The Fellowship of the Engineers

Bitter Leaf Processor

Final Report

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Executive Summary

Bitter leaf, a plant native to Africa, is a staple in the Cameroonian diet. However, due to its intrinsic bitter nature, it must be thoroughly beaten and washed prior to consumption, which takes well over an hour for the traditional hand processing method. The goal of this project was to create a mechanical process that will reduce the time and effort required to wash bitter leaves. Dr. Zama, a Cameroonian native, sponsored this project for rural, family use.

On a base level, the device must be able to remove any bitterness and contaminants from the leaves, and process a high enough volume of leaves that it is an improvement over the current manual process. Market research showed that it must be manually operated, low cost, and adaptable to additives in the process. Existing designs for processing leaves, such as wet grinders and food processors, are simply not designed specifically for the challenges of bitter leaf processing, but provide useful concepts for the design stage.

The task of processing bitter leaves was broken down into nine base level subfunctions, and five initial concepts were developed from these subfunction solutions. The best of these designs, the Lunchbox, was chosen as the preliminary final design. The design was further refined with additional market research, changing to a design inspired by manual food processors and french presses to replicate the hand processing of the leaves, and the functions were combined into a single nested cylindrical design.

Polypropylene was chosen for its low cost and food safety compliance, while 304 stainless steel is used for the blades. Each component of the mechanism was evaluated using FEA, the design was altered to address the risk points in the design, and a work analysis showed an estimated power input of 55 W for continuous operation.

Testing of prototypes manufactured with 3d printing and waterjet showed that the press design is very efficient at mashing leaves, achieving similar results to the traditional method while processing more leaves at a time. The blade assembly, while greatly improved after design refinements, requires additional work to improve the processing capability, especially once the wall material is changed to the injection molded surface characteristics of polypropylene. The prototype also helped confirm the ergonomics of the system.

After the iterative design process and prototyping, a fabrication package was made for the full design. The estimated cost per unit is $40.68 for basic materials and fasteners, and all the target goals were successfully met. The next steps for this project include further refinements of the blades are necessary, manufacturing and material sourcing for Cameroon, and having users test the prototypes to see if they would use it on a daily basis.

Nomenclature

CFD - Computational Fluid Dynamics

FDA - Food and Drug Administration

FEA - Finite Element Analysis

FoS - Factor of Safety, the yield stress divided by the actual stress

IUCN - International Union for Conservation of Nature

OECD - Organization for Economic Cooperation and Development

OSHA - Occupational Safety and Health Administration

Psi- Pounds per square inch

Technician - manufacturing workers in Cameroon who will be producing the product

W - Watts, joules per second

1. Introduction and Background

In Cameroon, bitter leaf is a vital component of the diet of many families. As Dr. Zama explained in a video conference on August 21st, 2019, in order to turn the raw leaves into an edible substance, they must be broken down and thoroughly rinsed to remove some of the bitterness. This process is very labor-intensive and time-consuming, taking upwards of an hour for a woman to manually prepare the bitter leaves for her family's dinner, according to Dr. Zama. The purpose of this project is to create a device that is hand-operated and significantly cuts down the time and effort required to prepare bitter leaf for cooking.

The project is focused on designing for household use, to lower the time and effort required for a woman to provide for her family. This usage would be in a primarily rural setting, likely without easy access to electricity. However, consideration will be given to the application of the device in a small business setting, as some Cameroonians in the cities are selling processed bitter leaves. In this context, users may have access to electricity, so the potential to power the device with a motor would be a bonus. Users of this product will be able to process bitter leaf in an easy and quick manner, as opposed to the time and labor-intensive process currently employed.

This project consisted of designing and prototyping a device to simplify bitter leaf processing. Initially, research was done to better understand the problem and any requirements for the device. A design was chosen from several concepts, and then went through analysis, prototyping and revision to optimize it as much as possible. The design was tested with bitter leaves to see how it would perform in a realistic scenario. This report covers all phases of the design process and serves as a summation of all work done by the design team, as well as a guide for potential future work on the project.

2. Existing Products, Prior Art and Applicable Patents

In order to prepare bitter leaves for consumption, the bitter taste needs to be removed through extensive washing and mashing. The mechanization of the bitter leaf washing and preparing process has not been greatly developed; however, there are many tools and technologies that accomplish similar purposes. These technologies may be modified to effectively wash and prepare bitter leaves with better results than traditional hand washed leaves.

An essential feature of the bitter leaf machine would be its simplicity and ability to be operated manually without any other power source. Purely mechanical washing is nowadays seen almost exclusively in manual clothes washing machines. However, the basic concepts can carry over into food washing. Furthermore, manually powered washing machines, such as The Laundry Alternative's WonderWash®, which is shown in Figure 1, utilizes a rotating vessel operated by a hand crank to fully soak and cycle through clothes in an efficient and effective manner while also being lightweight, easy to operate, and compact [1]. This could be easily translated to the washing cycle required to process the bitter leaves.

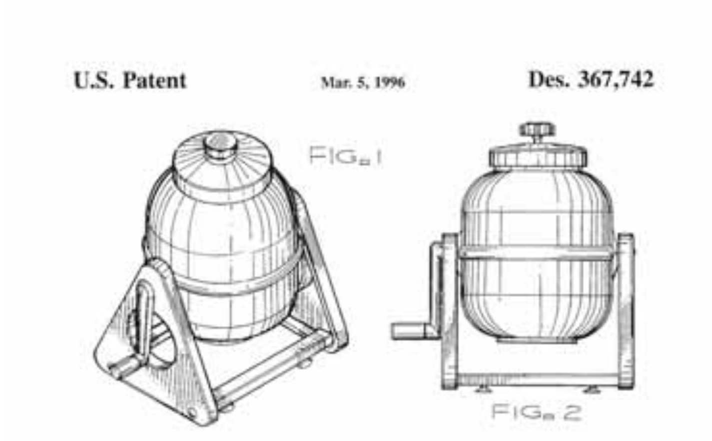


Figure 1: WonderWash Design [1]

While bitter leaves are more commonly prepared by hand, generic kitchen food processors can also be used to wash and grind bitter leaves into consumable forms [2]. When washing bitter leaves in a food processor, the user must be careful to not over process the leaves. They should be sliced, but not totally pureed. Generally, most food processors are electrically powered, but they can be modified to be run manually to fit the scope of this project. For example, the manually powered food processor by SpeedWing™, as shown in Figure 2, operates via drawstring to spin and slice its contents [3].

Figure 2: SpeedWing’s Manual Food Processor [3]

There are other products to find inspiration for the bitter leaf processor. Indian cuisine utilizes a tool called a wet grinder. Wet grinders are rare in Western culture, but very prevalent in Eastern food preparation, used for crushing and preparing of grains and lentils [4]. Figure 3 demonstrates the typical design of a food wet grinder, where a granite stone wheel rotates inside a containment drum, mashing the food into a paste as it rotates [5]. Wet grinders can be operated manually or with the aid of electric motors to power the rotation. Generally, the results of the grinding process have a paste-like consistency. However, bitter leaves should not be processed this heavily and should instead maintain their structural form.

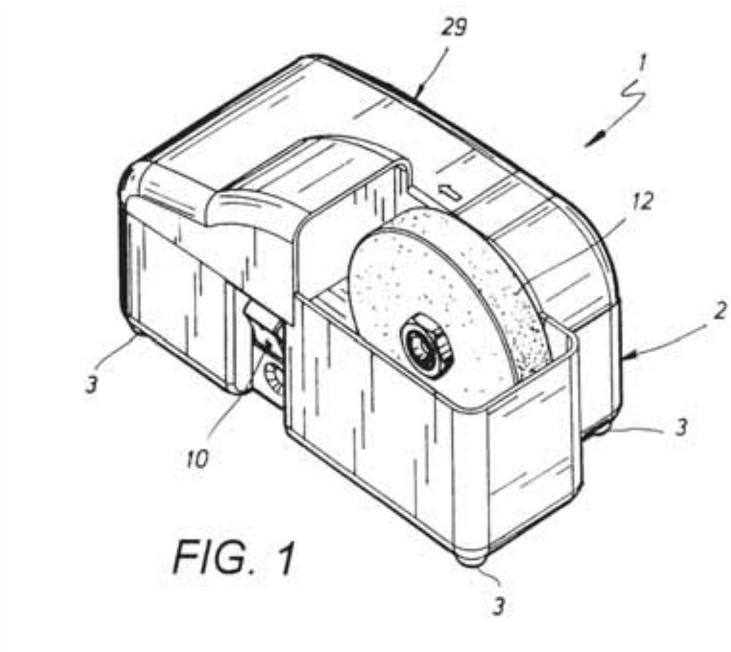


Figure 3: Wet Grinder Design [5]

Finally, the french press coffee maker, seen in Figure 4 provides a food-safe methodology for separating solids from liquids [6]. In this machine, a mix of coffee grounds and water are placed in the main chamber with the plunger in the topmost position and allowed to sit while the coffee brews. When brewing is finished, plunger is pushed down to trap the coffee grounds against the base of the chamber so the pure coffee can be poured off. At the end of processing bitter leaves, the water used during processing needs to be separated from the leaves--the french press provides a methodology to do that. However, it does not process any of the shredding or washing necessary for bitter leaf processing.

Figure 4: French Press Design [6]

Manual washing machines, food processors, wet grinders, and french presses all have components and characteristics that would allow them to work with bitter leaf. However, each has drawbacks since none of them are designed to work with bitter leaves. Wet grinders puree their contents to a level too extreme for bitter leaf processing, and standard food processors could do the same [2][4]. These devices are also not designed to wash any of their contents. These products are too costly for the intended economic demographic, so cheaper alternatives need to be designed. Manual washing machines, such as WonderWash, show potential. Unfortunately, the wash and grind cycle needed for bitter leaves is more strenuous than what can be provided from the WonderWash's wash cycle. The flour sifter provides an alternate processing mechanism, but there are potential issues with longevity when using an off the shelf sifter. However, the rotational action present in the food processor that allows it to quickly spin and grind its contents, as well as the crank handle present in the manual washing machine that allows the user to easily power the machine, are useful inspirations for the bitter leaf processor design.

3. Codes and Standards

Before progressing into the design phase, it is important to identify codes and standards which may affect the outcome of the design. There are two main agencies who have published codes which concern the bitter leaf processor: The Occupational Safety and Health Administration (OSHA) and the Food and Drug Administration (FDA). OSHA has standards that help keep the operator safe while the machinery is in use. Standard 1910.212 dictates that all blades must be guarded to prevent injury, two mechanisms that are included in the final design [7]. The standard also states that hand-powered gears do not require guards, but guards are highly recommended. Additionally, OSHA has Standards 1910.144 and 1910.145 which outline specifications for accident prevention signs [8].

In addition to the OSHA standards, the FDA has a set of codes to sustain the integrity of food as it is being processed. Title 21, Chapter 1, Subchapter B, Part 112, Subpart L,112.123 requires all seams to be smooth or well-maintained to prevent the collection of bacteria or contaminants [9]. Title 21, Chapter 1, Subchapter B, Part 110, Subpart C, 110.40 states that all equipment must be adequately cleanable and prevent contaminants such as lubricants and metal particles from entering the food [10]. It also dictates that machinery must be made of non-toxic materials, corrosion-resistant, and designed to withstand the environment. These are all important codes that will affect the design of the processor and help create a safe and effective machine.

To comply with standard 1910.212 [7], the central rotating column which holds the spinning blades is a separate part from the lid and the top handle. When the lid lifts off the main section, the blade piece stays as a separate piece, eliminating the opportunity to spin the blades with the handle while the lid and main body are disconnected. While the gear train is hand operated and therefore does not require guarding, the lid assembly uses three screws to cover and protect the gear train and make it difficult to spin the gears while they are accessible by hand.

Standards 1910.144 and 1910.145 will be used for appropriate signage, specifically 1910.145(c)(2)(i) will apply to the use of caution labels applied to the machine warning of unsafe practices, such as putting a hand inside the shredder section or pinch hazards between interlocking components [8]. Due to language difficulties, clear symbols will also be used to demonstrate the danger.

FDA codes [9,10] are met by using cylindrical chambers for all stages of processing, and making the top and bottom surfaces either removable (such as the lid) or with easy access for a human hand to reach in and clean or wipe the surface. The polypropylene and stainless steel materials are FDA approved materials and are resistant to corrosion in aqueous environments and highly resistant to calcium carbonate (or limestone), a common additive in bitter leaf processing [11,12].

4. Customer Requirements and Engineering Design Specifications

Stakeholders are a crucial consideration when designing a product. Dr. Zama is the most important stakeholder in a list that includes individual users, the Food and Drugs Authority of Cameroon [13], and the technicians who will be producing the machines. Dr. Zama and the design group rank as the most important stakeholders, while the technicians rank low since they do not use the final project and only provide guidance for the local manufacturability of the device (Figure 5). Individual users, as the primary focus, rank higher than businesses. At all times the project must comply with Cameroonian FDA and Georgia Tech regulations to assure the final product will be acceptable.

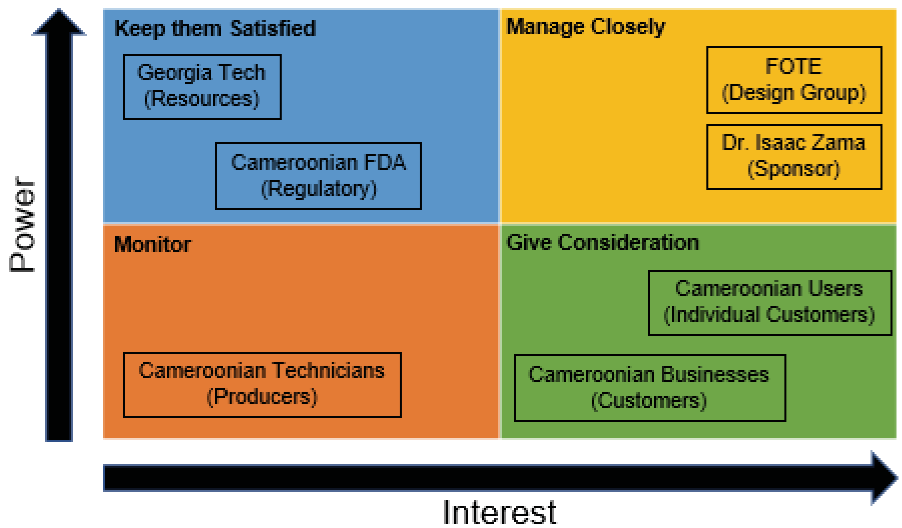


Figure 5: Stakeholder Analysis Chart

The primary customer requirements, generated from discussions with Dr. Zama and potential users of the product, are listed in Table 1. These show that one of the major concerns is having an adaptable design that can accept a variety of inputs and has different output options. Another major concern is the ease of use and simplicity of the design. To assure ease of use, the ergonomics of the design will be focused on a 5’3” woman’s dimensions to match the average female height in Cameroon [14]. Product satisfaction will be gauged through user test and focus groups. The variety of inputs will be replication-based, using the same ingredients as online tutorials and user descriptions.

Table 1: Explicit customer requirements

Can adequately wash the bitter leaves to remove bitterness and contaminants
Slices the leaves into different sizes for different applications
Can wash many leaves in a single cycle
Allows for other ingredients to be used during the slicing and washing processes
Easy to use
Easy to move between storage shed and kitchen
Cheap to buy and own
Durable
Does not rust
Electric motor upgradeable

The device is intended to process bitter leaves, a function that is broken down into: accept ingredients, exhaust products, and use mechanical energy (Figure 6). Each function is deconstructed further into nine basic subfunctions that must be performed. The most challenging functions to accomplish are grinding and washing the bitter leaves, which will be the primary focus of the design. These functions will be evaluated primarily on process efficiency, end product consistency, and cleanability. Indications of these functions being performed to a satisfactory degree will all be qualitative. The first indication is user satisfaction with the size and consistency of ground pieces, due to the diversity of customer preferences. The second is the proper taste and texture of the processed leaves leaving the machine.

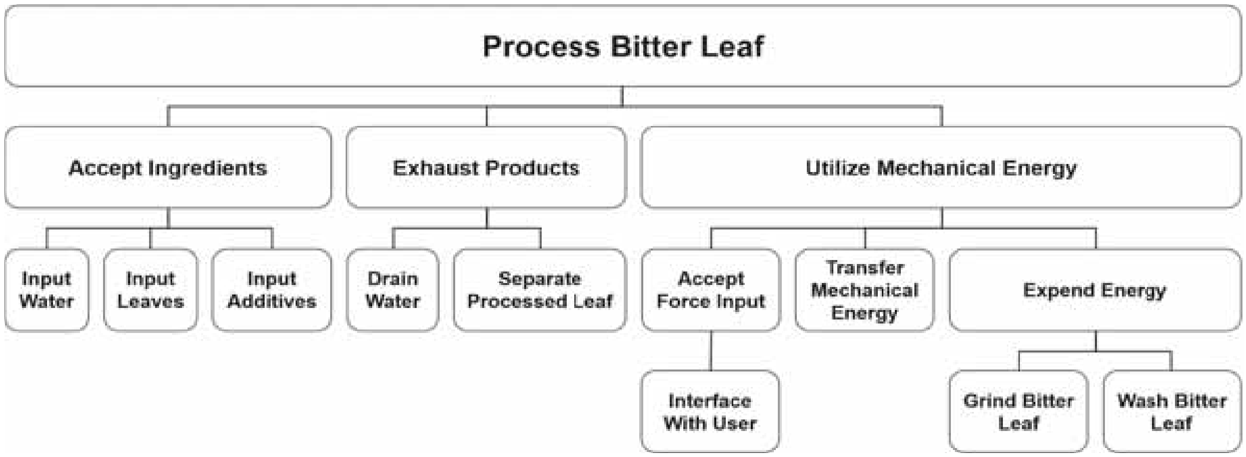


Figure 6: Function Tree for Processing Bitter Leaves

From discussions with Dr. Zama, a list of design constraints has been developed that the device must fall within, seen in Table 2. The first and most important constraint is the device must be entirely human-powered to be viable in the market. The sponsor believes that if it takes more than 30 minutes to process a load it will not be adopted, and similarly, if it costs more than $100 to manufacture, it will be too expensive to produce the volume of units he has set as a goal. If it is larger than 4’x4’, it will likely not be practical in the intended region. Another important constraint is adhering to FDA guidelines. Due to lesser developed regulations in Cameroon, the previously discussed American FDA standards will be applied to the product to better protect the consumer.

Table 2: Design Constraints

Operated manually (no electric power)
Fits within 4x4' space
Takes less than 30 minutes per load of leaves
Costs <$100 to manufacture
Locally manufacturable in Cameroon
Adheres to FDA material guidelines
Ergonomically comfortable for 5'2" woman

A basic specification list naturally evolves from the constraints (Table 3). Three important specifications generated by the design team are as follows: contain catastrophic failure of grinding mechanism, have components replaceable within 45 minutes, and require less than 60 Watts to function. The catastrophic failure of quickly spinning components has the potential to cause serious harm to the user if not properly contained. Replacing the components quickly ensures a modular design and easy repair in non-ideal conditions. The Standard Handbook for Mechanical Engineering states that the average woman can produce 60 watts of steady work [15]. Exceeding this threshold would reduce the ease of use and the adopting of the product.

Table 3: Specification Sheet

Changes	D/W	Requirement	Responsibility	Source
	D	Grinds and washes bitter leaves	Design Team	Sponsor
		Geometry		
	D	Fits in 4x4' space	Design Team	Sponsor
	W	Smaller than 16.5"L x 16.5"W x 21"H (size of 10-gallon drink dispensers)	Design Team	Sponsor
		Forces		
	W	Retains function after 4' drop	Design Team	Design Team
		Energy		
	D	Requires <75 Watts to function [12]	Design Team	Design Team
	W	Requires <60 Watts to function [12]	Design Team	Design Team
		Materials		
	D	Food safe materials	Design Team	Design Team
	D	Materials available in Nigerian communities	Design Team	Sponsor
9/2/19	W	Water and salt stable	Design Team	Sponsor
9/15/19	W	Thermally stable between 32F-140F [16]	Design Team	Design Team
	W	95% of blueprint leaf processing efficiency after 1000 loads	Design Team	Design Team
		Maintenance		
9/12/19	D	All components can be replaced in under 45 minutes	Design Team	Design Team

		Safety		
	D	Outside walls contain catastrophic failure of the internal mechanism	Design Team	Design Team
	W	All materials will have an impact resistance of at least 5 Pa(m^(½))	Design Team	Design Team
	W	Functions can be locked to reduce injury	Design Team	Design Team
		Ergonomics		
	D	5’ 2” woman can use comfortably [14]	Design Team	Design Team
9/10/19	W	Can be broken down into parts under 15 pounds for a 12-year-old to lift	Design Team	Design Team
		Assembly		
9/15/19	W	End-user assembly should take less than 60min	Design Team	
		Operation		
	D	Bitter leaves should be thoroughly cleaned in <30min	Design Team	Sponsor
	D	Shreds bitter leaves into 0.5x0.5 cm to 2x2 cm pieces	Design Team	Local Contact
10/12/19	W	Can process 2000 in^3 of leaves per load	Design Team	Design Team
		Signals		
	D	All inputs and outputs should be manual	Design Team	Sponsor
		Cost		
	D	Individual unit cost <$100	Design Team	Sponsor
		Schedule		
	D	Finish prototype by Dec. 2nd	Design Team	Sponsor

The customer requirements discussed earlier were expanded to include implicit requirements and combined with engineering requirements in a house of quality, in which the correlations between the two were combined with the requirement weights to understand the importance of the specifications, shown in Figure 7. There were no clear leaders in this comparison, as price, simplicity, materials and cycle time all had over 10% relative importance and only weight fell beneath the 10% mark. With the target customer living in more impoverished areas needing to conserve time in food preparation, this distribution is sensible as all these engineering requirements have a direct impact on the usability of the product.

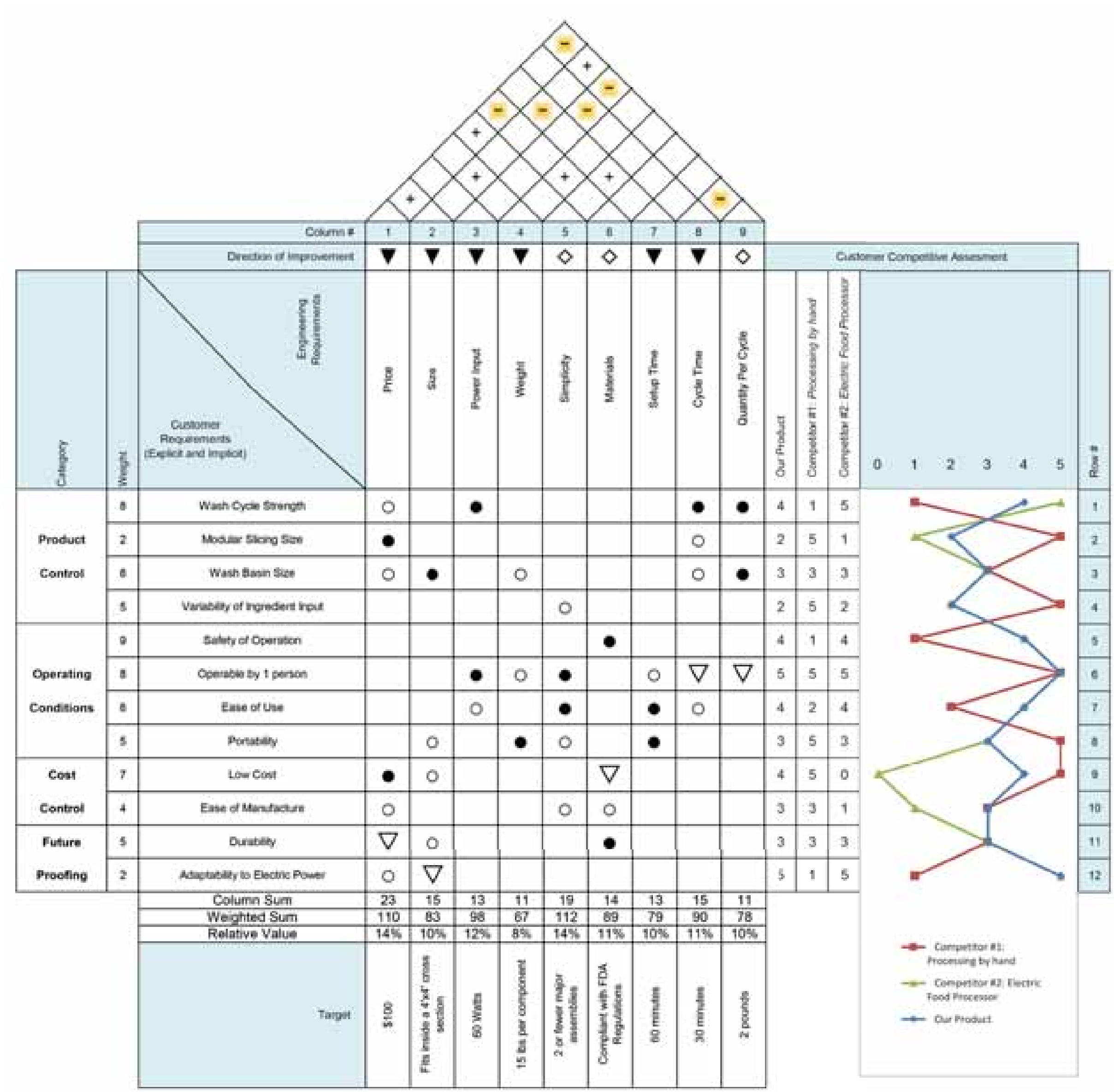


Figure 7: House of Quality

The targets identified in the house of quality contain many specifications directly from Dr. Zama and the prospective customers in Cameroon, mainly the $100/unit price and 30 minute cycle time. The rest of the targets were filled in by design team goals, such as components weighing less than 15 lb each, ability to process 2 lb of leaves at a time, and setup time under 60 minutes. These requirements were not explicitly defined after the research of the customers who will buy the product, though they should serve to improve the experience for the user.

5. Market Research

The sponsor emphasizes getting this product to Cameroon for distribution to people who rely on bitter leaves to supplement their diet and income through processing and selling these leaves. Since most of the wealthy Cameroonians and immigrants can use electric power to aid their bitter leaf consumption, the target demographic is challenging to reach and challenging to set up reliable communication lines. Dr. Zama has provided most of the background and is the primary research option for the project, but there are four other groups that have been or will be contacted for more extensive research.

The first group is the technicians who will be building the product in Cameroon. This group was contacted through WhatsApp during the prototyping stage, to ensure the planned manufacturing techniques were locally feasible. The second group, Cameroonians currently living in Atlanta, will assist with project and process background. A Cameroonian native living in Atlanta was contacted and provided useful demonstrations on how bitter leaf processing traditionally works, as well as a rough target for the amount of leaves processed per batch, which increased the scale of the design by a factor of two.

Third, some Johns Hopkins University employees are former residents of Cameroon and can provide advice in a more reliable manner than the Cameroonian users. The fourth group consists of potential users in Cameroon. Dr. Zama provided contacts in Cameroon who are available through WhatsApp. These users are a combination of relatives and friends who are willing to answer questions about their bitter leaf habits and what they are looking for in a product, but have proven very difficult to contact due to time zones and internet availability in Cameroon. Due to these issues it was very difficult to get actual user feedback about the design. However, Dr. Zama was able to interact with the device and was very happy and optimistic about its functioning.

This final group is the target market. However, since the manufacture of these devices is to be paid for by the sponsor and distributed free of charge in a market described by the sponsor as having no viable device to accomplish this function, the market strategy simplifies to getting the design to Cameroon promptly for manufacturing and distribution as quickly as they can manage. The sponsor's goal is to get two million units to Cameroon.

The major takeaways from the market research are the constraints on the device, discussed above (Table 2). The market size is potentially hundreds of thousands of people across Cameroon and West Africa, consisting mainly of lower-class families without steady access to electricity. The sponsor has a target price of $100 for mass manufacturing the device, and the marketing strategy is humanitarian focused, training local technicians to produce the device or sending easy to assemble kits to the target families. No competitive products exist on the market for areas without access to electricity, except for the manual food processors discussed above which are not optimized for bitter leaves. This research leads to the focus on simplicity and modularity in the final product and will guide the industrial design element towards clear assembly and processing steps.

6. Design Concept Ideation

As discussed above, the problem of processing bitter leaf was broken down into nine subfunctions, as seen in Figure 6. These functions were developed to ensure that every individual process the device needs to perform are independently and adequately addressed. To do this, several solutions addressing each function were prepared, and are presented in Figures 8-9.

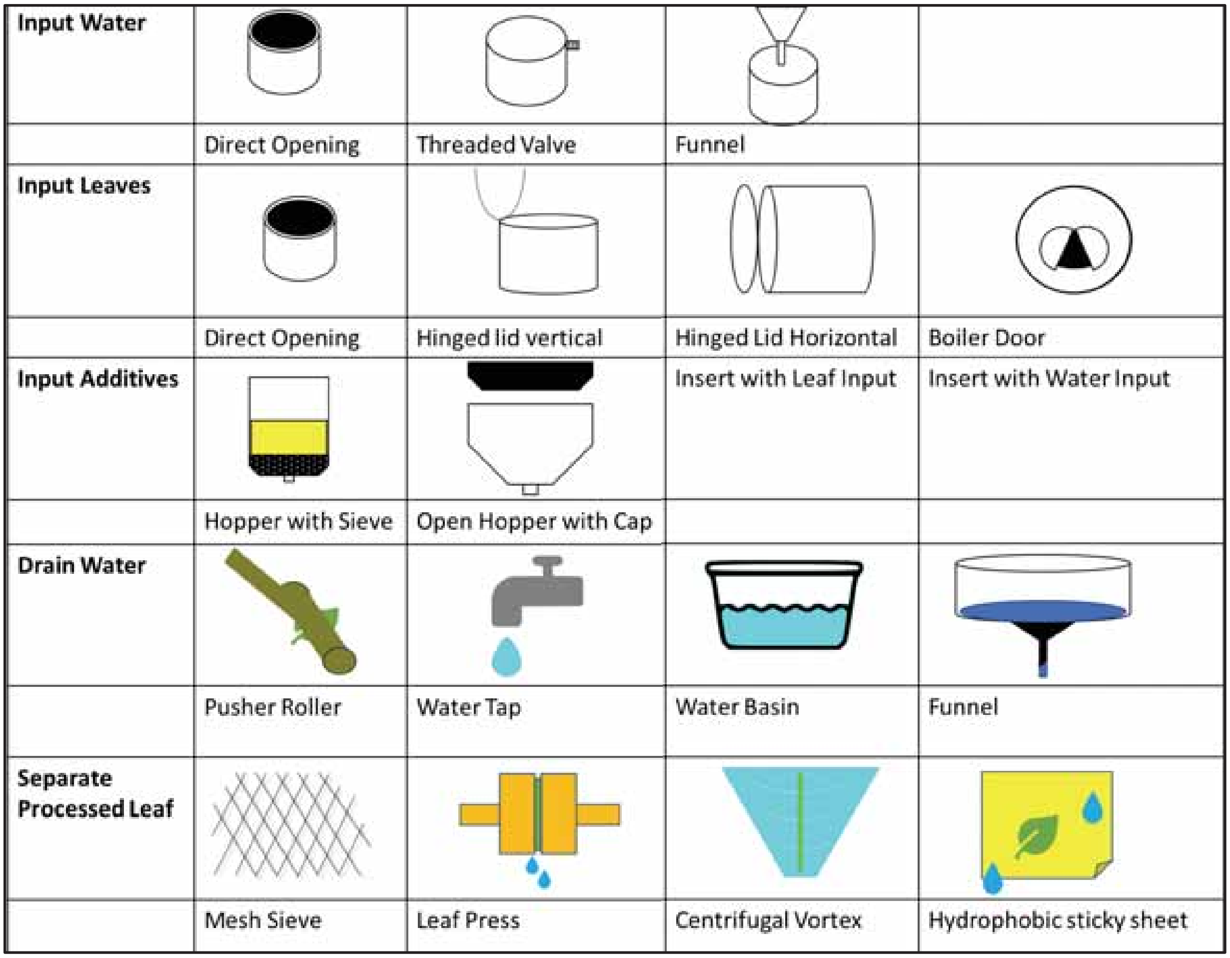
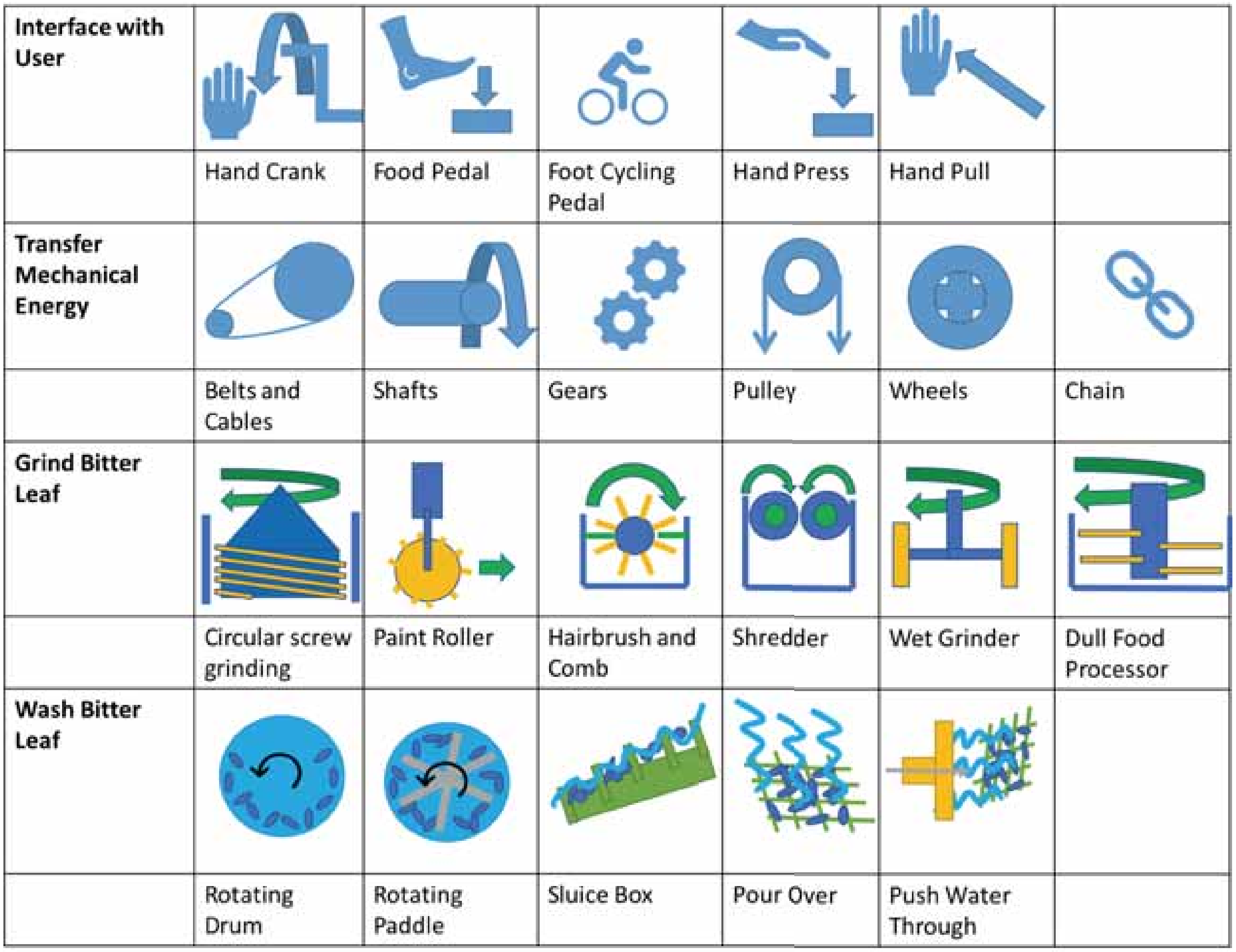


Figure 8: Morph Chart--Adding and Removing Materials



Interface with User						
	Hand Crank	Food Pedal	Foot Cycling Pedal	Hand Press	Hand Pull	
Transfer Mechanical Energy						
	Belts and Cables	Shafts	Gears	Pulley	Wheels	Chain
Grind Bitter Leaf						
	Circular screw grinding	Paint Roller	Hairbrush and Comb	Shredder	Wet Grinder	Dull Food Processor
Wash Bitter Leaf						
	Rotating Drum	Rotating Paddle	Sluice Box	Pour Over	Push Water Through	

Figure 9: Morph Chart--Transferring Mechanical Energy

While some of these ideas overlap, the intention is to come up with solution forms that address each individual function regardless of its originality. Finally, these solutions provide a framework that can be combined in different ways to produce overall solutions for the design. Four potential designs were developed using this method. First, the Concentricity design, shown in Figure 10, uses concentric rotating cylinders to grind and wash the leaves. The main benefits of this design is that it utilizes the intrinsic frictional forces of the system to grind and wash the leaves. Therefore it is very energy efficient. However, this design presents significant manufacturing challenges, as each of the cylinders need to be within a very tight tolerance zone for the rotational motion to function as intended.

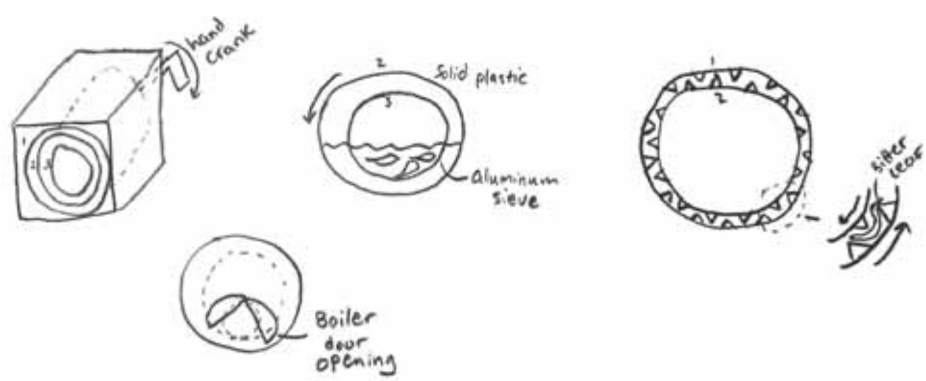


Figure 10: Potential Design 1, Concentricity

An alternative design, the Wet Grinder (Figure 11), utilizes the wet grinder mechanism discussed in the prior art section to grind the bitter leaves. This design uses proven technologies. However, the grinding done by a wet grinder would produce a much finer finished product than is desired. The bitter leaf should be in shreds, not in a paste.

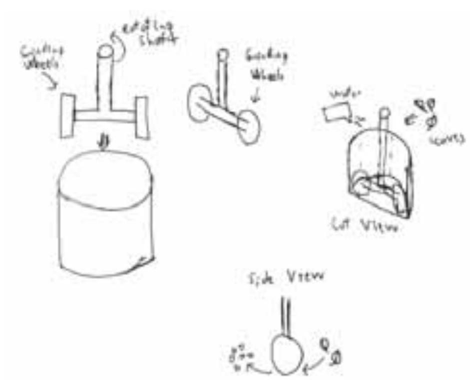


Figure 11: Potential Design 2, The Wet Grinder

The next potential design discussed is the Hairbrush and Comb, seen in Figure 12. This design uses a center rotating brush to shred and wash the bitter leaves along two rows of stationary teeth. This motion is used to both shred and wash the leaves. This design has a unique shredding mechanism that fits in the gap between mechanical shredding and manual grinding. However, due to the size of the bristles on the brush and comb components, there are concerns about the reliability and longevity of this design.

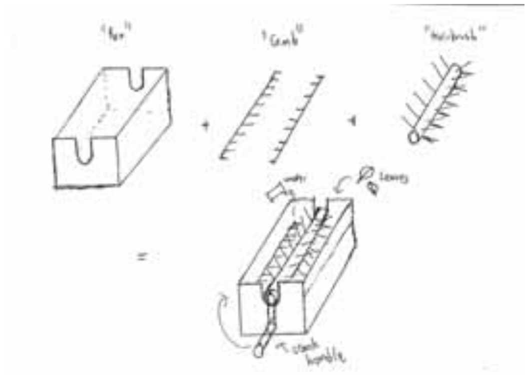


Figure 12: Potential Design 3, Hairbrush and Comb

The next potential design discussed is The Plunger, seen in Figure 13. This design uses a paint roller to pass over the leaves and grind them, and a plunger to mechanically push the leaves against a sieve to drain the water. This design would be easier to manufacture, and very closely matches the manual process currently in place. However, it is much less scalable to meet different potential customer needs.

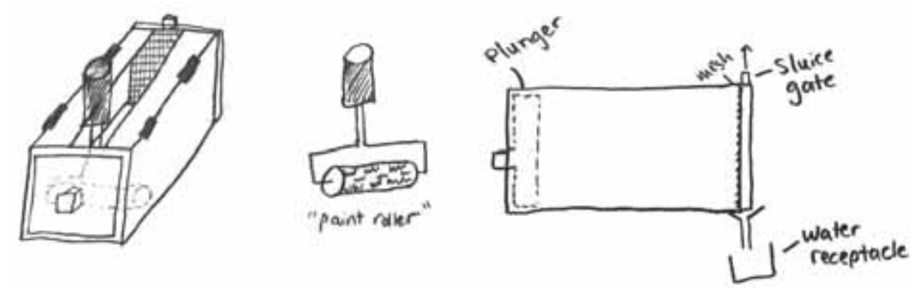


Figure 13: Potential Design 4, The Plunge

The final potential design developed is called The Lunchbox, shown in Figure 14. The main characteristic of this design is its box-like, compact shape and the modularity of its functions. Whereas the other designs have multiple functions intertwined, such as the grinding/shredding and washing functions, this design keeps nearly all of its functions independent of one another, in separate modules stacked on top of each other.

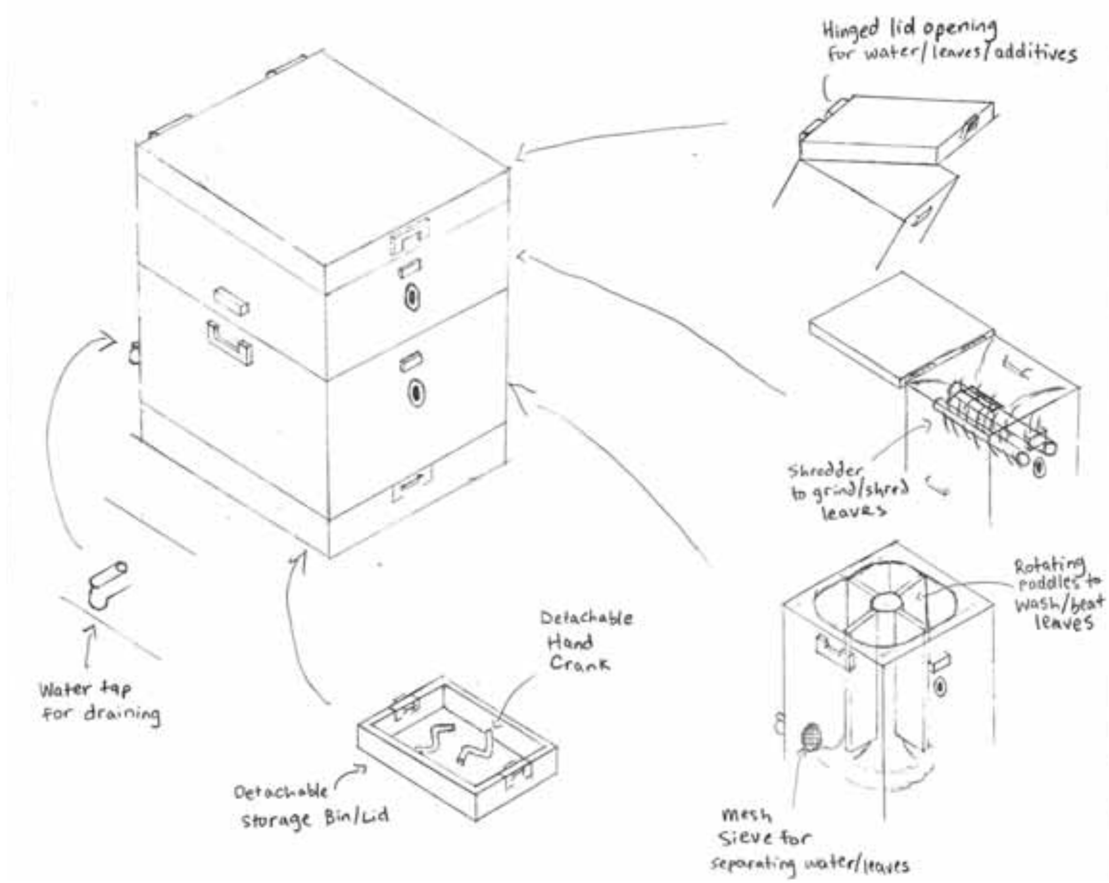


Figure 14: Potential Design 5, The Lunchbox

Initial feasibility analyses primarily focused on analysis, buildability, and usability. First, the ability to adequately analyze the design was considered. In this, concentricity is the most difficult design analyze and make design decisions, because most of the critical points rely on manufacturing tolerances, surface characteristics, and how the leaves react to shear forces. Therefore, this design would rely greatly on prototyping which is slower and less cost effective than standard analysis. The hairbrush has some similar issues, but would be easier to determine the forces placed on the leaves.

For buildability, the resources available for prototyping were considered first. With the combination of the Invention Studio and Montgomery Machining Mall, any metal pieces relying on traditional manufacturing can be easily created, albeit with moderate to long lead times. 3d printing (plastic and resin based) are the only plastic manufacturing resources easily accessed, and suffer from either tolerancing or size constraints compared to traditional methods such as injection molding. This consideration primarily applies to both concentricity and the hairbrush. For concentricity, only 3d printing could generate the complex surface geometries necessary, and the surface features would be difficult to replicate compared to production. For the hairbrush, the thin features (bristles) could prove challenging to replicate during prototyping and would have substantially different properties compared to large scale, accentuated due to the size of the bristles. The other buildability factor was how much the design could be split into smaller parts for testing. While concentricity relies substantially on the entire device being built before any can be tested, the lunchbox and other designs can be quickly tested with small models of the critical components.

For usability, the primary consideration was the anticipated force input. Without more specific plans for the drive trains of each, the biggest feasibility concern was with the plunger. Since the motion is horizontal, the weight of the person cannot be used to help generate force, and depending on the area the pressure exerted on the leaves and water could drop quickly, leading to more critical scale constraints than the rest of the designs.

At this point of the design process, the main potential risks that can be foreseen are the manufacturing costs and the effectiveness of the functions of the product. As there are many different parts and complex geometries in this product, it is feared that it would be too expensive to manufacture. As a countermeasure, the complexity of some of the parts can be simplified and the number of parts minimized if necessary. While the cutting and washing functions of this concept are based on proven methods, it is unknown if they'll be effective in the context of this application as the mechanical properties of the bitter leaves are largely unknown. However, it is known from the sponsor that collard greens can be used as a mechanical substitute if bitter leaves are not available to use. To counter this obstacle, the effectiveness of the current cutting and washing mechanism will be tested and if necessary, swapped for other feasible solutions from the morph chart as seen in Figure 9.

7. Preliminary Concept Selection and Justification

In order to make the selection, a 3rd-level evaluation matrix as shown in Table 4 points out the advantages and disadvantages with each design. The criteria used for the evaluation matrix were taken from the most important customer requirements from the House of Quality (Figure 7).

Table 4: Evaluation Matrix

Criteria	Relative Weight	Concentricity	Wet Grinder	The Lunchbox	The Plunger	Hairbrush and Comb
Safety of Operation	9	4	4	3	3	3
Ease of Use	6	4	3	3	4	4
Ease of Manufacturability	6	3	3	2	4	3
Cleanability	6	2	3	3	3	2
Modularity of functions	2	2	1	4	3	2
Input Capacity Range	5	3	2	4	3	2
Work input	8	3	3	3	2	4
Speed of Operation	9	2	2	3	3	3
Durability	5	2	3	3	3	3
Portability	5	1	2	4	2	3
	Total	166	169	189	182	184
	Relative Total	0.187	0.190	0.212	0.204	0.207
		4 = Very Good	3 = Good	2 = Satisfactory	1 = Just Tolerable	0 = Unacceptable

The evaluation matrix output very close relative totals between several of the designs. As more information and feedback is obtained from the contacts that the sponsor has provided, these weights and rankings could change to favor other designs. However, the Lunchbox's modularity of functions allows greater independence between components, meaning that an entirely new design does not have to be drafted if a major design change needs to be made or other designs incorporated into them. Therefore the Lunchbox was chosen as the preliminary final design.

Alongside this unique feature, this design is more portable than the other designs. Since bitter leaves are consumed quite frequently in the region where the device will be sold, and since this machine will, for most homes, be in a shed separate from the main home, portability is quite important. Due to the compact, box-like design of this concept and its handles, it is more ergonomic compared to the other designs. Since none of the components are susceptible to breaking if dropped from a 4’-6’ height, it is superior to design concepts like the Hairbrush and Comb where at least one of the major components has thin parts susceptible to breaking.

In addition, due to this design’s rotating paddle mechanism to wash leaves, the input capacity of leaves of this design was greater than the other design concepts that were considered. The rotating paddle mechanism can wash a decent quantity of leaves uniformly without a drop in quality, similar to a washing machine, a highly developed and proven piece of technology. However, further market research, specifically the personal meeting with a Cameroonian native, showed that bitter leaves require rubbing between palms to force the bitter flavors out. Previously, it was assumed that leaching out the chemical with highly agitated water would be sufficient. This new information made the paddle design less feasible, as the only way to achieve the necessary friction requires the paddles to fold up against the walls of the chamber, increasing friction in the system and making assembly much more difficult, increasing costs dramatically.

In the next design iteration from the Lunchbox, referred to as Stacks, the paddle system is replaced with a manual mashing system inspired by a commercial french press. A free-moving press is used to “juice” the leaves against a fine polypropylene mesh (Figure 15).

Figure 15: Stacks Bottom Washing unit and press

The mesh contains the leaf particles, but allows the water to drain off. The press allows the user to apply as much or as little force as they would like, and therefore allows them to control the amount of bitterness left in the leaves.

The original shredding mechanism of the lunchbox was based on a standard paper shredder, common in offices around the world. Initial market research indicated the dull blades and ripping the leaves was preferable to sharp blades and slicing the leaves, which inspired the initial designs. The shredder can easily match this constraint through the use of dull blades and larger gaps than standard issue devices. It is also very easy to manufacture shredders in multiple small components and quickly assemble them onto a central shaft. However, the same in-person meeting that showed the issues with the washing unit also lifted the dull blade constraint, greatly freeing up the design choices for the system. With the increased size (2000 in^3) of leaves, a design imitating a standard food processor (Figure 2, 16) uses less metal and has much less stringent tolerance requirements than a shredder design. It is also easier to change the blades or central column for the food processor design than the shredder design, increasing modularity.

Figure 16: Stacks top chamber

Another change between the Lunchbox sketch (Figure 14) and the Stacks design is an altered form factor. Since each of the components is cylindrical, the outer design can be a cylinder as well to avoid material waste with a double shelled design (Figure 17). The stacking of the shredding unit above the washing unit also allows easy transferring of the bitter leaves, using a swiveling panel between the bottom of the shredder and the top of the washing unit (Figure 18).

Figure 17: Stacks design

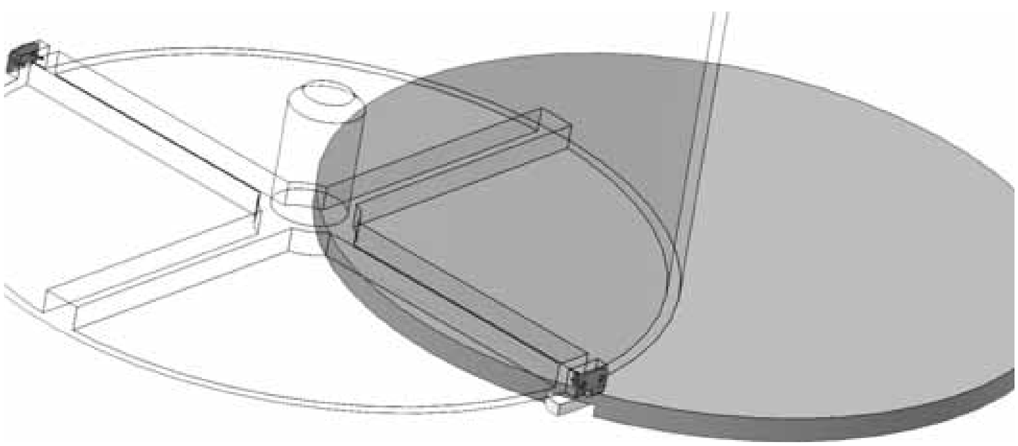


Figure 18: Swiveling bottom panel to top unit

The Stacks design was altered one more time to reach the final design, the Spaghetti. To simplify the design, the top and bottom units were compressed into a single, double-walled cylinder (Figure 19) that incorporates the shredding and the juicing into a single area. By combining the cylinders, a smaller form factor was achieved and the complexity of transferring leaves between units and requiring latches was eliminated. The polypropylene mesh screen nests inside the outer unit, as seen in Figure 20, and has two cutaway handles to assist with removing and replacing it easily.

Figure 19: Spaghetti Design Full

Figure 20: Spaghetti Design Nesting Functionality

Additionally, the Spaghetti has an updated lid assembly, incorporating a drivetrain with a 4:1 ratio to increase the speed of the blades (Figure 21). This necessitates a two-piece lid for assembly and to protect the gears, accomplished using standard plastic screws. Figure 22 shows the finger joint locking mechanism, which has six total tabs to prevent more than 120° of motion in either direction.

Figure 21: Lid Gearing Assembly

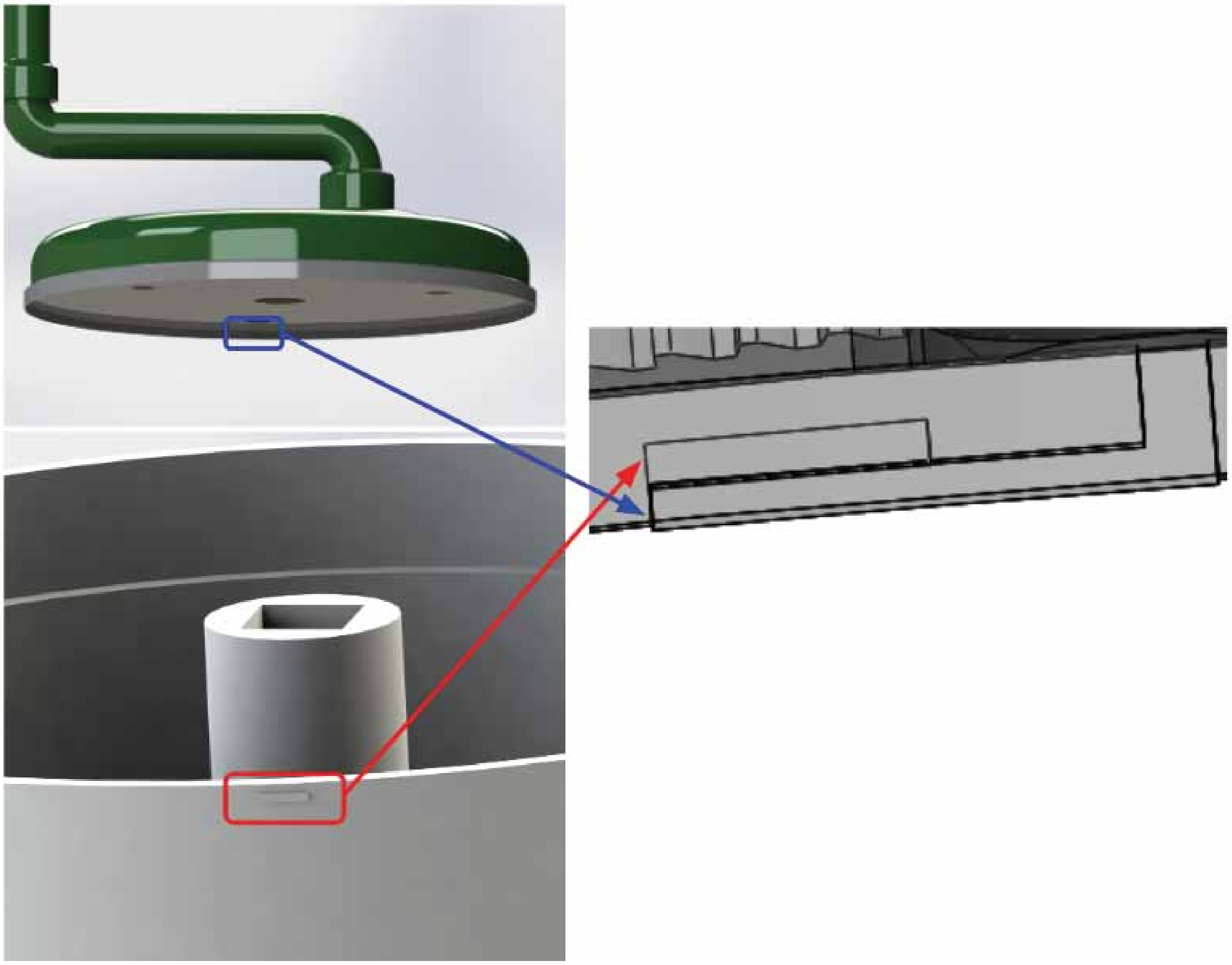


Figure 22: Lid and Body Finger Joint Mechanism

The outer body of Spaghetti has several important features. First, internal ribs provide support for the inner mesh, along with a ledge set against the inside of the wall (Figure 23). The ribs sit above a slanted floor (2° slant) and allow water to flow along the bottom and out the spigot as required. The ribs extend below the floor to provide additional stability against the tabletop and reduce the risk of tipping when using the press to mash the leaves against the bottom of the unit. A central peg provides rotational stability for the mesh and blade column.

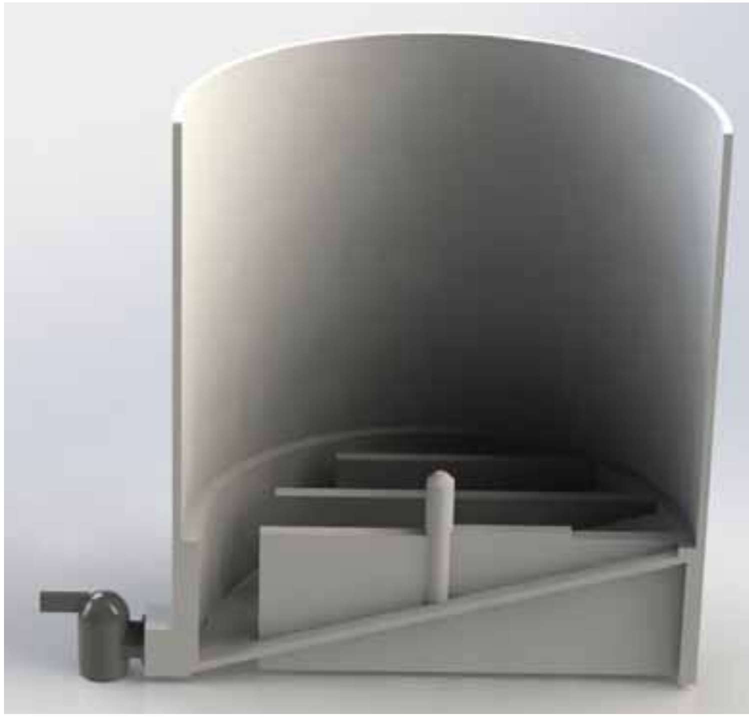


Figure 23: Cut View Outer Body (Inner Slant Increased from 2° to 15° for Clarity)

When combined, these features provide a convenient form factor for using the device while maintaining modularity and usability. This combination can be seen in Figure 24


Figure 24: Section View of Combined Spaghetti Design

The main risk of the Spaghetti design is that the blades will not slice the leaves properly. With the updated gearing assembly, additional speed should help properly cut the leaves, but many factors, including blade number, angle, shape, and sharpness, along with the fill amount of the leaves and the manufacturing of the gearing and components, can influence how the blades slice through the leaves. Optimization of this could move quickly once the initial plans have been set and build plans tested.

The next risk is in the safety of the design. Since the design is intended to be easily disassembled and reassembled by users, the multitude of components present a variety of pinch points which could harm the user. To mitigate this, each component will be made out of lightweight materials, and sharp edges will be chamfered or rounded with the exception of the blades (which require an edge). Furthermore, handles or holding area will be marked or intuitively designed to keep fingers away from the pinch points. Finally, usability checks can help find any dangerous points of operation that are not seen in the design phase.

It is also a risk that the chamber will not be watertight, especially over extended use. The main risk area is the spigot zone, which could become loose and result in dripping or contamination. The easiest solution to this is to apply replaceable O-ring dividers to help maintain the seal, if necessary.

Finally, the vibration of the central tube (holding the blades) could be a problem for the blade attachments. Even using nylon locking nuts, the blade attachments could vibrate loose. This could be dangerous both due to losing nuts and bolts within the processed leaves and because the blades might wiggle loose and could become projectiles in the processing unit. Initial research has started on using rivets or other attachment mechanisms, but have not been incorporated in the final design due to time and manufacturing constraints.

8. Industrial Design

In order to encourage widespread adoption of any device, ergonomics and industrial design must be considered. The Spaghetti design incorporates industrial design in several ways. The most important of these is that the size and shape of the machine is such that it can be moved and operated by a 5’2” woman. Additionally, the work required to operate the machine is designed to be below the sustained work output [15]. These limits will facilitate adoption and ease of use by the target demographic, Nigerian adult women [14].

Ensuring the end user can easily understand the steps necessary to use the device is a vital part of the design process. Due to the international and cross-cultural nature of the project, the device is designed to be intuitive without the use of language. Instead, the form of the design is designed to be intuitive for a variety of use cases. The single pot design allows for any order of usage, so that the user can decide on how to use the device for their needs. The most complicated part of the device is the gear train, which is already in use and would be simple to understand. Additionally, mesh pots (colanders) are already in use for bitter leaves which should make adoption easier. There will be warning labels on the device, which will be printed in English and French (the official languages of Nigeria and Cameroon) as well as various local languages, and any instruction manual will use diagrams to illustrate the potential workflows of the device.

This product is not intended to be sold commercially. The sponsor envisions a non-profit setup whereby the devices would be provided free of charge to the people who need them. Thus, the considerations for branding and logos are less important than if a distinct “brand identity” needed to be established. The use of materials, textures, and colors are important only in how they impact the potential for adoption among the target audience. Materials and textures will be food safe and easy to clean (for example, no rough surfaces will come into contact with food). Color will be used in conjunction with form to highlight locations where the user will need to interact with the device, and once the target area has been established the aesthetic colors of the device can be changed to help it appeal to the specific consumer markets.

9. Engineering Analyses and Experiments

Specific aspects of the design were more rigorously analyzed to determine potential modes of failure and inform design revision choices. These analyses are more thoroughly described below.

9.1 Material Selection

The initial analysis was for the material the unit was to be made out of. CES Edupack was the primary resource used to make these decisions. The design constraints were the driving force in making these decisions. All materials used need to be food safe, easily formable, and thermally stable between 20F and 150F. Additionally, the material needs to be strong enough to withstand the stresses of the bitter leaf process, including strong resistance to fracturing. The material must also be easily sourced for Cameroon, and maximize cheapness and strength. Using these constraints, the material polypropylene homopolymer was chosen as the best choice for the main design elements using CES Edupack (Figure 25). This material has a density of 0.033 lb/in^3 [17], and the current design has a total plastic volume of roughly 600 in^3, so this material meets the weight limit. Polypropylene has a yield stress of 4800 psi [14], which is shown in the analyses below to be higher than the maximum stress expected to be experienced by the device. For the blades, 304 stainless steel was chosen as it is strong, non-corrosive, and food safe, while also holding an edge well for its cutting application. This is also one of the most common stainless steels and is a cheaper grade. The endurance limit of the stainless steel is 34,800 psi [18] which is shown below to be plenty for this application.

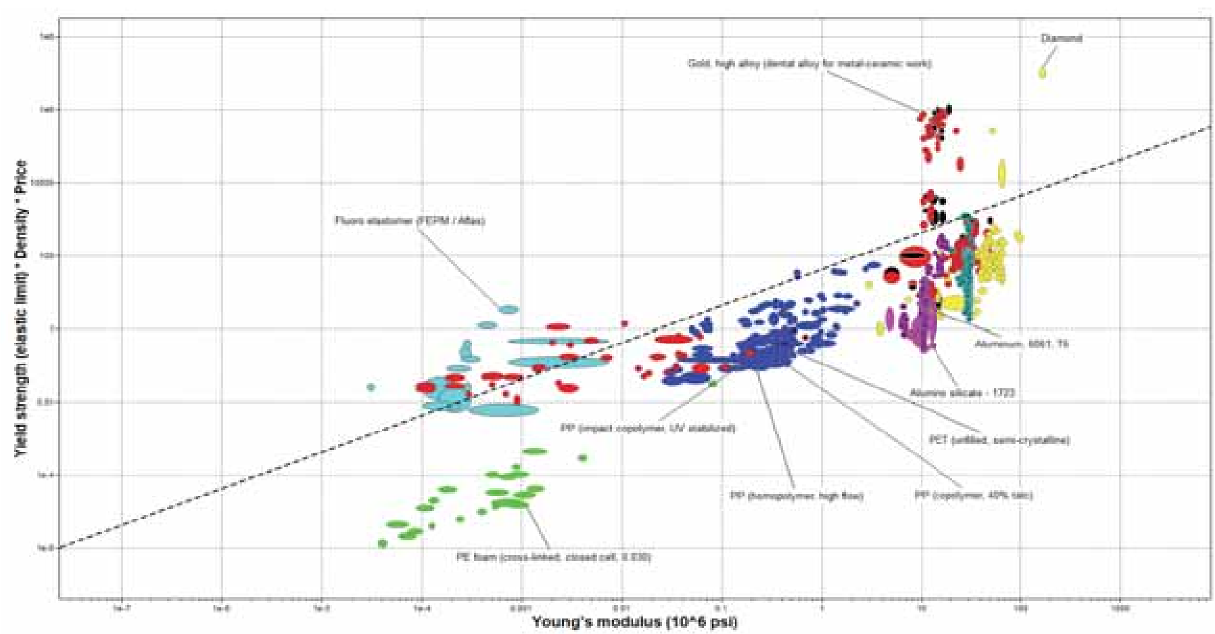


Figure 25: Material choice chart from CES Edupack selection project

9.2 Work required to operate

To calculate the work required to operate the device, lettuce was used to simulate bitter leaf. While this approximation has a relatively large potential error, there is very little formal research done into the mechanical properties of bitter leaves, while the mechanical properties of lettuce have been thoroughly explored. The pressure necessary to cut through the bitter leaves was therefore assumed to be 0.4 MPa [19], the yield strength of lettuce. It was assumed that the goal speed of the unit will be 1 rotation per second for the blades. Additional assumptions include that the basin is 100% filled with bitter leaf (no air), that only the outer 25% of each blade is cutting the leaf and half of the projected area is involved in the cutting, that there is no friction in the system, and that there is no stored rotational energy in the system. The full details of the calculations can be seen in appendix A, and the calculated work input is 55W. While there are many assumptions that could cause issues in this analysis, this is below the target work input of 60W.

9.3 Handle Loading

The handle that turns the blades is one of the more isolated parts of the design. Analyses were run to determine if applied pressure on the end of the handle, for example from a user leaning on it during the washing process, would like to critical failure of the part. Initial analysis, shown in Figure 26, indicated that there was a region of stress concentration in the lower bend of the handle (detailed view in Figure 27).

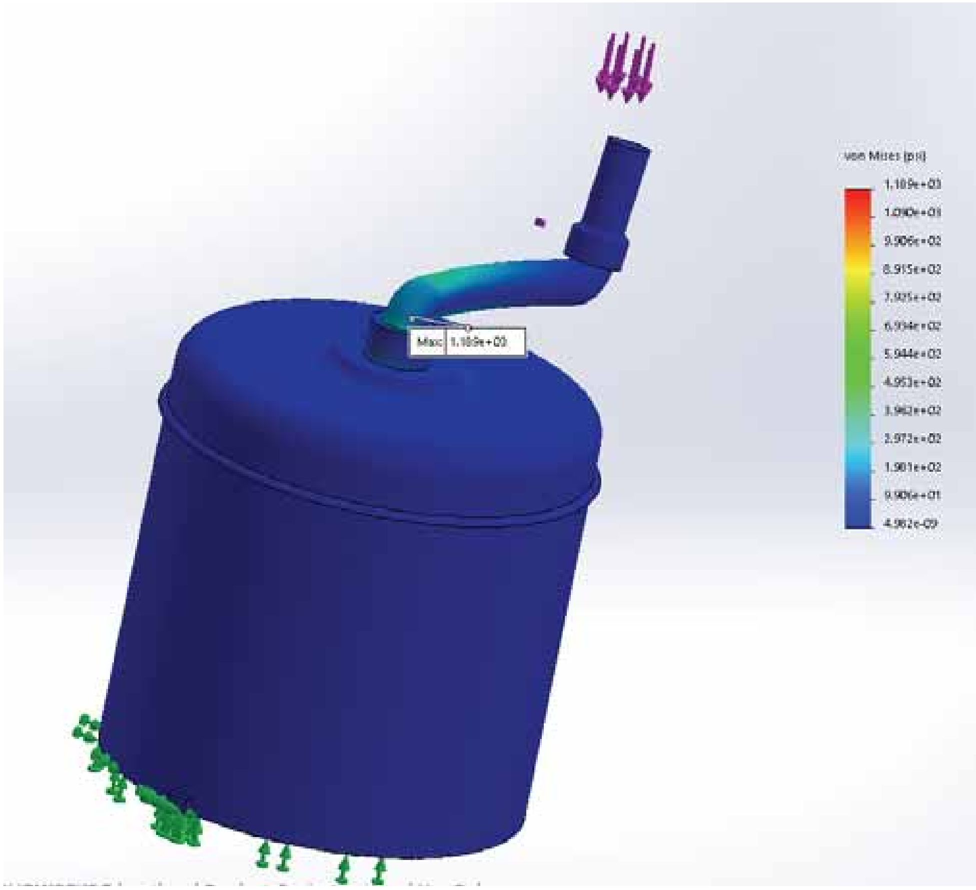


Figure 26: Stress under load in original handle design

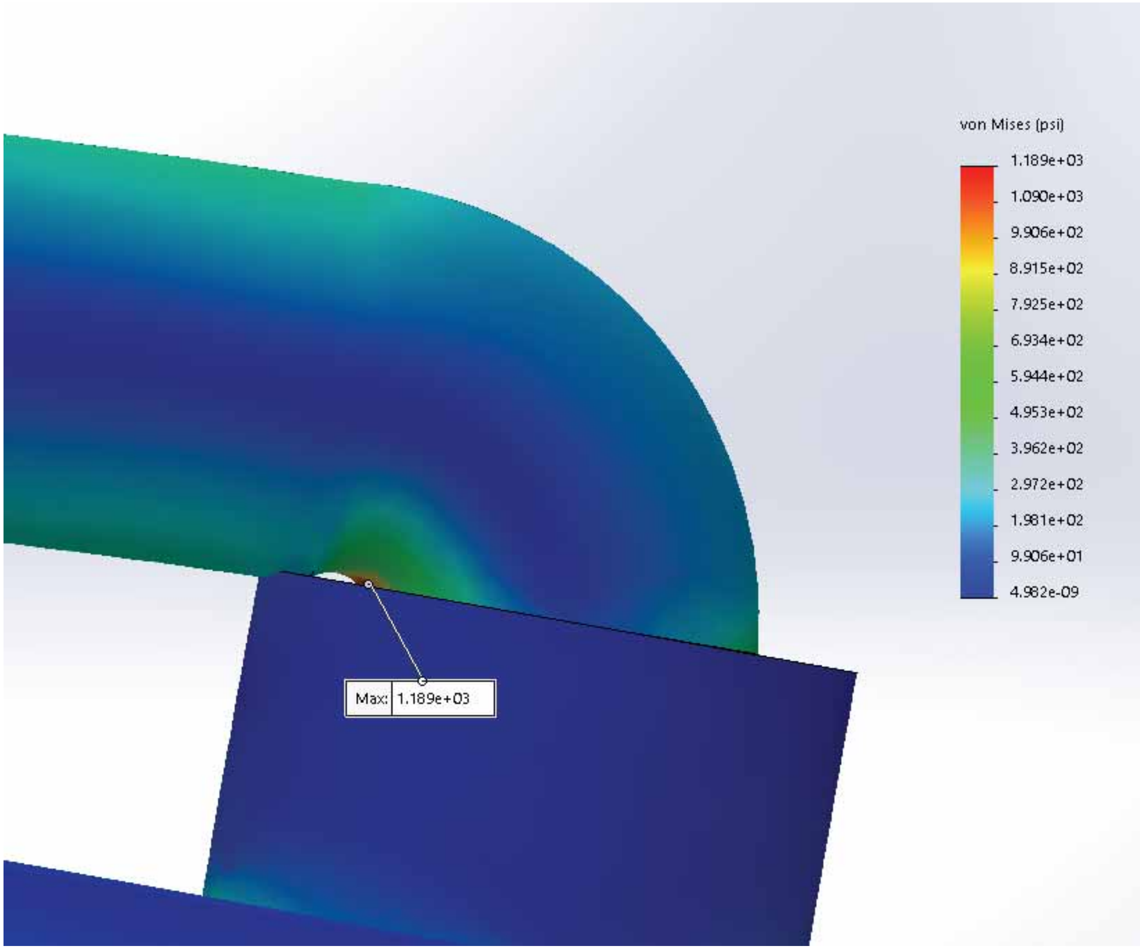


Figure 27: Stress concentration detail in initial handle design

This analysis was run with a downward force of 10 lb, and assumed the unit was held fixed at the bottom (as it is when sitting on a table). The maximum stress concentration seen in this design was 1189 psi. While this still falls under the yield strength of polypropylene of 4630 psi, in actual uses of the device, there will be a much more complicated load structure on the handle. Under higher loads and over time, this singular stress concentration point will lead to a higher likelihood of failure.

Due to this analysis, the design for the handle was adjusted slightly. The inner diameter of the handle was increased slightly to better accommodate for loads. Furthermore, the bend at the bottom end of the handle which was causing the stress concentration was lengthened to eliminate the problematic region. The same analyses were performed on the new design, shown in Figure 28. This analysis shows that with this design of the handle, the maximum stress is 583 psi, much lower than in the previous design.

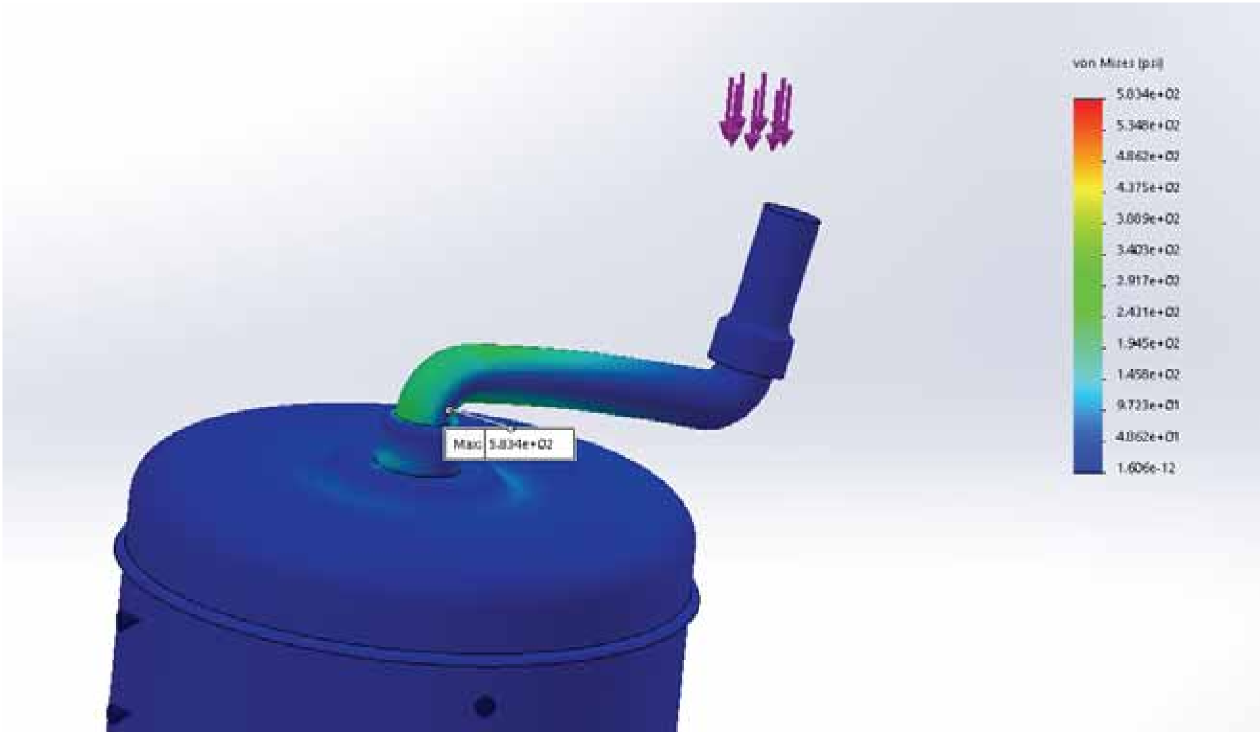


Figure 28: Top loading on revised handle

Furthermore, an analysis was conducted to simulate the load on the handle during washing. To simulate a worst-case-scenario, over twice the expected horizontal load of 23 lb (see section 9.2 Work Analysis) was applied horizontally to the handle in addition to the 10 lb vertical force applied before. This analysis, shown in Figure 29, shows that the maximum stress in the handle is 2448 psi, which still provides a Factor of Safety of roughly 2 before material failure.

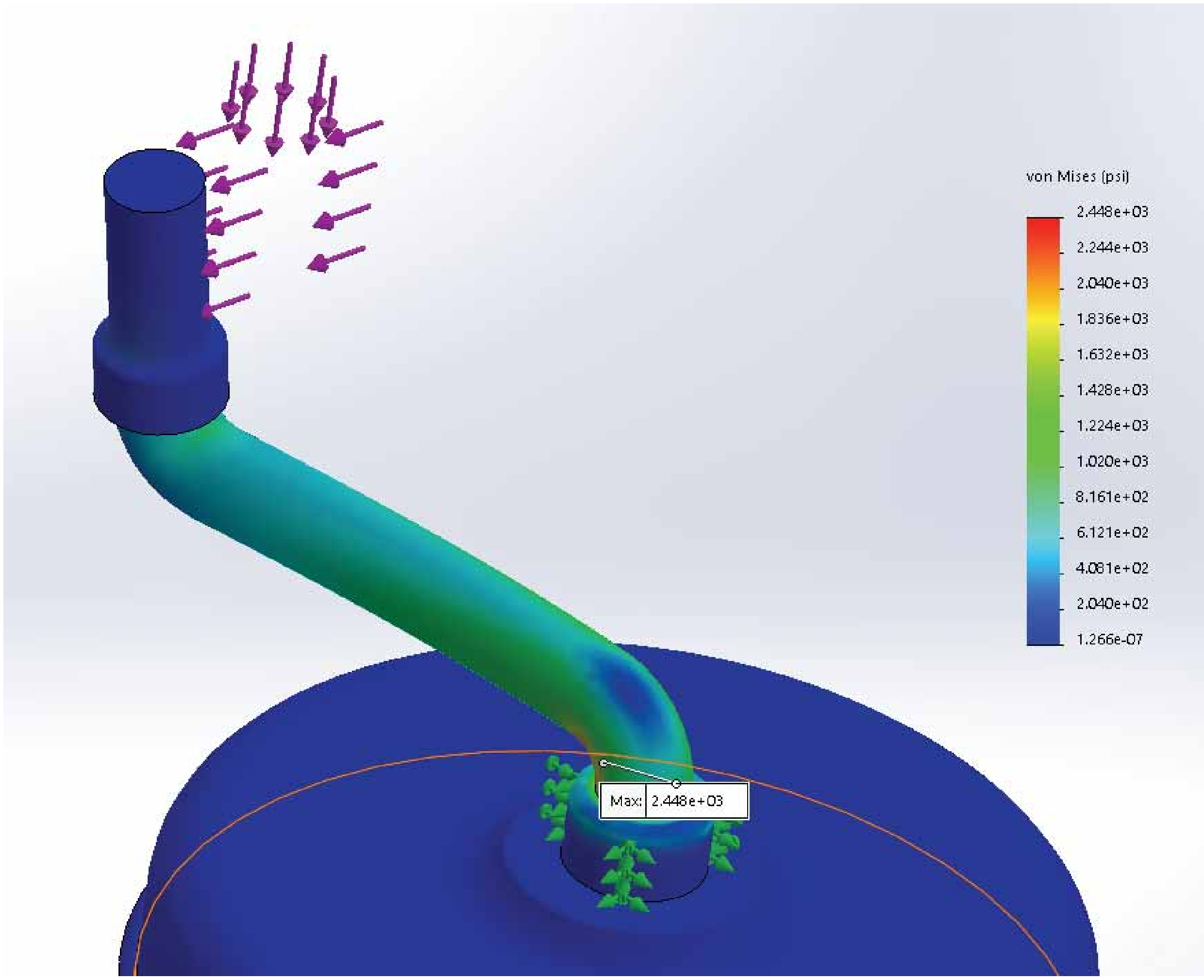


Figure 29: Combined load on handle

After the redesign incorporating the gear train, the combined loading situation was run again using a 30 lbs horizontal force and a 15 lbs, replicating a potential situation where the gears jammed (Figure 30). This resulted in a stress of 1719 psi and a factor of safety of 2.7 before failure, which is even better than the previous handle iteration.

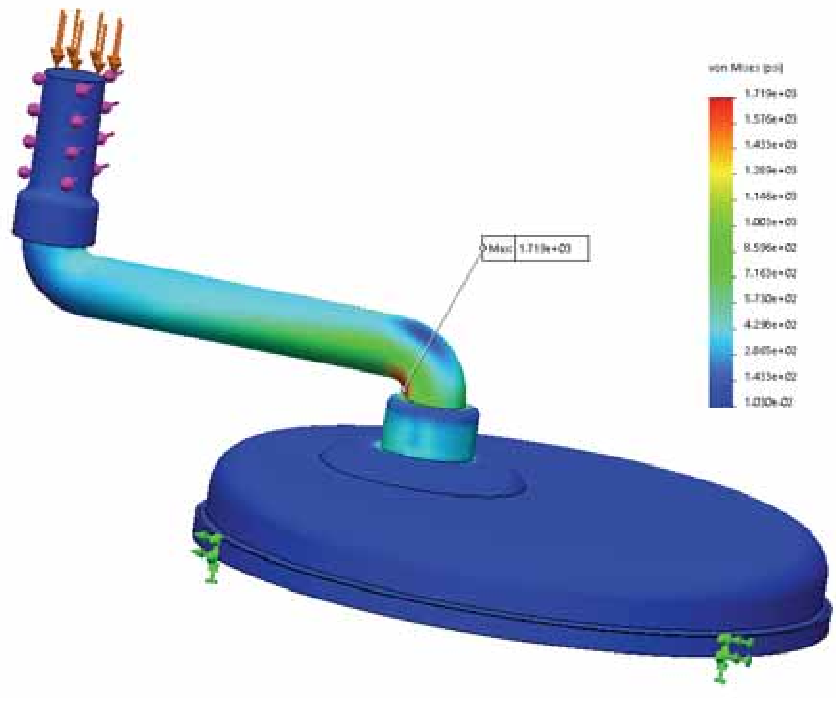


Figure 30: Combined Loading on Final Design

9.4 CFD

The area between the press surface and the bottom mesh is filled with a leaf-water mixture that must be compressed and agitated to release the bitter taste from the leaves. Solidworks Fluid Flow Simulation was used to observe the paths and velocities of the fluid particles. The analysis assumed 3 inches of water were sitting in the basin, draining at a negligible rate. The press is pushed into the fluid with 30 lb of force, contacting the fluid on the c-shaped pressure points, with hydrostatic pressure assumed to be negligible. The first iteration, shown in Figure 31 has a pressure on the top 1.12 psi above atmospheric. While the subsequent fluid trajectories are desirable, the fluid particles rarely exceed 0.04 ft/s, and have a maximum velocity of 0.497 ft/s , far lower than is acceptable to effectively agitate the mixture.

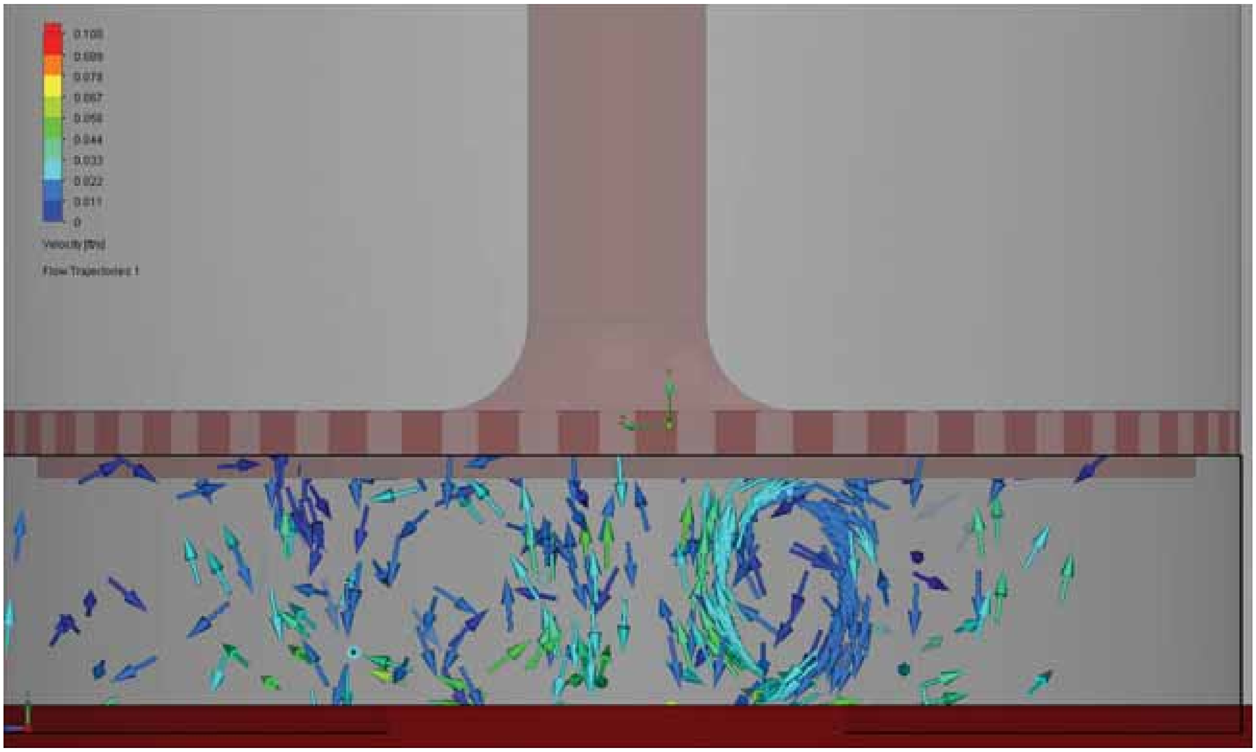


Figure 31: Flow Trajectories under the 14” Diameter Press

This analysis resulted in a design change in the press, mainly decreasing the diameter to 5” and narrowing the c-shaped pressure points to increase the maximum pressure. The fluid analysis of the system with the updated pressure size and other assumptions held intact is shown in Figure 32, with the smaller contact area resulting in a pressure from the top of 19.23 psi above atmospheric. This analysis shows trajectories of similar shape to that of the first iteration, but benefits from fluid velocities on average around 0.1-0.2 ft/s and attaining a maximum of 2.031 ft/s, which will be much better for mixture agitation.

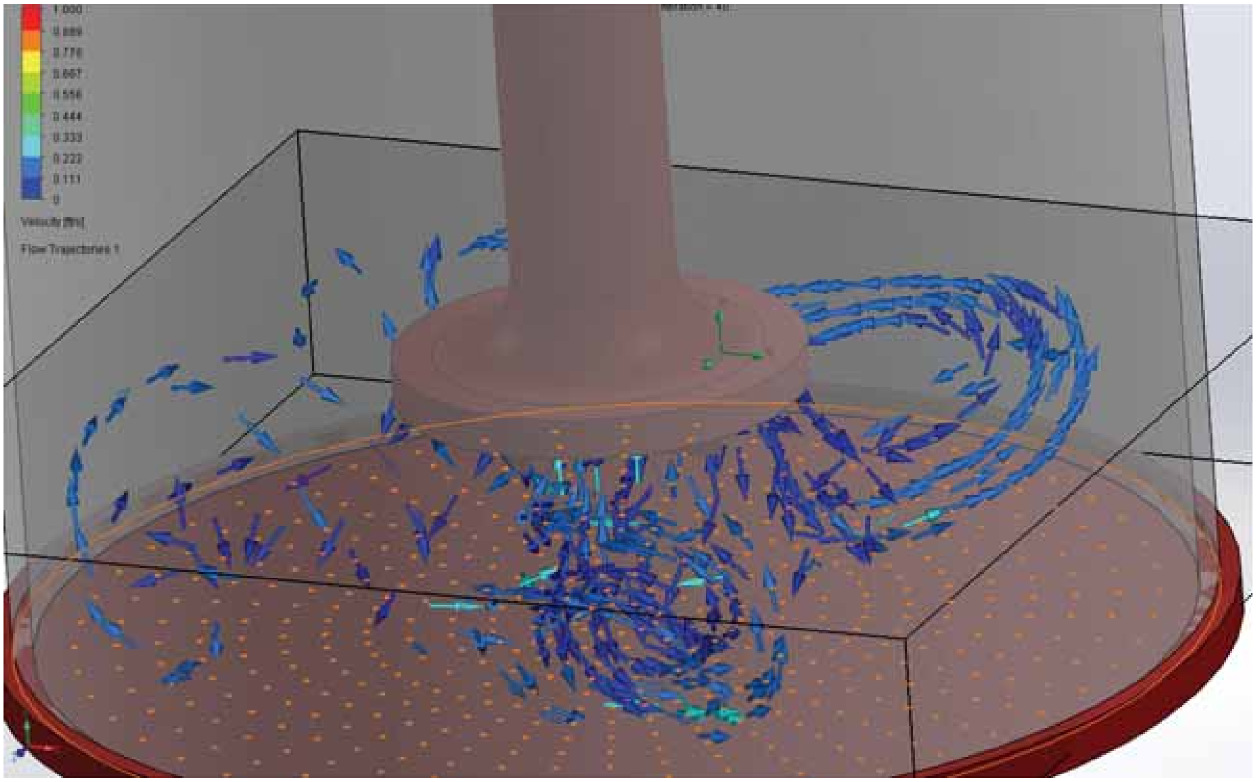


Figure 32: Flow Trajectories under the 5” Diameter Press

9.5 Blade attachment/fatigue

The food processor design is accomplished through 6 blades attached to a central rotating shaft. In the initial design, each of these blades was attached by a single screw and a single protruding holder coming off the central shaft. Stress analysis of this setup showed that it was incredibly prone to failure. Assuming 0.4 MPa pressure on the blades (as if they were cutting through lettuce), there was consistently failure both in the protruding holder and in the fastener between the blade and the holder. Additionally, extreme displacements were seen along the blades. Figure 33 shows one such analysis, where the maximum displacement of the blades was 5.16 in, an unreasonable amount for a small fixture. The maximum material stress in this design could not be calculated as the simulation failed before a final number could be obtained.

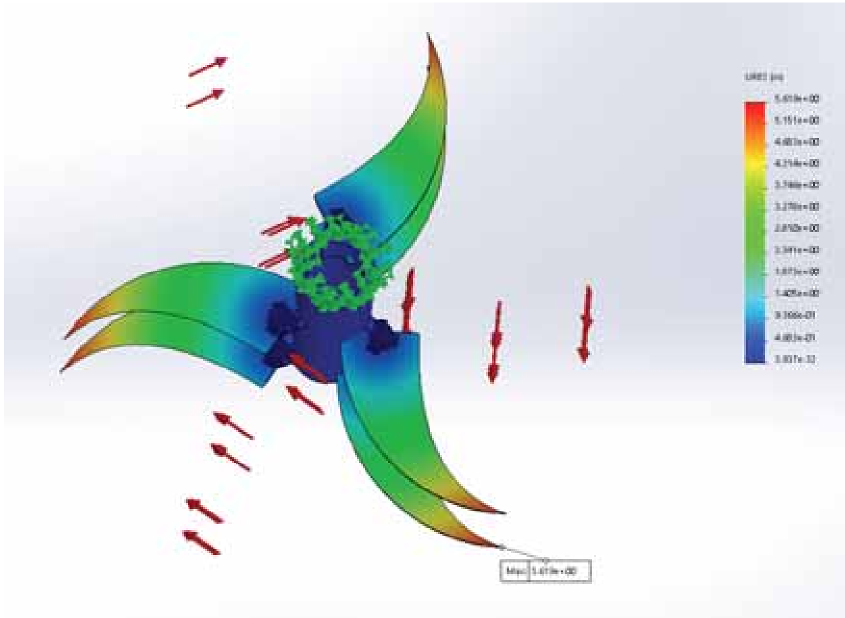


Figure 33: Original blade design displacement analysis

To combat these issues, the fasteners were doubled in thickness, and the protruding holders were doubled, so there is one on top of and below the blade. With these changes, the maximum displacement decreased to 0.263 in, as shown in Figure 34. Additionally, the stress analysis shown in Figure 35 shows that the maximum stress experienced in the shaft is 4960 psi. This value leads to a factor of safety of 0.93, as it is above the yield stress of the polypropylene (4800 psi).

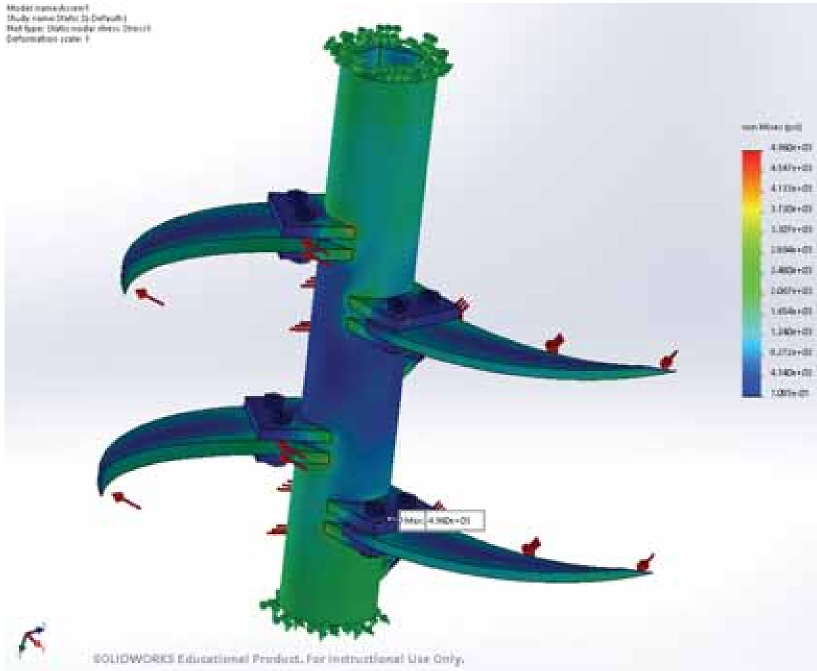


Figure 34: Blade Design v2 Displacement Analysis

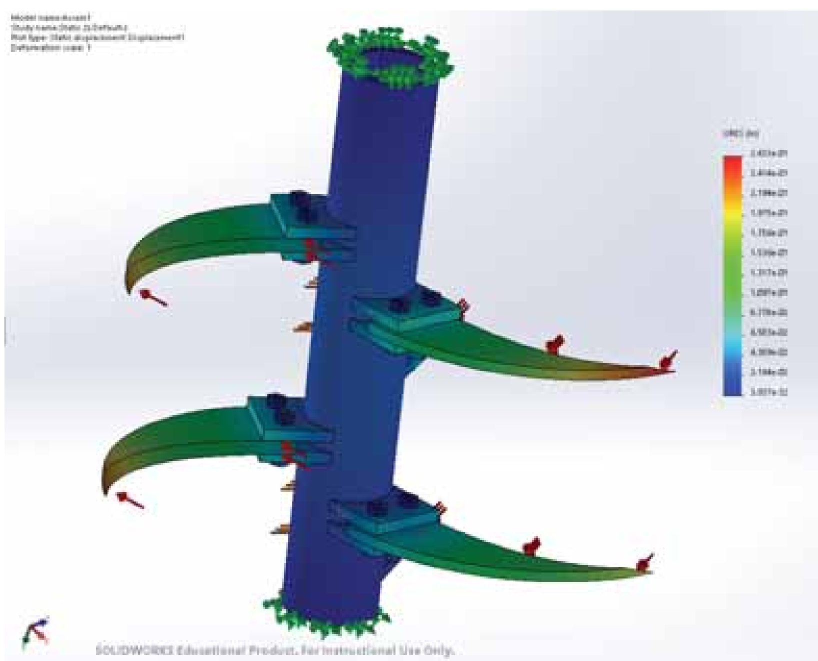


Figure 35: Blade Assembly Design v2 Stress Analysis

Due to this, further changes were made to the design, filleting the edges of the protruding attachments. These changes, shown in figures 36 and 37, further reduced the maximum displacement to 0.25" and the maximum material stress to 3893 psi. This final factor of safety of 1.19 is not as high as is ideal, so further adjustments may be carried out in the future.

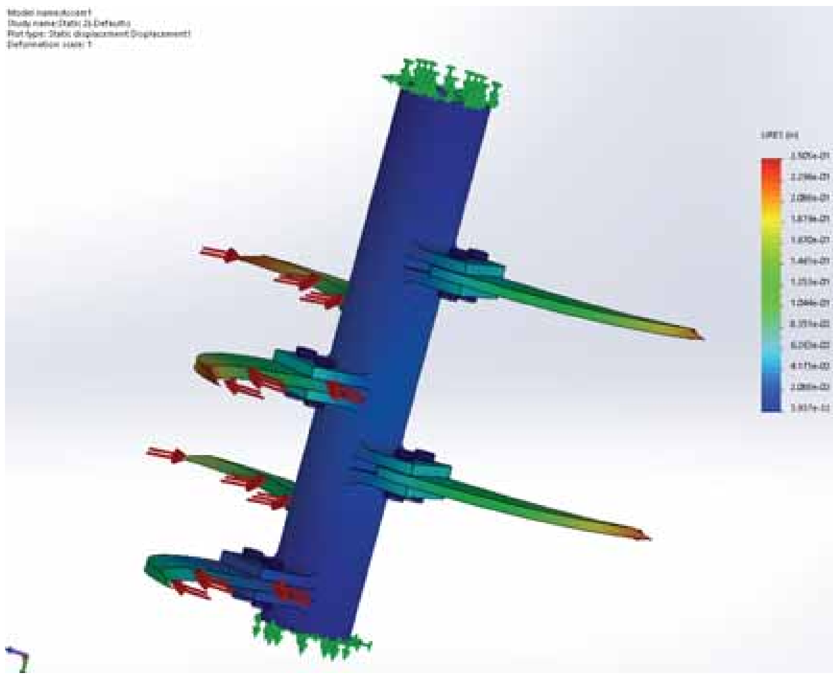


Figure 36: Blade Assembly Design v3 displacement analysis

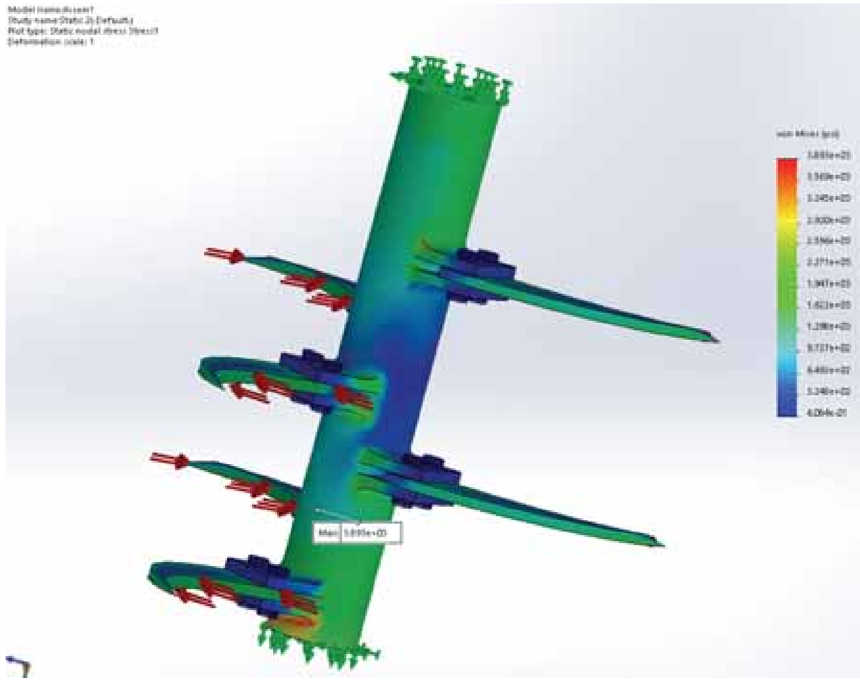


Figure 37: Blade Assembly Design v3 stress analysis

Next, the blades themselves were analyzed to see if they would fail at their attachment points over time. Figure 38 shows the result of this analysis. The maximum stress seen in the metal is 5936 psi, which is significantly below the endurance limit of stainless steel. This indicates that the blades will be able to be loaded and unloaded to this level indefinitely.

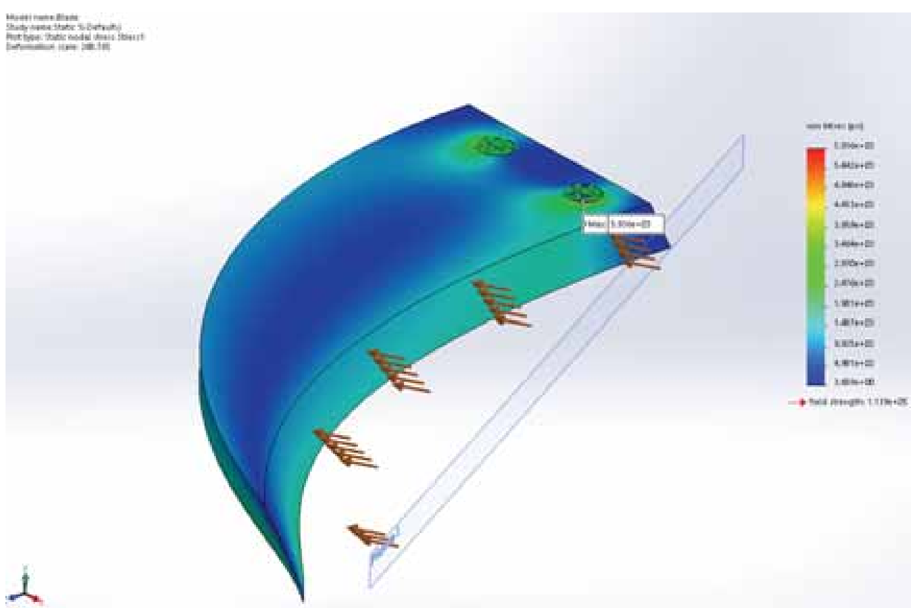


Figure 38: Blade stress analysis

Finally, the blade assembly was analyzed with the final setup, including the refined blades (Figure 39). The same logic was used as on the previous iterations, with the shear force of lettuce (0.4 MPa) applied to the cutting edge of the blades and the bottom of the tube fixed. With this, a max stress of 2571 psi was found, which leads to a factor of safety of 1.8. Since this makes the assumptions of the leaves being fixed in the tube and no sliding happening, the actual factor of safety should be much higher than was found in this analysis.

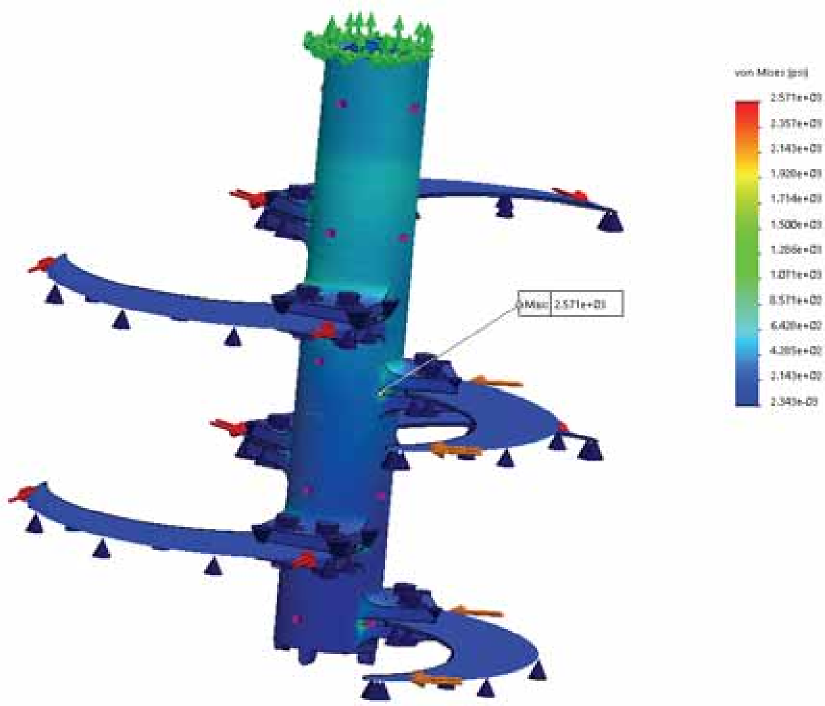


Figure 39: Final Blade Assembly Analysis

9.6 Press stress

The press was analyzed to ensure it would stand up to the rigors of processing the bitter leaves. The maximum potential grip force by a woman is around 100 lb [20]. Assuming a 2 handed grip, a squeezing force of 200 lb was applied to the outside of the press. Additionally, assuming the woman is applying the majority of her body weight to the press, a 150 lb force was placed on the bottom of the unit. The combination of these forces was analyzed to ensure the press would not buckle or break. Figure 40 shows the material stress experienced due to these forces, which reaches a maximum of 316 psi. Figure 41 shows the corresponding displacements for this force. These images show that the stress only reaches 316psi, much lower than the yield stress of 4800 psi. The displacement is 0.005 in, an almost imperceptible number on this scale. While these analyses were carried out on an earlier iteration of the press, the overall design form remained the same, so the high factors of safety indicate that the new designs would also be sufficient to withstand the necessary forces.

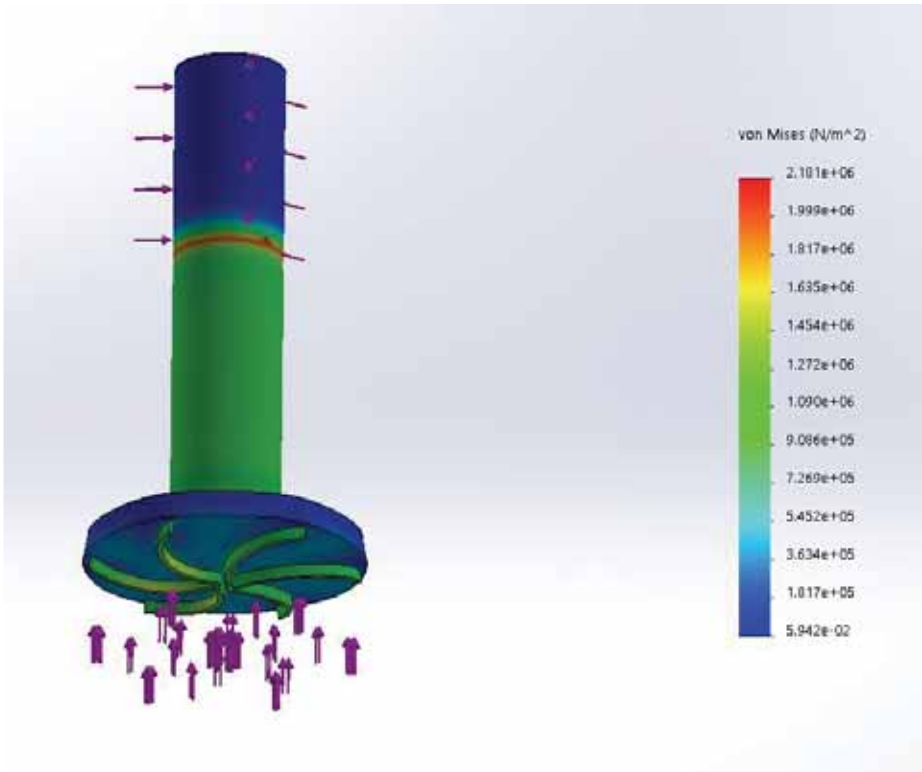


Figure 40: Press static stress analysis

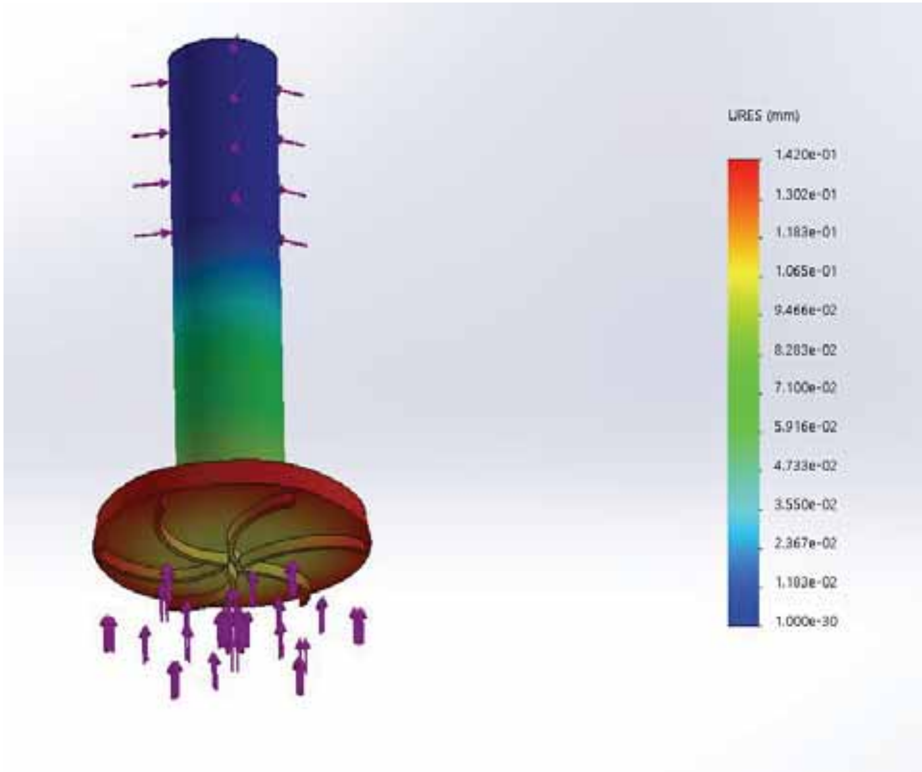


Figure 41: Press static displacement analysis

9.7 Full Unit Analysis

The entire unit was analyzed for two separate loading cases. In the first, a 250 lbf was placed on the top of the unit (Figure 42). This was meant to replicate if someone used it as either a seat or as a stepstool. With this applied, a 288 psi stress was seen at the top edge, giving a factor of safety of 16.1, more than enough to be considered safe for this misuse.

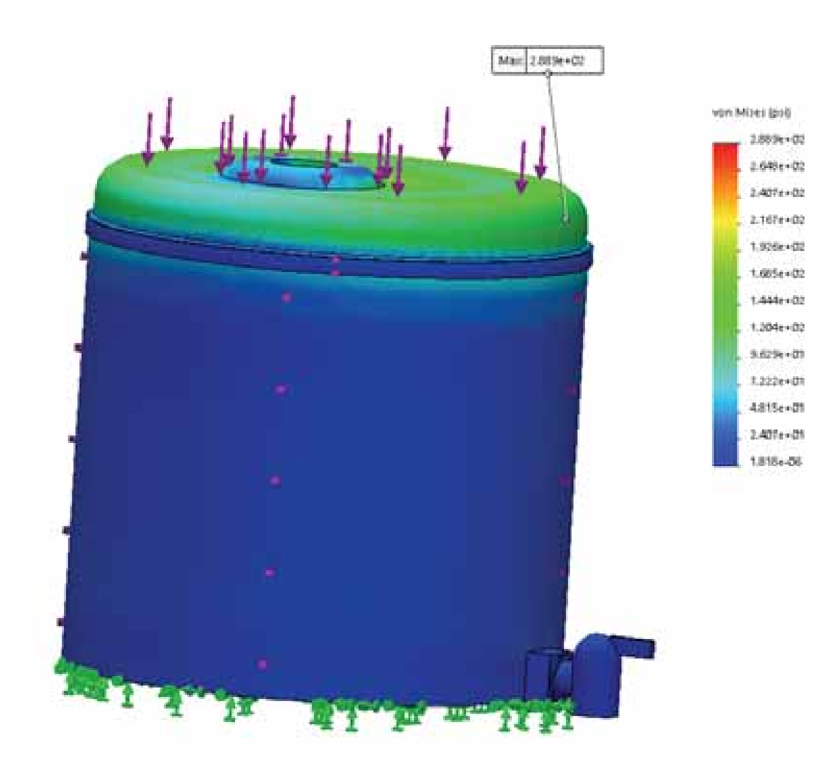


Figure 42: Top Loading on the Full Unit

Second, the sides of the unit had a 250 lbf applied, meant to replicate falling or sitting on the unit while it is laying on its side (Figure 43). Due primarily to the double walled design, the max stress was only 116.7 psi, giving an enormous factor of safety of 39.6. While this is a large factor of safety, the concerns with having a sharper point of impact or another variation in the loading conditions could easily cause increased stress and a much quicker fracture.

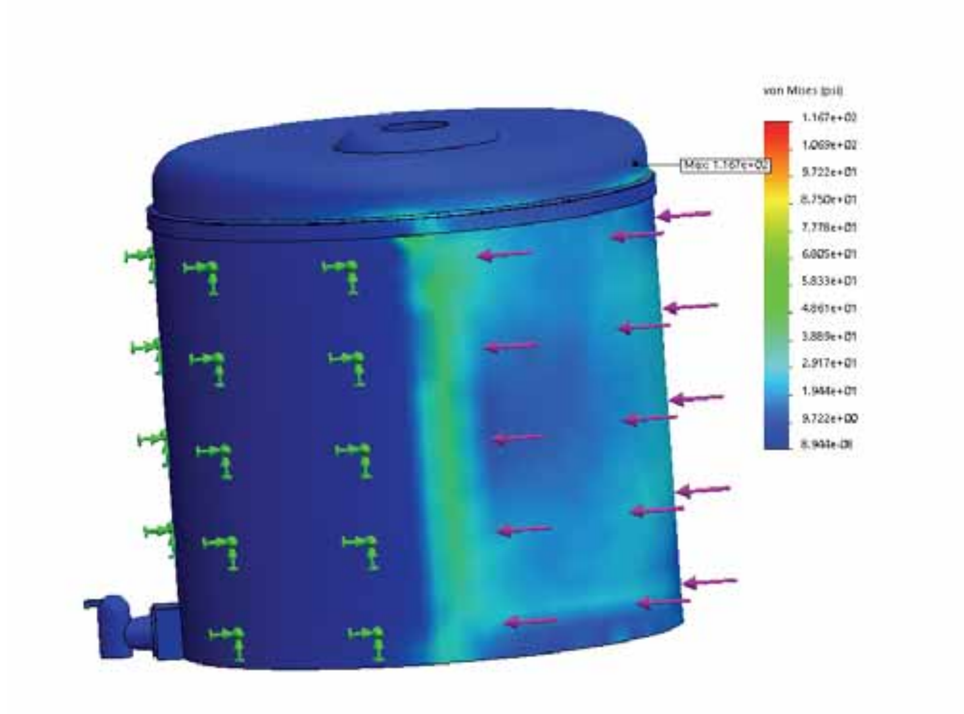


Figure 43: Side Loading on Full Unit

9.8 Press Testing

The validity of the washing portion of the unit was analyzed through testing the efficiency of the press. A control group and a prototype group of bitter leaves were separated and the mass and volume of each group were measured after being chopped. A controlled amount of water was added to each group of leaves. The leaves were then rinsed and drained and scrubbed for two minutes. The control group was scrubbed using the traditional washing method of pressing the leaves between the palms of the hands and using friction to agitate the bitter compounds out. The prototype group was scrubbed using the press to mash the leaves into the bottom of the pot with a downward, twisting motion. After the two minutes of scrubbing, water was added to the pot, the leaves were rinsed, and the wastewater was collected in separate bowls to be compared. The mass and volume of the leaves were also recorded for each group. Figure 44 and Figure 45 show the wastewater of the control group and prototype group after one cycle of being washed, respectively.

Figure 44. Control Group Washing Test Result after One Wash Cycle

Figure 45. Prototype Group Washing Test Result after One Wash Cycle

The darker wastewater from the prototype group indicates more bitter compounds were removed in the two minutes of press agitation than two minutes of traditional scrubbing. Ideally, the leaves would be tasted after each wash cycle and the bitterness levels compared. However, the prototype press was 3D printed using PLA, which is not food safe, thus the leaves could not be compared using taste. The measurements collected after each stage of the testing are recorded in Table 4. The consistently larger volume after each washing cycle indicates that the leaves processed with the prototype press produced a smaller volume of wastewater, meaning the new system is also more water efficient than the traditional method.

Table 4. Volume and Mass Values of the Washing Test after Each Stage

Before Washing		
	Control	Prototype
Volume (mL)	180	180
Mass (g)	16	16
First Wash Cycle		
	Control	Prototype
Volume (mL)	120	160
Mass (g)	22	29
Second Wash Cycle		
	Control	Prototype
Volume (mL)	80	100
Mass (g)	21	22

9.9 Cutting Testing

To test the validity of the cutting methodology, several tactics were used. First, leaves were placed in the prototype and cutting was attempted. With the first prototype created, there was a direct connection between the handle and the blades, without any sort of mechanical advantage. With this design, it was determined that in order to cut the leaves, the handle would need to be turned with a force and speed that were unfeasible. To combat this, the design was altered to incorporate a gear train with a 4:1 gear ratio. Issues with tolerancing in the gear train prevented this design from being tested directly, so more extreme measures were taken. An adapter was created that allowed the blade assembly to be directly connected to a standard hand drill. This allowed testing of a best-case scenario where the blades could be spun as fast as possible. With the first iteration of prototyped blades, this resulted in the bitter leaf spinning around the pot without being cut. This led to the revision of the blade shape to increase the cutting surface area as well as change the angle of attack so the sharp portion of the blade would be dragged along the leaves rather than just slamming into them to hopefully cut more effectively. This final blade design was tested in the same way, by being driven by a drill. Unfortunately, the blade design revision did not solve the observed problems. The leaves still rotated around in the pot with the blades instead of being cut by them.

The second way the cutting system was tested was with a commercial food processor. The general structure of the cutting mechanism is very similar to a food processor, so this testing provided an overall proof of concept in an ideal scenario where the gears, blades and overall structure were manufactured to a much higher standard. In this test, bitter leaves were placed in a commercial, manual food processor, and the device was turned for 1 minute increments. This test showed that the bitter leaves were easily and quickly cut by this device. After 1 minute, the leaves were significantly smaller, and after 2 minutes they were as small as would be required for the processing. This is a vast improvement over manual cutting, which could take over 15 minutes for the same quantity of leaves.

10. Final Design, Mockup, and Prototype

The final design is composed of two functional units that operates out of the same central body. The inner pot sits within the outer pot, and in the center of both of them lies a circular peg which sit on top of one another (Figure 46). The weight of the inner pot rests on ribs at the bottom of the outer pot to disperse the weight evenly (Figure 47). Adjacent to the pegs are slots which locks the rotation of the inner pot. For the cutting operation, the blade assembly, composed of 6 stainless steel blades bolted into a central tube (Figure 48), sits on the peg of the inner pot and rapidly rotates to slice the leaves. The bitter leaves are inserted by hand into the inner pot between the blades. The rotation of the blade assembly is completely hand-actuated, driven by a 2-part handle that interlocks with an 80 tooth gear (Figure 21). The handle is broken into 2 parts and are connected with a screw to allow for free rotation of the head of the handle while it is being grabbed and spun. The 80 tooth gear interlocks with a 20 tooth gear that locks into the blade assembly. This is done through a square protrusion on the 20 tooth gear that fits into a square impression on the top of the blade assembly (Figure 48). This results in a 4:1 work output to input ratio which was found from testing to generate enough momentum to easily cut down the bitter leaves to fine pieces. To keep the gears safe from human interference and to have them turning properly, they are placed between the upper and lower parts of the lid which features protrusions (finger joints) that keeps them in place (Figure 22). The 2 parts of the lid are held together by 3 screws.

Figure 46: Nesting Pot Design

Figure 47: Cutaway of Inner Pot Resting on Ribs (Angle Increased to 15 Degrees for Clarity)

Figure 48: Blade Assembly

After the cutting operation is complete, the whole lid assembly and blade assembly can be removed (Figure 49). The leaf shreds will remain in the inner pot, and the leaves can be washed using the press (Figure 50). Water goes in the inner pot to wash the leaves and can be drained out the spigot on the side of the outer body. The water goes through the holes in the inner pot and flows down the slanted ramp between the ribs towards the spigot. Once the damp leaves are in the inner pot, the press can be used to grind the bitter compounds off the surface of the leaves by pressing down on the leaf bunches and twisting the press back and forth while applying pressure. These steps can be repeated as many times as the user desires until the leaves have the right taste, which will be determined through user taste testing. When the user is done, the inner pot can be lifted out of the outer pot using the included handle cutaways (Figure 46), leaving the residual water behind so the finished leaves can be used in recipes traditionally.

Figure 49: Full Assembly Showing Removing the Center Pot and Blade Assembly

Figure 50: Press for Washing

A physical prototype of the model was created to help convey the functions of the product more clearly to interested parties, as well as verify certain design aspects. The prototype was 3D-printed as there are several complex geometries in the parts that would be difficult to manufacture through other methods that were available. 3D printing allows for rapid prototyping at small scales, and there are many 3D printing resources on campus. When testing the first prototype of the product, tolerancing was a significant issue that prevented the parts from fitting together and working properly. The design tolerancing was made with injection molding in mind, which has substantially different and much more predictable dimensioning. Several changes in the CAD had to be made so that the 3D printed parts worked together smoothly. As the resolution of the prints weren't of the best quality and as the plastic used to print (PLA) was not the plastic that was researched and chosen to use in the final design (Polypropylene), there were problems with friction as well. Friction between the gears and between the gears and the lid assembly were the main cause of concern as a significant amount of force had to be applied to overcome the friction and have the assembly spin at all, making testing extremely difficult with the initial prototypes. The tube of the blade assembly was adjusted to have fingers at the bottom of the tube to reduce friction as it spins, and resin printing was used for lower friction and wear. Food-safe Teflon lubricant and sanding were applied to further reduce the friction and better replicate injection molding gears. The cutting angle of the blades had to be lowered for the physical prototype as it was difficult to make parts with high angles with the technology that were available. The final 3D printed result can be seen in Figure 51, and the interior of the unit can be seen in Figure 52 with the leaves during the cutting test.

Figure 51: Fully Prototyped Design at 50% Scale

Figure 52: Interior of Spaghetti Design with Bitter Leaves

From developing the physical prototype, several changes to the design were considered and some were made to improve upon the functionality, efficiency, and ergonomics of the product. The main changes include the addition of the gear train and decreasing the thickness of the blades after discovering that the leaves would be cut more efficiently from an increase in momentum. The handle and the press were adjusted so that less force is required to operate them and to increase the comfort of using the product.

This physical prototype could then be compared to the original design requirements to assess its functionality. Against the design constraints of the project (Table 2), the design is very successful. The device is manually powered, and the rotational driving motion would be easy to replace with a motor if the user has that capability. The device has a footprint of 16”x16”x15” (LxWxH) so it falls well within the

4’x4’ goal. While the cycle time was not able to be fully tested, it is likely that the time will be significantly less than 30 minutes, as in tests the cutting and pressing time were each less than 2 minutes. Assuming a full batch of leaves in the full scale device doubles these times, and the user wants to complete 3 washing cycles, this time would still between 20 and 30 minutes. The cost of the material that goes into the device is $44.21 (Table 5). Due to the fact the device will be manufactured in Cameroon, it is difficult to judge exactly how much manufacturing will cost. However, because the material costs are less than half of the goal manufacturing cost, it is likely that the overall manufacturing cost will be less than $100. The device was specifically designed to be manufacturable in Cameroon, using materials and manufacturing methods that are locally available (see Section 11: Manufacturing). The materials chosen also comply with FDA food safety guidelines (see Section 3: Codes and Standards). Several aspects of the design are optimized for the ergonomics of a 5’2” woman. The handle and press are of the correct size to fit in a woman’s hand, and the overall work input required is within what a woman would be able to produce. Though there were some issues with the prototyping process, the design itself matches very well to the original project design constraints.

Table 5: Bill of Materials

Common Name	Technical Description	Part Number	Vendor	Units	Price Per Unit	Units Needed	Total Price
Polypropylene Pellets	Polypropylene 10 Melt - Black	PPR-PPCO06-G	Premier Plastic Resins [21]	lb	$1.10	23	$25.30
Stainless Steel	Multipurpose 304 Stainless Steel Sheet, 1/16" thick	S416	Metals Depot [22]	Sq. In.	$0.07	70	$4.96
Spigot	Polyethylene Plastic Drum Faucet with Vent 3/4 NPT Male Inlet	9886T11	McMaster-Carr [23]	indiv	$3.44	1	$3.44
Blade Bolts	High-Strength Grade 8 Steel Hex Head Screw, Zinc-Aluminum Coated, 1/4"-28 Thread Size, 1" Long	91286A135	McMaster-Carr [24]	indiv	$0.21	12	$2.51
Handle Screw	Passivated 18-8 Stainless Steel Pan Head Phillips Screw, 6-32 Thread, 3/4" Long	91772A151	McMaster-Carr [25]	indiv	$0.06	1	$0.06
Lid Screws	Pointed Screws for Plastic, 410 Stainless Steel, Number 6 Size, 1" Long	92325A305	McMaster-Carr [26]	indiv	$0.10	3	$0.30
Blade Nuts	Medium-Strength Steel Hex Nuts - Grade 5, Black Ultra-Corrosion-Resistant Coated, 1/4"-20 Thread Size	98797A029	McMaster-Carr [27]	indiv	$0.64	12	$7.64
						Total:	$44.21

11. Manufacturing

Design considerations due to intended manufacturing methods are vital for ensuring any potential final product can be realistically produced in the desired quantity and cost. This project is no -exception, especially due to the humanitarian goals it intends to accomplish. As previously mentioned, the two materials being used throughout the design are polypropylene homopolymer for the main design elements (body, lid, handle, strainer, blade mount, gears) and 304 stainless steel for the cutting blades. Due to the usage of two very different materials, at least two manufacturing methods must be utilized to process them and construct the design. For the polypropylene homopolymer components, injection molding has been chosen as the manufacturing methods, and for the steel blades, injection molding is the intended manufacturing methods.

Injection molding is an incredibly popular manufacturing technology that is easily scalable to mass production levels. The main benefits of injection molding are its low cost per unit when manufacturing large quantities of products, an intended result for this project, as well as offering high repeatability, design flexibility, and good tolerances [21]. However, injection molding does require a large initial start-up cost. This start-up cost is heavily connected to the design and manufacture of the mold that is used to create each component. The more complex the design, and in tandem the mold, the higher the cost for injection molding [21]. Secondly, if the design is very complex and the mold fails during processing, designing and building a new mold adds to further costs so it is important to achieve best results the first time. This requires following certain design considerations to minimize mold complexity to decrease the injection molding cost.

The final designs of the bitter leaf processor that will be manufactured through injection molding utilize a myriad of design considerations to decrease mold complexity and potential manufacturing defects. A common technique to minimize complexity is apply uniform wall thickness whenever possible [21]. Non-uniform wall can cause warping when the melted material begins to cool down, increasing costs. This design utilizes this technique throughout a majority of its components. However, there are components that have variable walls. To handle this, smooth transitions between different thicknesses is required. This is most notable in the handle component, due to the different grips and attachment points different radii were used; however, all transitions between so are rounded and filleted. Another design consideration is to avoid thick components. Thick sections can also lead to defects during the process, adding to the costs [28]. A workaround is to hollow how components. This is heavily apparent throughout all the polypropylene parts. Parts such as the body and strainer are mostly empty space with thin cross-sections and parts such as the handle and rotating blade mount are hollowed out.

The blades for the bitter leaf processor will utilize metal blanking to mass produce the blades needed. There are multiple methods for producing knife blanks such as laser cutting, water jet cutting, and mechanical or hydraulic presses [29], however, some methods are more cost efficient than others the final design has minimal complexity due to its simple, circular shape and flat edge making processes such as laser cutting unnecessary. This design has the design consideration of using thinner blade thickness ($1/16^{th}$ inch steel) which allows for the blanks to be stamped from sheet metal with a press, reducing cost. Finally, each blade can be grinded on edge to ensure sharpness.

Cost associated with injection molding and blanking can vary heavily depending on the country of origin and technology available. The intended goal of this design is to communicate technical specifications and drawings to technicians and manufacturers in the product's intended country of destination, Cameroon, for completion. Due to limited information of the potential producers in Cameroon, realistic cost analysis and estimates are not feasible at this moment; however, the project's sponsor has assured that these manufacturing methods are available in Cameroon.

Final component assembly needs to be possible when combining multiple manufacturing methods. A design consideration to reduce the complexity of assembly is to minimize the usage of auxiliary fasteners for components. A majority of the parts fit together either through a simple peg-in-hole or finger joint connection. The only auxiliary fasteners required are the screws to connect the two pieces of the lid together and the nuts and bolts needed to attach the blades to the mount. Injection molding provides quality tolerances which can handle the necessary fits used throughout the final design.

12. Social, Environmental, and Sustainability Considerations

Through the material selection analysis (section 9.1), polypropylene was chosen as the material best suited for this application. This is a food safe material that can be recycled relatively easily with proper infrastructure, and is one of the most common plastics found around the world. A local Cameroonian contact has confirmed that polypropylene is available, although further work on sourcing is required. Furthermore polypropylene is resistant to many of the common chemicals that would be used in a kitchen environment, and depending on the grade of plastic has UV resistance.

Given that this is a humanitarian project, the most likely outcome of this project on the target market is a net positive result. If the product is able to be successfully manufactured and distributed, it will save precious time and effort in millions of households across Africa. However, it is important to consider other product lifecycle stages to mitigate any possible negative social impacts.

The goal and scope section (Table 6) involved analysis of the manufacturing and product use lifecycle stages as they are the most likely points of direct human injury. These are addressed by using industry standard procedures (injection molding, stamping) for food-related product manufacturing in order to increase the likelihood that the manufacturing firm taking on the job will be able to do it safely. Second, the customer use of the product, specifically the possibility of customers getting injured by the blade assembly was considered. This was addressed by large FoS on the walls of the processor and the sealing off of the blades when they move.

Table 6: Goal and Scope Section Summary

Objective of Assessment	Design Function	Functional Unit	Lifecycle Stages Considered	Associated Activities
Speed up bitter leaf processing procedure	Shred and wash bitter leaves using mechanical energy only	1 shredding and 1 washing unit	Manufacturing	Injection Molding
				Metal Stamping
			Product Use	Customer use of product

The inventory analysis section (Table 7) selects value chain actors and the local community as the important stakeholders. The selected impact indicators checked against OECD databases, finding no consumers unions present in the country, however there are government branches that act in the national interest against unfair competition, fortifying confidence in the companies manufacturing the components to be competing fairly. Fortunately, Dr. Zama has contacts with individual technicians within the most rural communities in which these will be distributed, therefore they will be responsible for final assembly, ensuring small rural businesses benefit from the product. Furthermore, local legislation regarding disposal and recycling was also studied, yielding IUCN reports [30] on the current status. Most of the legislation is meant to protect the country’s national resources and stave off industrial pollution. That means this project is outside the scope of that legislation. This means the only guiding force to reducing end-of-life waste is the specific design choices, which led to the final design of two pots nesting within each other. This about halves the overall volume of waste produced at the end of product life.

Table 7: Inventory Analysis Section Summary

Product Lifecycle Stage	Stakeholder Group	Social Impact Category	Impact Indicators
Production	Value Chain Actors	Fair Competition	National law and regulation
			Sector is present in consumers unions
End of life	Local Community	End of Life Responsibility	Strength of national legislation covering product disposal and recycling

13. Risk Assessment

Every new product development must consider and mitigate the risks associated with using the device to prevent injury to the operator or damage to the product. This includes identifying potential risks and failure modes of the product, exploring codes and standards which apply to the product, and applying risk mitigation solutions. The applicable codes and standards for the bitter leaf processing unit are accounted for in section 3 of this report. There are not many parts to the unit and the motion of the parts is fairly simple, reducing the potential risk of injury to the user during operation. A risk assessment matrix for the final design of the bitter leaf processor is shown in Table 8, which notes potential failure modes, risk levels, and mitigation techniques.

Table 8: Risk Assessment Matrix for Spaghetti Design

Hazard No.	Hazard	Frequency	Severity	Initial Risk Level	Mitigation	Final Risk Level
	Projectile					
1	Blade Loose from Shaft	B	1	High	Dual sandwich shelves, dual stainless steel bolts	Low
	Structural					
2	Press failure	D	3	Low	Rounded handle top	Low
3	Wall failure	C	1	High	Dual cylinder walls, FEA approved wall thickness	Low
4	Lid failure	C	3	Medium	FEA approved thickness, dual lid structure	Low
5	Gear train failure	B	2	High	Stabilizers, dual lid structure	Low
	Food Contamination					
6	Blade chipping	C	2	High	Stainless steel material	Low
7	Press chipping	B	2	High	PP material, no small extrusions	Low

The most major risk which could result from mechanical failure of the bitter leaf processor is if the blades become loose from the shaft, either during spinning or during transportation, and become a projectile. While this failure would not be expected to occur often, the number of blades attached to the shaft increases the possibility of harm. The frequency, paired with the harm a projected blade could cause, generates a high risk level. To combat this, the blades have tight tolerances for the casings which sandwich the blades above and below to the shaft. Each blade also will have two nuts and bolts securing them to the casings, providing multiple layers of security before the blades could become completely free.

Other failure modes could occur from the structural failure of any of the unit's parts, leading to potentially sharp fractured edges. This is most likely to occur with the handle and press, the two parts which require the most human interaction. However, structural failure risk is low after the careful material selection of polypropylene and repeated FEA reports. Each part of the bitter leaf processor has a high factor of safety, attesting to their low risk of failure. The gear train is a likely source of user injury and unit damage due to its motion. The risk of minor injury from the gear train is mitigated by completely enclosing both gears inside of the lid assembly, preventing the user from directly interacting with the gears. Additionally, the gears are powered manually with the handle, causing the gears to stop as soon as the handle stops rotating.

The final source of major risk with the bitter leaf processor is the possibility of material chipping off of the unit and integrating with the leaves. A major concern for food processing units is always the possibility of contamination. This is reduced for the final design with the material selection of polypropylene and stainless steel. Both materials have a high fracture toughness, resisting chipping from repeated impacts. Additionally, the design of the unit lacks small extrusions, increasing the structural integrity of each component and reducing the risk of any part breaking off.

Safety has been a design consideration since the planning phase of the project, included in the House of Quality as a customer requirement. The conceptual designs were created and considered with safety as a constraint and was one of the most important factors when selecting design concepts. The blades were always a key aspect of risk in every iteration of the design. From the second iteration onwards, the blade assembly is designed such that it cannot turn properly without the handle and lid attached, reducing the risk of injury. When gears were introduced, it was immediately decided that they would be enclosed to reduce the risk of minor injuries, despite the dual lid system creating slightly more difficult manufacturing. The risk mitigations in the risk assessment matrix eliminate strict liability and negligence for the bitter leaf processor. As this device will be distributed to users as a humanitarian effort, there will be no express warranty, eliminating that liability for this device. For mass production, the proper signage would need to be printed and included with each unit to fully comply and completely reduce any liability for this design. If further care is necessary, blade shields should be distributed with each unit to further protect from negligence. Accessories such as that were not intended within the scope of this project, but should be considered again when the units are being professionally manufactured.

14. Patent Claims and Commercialization

The units are meant to be a humanitarian effort, distributed at no or low cost to the consumer. As such, the sponsor, Dr. Zama, has no interest in pursuing any patents or commercialization strategies for the design of the bitter leaf processor.

15. Summary & Future Work / Project Deliverables

A project as complex as the bitter leaf processor will require many steps to achieve a satisfying completed product. The problem has been sufficiently researched to understand the full scope of the project as well as the requirements and expectations set by the sponsor. Research was conducted to understand customer expectations and requirements, identify existing products, and draw inspiration from existing products with similar functions. Patents have been researched to prevent unintentional infringement. With consideration given to all prior research, a variety of unique concept sketches and overall product designs were created. From these concept designs, an initial design was analyzed based on an evaluation matrix. FEA and CFD were used to validate and refine elements of the design. A prototype was constructed and tested, resulting in several improved iterations of the design until a final design was constructed and presented at the 2019 Capstone Expo. A fabrication package was produced and manufacturing methods chosen, and the required materials and fasteners were sourced to evaluate the design cost. The full extent of the project is displayed in the Gantt Chart in Table 9.

Table 9: Gantt Chart for the Bitter Leaf Processor

Tasks	Weeks															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Understand Problem	X	X														
Perform Market Research		X	X	X												
Research Existing Patents				X	X											
Develop Concepts			X	X												
Select Design					X											
Report 1 and Presentation					X											
Perform Analysis & Calculations						X	X	X	X	X	X		X	X		
Formalize Drawings							X		X							
Produce CAD Model							X	X	X	X	X	X		X		
Report 2 and Presentation										X						
Construct Prototype												X	X	X		
Test Prototype												X	X	X	X	
Finalize Design															X	
Present Final Product																X

The design of the bitter leaf processor successfully reduces the time and effort required to chop and wash bitter leaves for a family. The initial cost, size, and work objectives that were specified in the House of Quality were met, achieving the goals of the team and sponsor. This device could easily be implemented into households based on its modularity and ease of use. Unfortunately, there was not enough time to refine the design to work as well as desired. The chopping assembly does not cut the leaves enough to implement the device as it stands now. The waterjet prototype blades did not perform well, but the overall design has proof of concept and could work in this unit with additional iterations. Many of the performance issues which occurred during the prototype testing can be attributed to the low quality prototypes which were produced. The 3D printed PLA gears did not have a smooth surface finish and the teeth often caught on each other due to flaws in the printing. On the interfaces between parts, there was significant friction due to the 3D printing which slowed the speed of the blades and increased the amount of work needed to turn the handle.

Beyond the limitations of the prototyping, there are improvements that can be made to the design of the processor. To aid in the cutting process, extrusions to the inner pot will increase friction and keep the leaves from spinning with the blades. A large handle or handles could be attached to the outer pot to aid in carrying the device if necessary. A larger gear ratio could be explored to further reduce the required input work. After achieving a satisfactory prototype, future steps would include ordering or creating a professionally made prototype with the proper manufacturing methods. This will allow for accurate conclusive time reduction results. Additionally, the local technicians should be contacted to discuss the manufacturing methods and any design choices that may be of concern for local manufacturing. Once the manufacturing is established, the production and distribution of the bitter leaf processor could begin.

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Appendix A: Work Calculations

Assumptions

Each blade is cutting 100% of the time

No stored rotational energy

Only the outer 25% of the blades can use the walls to achieve shear forces

Blade effective area is the projected area to the rotation

Force on blade

.4 MPa of force on the front (turning edge of blade) = 58.0151 psi

Projected blade area: 0.11 in^2

6 total blades

Only half of the blade edge is the actual cutting part

Total effective area = .33 in^2

19.14 lbf applied across all blades

Torque on Central Column

Center of each blade face is 4.021 inches away from center of main shaft

76.98 lbf-in of torque on central shaft

Gear Train

Gears have a 1:4 input to output ratio

307.92 lbf-in of input torque required

Force Required on End of Handle

Handle is ~8.33 inches long (middle of end grip to middle of central column)

36.97 lbf required to make it work…

Wattage of Work Required

Every rotation, the end of the handle travels 52.34 in

Work: 1934.8 lbf-in = .22 kJ

0.25 handle cycles per second: 55W