down to circulate the water within the drum creating an effective clean. The specific measurements of this piece are based on the requirements of the inner drum and the broom handle that would be used to move the agitator. Because the primary idea behind this concept is allowing people to use many of the things that they already possess, a decision was made to use a standard broom handle for the agitator. The broom will be secured to the agitator using a pin, the selection of the pin was due to the fact that no specific international thread was found. The broom was the factor that determined the thickness of the agitator, since it would need to be thick enough to attach to a broom handle but thin enough to take up the least amount of space within the washer. The varying sizes of the holes are meant to provide enough movement of the water to create friction while still ensuring that the agitator is strong enough to withstand impact.

Another idea was an agitator that would imitate the movement of hands washing the clothes (figure 4b). For this a brush shape was adapted, this shape would allow the agitator to move through the clothes easier and would be a bit kinder to the clothes as it would allow the clothes to circulate within the wash. This shape would work like fingers to penetrate the clothes and create the necessary movement and friction for cleaning. The third concept was a conical shape that would move the clothes and agitate the water shown in figure 4a. This concept would expand when in contact with the water within the drum, it would pick up some of the items within the drum and would release them in another space within the drum, thus circulating the clothes.

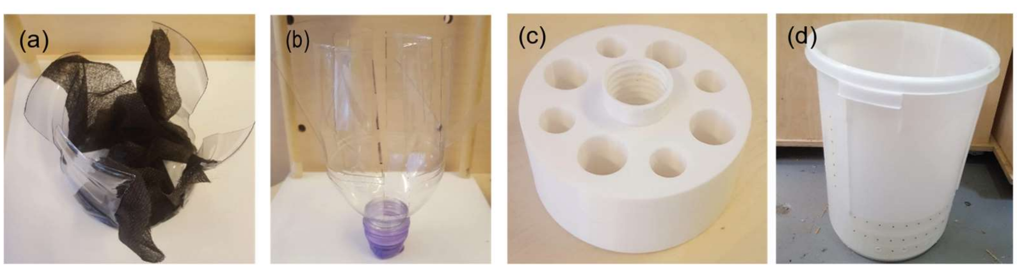


Figure 4. Pieces used for the prototype

Drum

The inner drum, shown in figure 4d is a cylinder made of a starch-based thermoplastic with 26, 1cm holes that would allow the water to flow to the outer drum while cleaning and to drain the washer easily after each cycle. It would also have handles on the sides to allow for easy pick up.

Material Selection

The process of material selection is a complex and extensive challenge, that according to researchers in the University of Wisconsin can be divided into four primary steps: translation, screening, ranking, and supporting information. The figures detailing this process are presented in Appendix S2. In Translation the primary goal is to express design requirements as constraints and objectives. For this concept the requirements for the material where first divided into the different modules that make up the product and each component was evaluated individually. The functions, constraints and objectives of each item are detailed in table 1, these were used as the basis for the selection of the materials to be used.

Item	Function	Constraint	Objective	Material Selected
Agitator	Agitate water and circulate clothes during wash	Impact resistant Water resistant Durable Light weight	Maximize movement of water and clothing	Starch-based Thermoplastic
Drum	Contain water and clothes during the wash	Withstand load Impact resistant Durable Water resistant	Maximize contact between clothes and facilitate drainage	Starch-based Thermoplastic
Filter	Purify water to be used during the wash	Impact resistant Water resistant	Minimize contaminants in the water being used	Natural Rubber

Table 1: Translation of requirements for items

The following steps (screening, ranking and supporting information) were analysed using the Cambridge Engineering Selector software at the University of Glasgow, although not a primary constraint, sustainability was a factor used to determine the materials to be used. This factor helped limit the materials available for selection, the materials were analysed in terms of fracture toughness, price, water resistance, yield strength and moldability. The materials were also evaluated for their ability to be recycled as the company intends to provide customers discounts on replacement pieces if they return their used ones to the company, these pieces would be recycled and would then reduce the cost of materials in production.

Prototype Construction and Testing

Various prototypes were developed to evaluate the different modules of this concept. These prototypes demonstrated the usability and efficiency of each of the modules. To ensure the proper function of the washer and select the best method for washing, four white shirts were stained with chocolate, strawberries, lipstick and a washable marker as a control stain. One of the shirts was washed with the brush-shaped agitator, one was washed with the disk agitator, one was washed by hand using the traditional method and one was kept as a control for further comparison (figure 5). They were mixed within a full load of laundry, initially the same type and amount of detergent and water were used. The time required to complete each load was documented and the effectiveness of each wash was evaluated with the white shirts. Because users generally use intuitive methods to determine the moment when clothes are clean, the shirts were used as the determining factor to establish the time required to wash.

Another method used to determine the efficiency of the product was the water factor (equations A & B), which is a rating of water efficiency and is measured by the quantity of water used to wash each cubic foot of laundry. Because the measurements for washers and their comparisons are established in cubic feet and gallons the measurements had to be converted to allow proper comparisons with products in the market. This calculation was established using both the minimum amount of water needed to complete a wash, meaning the amount of water necessary if the water is re-used and the amount of water necessary if the water is not re-used.

$$(A)\ \ 22L = 5.81\ gallons$$

$$0.0404\ m^3 = 1.3984\ ft^3$$

$$5.81\ g \big/ 1.3984 ft^3 = 4.15$$

$$(B)\ \ 44L = 11.6236\ gallons$$

$$11.6236 / 1.3984 = 8.31$$

Fig. 5 Shirts used for comparison for washing efficiency

The capacity of the washer (equation C) was also determined to establish a comparison with washers available in the market. Once more the standards for these measurements are established in cubic feet and the measurements had to translated.

$$(C)\ capacity = \pi * r * r * h$$

$$r = 17.5\ cm = 0.57\ ft$$

$$h = 42cm = 1.37ft$$

$$capacity\ (ft) = \pi * 0.57 * 0.57 * 1.37 = 1.39ft^3$$

$$capacity\ (m) = \pi * 0.175 * 0.175 * 0.42 = 0.0404\ m^3$$

The final method used to measure the efficiency of the washer was the Litres of water required to clean each kilogram of clothing, equation D was used to determine this.

$$(D)\ {}^{22L}\!/_{3kg} = 7.33\ L/Kg$$

Filters

The first module evaluated was the filter, using the suggestions made by the University of Glasgow professors as a basis for design the fist filter tested was constructed from egg cartons. This idea represented the most cost-effective solution and the most accessible to users. Unfortunately, the egg cartons were not stable enough to filter water. After being exposed to 100ml of water they began to lose its strength and shape. Therefore, this solution would only be applicable as a single use filter. The next prototype tested was a combination of coffee filters

Granular Activated Carbon (GAC), this prototype was also tested with coloured water. Another version developed included a muslin cloth, sand and GAC. All prototypes were evaluated to determine the optimum filter. The combination of GAC, muslin cloth and sand proved to be the optimum solution for filtering the water.

Washer

For the washer module a plastic mixing bucket (42cm x 35 cm; height, diameter) was used as the inner drum (figure 4d). 1 cm holes were symmetrically drilled into it throughout two of its sides and the bottom of the drum. Initially only 18 holes were drilled in the lower portions of the bucket, to test how efficient a wash it would produce and how quickly it could drain. The size of the hole was selected to ensure that although water could flow freely between the inner and outer drum there would be no possibility of a garment getting stuck in a hole. This drum was placed within a 70cm x 48cm garden bin and a 3kg load wash was attempted. Attachments were also created to allow the drum to be elevated and drain without assistance from the user, see figure 6A.

Agitator

The disk-shaped prototype was 3D printed to ensure the accuracy of the measurements and the strength of the prototype itself. The primary concern with this prototype was its ability to wash the clothes and the comfort of the user during the wash cycle. To find the best motion for washing different agitators were evaluated, the brush-shaped prototype was created using a water bottle. The idea behind it being that the agitator would open and imitate the movement executed by hands when washing. This prototype was tested on a small version of the drum. The efficiency and effectiveness of this wash was evaluated and compared to the other methods created. The reduction in size of the prototype was due to the relative weakness of the prototype, because it was created out of water bottles it did not posses the strength necessary to wash a complete load but could still perform the required movements for washing. Therefore, the primary form of comparison was the time required to remove the stains from the test shirt and the effort needed to do it.

The final agitator prototype consisted of a cone-like structure that would open when the agitator reached the bottom of the drum collect some of the clothes and deposit them elsewhere this would create movement in the water to clean the clothes. This prototype (figure 4B) was created using water bottles and garden fabric, this fabric was folded into an accordion shape to allow the cone to stretch and collect pieces of clothing as well as retain some water to promote its movement. When initially tested this prototype proved to be ineffective and uncomfortable to use and was therefore not tested with a full load of laundry.

Results & Discussion

The washer proved to be efficient both in theoretically and in practice. For example, the water factor using equation A, which is the least amount of water necessary resulted a 4.15. Front loading washers typically have a water factor between 8.5 and 5.5, since this is a measurement of how much water is required to wash a cubic foot, the lowest water factor is best, meaning that this washer is very efficient. When the maximum amount of water was evaluated in equation B the 8.31 the washer once again resulted as extremely efficient. Later, when the capacity of the washer was compared the washer proved to be a bit smaller than most compact washers as these have a capacity of 2.30ft^3 and the proposed washer kit has a capacity of 1.39ft^3 or 0.0404 m^3 .The final efficiency measurement was the Liters of water needed per kilogram of clothing, most high efficiency washers use approximately 7.5 L/Kg, meaning that the 7.33L/Kg required to complete a load in a this washing kit is a competitive product in terms of water efficiency.

This difference in water requirements between standard washers and the washing kit is since most washers use the same amount of water no matter the size of the load placed in the washer. They also use many rinse cycles, when some detergents do not require as much water to dissolve it. These rinse cycles increase the time required to wash the clothes, the water used and the energy consumption because they generally use heated water. Which is not necessarily conductive to proper cleaning, hot water is better at removing certain stains but in general does not produce a better wash than cold water. Therefore, the manual aspect of this product allows it to be customizable to the needs of the user and consequently increases its efficiency.

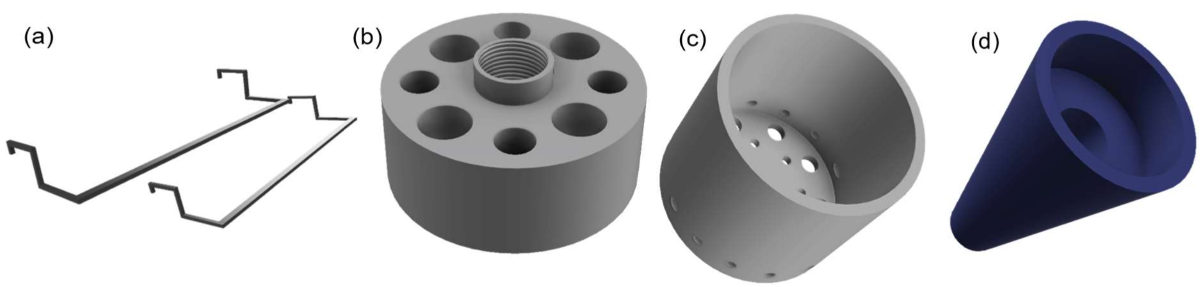


Figure 6. Components to be sold in the washing kit.

Agitator

Each agitator was tested for its efficiency and comfort, the disk agitator and the brush agitators resulted as the most effective as they reduced the wash time from approximately 50 minutes when washing clothes by hand to 30 minutes when the agitator was used. These agitators required less time, less effort and less detergent to wash. They also proved to be more comfortable to use. The primary difference between the disk shape agitator and brush-shape was that the disk shape agitator tended to only come in contact with the top layer of the load, causing users to believe that the wash was not effective enough. Nonetheless, tests proved that this was an effective method for washing requiring only 10 minutes to complete the wash cycle and eliminate all the required stains. Washing by hand on the other hand required approximately 35 minutes for the wash cycle alone and was determined to be extremely uncomfortable as it required the user to bend down at an uncomfortable angle for an extended period. Taking into account the need for a cost-effective design the disk-shaped agitator was selected due to its simplicity for production, as the brush-shaped agitator (figure # b) would require a combination of materials and production methods whereas the disk could be easily moulded.

Drum

One of the observed factors of the drum was whether the stability of the drum would be affected after being submerged in water. Although the drum was not centred the motion of the drum did not affect the effectiveness of the wash or the comfort of the user when washing. This was since the separation between the inner and the outer drum was limited to 3cm, therefore the drum did not have a lot of space to move, but just enough to allow the water to circulate throughout the two drums.

Filter

Initial testing of the filter shown in figure 6D proved that Granular Activated Carbon could not by itself eliminate the sediment within the water. Although many studies suggest that it will eliminate any microorganisms and substances within the water it is not capable of eliminating the colour that the sediment provides. Which is why this component was later combined with sand and muslin cloth to complete the purification process. This filter will be conical in shape and of a depth of 10cm, 3.5cmbfilled with sand, 3.5ch cm filled with Granular Activated Carbon and 1cm of muslin cloth.

Conclusion

After detailed testing was conducted the brush-shaped agitator was selected as the best option due to its ability to clean clothes effectively and efficiently. The drum required 26 holes to provide rapid drainage. The success of the experiments proved that the design is capable of cleaning clothes both efficiently and effectively. A small load of laundry required approximately 22 L of water which is 44% of the water necessary for a modern washing machine, when compared to washing by hand it required approximately the same amount of water, but more detergent was used, and more time was spent washing the clothes. Therefore, it can be concluded that the methodology developed can meet its purpose. When users were interviewed they believed that the time and effort required would be appropriate for both the task and the emergency situation. They were able to perform all tasks with relative comfort and ease.

The objective of this project was to provide a washing solution that maximized the use of the available resources and did not depend on the governmental grid. The creation of the washing kit provides a portable, manual and comfortable solution to this issue. Therefore, it can be concluded that the objectives of this project were properly met.

Future Considerations

Due to lack of time and resources further iterations were not completed, priority was given to the concepts that could be used by most users. Therefore, after completing this design concept further research will be conducted to develop an automatic version. This automatic version of the washer would provide a similar washing experience to that of everyday washing. This concept was studied and evaluated during the design process, but a more manual approach was selected to accommodate those of lower income. An agitator displayed in figure 7 was designed specifically for this automated version and will be tested upon the construction of this prototype.

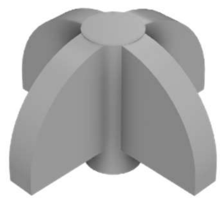


Fig. 7 Proposed automatic agitator CAD

This concept would bring forth the possibility of evaluating electrohydraulic energy to help restore the power lost during the wash. This design could be powered by a battery attached to a trickle charger, the power required to power this motor must then be evaluated and the power source must be studied in detail. The inefficiency of solar panels is a problem that must be overcome in order to avoid requiring a large panel for a small motor or many hours to charge.

The disk-shaped agitator will also be studied in further detail to evaluate the improvements that can be made on it. For example, ridges could be added to maximize friction, a different handle can be tested to facilitate the movement needed for agitation and increase comfort of use and possibly increase the speed of agitation. Furthermore, the drying portion of the process must me studied in further detail, although the best way to dry the clothes is by laying them out in the sun measurements should be taken to facilitate the wringing of the clothes.

References

Ahmad, A. and Hameed, B. (2010). Fixed-bed adsorption of reactive azo dye onto granular activated carbon prepared from waste. *Journal of Hazardous Materials*, 175(1-3), pp.298-303.

Allianceforwaterefficiency.org. (2018). *Residential Clothes Washer Introduction*. [online] Available at: http://www.allianceforwaterefficiency.org/Residential_Clothes_Washer_Introduction.aspx [Accessed 6 Aug. 2018].

Alibaba.com. (2018). *Mini Washing Machine-Mini Washing Machine Manufacturers, Suppliers and Exporters on Alibaba.comWashing Machines*. [online] Available at: https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=mini+washing+machine [Accessed 6 Jul. 2018].

Amazon.com. (2018). [online] Available at: https://www.amazon.com/Panda-Counter-Washing-machine-basket/dp/B01AGQ4MH4/ref=sr_1_20?ie=UTF8&qid=1530908401&sr=8-20&keywords=mini+washing+machine [Accessed 6 Jul. 2018].

Aoml.noaa.gov. (2018). *TCFAQ A BASIC DEFINITIONS*. [online] Available at: http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqA.html [Accessed 25 Jul. 2018].

Ashby, M. (2015). *Materials selection in mechanical design*. 3rd ed. Amsterdam: Elsevier.

Asq.org. (2018). *Decision Matrix - ASQ*. [online] Available at: http://asq.org/learn-about-quality/decision-making-tools/overview/decision-matrix.html [Accessed 17 Jul. 2018].

Cae.wisc.edu. (2018). *Computer-Aided Engineering | Computing in the College of Engineering*. [online] Available at: http://www.cae.wisc.edu/ [Accessed 30 Jul. 2018].

Cdc.gov. (2018). *Leptospirosis | CDC*. [online] Available at: https://www.cdc.gov/leptospirosis/index.html [Accessed 29 Jun. 2018].

Circulardesignguide.com. (2018). *The Circular Design Guide*. [online] Available at: https://www.circulardesignguide.com/ [Accessed 23 May 2018].

Cse.org.uk. (2018). *How much electricity am I using? | Centre for Sustainable Energy*. [online] Available at: https://www.cse.org.uk/advice/advice-and-support/how-much-electricity-am-i-using [Accessed 11 Jun. 2018].

Easter, E. (2013). Assessing the Impact of Wash Water Temperature, Detergent Type and Laundering Platform on Basic Clothing Attributes.

Energuide. (2018). *How much energy do my household appliances use?*. [online] Available at: https://www.energuide.be/en/questions-answers/how-much-energy-do-my-household-appliances-use/71/ [Accessed 11 Jun. 2018].

Garden, H., Garden, H. and Laundry, B. (2018). *How Washing Machines Work*. [online] HowStuffWorks. Available at: https://home.howstuffworks.com/washer2.htm [Accessed 20 May 2018].

Gerhartz, W., Yamamoto, Y., Kaudy, L., Schulz, G. and Rounsaville, J. (1987). *Ullmann's encyclopedia of industrial chemistry*. Weinheim: VHC.

Gilbert, L. (2013). *The History Of The Washing Machine | Ransom Spares*. [online] Ransomspares.co.uk. Available at: https://www.ransomspares.co.uk/blog/news/history-of-the-washing-machine.htm [Accessed 23 May 2018].

Godfrey, S. (2018). *An introduction to thermoelectric coolers | Electronics Cooling*. [online] Electronics Cooling. Available at: https://www.electronics-cooling.com/1996/09/an-introduction-to-thermoelectric-coolers/# [Accessed 23 May 2018].

Gubin, A. (2018). *Crean dos ingeniosas lavadoras, manual y con bicicleta, que operan sin electricidad (Vídeo)*. [online] www.ntd.tv. Available at: https://www.lagranepoca.com/internacionales/africa/261549-crean-dos-ingeniosas-lavadoras-manual-y-con-bicicleta-que-operan-sin-electricidad-video.html [Accessed 24 May 2018].

Home-water-works.org. (2018). *Clothes Washer | Home Water Works*. [online] Available at: https://www.home-water-works.org/indoor-use/clothes-washer [Accessed 6 Aug. 2018].

How-to-save-water.co.uk. (2018). *Water Efficient Washing Machines | How To Save Water*. [online] Available at: http://www.how-to-save-water.co.uk/washing-machines/ [Accessed 11 Jun. 2018].

Irrizarry-Alvarez, F. (2017). *Tremendo resuelve para lavar ropa*. [online] Primera Hora. Available at: http://www.primerahora.com/noticias/puerto-rico/nota/tremendoresuelveparalavarropa-1255255/ [Accessed 23 May 2018].

James Dyson Award. (2018). *Design and Build of an Atmospheric Water Generator | James Dyson Award*. [online] Available at: https://www.jamesdysonaward.org/en-IE/2017/project/design-build-atmospheric-water-generator/ [Accessed 23 May 2018].

Johnston, I. (2018). *Solar-powered device can create water out of thin air, even in deserts*. [online] The Independent. Available at: https://www.independent.co.uk/news/science/solar-water-harvester-thin-air-deserts-mof-metal-organic-framework-omar-yaghi-a7683451.html [Accessed 23 May 2018].

Karlsson, S. (2018). *How Does a Front Load Washer Work With so Little Water and Detergent?*. [online] The Spruce. Available at: https://www.thespruce.com/how-does-front-load-washer-work-2145864 [Accessed 11 Jun. 2018].

Katsigiannis, A., Noutsopoulos, C., Mantziaras, J. and Gioldasi, M. (2015). Removal of emerging pollutants through Granular Activated Carbon. *Chemical Engineering Journal*, 280, pp.49-57.

Kaur, A., Kumar, B., Kumar, A., Choudhary, Y. and Solanki, M. (2015). Portable Solar Washing Machine. *International Journal of Recent Research and Review*, 8(2).

Leptospirosis Information. (2018). *Overview of the leptospira bacterium itself - Leptospirosis Information*. [online] Available at: http://www.leptospirosis.org/bacteria/ [Accessed 29 Jun. 2018].

Marlowe-Leverette, M. (2018). *What is the Laundry Load Capacity of My Clothes Washer?*. [online] The Spruce. Available at: https://www.thespruce.com/formula-to-calculate-washer-tub-capacity-2145871 [Accessed 11 Jun. 2018].

Marlowe-Leverette, M. (2018). *Xeros Future Of Laundry - Washing Clothes With Nylon Beads*. [online] The Spruce. Available at: https://www.thespruce.com/xeros-future-of-laundry-washing-2146250 [Accessed 12 Jun. 2018].

Medialabamsterdam.com. (2018). *Design method toolkit Backcasting*. [online] Available at: https://medialabamsterdam.com/toolkit/method-card/backcasting/ [Accessed 23 May 2018].

OpenIDEO Stories. (2018). *3 Reasons Why Creativity is Necessary for Emergency Response*. [online] Available at: https://stories.openideo.com/3-reasons-why-creativity-is-necessary-for-emergency-response-b1af2c9c1a93?_ga=2.241326146.1753671305.1527098117-1973767446.1527098117 [Accessed 23 May 2018].

Pakula, C. and Stamminger, R. (2010). Electricity and water consumption for laundry washing by washing machine worldwide. *Energy Efficiency*, 3(4), pp.365-382.

Plc, X. (2018). *The Xeros Washing Machine | Commercial Laundry | Xeros*. [online] Xeroscleaning.com. Available at: http://www.xeroscleaning.com/the-xeros-machine [Accessed 12 Jun. 2018].

Primera Hora. (2017). *Se vuelve viral vídeo de invento para lavar ropa sin electricidad*. [online] Available at: http://www.primerahora.com/noticias/puerto-rico/nota/sevuelveviralvideodeinventoparalavarropasinelectricidad-1252257/ [Accessed 23 May 2018].

Primera Hora. (2017). *Aquí puedes lavar tu ropa*. [online] Available at: http://www.primerahora.com/fotogalerias/noticias/puerto-rico/aquipuedeslavarturopa-1248161/foto-8/ [Accessed 23 May 2018].

Products.geappliances.com. (2018). *Washers - Water Level and Load Size*. [online] Available at: http://products.geappliances.com/appliance/gea-support-search-content?contentId=17041 [Accessed 12 Jul. 2018].

Radjou, N., Prabhu, J. and Ahuja, S. (2012). *Jugaad innovation*. San Francisco, CA: Jossey-Bass.

Rosling, H. (2010). *The magic washing machine*. [online] Ted.com. Available at: https://www.ted.com/talks/hans_rosling_and_the_magic_washing_machine/up-next [Accessed 23 May 2018].

Seliger, G. (2007). *Sustainability in manufacturing*. Berlin: Springer.

Smith, D. (2018). *Water filtration*.

Soto, M. (2017). *Familia en Caguas hace su agosto con tablas para lavar ropa*. [online] Metro. Available at: https://www.metro.pr/pr/noticias/2017/10/05/familia-en-caguas-hace-su-agosto-con-tablas-para-lavar-ropa.html [Accessed 23 May 2018].

Temple, J. (2018). *How to pull water out of thin air, even in the driest parts of the globe*. [online] MIT Technology Review. Available at: https://www.technologyreview.com/s/604137/water-from-desert-skies/ [Accessed 23 May 2018].

Tide.com. (2018). *How Do I Know Load Size for My Washing Machine? | Tide*. [online] Available at: https://tide.com/en-us/how-to-wash-clothes/how-to-do-laundry/how-do-i-know-load-size-for-my-washing-machine [Accessed 11 Jun. 2018].

T&L Equipment Company | Commercial Laundry Equipment Experts. (2016). *What Are The Main Washing Machine Parts | Coin Operated Washers and Dryers in Greensboro, NC*. [online] Available at: http://www.washcycle.com/main-parts-washing-machine/ [Accessed 23 May 2018].

Valyrakis, M. (2018). *Water filtration systems*.

Wang, L., Hung, Y. and Shammas, N. (2007). *Advanced physicochemical treatment processes*. Totowa, N.J.: Humana Press, pp.573-633.

Waterwise.org.uk. (2018). *Save Water – Waterwise*. [online] Available at: http://www.waterwise.org.uk/save-water/ [Accessed 6 Aug. 2018].

Weather.gov. (2018). [online] Available at: https://www.weather.gov/media/owlie/ciclones_tropicales11.pdf [Accessed 25 Jul. 2018].

Yang, D. (2018). *Water Filtration Systems*.

100resilientcities.org. (2018). *Resources – 100 Resilient Cities*. [online] Available at: https://www.100resilientcities.org/resources/ [Accessed 23 May 2018].

Appendices

S1. Market Comparison Tables

Mini Washing Machine Comparison				
Item Name	**Item No**	**Voltage (V)**	**Power (W)**	**Capacity (Kg)**
SMOD		220	135	2
Mini Washer		220	180	3
VIREX		220	240	3
	XPB40-2008	220	170	4
	XQB27-188P	220	220	3
	XPB40-160D	220	240	4
Haifei	XPB25-09	220	150	2.5
One-concept Ecowash		220	380	3.5
	XPB45-160D	220	240	0.5
	XPB25-218	220	60	2.5
	GB35	220	200	2.5

Table S1a. Mini washing machine market comparison of washer specifications for benchmarking in product development, summary of results is highlighted

Solar Washing Machine Comparisson						
Item Name	**Item No**	**Voltage (V)**	**Power (W)**	**Capacity (Kg)**	**Dimensions**	**Water consumption (L)**
Basei	XPB40-8SC	12	210	4		
Mizi	MZXPB80-288	DC12/24	190	5		200
Vestar	VMZXPB80-288	48	190	5		200
Mizi	HM30B-02	24	180	3.6	362*342*510mm	
Mizi	XPB80-288	24	320	8	362*342*510mm	
Average		24	218	5	362*342*510mm	200

Table S1b. Solar Washing machine comparison of washer specifications for benchmarking in product development

S2. Materials Analysis Tables

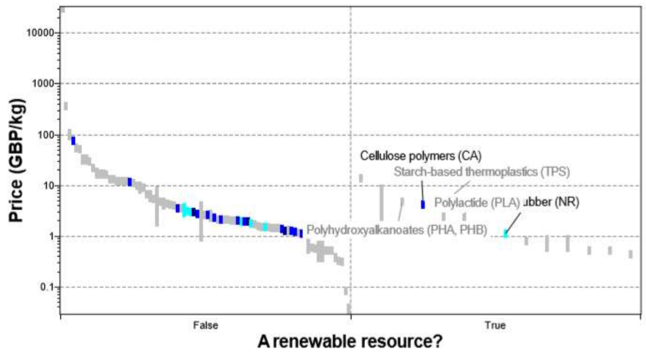


Figure S2a. Comparison between price and type of resource used

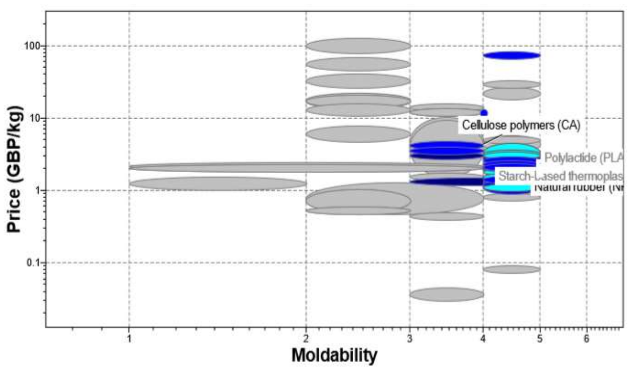


Figure S2b. Analysis of cost of material in comparison with its ability to be moulded

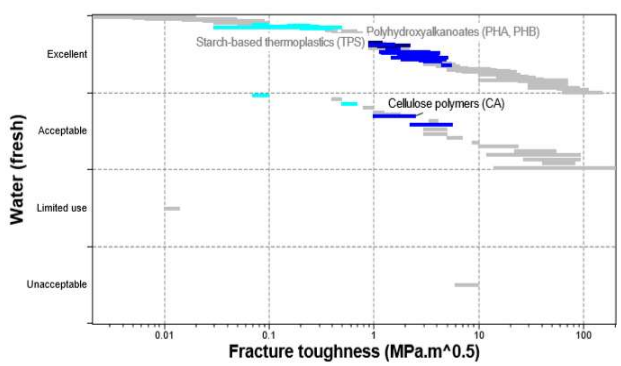


Figure S2c. Analysis of Fracture toughness with respect to contact with water

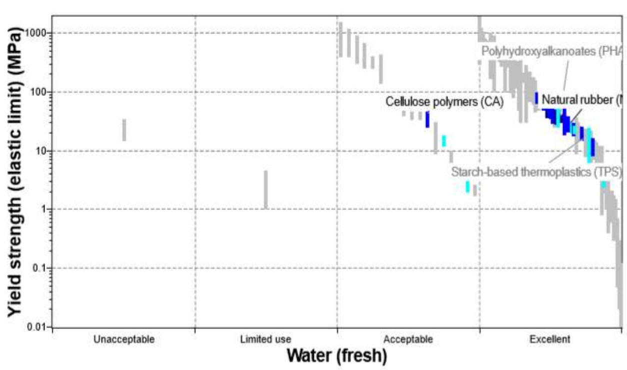


Figure S2d. Analysis of Yield Strength with respect to contact with water

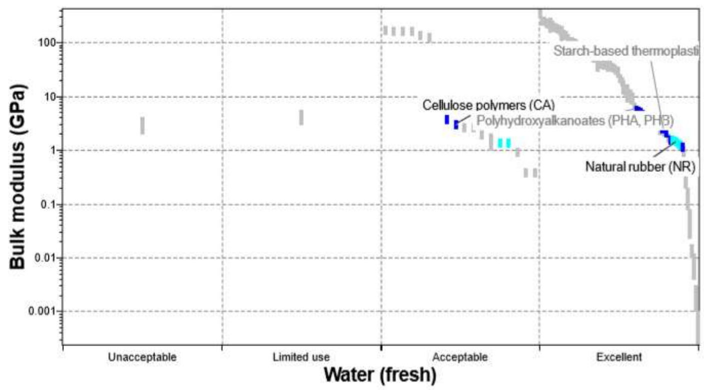


Figure S2e. Analysis of Bulk modulus in water

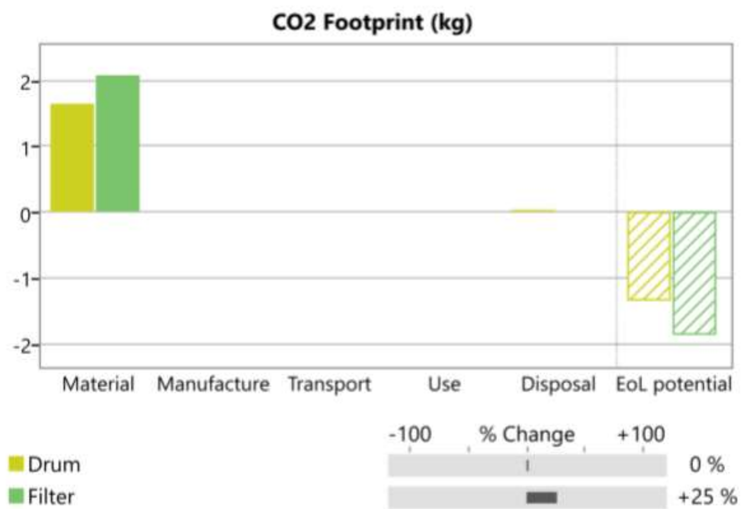


Figure S2f. CO_2 Footprint caused by material during manufacture in ecological analysis

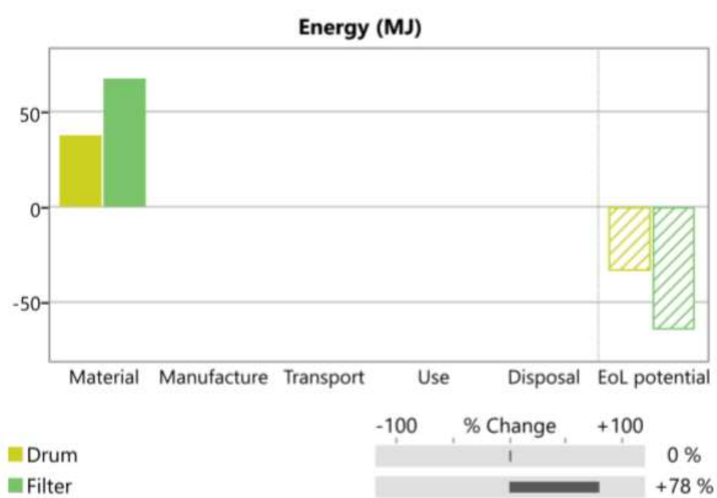


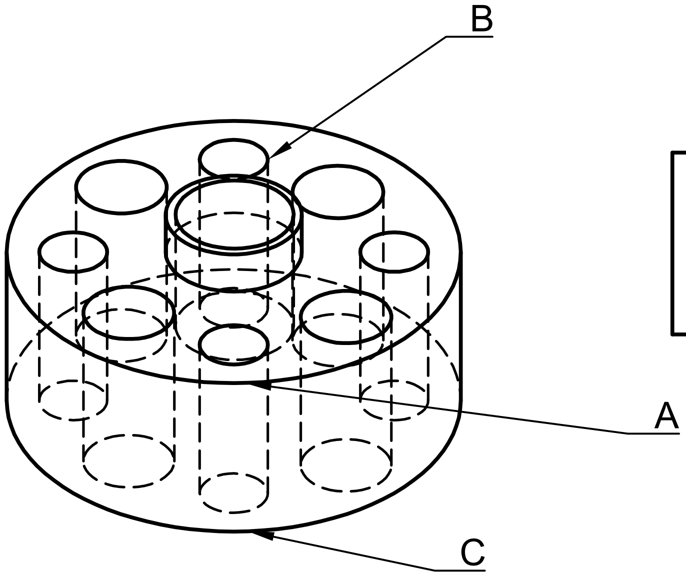
Figure S2g. Ecological analysis of energy consumed during manufacture

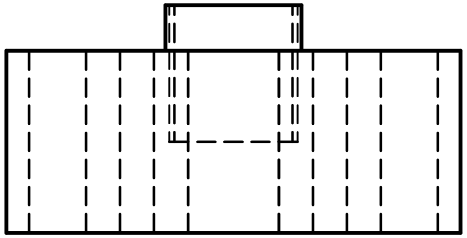
S3. Engineering Drawings in Labelled view method

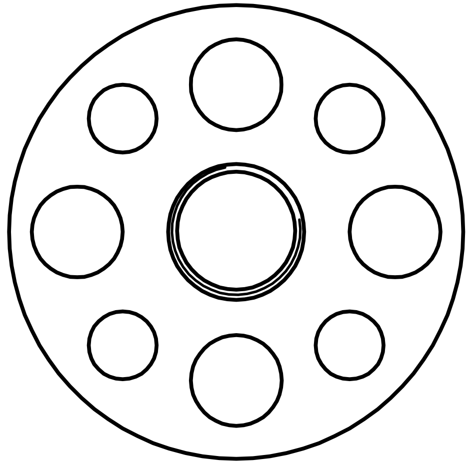
S3a. Drum

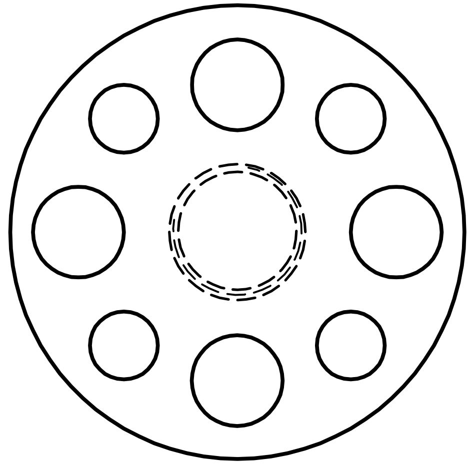
S3b. Agitator

S3c. Filter









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Design		Nicole Mendez-Santos 8/12/2018	NMS
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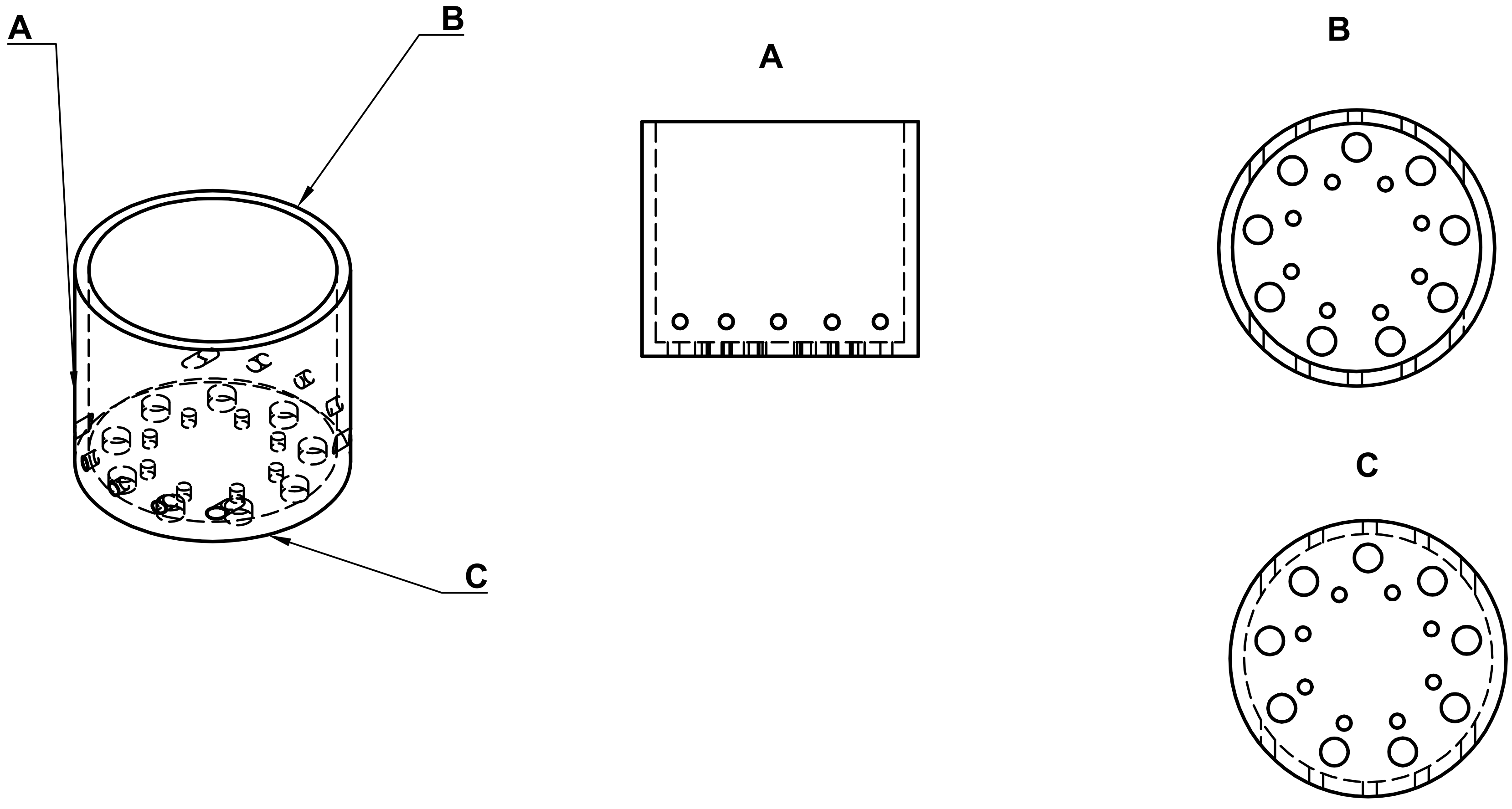
			Rev. / Date of issue / Sheet 1/1



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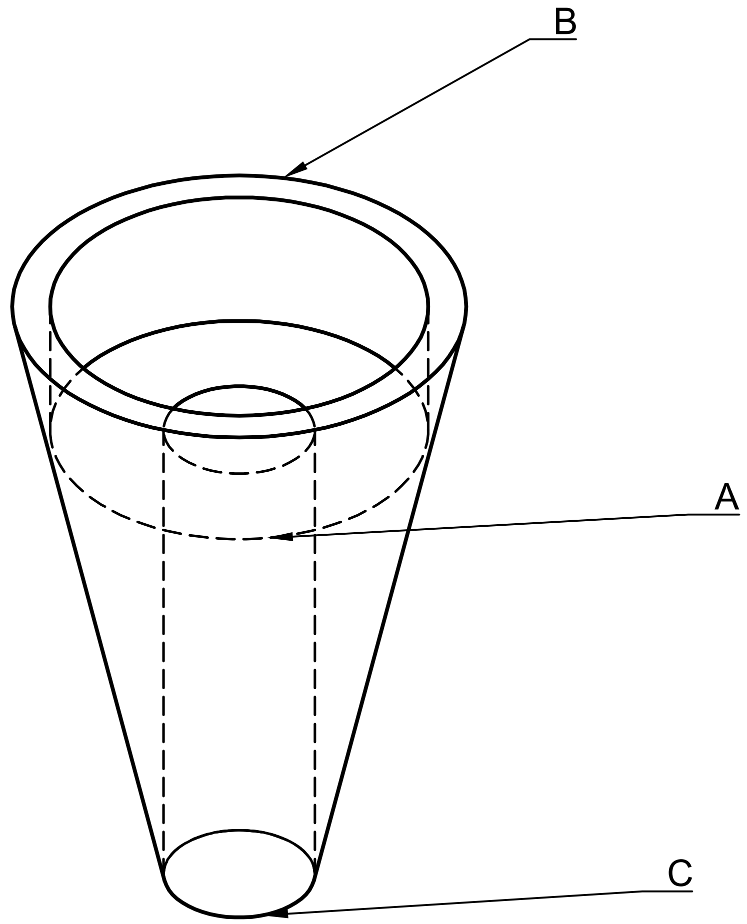
			Rev. / Date of issue / Sheet 1/1



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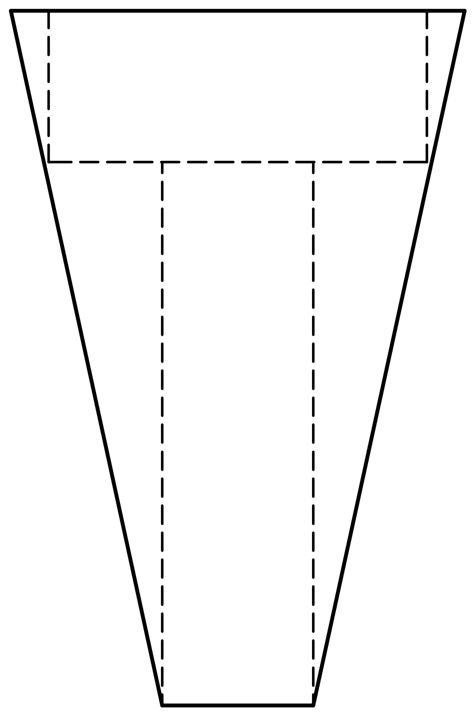

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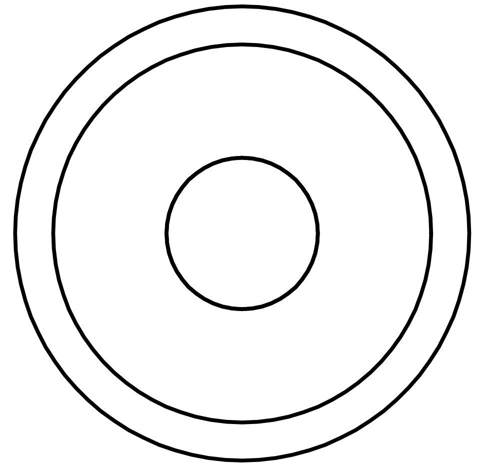

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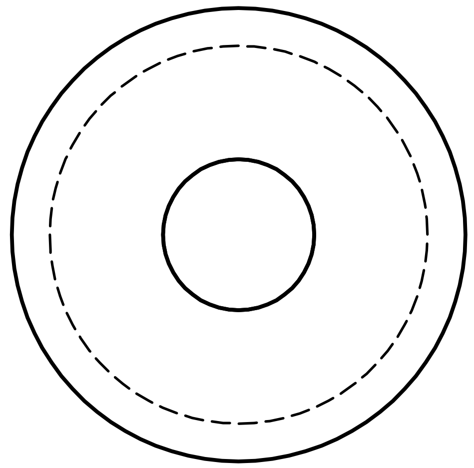

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