Design for Dissemination of a Low Cost Washing Machine

by

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B.S, Aeronautics and Astronautics (2005)

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2008

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Abstract

Throughout much the developing world, laundry is done the same way today as it was thousands of years ago. The strenuous and time consuming task of clothes washing often falls on the women, who spend many hours every week on household chores. A low cost mechanical washer can reduce the time and physical toil of doing laundry by hand.

The washer was designed for the lowest cost, using a hybrid manufacturing strategy that leverages the flexibility of industrial manufacturing with the low cost advantages of local assembly. The washer can be constructed from a kit that weighs only 8 lbs and packs in less than one cubic foot. The kit is centrally manufactured at at estimated cost of $25, and would reach the final user at maximum of $45. The washer is then assembled on location by a local welder, using locally available materials. The installation costs for rural Guatemala are estimated at less than $90, for a total installed unit cost of $135. Marketing partnerships with producers of chemical powder detergents, who could use the washer as a promotional effort, can further reduce the cost.

The unit is affordable, especially when shared by groups of families or larger communities. It is designed to be easily serviced on location, and can be easily adapted and enhanced by a skilled local worker based on the needs of the user.

In order to meet the dissemination goal of 1 million units installed in Guatemala over 5 years, the design had to be optimized not only for low production cost but also ease of dissemination. Because of the reduced weight and volume, the washer can be disseminated along existing product distribution channels in the form of a kit. By simplifying local assembly, the dissemination of the design can be done through a simple set of instructions. Since all distribution costs are paid for by the end user, this dissemination approach is not only sustainable, but also scalable, allowing the product to succeed based solely on its level of usefulness and affordability.

Thesis Supervisor: Dr. David Wallace
Title: Associate Professor of Mechanical Engineering

Acknowledgments

I would first like to thank my parents, especially my mother Mihaela, for their unwavering trust, unconditional support and immense patience over the many years. I would not be here without the love they gave and the wisdom they imparted on me.

A special thanks goes to Amy Smith, who helped open my eyes to the possibility of getting a degree while also working towards improving the lives of some of the other 90%, and who helped me and many others in making that a reality at MIT.

This project would happened without the wonderful people that made the Bicilavadora project possible: Alison Hynd and Sally Susnowitz of the MIT Public Service Center, the IDEAS competition staff, Jessica Vechakul, Teresa Baker, Alex Yip and the many others that have helped through the years.

I would like extend my gratitude to my friends at Maya Pedal, especially Carlos Maroquin, who inspired me in so many ways, and to Gwyndaf Jones who became my friend first before becoming my role model. To Tim Anderson who taught me to dream big and keep an open mind. And to the many people I've met at MIT who took the time to share their thoughts and ideas.

I am very grateful to my friends, especially Stan Zanarotti, Sandy Lipnoski and Amy Fitzgerald for their support through the hard times and the good.

But most of all, I want to thank Laureli Mallek, who made the process of writing this thesis bearable through her superhuman powers of care and attention, patience and wisdom. Nobody would be reading this thesis had you not read it first.

Contents

1 Introduction **9**

1.1 Objective . . . 9

1.2 Need for Product . . . 10

1.3 The Final Design . . . 12

1.4 About this Thesis . . . 13

2 Prior Art **15**

2.1 Clothes Washing Principles . . . 15

2.2 Other Human-Powered Washer Efforts . . . 18

3 The Dissemination Challenge **23**

3.1 The Wide-scale Dissemination Requirement . . . 23

3.2 Challenges of Local Manufacturing . . . 24

3.3 The Costs of Dissemination . . . 26

3.4 Opportunities for Marketing Partnerships . . . 29

3.5 Designing for Dissemination . . . 30

4 Design Approach **32**

4.1 A Hybrid Manufacturing Approach . . . 32

4.2 Component Analysis of a Horizontal Axis Washer . . . 34

4.2.1 Automation components - central timer, pumps, valves and other actuators . . . 35

4.2.2 Outer Drum and Structural Frame . . . 35

4.2.3 Bearings and Drive System . . . 36

4.2.3.1 Bearing Selection . . . 38

4.2.3.2 Power Source . . . 39

4.2.4 Inner Drum . . . 39

4.3 Analysis Conclusion . . . 41

5 Design Evolution of the Inner Drum **42**

5.1 Design Requirements 42

5.2 Material Selection 44

5.3 Geometry 47

5.3.1 One-piece Drum Design 47

5.3.2 Segmented Drum Design 48

5.3.3 Steel Frame and Lining Panels 51

6 The Final Design **56**

6.1 Distributed Components 57

6.1.1 Inner Drum Panels 60

6.1.2 Bearings and Drive Shaft 62

6.2 Local Machine Assembly 63

6.2.1 Frame Construction 64

6.2.2 Outer Drum or Basin 66

6.2.3 Drive Mechanism 66

6.3 Operation 68

6.4 Maintenance 70

6.5 Installed Cost Estimate 70

7 Future Work and Conclusion **73**

Bibliography **75**

A Structural Analysis of Inner Drum Panels **76**

List of Figures

1-1 Guatemalan women hand-washing clothing 10
1-2 Final Design of Washer 13

2-1 Operation principles for modern washers 16
2-2 The *WonderWash* hand powered washer 18
2-3 Examples of household washers adapted to pedal drive 19
2-4 The *Cyclean* pedal powered washer 20
2-5 Maya Pedal's agitator washer 21
2-6 Bicilavadora proof of concept entered in the IDEAS competition . . . 21
2-7 Bicilavadora prototype constructed at Maya Pedal 22

3-1 IDEI treadle pump components sold in Indian store 25
3-2 Local adaptations of the IDEI treadle pump 26
3-3 Product dissemination through advertising 27
3-4 Detergent stall at local market in San Andres Itzapa 30

4-1 Functional diagram of horizontal washer 34

5-1 Wooden drum prototype 45
5-2 Designing with locally available plastic drums 45
5-3 CAD model of the one-piece drum design 47
5-4 CAD model for segmented side-loading drum 49
5-5 Prototype side panel produced through vacuum forming 49
5-6 Side-loaded, multi-part, structural drum prototype 50
5-7 Final inner drum design - steel member frame and inner ABS panels . 52
5-8 ABS side panel geometry 53
5-9 Side door assembly 54
5-10 Door and end cap parts - two of each are used in the final design . . . 54

6-1 Final Design of Washer 57
6-2 Final Prototype 58
6-3 Inner Drum Assembly 59
6-4 Kit Package 59
6-5 Side panel geometry 61
6-6 End cap geometry 62
6-7 Bearing and shaft assembly 63
6-8 Frame assembly steps 1-3 65

6-9 Frame assembly steps 4-6 65
6-10 Sample design for concrete basin 67

A-1 Initial side panel geometry 77
A-2 FEA results for stress distribution for loaded side panel 77
A-3 FEA results for displacement for loaded side panel 78

List of Tables

1.1 Design Specifications 11

3.1 Comparison of estimated costs based on manufacturing and dissemination strategy 28

4.1 Summary of component analysis 41

6.1 Total washer kit cost - unsubsidized 71

6.2 Local assembly costs in Chimaltenango, Guatemala 72

A.1 ABS material properties used for FEA stress calculations 76

Chapter 1

Introduction

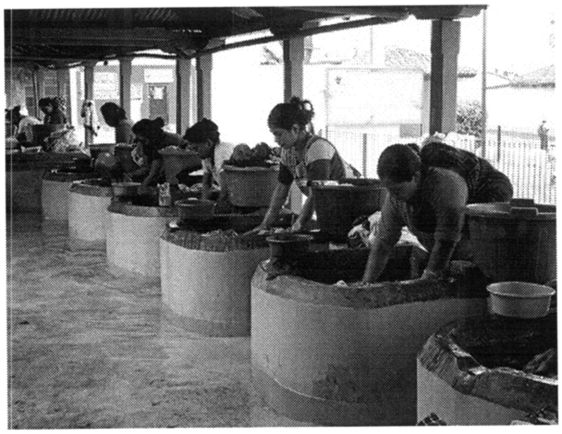
1.1 Objective

The goal of this thesis is to design a low-cost clothes washing solution for developing countries. The principal objective for the washer is to improve the ergonomics and reduce the time and effort required to wash clothes. The design must be affordable to purchase, install, operate and maintain, and must be usable in areas where running water and electricity are unavailable. Specific design criteria are presented in Table 1.1.

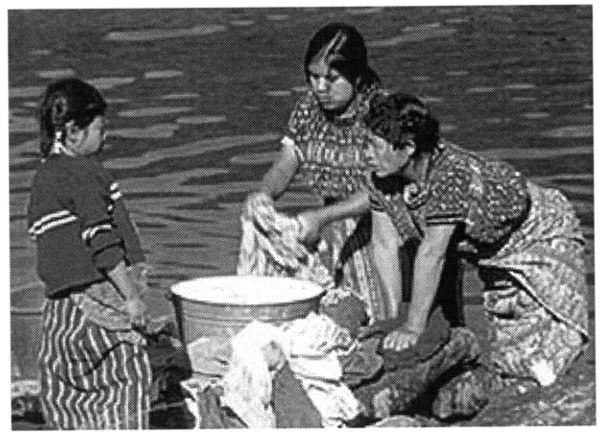
Although the design would ideally be applicable in many developing countries, the rural areas of Guatemala are chosen as an initial target location, because of a pre-existing relationship with the local NGO Maya Pedal. The design is aimed at community installations, women's cooperatives, or other local institutions. Small laundromat businesses should also be able to use the design to provide a service to their community.

In order to have the desired impact, the proposed solution should be designed to reach as many users as possible by lowering barriers to dissemination. Cost is often the first barrier to the adoption of new technology in developing areas. Because of the lack of supporting infrastructure, dissemination costs can add significantly to the final cost of a product. An integrated approach to lowering the final cost of the product is needed, which includes both manufacturing and dissemination costs.

For the long-term success of the product, the dissemination step must itself be financially sustainable, and add as little cost as possible to the total cost for the final user. The approach taken in this design is to rely on local materials, manufacturing and assembly as much as possible. Additionally, all specialized parts that need to be distributed are designed for a low cost to the user, which includes not only



(a) at a central Pila



(b) in a river

Figure 1-1: Guatemalan women hand-washing clothing

manufacturing cost but also distribution costs.

1.2 Need for Product

In developing countries, rural women are among the least privileged. Women are essential to the family unit and are an integral part of the economy, yet they rarely have equal opportunities for education, career development, or social status when compared to men. One factor behind the inequality is the long list of responsibilities traditionally allocated to women. Not only do women perform agricultural duties and care for livestock alongside men, they are also responsible for many domestic chores. Despite the long list of tasks they have to perform, for a variety of cultural and economic reasons, rural women tend to be the last to benefit from new technologies. The household tasks rural women perform in developing countries have remained largely unchanged for thousands of years.

Among the most time consuming household chores is the task of washing laundry by hand. Washing is usually performed in rivers, in communal wash houses (called Pilas in Guatemala), or along river beds where large quantities of water are readily available. This means the clothing has to be transported to the washing location and then again back to the household, a time consuming and back-breaking task by itself. In Guatemala, it is normal for women to spend 10 hours or more each week hand washing clothes for their families, which normally entails leaning over a concrete basin, laboriously scrubbing each piece of clothing. Widespread use of chemical detergents means the women's hands are immersed for long periods in compounds that are

Overarching goal: Design must be functional, and be accessible to millions of poor families

1. Functional requirements
   (a) Provide for a means to wash a bulk load of laundry faster and with less effort when compared to manual washing
      i. Load capacity - 15 lbs minimum dry
      ii. Wash time - 30 minutes for a full load of lightly soiled clothing
   (b) Be able to function in the absence of running water and electricity
2. Dissemination goals
   (a) One million installed throughout rural Guatemala over 5 years
   (b) Must easily reach all areas of Guatemala where chemical detergent is sold
   (c) Design should lend itself to adaptation other developing areas
3. Manufacturing
   (a) Central manufacturing of key components, but capital investment must be low
   (b) Scalable manufacturing to allow for economies of scale
   (c) Local assembly must require only basic tools, and techniques
4. Materials
   (a) Must not stain or damage clothing during the was process
   (b) Strong, long-lasting
   (c) Should withstand the use of warm water and the presence of chemical detergents
5. Dimensions of commercial kit
   (a) Should be small enough to transport by one person
   (b) Lightweight
   (c) Geometry should facilitate dissemination
6. Cost
   (a) Purchase cost - less than $75
   (b) Assembly cost - less than $50
   (c) Maintenance cost - less than $25/year

Table 1.1: Design Specifications

harmful for their skin.

Guatemalan women related these issues to the author repeatedly during a number of interviews while the author was working on a previous project in the area[1]. When asked about ways that technology could play in their lives, Guatemalan women consistently ranked the task of doing laundry at the top activity they would like to have some assistance with. Reducing the required effort and improving the ergonomics of the task, as well as reducing exposure to chemical detergents would significantly improve these women's comfort and health.

Interviewed women were very interested a low-cost washing machine that would allow them to wash clothes faster. They would use the freed time generating income by making crafts or food to sell. Young daughters who help their mothers with domestic chores would also have the opportunity to concentrate more on their studies. Laundromat micro-enterprises could emerge which would contribute to the local economy. Additionally, a well-designed machine could conserve water, and detergent, reducing the cost and the environmental impact of doing laundry.

Laundry needs vary across the developing world, yet in all rural areas laundry is washed by hand the same way it was done throughout Europe and North America up until the beginning of the 20th century. The introduction of an automatic washing machine aided greatly in improving the social status of women in industrialized countries. It is the author's hope that an appropriate design for a washing machine which can be widely distributed in rural areas may contribute to a similar empowerment of the 90% of women which live in developing areas of the world.

1.3 The Final Design

The final design for the washer, shown in Figure 1-2 and presented in detail in Chapter 6, meets all the design requirements outlined in Table 1.1. The washer has a clothing capacity of 15 lbs of clothing, and can wash mildly soiled load in 30 minutes, requiring only moderate effort from a seated user. Aside from the increase in comfort, the design would reduce the time spent doing laundry for a family of eight from the 8-10 hours to only 2-3 hours per week.

The machine is locally manufactured from a distributed kit which would retail locally for $45, in the absence of any strategic corporate partnership. By working with a detergent manufacturer to distribute the washer, the cost of the kit can be further reduced to $25 or even less if the kit is subsidized as a promotional product.

[1] see Baker [2] and Section 2.2 for a brief description of the 2005 Bicilavadora project

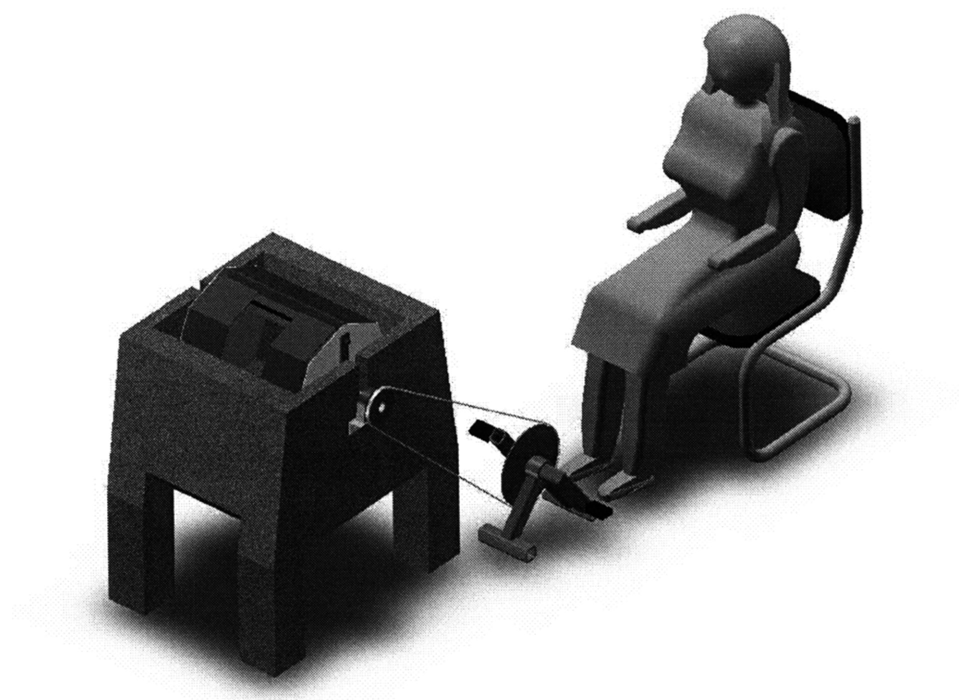


Figure 1-2: Final Design of Washer

The total installed cost of the machine is estimated to be $135 in the Chimaltenango area of Guatemala, which should be affordable to groups of families, laundromat businesses, women's cooperatives, and municipalities interested in providing such a machine as public infrastructure to their constituents.

1.4 About this Thesis

This thesis explicates the rationale behind the chosen design focus, presents the design process followed, and the final result that emerged from it. The different chapters of this document should be useful individually, based on the reader's interest in this project.

Chapter 2 aims to familiarize the reader with the two types clothes washers in wide use in industrialized areas, the horizontal and vertical-axis washing machines. The model of a horizontal-axis washer has been selected for this design, owing to its water and energy efficiency, which are essential features in areas where the energy and water infrastructure is expensive, unreliable, or non-existent. The chapter also presents a number of low-cost, human powered washers previously developed by other individuals.

Chapter 3 goes into further depth regarding the challenge of disseminating a technological solution to developing areas. The merits and of local and central manufacturing are considered, and an argument made for the need of a comprehensive process for considering the challenges of dissemination during the product design process.

In Chapter 4, the thesis outlines the design method used in this project, and delves into the task of analyzing the functional components of a horizontal-axis washer. Material in this chapter should be of use to those aiming to implement a similar design approach for other projects.

One particular component of the washer, the inner drum, is the central functional component, and posed the most difficult design task. Chapter 5 outlines the evolution of the design of this particular component, and its impact on the design as a whole.

The final product is presented in Chapter 6. The finalized design of the distributed parts of the washer is presented, along with engineering drawings and estimated production costs. Suggested designs are also presented for the locally manufactured parts, including the drum frame, outer drum, and drive mechanisms. The author expects these designs to be considerably adapted by the local communities, with the potential for reductions in cost and improvements in functionality. Operational and maintenance aspects of the designs are also discussed.

Suggestions for future work, as well as a brief conclusion, round up the main part of the thesis in Chapter 7.

Appendix A details the structural analysis of the drum of the machine, showing that the design can withstand the loads encountered during the wash process.

Chapter 2

Prior Art

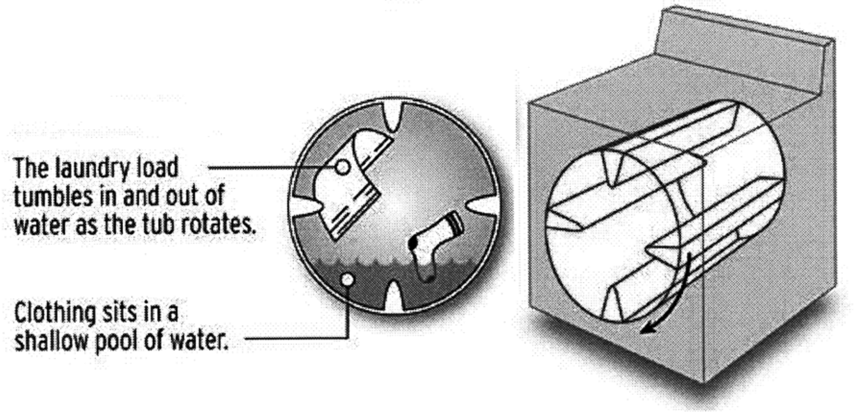
2.1 Clothes Washing Principles

Clothes washers, *washing machines*, use water, mechanical agitation, chemical surfactants, and heat to remove dirt and other soiling particles from clothing in a few simple steps. Washing machines have taken many shapes and sizes over the years, and a number different and ingenuous mechanisms have been developed to provide the mechanical agitation required. Two designs in particular have proved successful due to their simplicity and reliability. They are known as top-loading *(vertical-axis)* and front-loading *(horizontal-axis)* washers. Today, these designs prevail in the market of automatic washing machines.

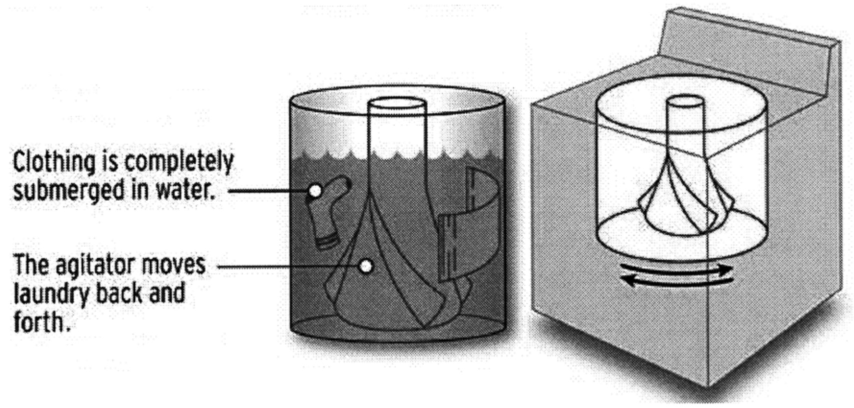
Both types of washer use the same operational principles. First, clothing is submerged in warm water containing laundry detergent, a chemical surfactant. Then clothing and water are agitated, which mechanically separates dirt particles from clothing. The presence of hot water speeds up this process significantly. The detergent surrounds the dirt particles, causing them to become water soluble, while also reducing their propensity to re-attach to the clothing. Finally, the foreign material is flushed out together with the water, and any remaining soap residue is rinsed with clean water.

In a top-loading washer, the clothes are placed in a vertically-mounted perforated drum, that is itself contained within a watertight tub. A propeller-like agitator oscillates left and right, inducing the mechanical energy necessary to separate the clothing.

Front-loading washers also utilize two nested drums, the inner holding the clothing while the outer contains the water, but their axis is oriented horizontally. Instead of employing an agitator, this type of washer relies on a tumbling motion, imparted on



(a) Front loading washer



(b) Top-loading washer

Figure 2-1: Operation principles for modern washers

the clothing by fins in the inner drum which rotates along its axis. The drum is filled only partially with water, the fins lift the clothing out of the water and drop them back in as the drum rotates.

Horizontal-axis washers have number of advantages that make them particularly attractive for this project as compared to vertical (agitator type) washers.

water economy: the water needs to fill the drum only 1/3 of the way, whereas a top-loader requires a complete filling

lower power consumption: the continuous rotation of the drum means less energy is expended starting and stopping, compared to the back-and-forth motion of vertical axis agitator.

simpler design: by integrating the agitating function into the inner drum, the drum becomes the only moving part. The reduced part count and lower complexity of the drive mechanism result in a simpler design overall.

These advantages translate well to the needs of a user in rural countries. Running water is generally not available, and has to be sourced from a well or river. Reducing the amount of water consumed can significantly reduce the overall effort required for doing laundry.

In rural areas, human power is often the cheapest, most versatile and most available form of energy in remote areas. The accepted limit of power output for a fit individual is 100 Watts for long durations according to Wilson [11], which should be sufficient for a horizontal axis washer of moderate size. Section 2.2 presents a number of human-powered washers in existence. Although not widely successful as solutions in developing countries , these designs proved that clothes washers can be adequately human powered.

While the ability to operate using human power alone is one of the design requirements, the design should allow the user to employ another energy source if that is available. A small electric motor can not only relieve the user from the effort of powering the washer, but also free their time while during the wash cycle. Even in this case, the low-power requirements of a horizontal-axis washer remains a key advantage by significantly reducing the operating costs of the machine..

Horizontal axis washers are not without drawbacks. The simplicity of the top-loading design is lost when the drums are laid on their side. Since the inner drum serves to agitate the clothing, its shape is necessarily more complex. The most widespread commercial design, the front-loading washer, uses a cantilever mounted inner drum in order to enable access through one of the ends. This requires a stiff drum and a stiff bearing mechanism, which is heavy and expensive to produce. In addition, a large vibration dampening system must employed in order to reduce the vibrations of the machine.

This drawback can be mitigated by using two bearings, one on either end of the inner drum. Since the end of the drum is no longer accessible, the interior of the drum is accessed through an opening on its side. The added complexity of a door that locks securely on the side of the spinning drum has led to few commercial washers adopting this design.

Figure 2-2: The *WonderWash* hand powered washer
(source: `http://www.laundry-alternative.com`)

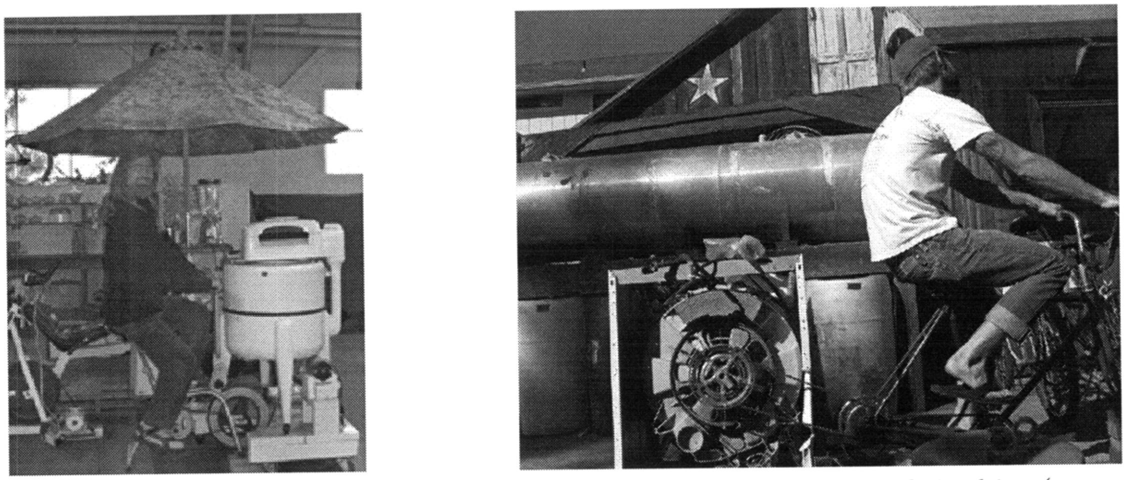
2.2 Other Human-Powered Washer Efforts

During the background research, a number of other human powered washer design efforts were discovered. While many of them, including some listed in this section, stemmed from curiosity and concern for environmental issues, a few designs, most notably the ones developed at Maya Pedal, as well as the very recent design that emerged in India, attempt to address the needs of low-income rural populations.

The only commercial human powered design found is the Wonderwash, which is a small, hand cranked design. The machine is marketed as a solution for "campers, boaters, single persons and even for the housewife with small frequent loads". While the the unit retails for the relatively low price of $50, its small 5lbs capacity make it unsuitable as an everyday solutions for most rural families. The washer is shown in Figure 2-2, and more information about the washer can be found at the website manufacturers website[1].

There have been number of attempts at adapting household washer units to human power, with most employing some form of pedal powered drive. A prototype using an old top-loading washer, connected to an exercise bicycle, is featured on the website of Humboldt University's Campus Center for Appropriate Technology [7]. Another design was constructed by the students in the Whole Earth Engineering class at the same university during the Fall of 2006 [1]. Both of these projects were successful in meeting their goal, but neither design is appropriate for mass dissemination to rural areas because of the reliance on existing washer units.

[1] `http://www.laundry-alternative.com`



(a) exercise bike driving Maytag washer-wringer (source: `http://www.humboldt.edu`)

(b) front-loading washer direct chain drive (source: `http://www.appropedia.org`)

Figure 2-3: Examples of household washers adapted to pedal drive

The Cyclean washer, shown in Figure 2-4, utilizes a similar concept to the HSU design. Instead of adapting an existing washer, it utilizes a number of mass manufactured washer components, and assembles them into a bicycle drive friendly design. The size and cost of the components used are not suitable for adoption in developing areas.

A more appropriate design was recently developed in India, and its development is currently being funded by the Honeybee Network foundation[2]. This is a very new development, and photographs were not available at the time this thesis was written. A video of the device which circulated in various new channels in the spring of 2008 show it to be a self-contained unit, operating on the horizontal axis tumbling principle. The unit is powered through a set of bicycle pedals attached to either side of the device. The unit forms a watertight cavity, which contains an inner drum made of a stainless steel mesh. Due to the compact design, the unit would be easy to transport, but because the capacity and cost of the device are unknown, the likelihood of its success is hard to assess at this point.

The Guatemalan NGO *Maya Pedal*[3], which produces a number of pedal power devices aimed at low-income rural farmers, attempted to design a washer based on a top loading design. An early prototype, shown in Figure 2-5, was constructed, but it was hard to power and had a propensity for damaging clothes. The project was

[2]http://rahulbrown.wordpress.com/2008/05/23/indias-national-innovation-foundation-and-honeybee-network/

[3]`http://www.mayapedal.org`

Figure 2-4: The *Cyclean* pedal powered washer
(source: `http://www.cyclean.biz`)

subsequently abandoned, but their recent partnership with MIT reinvigorated the interest in a solution they could produce locally.

The Bicilavadora effort at MIT, which the author was part of, aimed to develop a design that Maya Pedal could construct in their workshop in Guatemala [2]. A proof of concept prototype based on the horizontal axis design was constructed at MIT using materials that are easily available in Guatemala (shown in Figure 2-6) . The project received an INTERNATIONAL TECHNOLOGY AWARD in 2005 in MIT's IDEAS competition[4], and was subsequently funded through a fellowship by MIT's Public Service Center[5] to transfer the technology to Maya Pedal [2].

The design was further adapted, and a prototype was constructed on site at Maya Pedal in the spring of 2006 by the author with the help of Gwyndaf Jones. The inner drum, which was built from an utility bucket, was replaced with a stronger barrel. The capacity of the machine was increased, and reliability improved by supporting the open end of the drum through the use of support wheels running on the inside of the outer drum. The prototype was subsequently adapted by Maya Pedal volunteers, who modified it for side loading. The original prototype, and subsequent modified version, are shown in Figure 2-7.

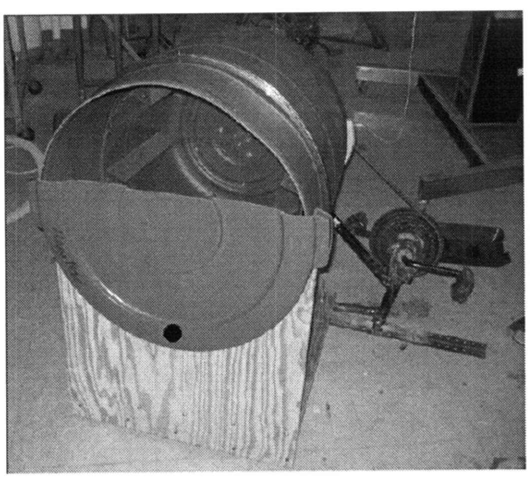
Although the design was much gentler on the clothing than Maya Pedal's original prototype, the construction relied on materials that were available locally, but only in limited quantities. Maya Pedal anticipated that the design would have to be adapted

[4] `http://web.mit.edu/ideas/www/pastprojects_0405winners.htm`
[5] `http://web.mit.edu/mitpsc`

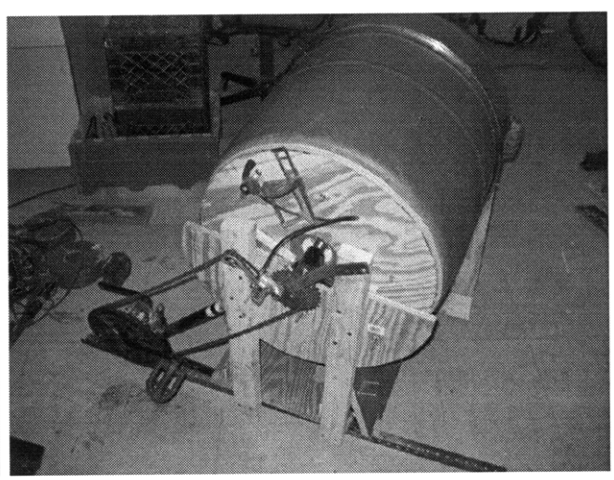
(a) machine is actuated by strings tied to the end of the pedals

(b) washing drum detail

Figure 2-5: Maya Pedal's agitator washer



(a) front view



(b) rear view

Figure 2-6: Bicilavadora proof of concept entered in the IDEAS competition

(a) original construction

(b) subsequent local adaptation

Figure 2-7: Bicilavadora prototype constructed at Maya Pedal

from unit to unit depending on the particular availability of parts at the time of construction.

Relying only on locally available components, not optimized for the needs of the product, resulted in reliability issues and high costs. A complex assembly process also increased manufacturing price, raising the price of the product, and limiting the number of machines Maya Pedal could build to a maximum of two machines per week. Because of the size of the product, they would have to be transported by pickup truck to the final destination, further increasing costs, and limiting the effective distribution area to a 50 mile radius around San Andres Itzapa, where Maya Pedal's workshop is located.

This thesis is in many ways a continuation and expansion of the Bicilavadora project, seeking to deliver a solution that is simpler, less expensive, and most importantly, easier to disseminate at a large scale.

Chapter 3

The Dissemination Challenge

In the context of this thesis, by dissemination we mean all of the steps necessary to bring a product to its final user. While in a developed country context, dissemination could be equated with shipping, in the context of developing areas the dissemination equation is significantly more complex. The dissemination challenges must be paid special attention to when designing for a product for developing areas, as they can significantly limit the reach and increase the final price of a product,

A typical solution to the dissemination problem is to design products that can be constructed using modest tools and available materials, and disseminate the design to local shops throughout the country. The Bicilavadora effort[1] pursued this approach in trying to produce a washer that could be manufactured locally in Guatemala, but the inherent limitations of local manufacturing prevented the team from reaching a satisfactory design solution. Even if a design had been completed, disseminating it at a wide scale would have required a subsequent effort, which could have failed for a number of reasons unrelated to the merits of the design itself.

3.1 The Wide-scale Dissemination Requirement

One of the design goals for this thesis is to develop a final product capable of reaching a large number of potential users without requiring an expensive, externally funded dissemination effort. As in the case in most product development projects, the number of units that will be produced, sold and used is difficult to assess, but a goal will be selected in order to guide the progress of the design.

Just like selecting a target price, selecting the target number of units of the product

[1] see Section 2.2 and Baker [2]

must be based in knowledge about of the target product user. The design targets for unit price and the number of units to be produced are related in a number of ways. More expensive products will be affordable to a smaller number of potential users in a target market. The pricing of a product must be low enough for the target user to afford, but a product that can be effectively shared between many users could command a higher price, assuming shared ownership is accepted for the specific location and type of product.

Guatemala is the first targeted dissemination area for the low cost washer. Of the 12 million people living in the country, an estimated 5.5 million (60%) are classified as rural poor, with 2 million people (16%) living on less than $1/day, according to the World Bank [3]. The design targets rural households, but is not expected to be affordable to families living in extreme poverty. The total market segment of the design is therefore estimated to be 5 million people, living in 2 million households.

The target production volume of 1 million washer units installed over 5 years would reach 50% of the targeted users, more if the units are shared between households. A successful design should be able to be manufactured at these volumes. The ideal design would allow for easy expansion into other countries and markets.

3.2 Challenges of Local Manufacturing

Designing for local manufacturing using locally available materials is often a good strategy, providing a number of benefits. Relying solely on local manufacturing allows for the device to be adapted based on the user needs and material availability. Additionally, it eliminates reliance on imported components and parts that could limit the ability to do local repairs. Due to the lack of proper infrastructure in many developing countries, transportation costs can add greatly to the final cost of the product. Manufacturing the product closer to the location where it will be used can be an important tool for controlling the final product cost in many situations.

Complete reliance on local manufacturing adds significant limitations during the design process. The Bicilavadora effort, described in Section 2.2, failed to develop a simple and cost effective design in large part due to limitations in the local availability of materials and equipment. These limitations are also a major reason why appropriate solutions have not been developed by the local communities.

A dissemination strategy that relies on local manufacturing requires the ability to disseminate design of the product, including manufacturing methods, to all the sites where it will be produced. The dissemination of the design as *information only*

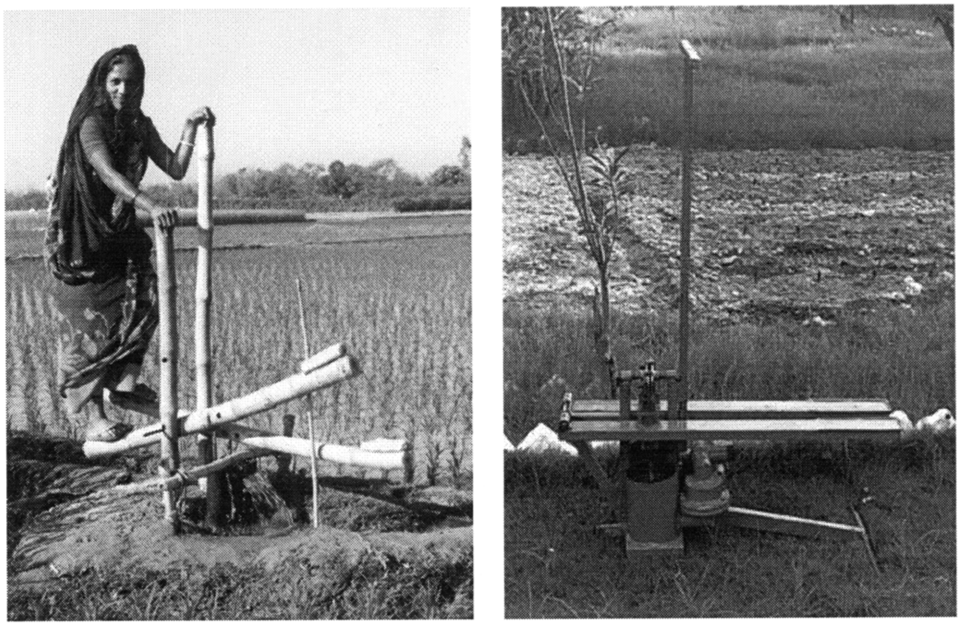
Figure 3-1: IDEI treadle pump components sold in Indian store

is often tasked to an NGO, local or central government entity or other organization, which would employ a skilled trainer to deliver the design to local manufacturers. For designs that are simple to replicate, dissemination via photographs or simple verbal descriptions may happen locally without external intervention. Relying on these strategies can become a barrier to large-scale dissemination, as we will discuss in Section 3.3.

In the particular case where only a small component of the design is missing locally, a solution can be reached by disseminating only that specific component. This is the approach used by IDEI (International Development Enterprises India) for dissemination of its low-head treadle power pump solution used for irrigation[2]. Pump pistons, the only parts of the design that are difficult to manufacture locally, are distributed via existing product distribution channels, like local markets and small shops such as the one shown in Figure 3-1. The complete pump unit is then assembled locally, using locally sourced materials. In locations where bamboo is easily available, it is often used because of its durability and low cost. In areas where structural steel members are locally available and affordable, they can be welded to produce longer lasting units (see Figure 3-2)

IDEI's dissemination strategy uses a very successful combination of programs such as aggressive local advertising (see Figure 3-3), manufacturer training and machine

[2] `http://www.ide-india.org/ide/treadlepump.shtml`



(a) bamboo unit in use (b) welded steel design

Figure 3-2: Local adaptations of the IDEI treadle pump

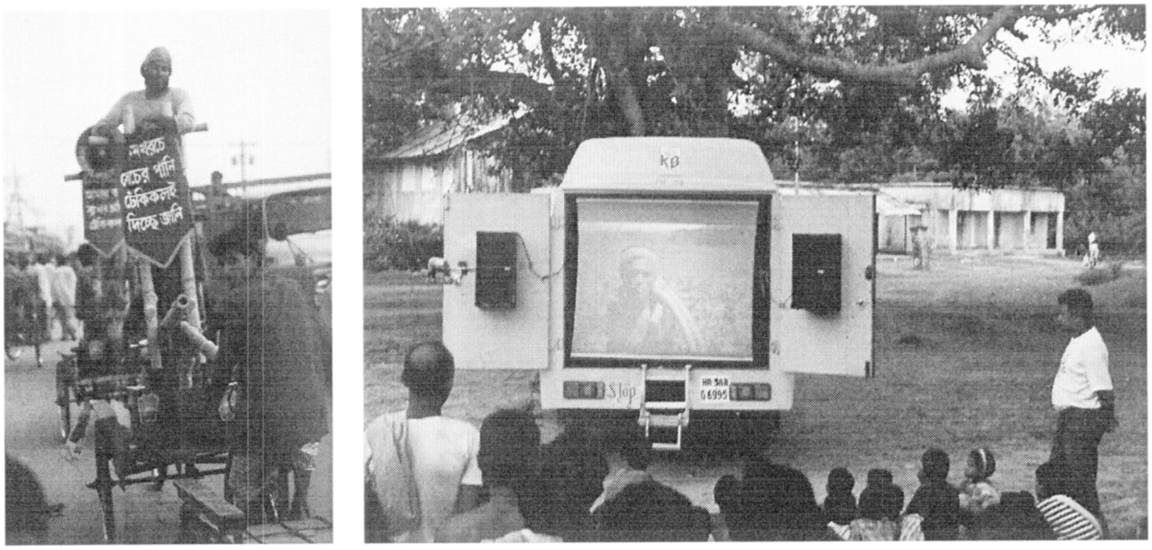
tracking in every region that they operate. The success of their product is in large part a result of successful dissemination operation, working in concert with a design that simplifies the task of local assembly.

The IDEI treadle pump dissemination methods are a good model for this project, but their success is dependent on the fact that the only component needs to be disseminated, the pump pistons, is inexpensive to produce in large quantities, and is small enough that shipping is easy and inexpensive, even to remote areas.

For a washer modeled after commercial units, the inner drum is the most difficult component to manufacture locally. But unlike IDEI's pump pistons, the drum must be at least three cubic feet, which makes it considerably more expensive to transport. The drum is not only large, but the material normally used is stainless steel, which makes the traditional drum expensive to produce even in large volumes. Therefore, a different design is required in order to replicate the success of the IDEI treadle pump program.

3.3 The Costs of Dissemination

Designing for extreme affordability, first championed by Schumacher [8], has become a key component of international development focused projects, and a keystone of



(a) street advertisers (b) mobile theater showing promotional film

Figure 3-3: Product dissemination through advertising

comprehensive approaches to international development [6]. It is an accepted standard to consider affordability for the poor, who often live on less than \$2/day, as a principal requirement for any product aimed at underdeveloped regions of the world.

In the face of the dissemination challenge, designing for affordability must go beyond the traditional design for low cost manufacturing. Due to the poor state of transportation infrastructure in most developing countries, shipping a centrally manufactured product to remote areas, especially one the size of a washing machine, can be extremely cost prohibitive. Even at large manufacturing volumes, any savings in costs due to economies of scale can be entirely negated once shipping costs are factored in.

While transportation costs are reduced by the product is manufactured locally, large scale dissemination requires that the design be transferred to many local manufacturing locations throughout the targeted area. For a complex product, the costs of information transfer can be significant, but these costs are often hidden when this task is performed by governments or other large organizations. Even if the funding is external, these additional costs still raise a barrier to dissemination through the reliance on the limited resources of an external entity.

A market driven dissemination approach, such as the one championed by IDEI, requires that the final user pay all the costs associated with the product. Such an approach has the advantage of eliminating the potential of funding shortages, allowing the product to disseminate based solely on its merit and total cost. In optimizing

Cost item	Central manufacture	Local manufacture
Manufacturing	$130	$250
Shipping and handling	$220	$0
Total per unit, delivered	$350	$250
Setup (one-time)	included in manufacturing	$1.2 million - external

Table 3.1: Comparison of estimated costs based on manufacturing and dissemination strategy

the design for the lowest cost, all distribution related costs must be considered along with the cost of manufacturing. This concept is further elaborated upon in Section 3.5.

Based on previous experience of working in Guatemala, an informed estimate has been made regarding the costs associated with dissemination of a washer based on the manufacturing and distribution strategy used. The traditional central manufacturing and local manufacturing approaches are compared in Table 3.1

For the central manufacturing scenario, we will assume that an appropriate washer that meets all the functional requirements can be constructed in a central facility for $100, an optimistic cost relative to household unit prices. The resulting unit would be assumed to be 2"x3"x3" in size, and weigh 75lbs. The manufacturing location is assumed to be Guatemala City, and the factory-door price set at $130. The cost of shipping the product to a village 250 miles away would add an additional $100 to the cost of the unit. Assuming the machine changes hands twice before it reaches the final user, with a reseller charging a 30%, the final cost to the user would be $350.

Estimating the costs for the local manufacturing scenario is more difficult. We will assume that the unit could be manufactured in a local workshop for $200[3], and sell for $250 after after manufacturer profit. This does not however consider all dissemination cost, as we must include the cost of teaching the local manufacturer how to build the unit.

A small workshop could produce machines at a rate of 1 every two days, and by working 200 days a year they could provide 100 units each year. To supply one million units throughout Guatemala over 5 years in order to meet our dissemination goal, 2,000 small workshops would be required. Traveling to a location, finding a workshop and training the workers to build a complex product could take 6 days for a skilled trainer. Compensating the trainer at $75 per day, and considering $50 for transportation and $100 in additional costs incurred would bring the total cost

[3]based on the results of the Bicilavadora project, see Baker [2]

of training a single workshop to $600, excluding any organizational overheads which could be significant depending on the organization.

When distributed over the 500 machines each workshop would produce, the total cost of training would be less than $2 per unit, which would not add significantly to the final cost of the final product. The small workshops would however be unlikely be unable to pay for the cost of training upfront, and the lack of reliable legal mechanisms for enforcing per-unit royalties means that these costs would be very hard to recover. Finding an organization that would contribute the $1-2 million be needed to train the network of manufacturers without expecting any financial return would be difficult, if not impossible.

Neither of these models can adequately support the distribution of the target number of units at the target cost. A successful dissemination strategy would retain the low production costs and scalability of central manufacturing, while lowering the costs associated with distribution.

3.4 Opportunities for Marketing Partnerships

By combining central manufacturing of key components with local assembly, IDEI was able to reduce the distribution costs for their treadle pump, making it affordable to millions of low-income farmers. Their ability to utilize existing market structures in their target areas was an important part of their success.

The target production volume of 200,000 units per year is not large enough to be able to support a dedicated distribution system and advertising operation. A successful product should leverage distribution channels already in place.

While researching researching clothes washing practices currently used in rural areas of Guatemala, the author learned that most women use powdered chemical detergents. This type of detergent is sold in every marketplace, and is available even in remote rural areas (see Figure 3-4). The detergent distribution networks reach all potential users of the washer, and therefore would be an ideal dissemination channel.

Because of the competitive nature of the detergent market, manufacturers compete to differentiate their product through advertising. A co-branding partnership between the washer and a detergent manufacturer would provide access to their existing advertising and distribution networks, while providing the company with a novel way to promote their products. By subsidizing the cost of the machine, the detergent company could increase adoption rates and further promote their brand.

A well structured marketing partnership would be mutually beneficial, and could

Figure 3-4: Detergent stall at local market in San Andres Itzapa

add greatly to the success of the low cost washing machine.

3.5 Designing for Dissemination

Product development is the process mapping the design requirements into a product can be manufactured and marketed [9]. The functional requirements for a clothes washer are relatively simple to accomplish. Many laundry devices exist, as discussed in Chapter 2, but are not in wide use in rural Guatemala because they are not available in local markets a price low enough to be affordable for the local population.

In developed country situation, low product cost is achieved by optimizing the design of the product for low cost manufacturing. Bringing the product to the market in this context can be accomplished using the wide reaching, reliable and inexpensive shipping and transportation services which exist in industrialized countries.

In order to achieve low product cost for a product addressing the needs of low-income rural populations, a more comprehensive approach to design and and dissemination is required. As discussed in Section 3.3, the cost benefits of central manufacturing can be quickly offset by the high transportation costs in underdeveloped areas. This is especially a problem for products that are large and/or heavy, such as a laundry washer.

Optimizing the design for the lowest total cost requires an integrated analysis of product manufacturing and distribution costs, making use of opportunities like local assembly and marketing partnerships to reduce the final cost to the user. The approach used in this thesis and presented in the following chapter allowed the development of a product that meets the functional requirements, and also lends itself to low-cost production and wide scale dissemination.

Chapter 4

Design Approach

Designing a horizontal axis washer that meets the design requirements outlined in Table 1.1 and addresses the dissemination challenges described in Chapter 3 requires a careful and comprehensive design approach. This chapter presents the design methodology used, as well as describing its application to the specific case of the clothes washer.

The Bicilavadora project attempted to devise a washer design that could be constructed locally by Maya Pedal, a Guatemalan NGO, using only locally available materials. The effort was not successful in developing a repeatable, low cost and durable design. It did however prove that large portions of a horizontal washer could be constructed on-site, using local materials and techniques at a relatively low cost.

Delivering a complete design for an inexpensive, long-lasting washer suitable for mass dissemination required a comprehensive analysis of the product life-cycle, with a particular focus on manufacturing and distribution. The resulting hybrid manufacturing approach leverages the respective advantages of both large-scale central production, as well as local construction and assembly.

This design method can be generalized, and may be useful for developing any number or products targeted at income limited users in remote areas. The lessons in this chapter should be especially applicable in the design of large products that, like the clothes washer, would be expensive to transport as complete products to remote rural areas.

4.1 A Hybrid Manufacturing Approach

With respect to meeting the low cost and dissemination goals, both central and local manufacturing approaches have distinct trade-offs as discussed in Chapter 3.

As outlined in Section 3.2, local production contributes to building local capacity and self-reliance. It also allows the product to be maintained and adapted to various needs of the user. Relying on locally available materials and construction techniques is severely limiting from a design perspective, to the point where it might render certain tasks entirely intractable without the use of a specialized part or piece of equipment. Furthermore, relying on word of mouth, NGOs or government agents to distribute paper only design solutions can severely inhibit dissemination, as discussed in Section 3.3.

Conversely, manufacturing a product in large volumes centrally can increase design options, and reduce production costs. This method has the added advantage that the final product dissemination can *just happen* if the product is successful on the market. This approach would not however work for over-sized or heavy products, such as a washing machine, which are expensive to ship.

Even for products that are small and light enough, distribution can still become an expensive problem. Gains made by volume manufacturing can be entirely negated or reversed due to the high, percentage based distribution tariffs charged as a product changes hands on the way to the remote rural markets. Creative approaches such as the marketing partnerships method outlined in Section 3.4can be employed in order to minimize the costs of distribution.

Based on these observations, an optimized design approach would seize on the particular strengths of the two manufacturing options, by designing specifically for a hybrid manufacturing strategy. This involves central manufacturing and shipping of some components, while the manufacturing of other components and the final assembly is done on site to reduce distribution costs.

In the case of the clothes washer, the functional model of the machine is based on the horizontal axis washer design. The next step of the design process requires a decision about how and where the different functional components are to be manufactured. This was performed through a careful analysis each functional component of the design against the following list of guiding principles:

1. Make use of local materials, expertise and labor as much as possible, in order to eliminate transportation costs. In particular, large components and sub-assemblies, should be locally constructed, and heavy structural elements should be locally sourced if at all possible.

2. Any parts designed for local manufacturing should be low precision parts, and not require any specialized materials or equipment not likely to be found in an

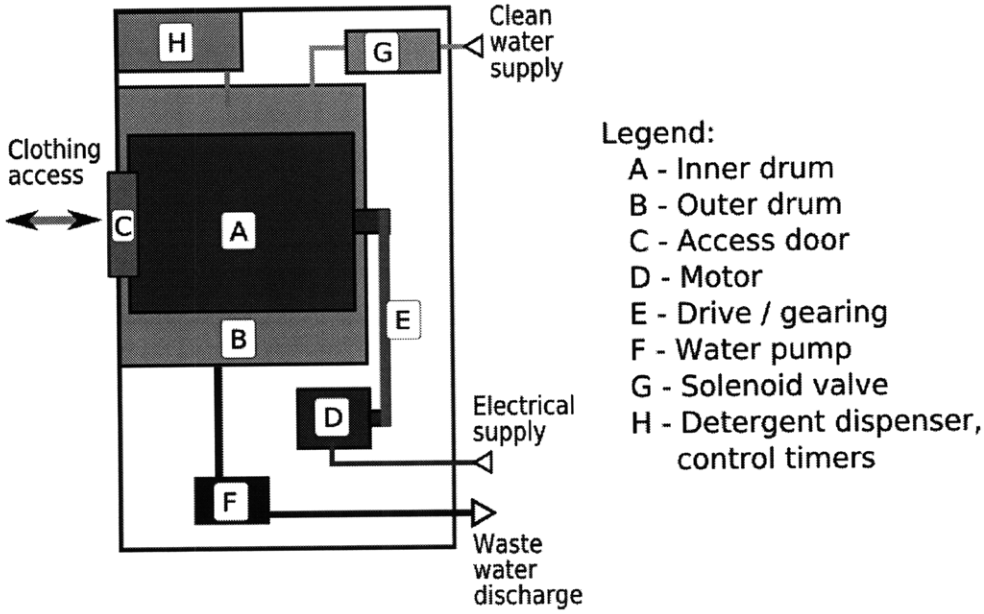


Figure 4-1: Functional diagram of horizontal washer

auto repair or similar local workshop.

3. Identify any components that are exceedingly expensive to produce locally, when compared to central manufacturing. Design those parts for low manufacturing cost, and to be as small and light as possible for easy transportation. The flexibility inherent in designing a custom part should be used to simplify the rest of the design as much as possible.

4. Finally, design for on-site assembly.

4.2 Component Analysis of a Horizontal Axis Washer

Figure 4-1 shows a functional diagram for a commercially sold front-loading washer. Each functional component will be analyzed in turn by assessing the specific design requirements for that component, and determining the best way these requirements can be met using a hybrid manufacturing approach. The analysis will progress in order of design difficulty, starting with the simplest elements and working up to the most challenging component, the inner drum.

4.2.1 Automation components - central timer, pumps, valves and other actuators

Modern commercially sold household washers are automated units. Once connected to the electric system, water supply and drain system, they require no user intervention after the clothing is loaded. This is accomplished by using a series of automation components, including actuated valves, electric water pumps, and other small actuators to dispense detergent and other laundry aids at the appropriate time in the cycle. The sequence of operations is driven by a central controller. In older units, this was accomplished by a timing cam driving a series of mechanical switches, with modern machines using increasingly complex microprocessor controllers.

The presence of these automation features is certainly appropriate for a machine which is connected to the electrical and water infrastructure and driven by an included electric motor. Considering the need to operate the absence of electricity and running water, an unattended washing solution would be exceedingly costly and complex and therefore not appropriate. The tasks performed, including adding and draining water, and adding detergent at the appropriate time, can be performed manually with minimal inconvenience, especially in the case of a human powered machine which by design already requires the user to be engaged throughout the entire wash process.

Given the simplicity and modular nature of the final design, nothing prevents the addition of such automation features by the user, and aftermarket solutions could become successful where appropriate. They are, however, beyond the scope and design goals of this thesis.

4.2.2 Outer Drum and Structural Frame

The water and detergent that the laundry is washed in is contained by the outer drum. The design need are limited to being structurally able to contain the required quantity of water, being water tight and resistant to the chemical products used.

The modest design requirements lead to a number of simple design, many of which can be easily manufactured using commonly available materials. The size of the component is also necessarily large, because of the need to contain an inner drum with a strict minimum volume requirement. This component should therefore be designed for local manufacturing, in accordance with the first design guideline.

In a commercial washer, the outer drum, along with the rest of the components of the washer, are mounted inside a welded steel-member structural frame, which holds all elements in proper alignment without adding exceedingly to the weight of the unit. The low weight is important for easy shipping, but a light washer unit may vibrate significantly during operation due to inevitable imbalances of the inner drum when it is filled with wet and heavy clothing. As a result, traditional horizontal washers also need to incorporate a method of reducing the vibrations. Most often the inner drum, outer drum and drive system are made into a separate sub-assembly, which is mounted to the frame of the machine through a spring and damper system. Since the imbalance is most pronounced during the high speed centrifugal *spin drying* operation, this passive damping system is tuned to absorb the frequency matching the rotational speed of the machine during this cycle. Newer designs also employ fluid balance rings.

The ability to remove water from the clothing by centrifugal action is extremely desirable. Aside from allowing for almost half of the water content of the clothes to be removed at the end of the cycle, as compared to simple draining, the spin drying operation also helps to remove the dirty water from the clothes at the end of the wash cycle, which allows less water to be used for rinsing. Although the very high speeds reached by commercial washers are hard to achieve with human power without the use of complex gearing, high enough speeds can be used to still make a significant difference.

By building the drum at the site where the washer will be used, the construction of the machine can be simplified significantly by using a very heavy drum that also serves as a structural base for the machine. The cast cement basin design proposed in Section 6.2 eliminates the need for both external frame and damping system, by allowing the inner drum to be directly mounted onto the basin. The sheer weight of the basin eliminates machine vibrations, but effectively prevents the relocation of the machine as a whole.

The local manufacturing of a structural and heavy basin is therefore the recommended solution. If relocation becomes necessary, the simple construction allows for the old basin to be disassembled, and a new basin to be constructed at the new site.

4.2.3 Bearings and Drive System

The washing action of the horizontal axis design is a result of the tumbling of the clothing that occurs as the inner drum of the machine rotates. If the ability to spin dry the clothing is desired, high speed rotation is needed as well.

Allowing the drum to rotate can be easily achieve by attaching a shaft along its axis and using a rotational bearing system to mount it to the stationary frame.

The bearings used in the final design will have to withstand the loads and rotational speeds encountered during operation, provide long life even in a moisture environment, tolerating of contaminants and even the occasional splash of water, while remaining relatively inexpensive.

The rotation speeds required are determined by the diameter of the inner drum. For the wash cycle, the ideal tumbling motion is achieved when the centripetal acceleration experienced by the clothing is slightly less than the gravitational acceleration. At that speed the clothing, entrained by the fins of the drum, stick to the outer wall until they reach a location close to the the top of the drum. At that point, the gravitational force takes over and the clothes fall back down into the water.

For a drum of radius R, the critical angular velocity at which this happens is:

$$\omega_{wash} = \sqrt{\frac{g}{R}}$$

where g is the gravitational constant and R is the radius of the drum. For a radius $R = 10\,in$, this critical speed is $\omega \approx 6.3\,rad/s$, or around 60 rpm. A drum of larger radius will require a smaller angular velocity during the wash cycle.

The spin drying of clothing relies on a forced separation that occurs as the clothes are rotated inside the drum at high speed and experience a centrifugal force. While the clothing items themselves are contained by the drum, the water is free to escape through perforations in the drum walls. In order to see any benefit from this action, the centripetal acceleration the clothes are subjected to must be significantly higher than the gravitational constant which what clothing normally experienced during normal drip drying. The corresponding formula for determining the centripetal acceleration experienced is well known:

$$a_c = \omega^2 \cdot R$$

where ω is the rotational speed, and R is the drum radius. As intuition confirms, higher rotation speeds and larger drums result in acceleration and faster water extraction as a result. Because of the quadratic relationship, increases in the rotational speed can significantly improve the spin drying efficiency. Commercial front-loading washers use speeds of up to 2000 rpm, producing accelerations in excess of 400G and reaching over 1000G for some machines.

The goal of our unit is a modest 150 m/s^2, just 15 times the gravitational acceleration. For a 20 inch diameter drum, this requires a speed $\omega \approx 24\,rad/s$, approximately

230 rpm. This speed has been shown to extract half of the water from cotton clothing that has been soaked, leaving the clothing with a water content roughly equal to the weight of the dry fabric. This level of performance is far below the of the best front loading washers, which produce clothing that is merely damp, but is comparable with the results rendered by traditional top loaders. Most notably, for our target user, spin drying even at these low speeds will provide a way of removing 50% more water from clothing with significantly less effort when compared to wringing of clothing by hand.

4.2.3.1 Bearing Selection

Because rotational speeds required for a washer are low enough to be tolerated by almost any type of bearing, the type selected will depend on the loads the bearing will experience during operation. The load requirements will vary greatly depending on whether the drum is cantilevered from one end or supported at both ends. The cantilevered design would require a much stiffer thrust bearing, which would raise the cost and complexity of the design significantly.

The final design utilizes two bearings, located either end of the inner drum precisely because of the much lower load requirements in places on bearings, as well as the the inner drum. In this configuration, the bearings must be able to jointly support the static weight of the inner drum when filled with wet clothing, as well as any vibration loads encountered during operation.

The static load bearing requirements is determined by the total weight of the drum and wash load. The maximum laundry capacity of 15 lbs dry, assuming all cotton, would translate a 45 lbs wet capacity. Adding an estimated 20lbs for the outer drum results in a total load of 65 lbs, or 100lbs with an included 1.5 safety factor. This load needs to be supported jointly by the two bearings at speed up to the maximum of 230 rpm.

These requirements are easily within reach of low-cost bearings. For a generic 1" length, 1" diameter plane bearing, the 50 lbs/bearing load result in a pressure load of 50 psi, and 240 rpm rotation speed translates surface speed of 63 fpm. The load at capacity requirement of $PV = 3150$ can be easily achieved using inexpensive, self-lubricating, oil impregnated bronze (Oilite) bearings.

Aside from their low cost, Oilite bearings have the advantage of being moisture resistant, and the lack of moving parts and large mating area increase resistance to foreign contaminants. These bearings can easily be obtained off the shelf in any industrial area, but might be hard to find in remote areas, and thus would be best to be included in the production kit, along with a shaft of matching size.

4.2.3.2 Power Source

Human power is the most appropriate means of propelling the inner drum at the required speeds in the absence of an low cost energy supply. Powering the wash cycle for 15 lbs of laundry was subjectively estimated to require 60-80 Watts of continuous power, and lower for a smaller load size. The requirements during the spin dry process is a much lower 20-30W.

A bicycle drive train provides an inexpensive, reliable and highly efficient way to transfer that power. The power requirement of 60-80W is within the 100W limit generally recommended for human powered devices according to Wilson [11]. The operating range of 60-230 rpm is also within the capabilities of a generic multi-speed derailleur driver. With such a system, the user would select the lowest gear ratio, which is usually nearly 1:1 for most drive systems, and pedal at a comfortable rate of 60 revolutions per minute, which is considered most efficient. For spin drying, the highest available gear should be employed. A 3:1 ratio is available even on the lowest end drive trains, which would require a 75 rpm cadence to achieve the highest spinning speed of 230 rpm. Since the power requirements are very low 20-30W, this cadence is achieved comfortably.

Because of durability, efficiency, low cost and local availability of bicycle components, a locally manufactured drive-train using bike components is the recommended design solution in Guatemala as described in Section 6.2.3.

4.2.4 Inner Drum

The inner drum is the most important functional element of the washer. It fulfills the following roles:

- holds the clothing during wash and spin cycles
- provides agitation through integrated ribs
- allows for water to be drained/spun out through perforations in the drum walls

Most often a cylindrical shape, the drum contains 3-5 internal ribs that engage the clothing, providing agitation as the drum rotates. The ribs are sometimes an integral part of the drum shape, but in most inexpensive designs they are separate parts which are fastened to the drum. The number, size and shape of the ribs vary from model to model.

Because it is the innermost component of the washer assembly, the size of the inner drum determines the size of the machine as a whole. Functionally, the drum must provide enough volume to accommodate the desired wash load. Commercial front-loading washers range in volume from 2.4 to to 4 cubic feet, with advertised capacities ranging from 12 to 20 lbs of dry laundry. A larger drum will provide greater capacity, but it would also be more expensive to produce and transport, and increase the water and power consumption of the machine.

Most commercially sold horizontal-axis household washers are front-loaders, meaning that one end of the drum is open to allow access to its interior. The drum is therefore cantilever mounted on the other end. This configuration creates significant bending moments in the drum, which must be designed for withstand the static and vibration loading encountered during operation, in particular during spin drying.

The inner drum is the only part of the washer that comes in direct contact with the clothing during normal operation. Its inner surface must be smooth, in order to avoid damaging the clothing. Additionally, because many clothing items contain metal parts, in the form zippers and buttons, the drum must be able to withstand repeated abrasion. And because the drum functions in a wet environment, it must also resist oxidation which could stain the clothing and over time compromise the integrity of the drum.

Combining the strength requirements with the corrosion and abrasion resistance significantly limits the material options. While old horizontal washers employed enameled steel drums, all modern designs use an aluminum or stainless steel inner drum in order to prevent staining of the clothing.

In accordance to our design guidelines the large size of the inner drum dictates that every attempt should be made to construct this part locally and thus avoid transportation costs. This conflicts with the material constraints, since all appropriate materials are expensive and hard to shape locally.

Due to the difficulty of resolving this conflict, the entirety of Chapter 5 is dedicated to describing the design evolution of the inner drum. The final solution consists of a drum composed of a simple mild steel structural frame which is locally manufactured, and a set of ABS resin panels which line the inside of the frame. The ABS panels can be manufactured cheaply in high volumes, are lightweight and nest for easy transportation. Because the panels protect the steel frame from abrasion, the mild steel can be adequately protected from oxidation by using an adequate metal paint.

The hybrid manufacturing approach of the inner drum is is accordance with the overall design method, leveraging the advantages of both central and local manufac-

Functional component	Manufacturing	Notes
Inner drum	Hybrid	ABS panels distributed. Metal frame constructed locally.
Bearings and shaft	Central	Off-the-shelf components, may be hard to source locally.
Power source	Local	Locally sourced bicycle components.
Automation	N/A	Not essential for human powered design.
Outer drum	Local	Manufactured on site.
Frame and damper	N/A	Integral to the outer drum.

Table 4.1: Summary of component analysis

turing.

4.3 Analysis Conclusion

The results of the component analysis is summarized in Table 4.1. Compared to shipping a complete product, dissemination to remote areas is eased by vastly reducing the volume and weight of the product during shipping. The large selection of materials and manufacturing techniques available with central high-volume manufacturing is used to significantly reduce the cost of complexity of constructing a washer in the field.

For target dissemination locations other than Guatemala, some of the decisions might have to revisited to account for different locally available materials and manufacturing capabilities.

Chapter 5

Design Evolution of the Inner Drum

As detailed in the previous chapter, the inner drum is the key component of a horizontal axis washer for a number of reasons. Functionally, it is essential for the operation of the washer, being responsible for holding the clothing, providing the agitation during the wash cycle, and separating the water during the spin cycle. The design features of the drum, such its size and the way the space inside the drum is accessed, have a significant effect on the the overall design of the machine.

Due to its critical importance and the difficulty of the design challenge for the inner drum, as described in detail in Section 4.2.4, this chapter discusses the design evolution of this component. It showcases a number of milestones in the iterative design process that culminated in the final inner drum design.

5.1 Design Requirements

We will review all of the requirements considered during the design of of this component, keeping in mind the overall project goals. Some of the design requirements for the drum have been discussed previously in Section 4.2.4, as they relate specifically to manufacturing and dissemination. This section will focus on the functional requirements.

The main function of the drum is to contain the clothing during washing and spin drying, and provide the mechanical agitation required to separate soiling agents from the clothing. In a horizontal axis washer, this is accomplished though the geometry of the inner surface of the drum, which contains a series of ribs that entrain the clothing as the drum rotates. These ribs must be present for the drum to perform its function. The geometry requirements are discussed further in Section 5.3.

Once the shape constraints are met, the drum must be sized to accommodate a sufficiently large amount of clothing, eliminating as much as possible the need for multiple loads. However the drum should not be too large as it would increase the water and power consumption as well as the footprint of the unit. The goal for this project was to provide a washing capacity comparable to a the household washers commercially sold in North America and Europe, with the requirement set 15lbs of dry laundry, which for a horizontal washer requires a drum size of 3 sq.ft.

The aspect ratio of the drum can be varied, with a shorter and larger diameter drum requires lower rotation speeds, but having the disadvantage of a larger footprint for the same volume capacity. The diameter considered for this particular design was limited to 22in, in order to allow the use of standard 55 gal containers as an outer drum.

The inner drum must be structural to the extent that it can withstand the loads encountered during normal operation. The highest loads will be encountered when spinning a full load of wet laundry at the maximum spin-drying speed of 240 rpm. Assuming a clothing capacity of 15lbs of dry clothing, which can become up to 45lbs when the clothing is wet, the force exerted by the clothing on the outer walls of the drum will be 450 lbf, or 2,000 N. Assuming a drum of radius R=10in, and depth d=20in, and a uniform distribution of clothing, the pressure loading on the surface of the drum will be on the order of 0.36 psi. The actual loading profile is likely to be far from uniform, and therefore a significantly higher 1 psi load is a safer design goal. The final drum design was analyzed for this loading scenarios, and the results can be found in Appendix A. Aside from the uniform loads, the vibration loading that results when the load is unbalanced must also be considered.

The drum must withstand these loads, and be able to properly transfer them to the frame of the washer through a rotating interface. The design requirements for the drum bearings were discussed in depth in Section 4.2.3.

A closely related requirement is the need for easy access to the interior of this drum, for insertion and removal of clothing. Commercially successful front-loading units provide easy access through one end of the drum, requiring the whole drum to be cantilevered from a bearing on the opposite end. This approach necessitates a very rigid drum, and a very rigid bearing, which can add significantly to the cost of the unit. If both ends of the drum are used for supports, the loading and unloading of clothing must happen through the side of the drum.

In order to allow for a complete *wash, drain, and spin* operation cycle, the drum must allow the water to be separated from the clothing, which is normally done through perforations in the drum walls. These perforations must be large enough to allow for the water to pass unimpeded, but not too large so as to let parts of the clothing to get jammed in them or escape the drum altogether.

The most challenging design requirement is a the ability to withstand oxidation and corrosion of the wet environment, while also resisting the constant abrasion with the clothing during operation. The problem of selecting a material for the drum is complex enough to warrant further discussion in a separate section.

5.2 Material Selection

The previous Bicilavadora effort, introduced at the end of Section 2.2, attempted to produce a washer design that could be manufactured using locally available materials in rural Guatemala. The lessons learned from that experience are easily summarized: no materials are available locally that allow for a simple, inexpensive, and durable drum to be constructed on site.

The inner drum must operate in a harsh environment. The inside of a washer is flooded with water and allowed to slowly dry during each use. This presents a serious problem for the most versatile, easily available and inexpensive structural material, mild steel. Expanded steel sheets are inexpensive, commonly available, and would be relatively easy to shape and weld to form an inexpensive drum, were it not for the requirement to withstand a wet environment.

Simply painting the washer is not an acceptable long term solution, as the inner side of the drum encounters significant abrasion with the clothing during operation. The presence of metal components in clothing such as buttons and zippers would present an issue for even the most durable of paints.

Other surface treatment options were also considered. Electroplating would suffer from the same abrasion resistance issues as paints, and enameling is prohibitively expensive and can suffer from chipping and cracking unless all manufacturing conditions are perfect.

Other locally available materials were investigated. Aluminum and stainless steel, the natural engineering choices for this application, are both extremely expensive locally, and they require special tools and techniques to shape and assemble, which is beyond the capabilities of most local shops.

Locally available varieties of wood exist that offer similar water resistant qualities as teak and cypress, due to naturally high oil content. A wood drum construction was attempted (shown in Figure 5-1), and found to be expensive, cumbersome and exceedingly heavy. Developing a solution to join the wood that would resist both

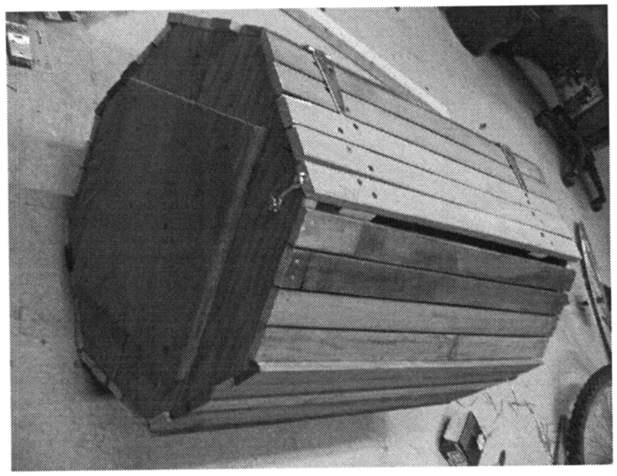
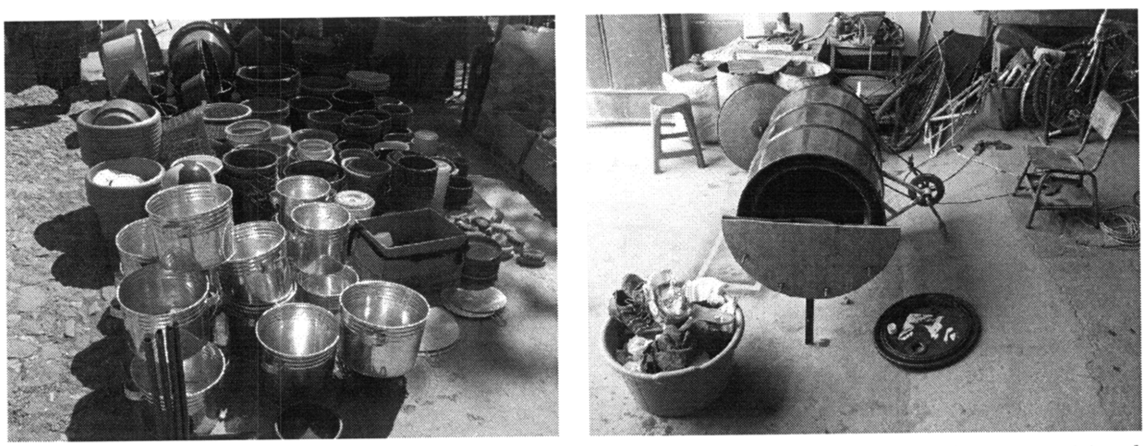


Figure 5-1: Wooden drum prototype



(a) selection of utility baskets at a local market

(b) design built at Maya Pedal using a 34 gal plastic barrel

Figure 5-2: Designing with locally available plastic drums

corrosion and the changes in shape the drum would encounter under load, and also as it wets and dries proved to be a difficult issue.

Plastic materials are another natural choice, but they are also hard to work with on site. One prototype constructed in Maya Pedal's shop used a standard 34 gallon plastic drum, which was purchased at a regional market. The price of the drum was relatively high, but within the project budget. The local supply of suitably sized drums is however very limited, and even sourcing the particular drum used in that prototype took much longer than expected, requiring visits to a number of markets in different towns.

If a drum of the proper size and the required stiffness can be located, it requires additional modifications to serve as a washing machine drum. Attaching fins, creating an access panel and mounting the drum to shaft to allow it to be driven are challenging because of the lack of suitable fastening mechanisms. The proper adhesives are usually not available locally. Heat or ultrasonic welding equipment are too expensive and limited in use for a small rural shop. Mechanical fasteners, even if they are rust resistant, generally protrude at both ends, and are therefore not appropriate to use with clothing.

Plastics are extremely attractive for this application, but are hard to work with locally. A plastic inner drum could be designed that would be very easy and extremely cheap to produce in large volumes. A number of polymer plastics are suitable for the application - see Harper [4].

The material ultimately chosen for the design was ABS (Acrylonitrile Butadiene Styrene), because of its adequate mechanical properties, wide availability and design versatility. As a thermoplastic, ABS and can be vacuum formed, rotationally molded, or extruded into the desired shape.

Since it is a blend of polymers, the mechanical properties of ABS vary slightly depending on the exact formulation used. For most generic ABS products, the maximum recommended operational temperature is around 60C.

As is the case with most polymers, the strength of ABS varies significantly with temperature. The yield stress at room temperature is generally between 35-40MPa, generally dropping by 1MPa for each 4C increase in temperature, down to the 25-30MPa range at 66C for standard ABS blends. High temperature resistant formulations generally show higher strength throughout the temperature rage, and can operate at temperatures approaching 80C. Detailed graphs of the influence of temperature on the stress-strain curves of a variety of ABS brands can be found in McKeen [5].

A general purpose ABS product was used in the construction of the prototype, and the analysis of the weight bearing characteristics is shown in Appendix A. The ability to operate using warm water is critical to the design, and even the lowest cost ABS blends meet the 20MPa yield stress requirement even at a relatively high 66C. Ideally the drum would be able to withstand any water temperatures up the 100C boiling point, but realistically we do not expect water warmer than 50C to be used in the field.

The limit to hot water temperatures which are compatible with the inner drum should be made exceedingly clear to the local manufacturer, as well as the final user.

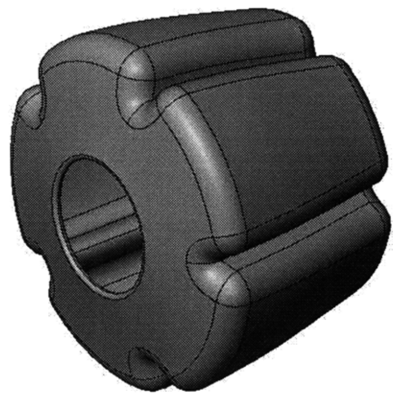


Figure 5-3: CAD model of the one-piece drum design

5.3 Geometry

Choosing a suitable material satisfies one of the design requirements. Selecting the proper geometry and construction for the drum proved to be an engaging engineering challenge all of its own. The presented evolution of drum geometries should give insight into the process used, as well as providing some justification for the final design selected.

5.3.1 One-piece Drum Design

As previously mentioned, the original Bicilavadora project aimed to devise a way of constructing the inner drum locally, by adapting existing plastic drums. This approach proved intractable because of the limited selections of drums available and the lack of local capacity to modify the shape as required.

The next logical step to consider was the possibility of manufacturing a drum with the required shape and strength. A single piece drum incorporating all the features needed, including the ribs and access panel is simple to manufacture through rotational molding. The process is relatively simple, and the mold and equipment costs are moderate. At this stage of the design process, a cantilever mounted, open ended inner drum design was favored because of it simplicity by not requiring a door, and user friendliness. Such a design is shown in Figure 5-3.

A single piece drum of the required capacity would be too large to ship alone in a cost effective manner. Two approaches for disseminating the drum were considered to mitigate this expense. One of the option was designing the drum to be independently useful as a replacement for existing utility drums or for another function such as a water storage. The hope was to reduce the final cost by making the design ubiquitous.

The transportation costs are likely to remain high irrespective of the other uses for the drum, because the design cannot stack for shipping. At the same time, it became obvious that the stiffness requirement of the drum would result in a heavier and more expensive drum than would be desirable for other household purposes, which are traditionally very thin and inexpensive blow-molded or vacuum formed designs.

The second approach considered the possibility of using the drum to transport goods already being shipped to rural markets. In the most obvious example, the drum would be packed with the components necessary to construct the rest of the machine, and the excess space in the drum could be used to transport detergent. This *washer kit* could be disseminated by the same people who transport and sell powder detergent to every local market in Guatemala. Filling the drum with detergent in order to reduce the volume wasted would result in a very heavy drum - 2 cu.ft. of powder detergent weigh in excess of 300 lbs. Filling the drum only partway may help offset part of the shipping cost, but the distributors are likely to still charge a premium for transportation due to the large size.

For a single piece drum design, functional size requirements and low distribution cost requirement are remain in direct conflict. This concept never developed into a prototype, and remains at the CAD model phase.

5.3.2 Segmented Drum Design

The drum must have a large enough volume to meet the functional specifications. At the same, in order to achieve the requirement for low cost distribution, it must occupy a significantly smaller volume during shipping. The challenge is to devise a method that will allow drum must be able to change size and shape between transportation and operation.

To achieve this, the drum shape was split into a series of segments that can be assembled on-site. The segments are designed to nest while shipping, making the size of the package acceptable for transporting to remote areas through existing distribution channels. The individual panels feature overlapping external flanges, which would be used to join the panels during assembly. Such an assembly is shown in Figure 5-4.

Because a front loading drum was still considered optimal at this stage, the stiffness of the assembled drum was critical. The presence of the central rib and the flanges along the side of the molded panels creates a large cross-sectional profile. The resulting panels are therefore able to support large loading moments required to hold

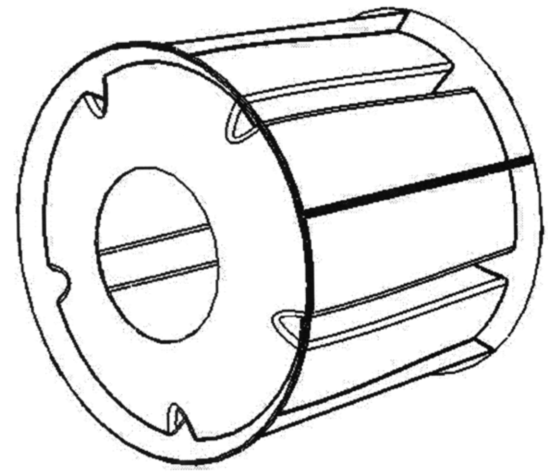
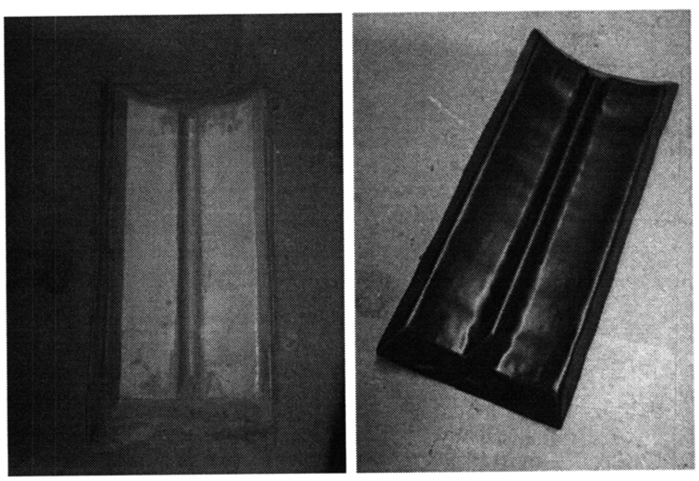


Figure 5-4: CAD model for segmented side-loading drum



(a) fiberglass mold (b) resulting panel

Figure 5-5: Prototype side panel produced through vacuum forming

the weight of wet clothing during operation.

Aside from the static loading, a cantilevered drum spinning along its axis would also encounter high vibration loads as a result of any eccentricity that would be experienced when the clothing inside is unbalanced. The resulting loads on the joint interface between the panels would be significant.

The construction of a prototype based on the model shown in Figure 5-4 was attempted, by vacuum-forming sections containing one rib each. Figure 5-5 shows the mold used and resulting panel shape.

The failure mode for a drum constructed in this manner would likely occur through the shearing of the joint between the individual panels. Both axial torquing of individual panels, as would be experienced when the rib is side loaded by entrained

Figure 5-6: Side-loaded, multi-part, structural drum prototype

clothing, and outward pressures exerted on the inner drum by clothing during the spinning operations, result in high shearing loads along the mating flanges.

A number of options were considered for joining the panels into a complete drum, including gluing, ultrasonic or heat welding, an mechanical fasteners such as rivets. Welding could yield a joint that is strong enough, but the high cost of the equipment needed makes it inappropriate for local assembly. Mechanical fasteners would have to be rust resistant and strong, easy to use and inexpensive, a combination that was not found in any locally available fasteners. They would also need to engage a large surface area on the flange in order to keep them from ripping through the ABS sheet when loaded.

The loads that the drum is subjected to can be significantly lowered by supporting both ends of the drum instead of using the cantilevered design. Such a prototype was constructed from the same vacuum formed panels. As the ends of the drum are now closed, the design was adapted for side loading, by hinging one of the panels along one side flange and using a latching mechanism on the other side. This transforms one quarter of the drum into an access hatch (see Figure 5-6).

Despite the reduced loading requirements on the drum, an adequate solution for attaching the panels together was still not available. The addition of a swinging door adds complexity, and further increases the number of failure modes. Despite meeting both the functional capacity and the low volume transportation requirements, a lack of simple and durable method of performing the local assembly and the associated durability concerns stemming from that limitation required another design iteration to be performed.

5.3.3 Steel Frame and Lining Panels

While a single-piece drum of the necessary strength can be designed for plastic manufacturing, its dimensions would be unsuitable for transportation. The segmented drum approach delivered a design that could be transported in a small volume, it was not able to meet the durability and local assembly requirements. Each component can be made to individually be strong enough to withstand the loading it would encounter, yet no method was found for assembling these components in the field that would produce a sufficiently strong assembly.

ABS resin was chosen for constructing the inner drum because of its ability to resist abrasion and wet environments. Structural components of adequate strength can be constructed using this material. But the lack of sufficiently strong methods for joining ABS components in the field is problematic, given our need to assemble a majority of the structure on site from smaller, easy to ship components. Polymer resin materials are clearly not an ideal material when local assembly is needed, but they are the only materials able to resist the harsh environment of the washer while being affordable enough for our application.

The difficulty of the challenge stems from the multitude of design requirements for the drum component, which in turn derive from the fact that the drum serves a multitude of functional roles in a horizontal washer. The problem can be simplified breaking down these requirements, and allowing them to be fulfilled separately. Two design requirements are especially limiting from a material selection perspective, especially in light of the decision to rely on local assembly: the structural stiffness or strength requirement, and the abrasion resistance and associated clothing interfacing requirements.

A two-part construction, in which the structural support role is provided an external frame, while another inner part interfaces with the clothing, decouples the conflicting material selection constraints. As noted in Section 5.2, an adequately strong structure can easily be constructed from steel, which is inexpensive, easy to work with, and commonly available. Once it is relieved of the abrasion resistance requirement, steel becomes an adequate material for the application, being able to operate in the wet environment when protected by an adequate paint coat.

An all-steel drum construction lined with an abrasion resistant plastic liner is one possible design option. It is not an optimal solution for local assembly, as facilities

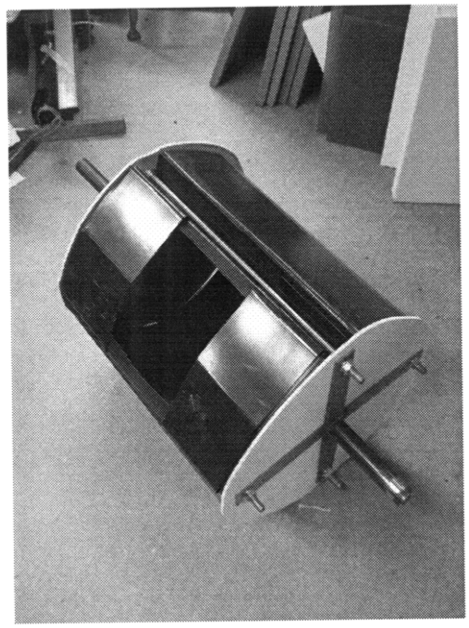


Figure 5-7: Final inner drum design - steel member frame and inner ABS panels

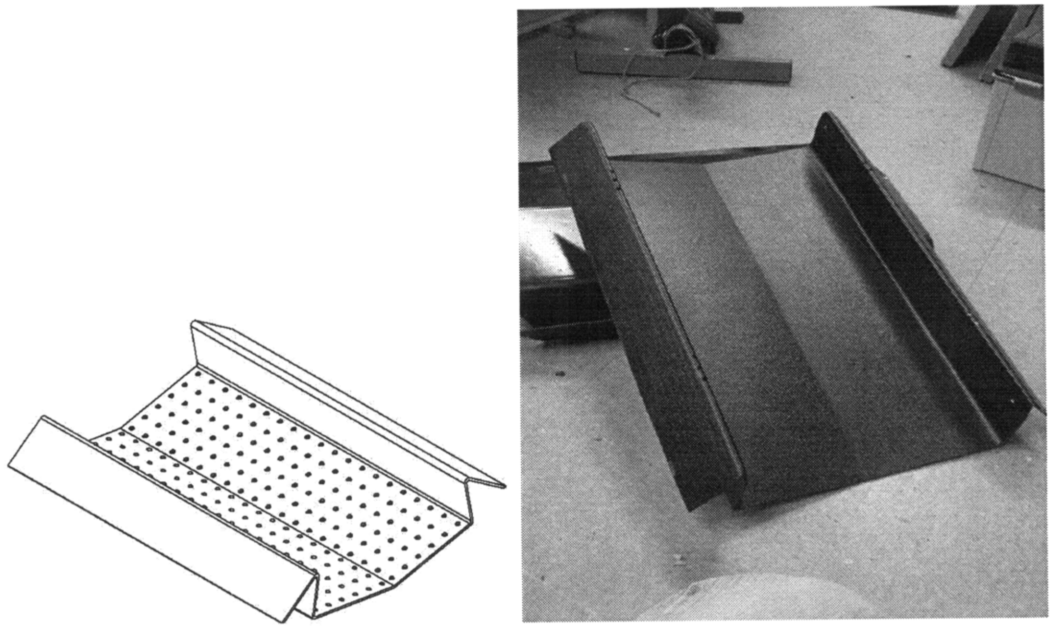
for rolling and bending metal sheet are rarely available in small rural metal shops.

A better design can be achieved by adapting the segmented drum concept to rely on a simple, locally assembled frame for its rigidity, which eliminates the need for strong joints between the plastic components. The final drum design, shown in Figure 5-7, utilizes this approach.

ABS resin panels serve to contain the clothing, and have adequate strength to resist the highest pressures exerted during the spinning process by the clothing. The particular geometry of the panels, shown in Figure 5-8, has a number of advantages. Because the highest loads encountered during operation are radial and outward, the panel is designed to carry this principal load direction in tension, but transfer it onto the frame in compression, which eliminates the need for high-strength fastening methods. The ability to withstand the loads normally encountered during washing was verified by non-destructive empirical testing on the prototype, as well as a finite element analysis simulation in accordance with the expected loads. The details of the numerical design analysis can be found in Appendix A.

The design is elegant and extremely simple, with the key feature being a set of fins which run the length of the panel to either end. These fins serve as agitators during operation, doubling in function as a means to engage and positively locate the panels onto the steel frame.

Compared to steel, the use of ABS allows for the design of a lighter and less expensive load-bearing drum wall. Their simple geometry means that the ABS panels



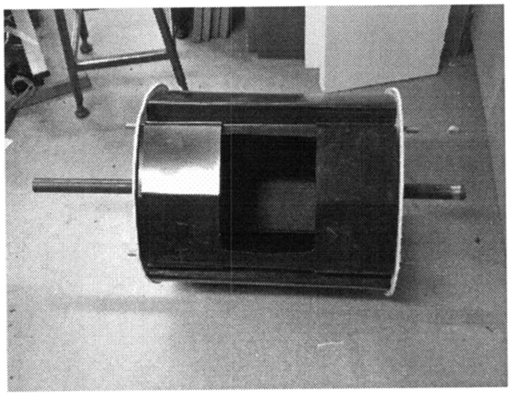
(a) CAD model (b) prototype panel

Figure 5-8: ABS side panel geometry

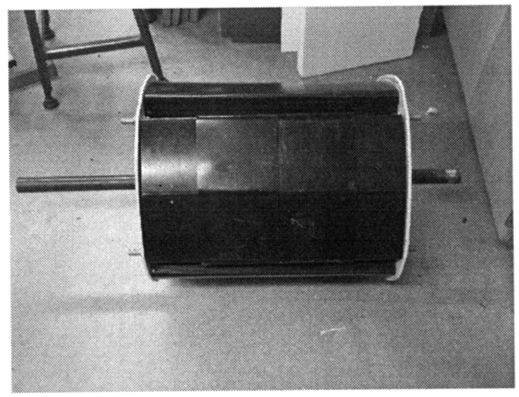
can be manufactured cheaply. While the original prototype used panels obtained through vacuum forming, the simple constant profile allows it to be manufactured by profile extrusion, a continuous low-cost production process.

A number of design options are available for providing access to the inside of the drum. The final design chosen does not require any fasteners or hinges, simplifying local assembly and reducing the number of parts that can fail. The access door assembly is shown in Figure 5-9. It is constructed by cutting out a section in the center of one of the side panels. A rounded shape helps reduce corner stresses. The hole is covered on the outside by two parts that attach to the metal frame, which slide along the length of the drum for opening and closing. The parts which construct the door have the same profile as the side panels, and can be easily produced, or replaced, by shortening a side panel piece.

The ends of the drum must also be closed in order to prevent clothing from escaping the inner drum. This can be accomplished by using another ABS panel. This part only needs to function as a barrier to prevent the clothing from falling out and will not experience any significant loading. It can be manufactured simply by cutting the appropriate profile from a sheet of thinner ABS. The piece is held in place between the frame and the side walls. The side door and end cap parts used in the final prototype are shown in Figure 5-10.

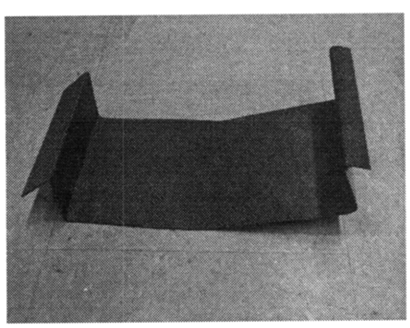


(a) open

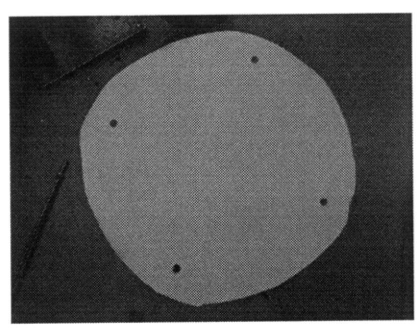


(b) closed

Figure 5-9: Side door assembly



(a) door cover



(b) end cap

Figure 5-10: Door and end cap parts - two of each are used in the final design

By leveraging the design flexibility of these mass-produced ABS panels, the design of the frame can be simplified for low cost local manufacturing. A welded structure comprised of flat stock and re-bar members can be easily assembled on site, requiring only metal cutting and welding capabilities. This construction results in a drum that is stiff, making best use of the load bearing capacity of the individual members. Two short pieces of shaft can be easily attached to the ends of the frame along its axis, which allows the drum to rotate when mounted on bearings.

The final design and geometry of the drum is in accordance with the design approach presented in Chapter 4, and the specific requirements outlined in Section 5.1.

Chapter 6

The Final Design

This chapter will present the final design of the washer, with a focus on manufacturing and assembly. Little emphasis will be placed on providing justifications for the design decisions, as the design of the washer as a whole derives quite directly from the configuration of the inner drum, the evolution of which was presented in the previous chapter.

The washer meets the design goals outlined in Table 1.1. The large capacity reduces the time and effort required to clean clothing. The design is appropriate for remote rural areas, being affordable, robust and operational without the need for household electricity and water services. The unit can be assembled and maintained in the field using locally available materials and simple construction techniques.

The design can be disseminated widely and reach remote areas in a sustainable and cost effective manner. This is accomplished by reducing to a minimum the number and size of specially designed components, enabling them to be packaged as a kit which can be easily transported by leveraging already existing product distribution channels.

The total weight of the shipped components is 7 lbs, while the total volume of the kit is less than 1 cu.ft. A critical *design for dissemination* feature is the design of the kit which allows a 20 lbs powder detergent bag to be nested in the package. In this configuration, the marginal volume to be transported is only 300-400 cu.in., with a weight increase of only 35%.

The main functional part of the machine is the the inner drum, comprised of a field-manufactured welded steel frame and a set of ABS resin panels distributed in the kit. Assembling the drum on site allows for a large washing capacity machine to be disseminated without the necessity of transporting a large drum. The particular geometry of the ABS panels allows for a simple frame design, eliminating the need

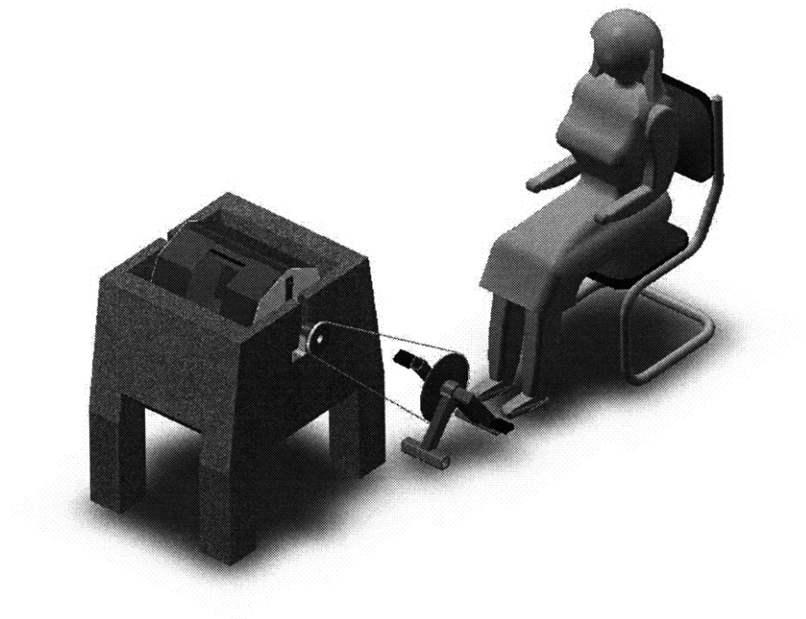


Figure 6-1: Final Design of Washer

for any steel bending or rolling operations to be done on site. Any metal shop that has metal drilling and welding capabilities will be able to construct the washer with minimal difficulty.

Figure 6-1 shows the final design as would be installed at a communal wash station in Guatemala. It features a cast concrete wash basin and a bicycle drive train. A roof-mounted solar hot water system could provide a gravity-fed hot water supply for the washer. The warm water dramatically improves the quality of the wash and reduces wash times, a gravity-fed water supply line makes filling the washer with water significantly easier in areas lacking a pressurized water supply.

While no installation was done in the field prior to the completion of this thesis, a works-like prototype was constructed on the MIT campus. The prototype, shown in Figure 6-2 shares the inner drum components, but rather than employing the concrete basin, it utilizes a simple wooden frame and a bent ABS sheet as a drum. This allows the prototype to be easily transported for demonstration purposes, and store compactly while not in use.

6.1 Distributed Components

As described in Chapter 5, it was determined that the optimal design of the inner drum would utilize specially designed ABS panels. The complete inner drum assembly

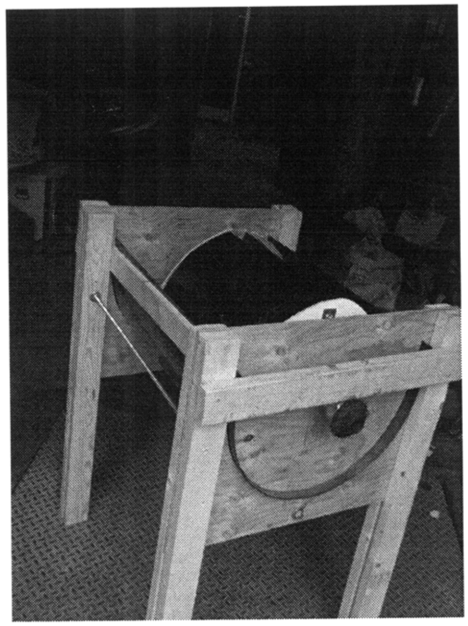


Figure 6-2: Final Prototype

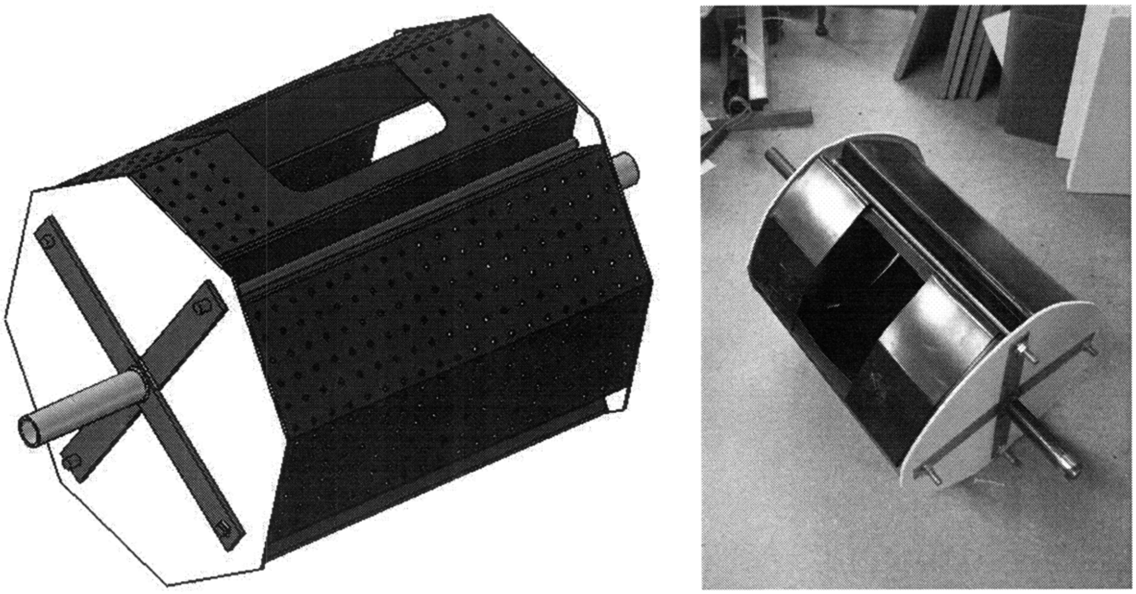
is shown in Figure 6-3.

Due to the fact that ABS resin and the required manufacturing equipment are not available in the areas targeted for dissemination, these panels need to be centrally produced and shipped to the final location. The stack-able panel design reduces transportation costs, and allows for the whole kit to be transported alongside powder detergent bags.

The process of sourcing the required materials for local assembly can be greatly simplified by including some components that may be hard to find locally, namely a set of bearings and matching shaft. Unlike the panels, these are off-the-shelf parts, and thus can be sourced at any point in the distribution process. For example, a central facility in Guatemala City that manufactured the ABS panels might ship them to distribution centers throughout the country, where they could be bundled with the rest of the off-the-shelf components and sold to distributors as complete kits.

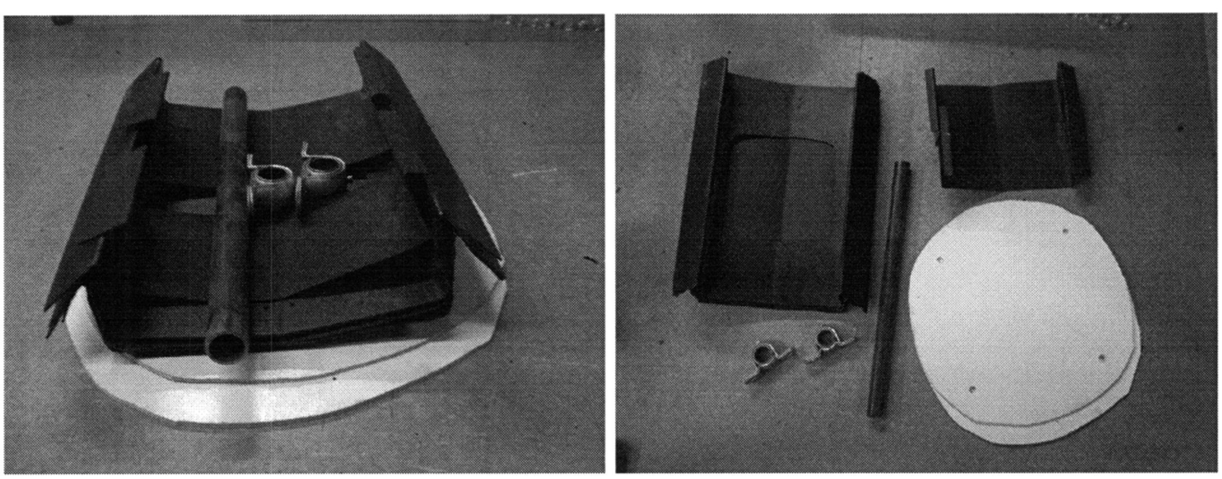
A complete kit consists of the following items:

- four constant-profile ABS side panels, one of which is modified with a door.
- two flat ABS end cap sheets.
- one 12" length of thick-walled tubing to serve as a rotation shaft.
- two pillow block bearings matched in size with the shaft.



(a) CAD model (b) Prototype drum

Figure 6-3: Inner Drum Assembly



(a) Packed kit (b) Kit contents

Figure 6-4: Kit Package

The kit package is shown in Figure 6-4. These components should allow a skilled metalworker to construct the machine in a modestly equipped workshop without any specialized equipment. Only commonly found construction materials need to be sourced locally.

6.1.1 Inner Drum Panels

Construction of the inner drum requires six ABS components of two types: four side panels and two end caps. The side panels have a custom geometry and are load bearing. The drum ends simply serve to prevent the clothing from falling out, and should encounter much smaller loads during operation.

The side panels are designed to hold the clothing and distribute the load onto the steel frame. The ABS resin material was chosen for its impact and abrasion resistance and chemically inert nature, and should provide long lasting service. HDPE or other similar plastics could be substituted, as long as the thickness is adapted to ensure the strength requirements are met.

The particular geometry of side the panels is a function of the different needs identified in Chapters 4 and 5:

- supporting the clothes during the washing process - the shape of the panels ensures that the loads encountered during the wash and spin-dry operations are effectively transferred to the load-bearing steel frame

- simplifying the design and manufacturing of the machine - the panels fulfill a majority of the functional requirements for the inner drum assembly, meaning the only component to be manufactured on-site is a simple four-member load-bearing frame. Due to the particular shape and the flexible nature of the ABS material, the tolerance requirements for the locally manufactured parts is on the order of 1in.

- inexpensive to produce - the simple shape of the side panels means they can be easily stamped from sheets or manufactured as a profile extrusion in large volumes. The end caps are also simply cut to shape from pre-rolled ABS sheet.

- small volume for shipping - the panels nest for shipping and are shaped to ship alongside powdered detergent bags

The shape and dimensions for the side panels are shown in in Figure 6-5. The shape of the panels need not precisely match that of the frame, as the ABS resin is

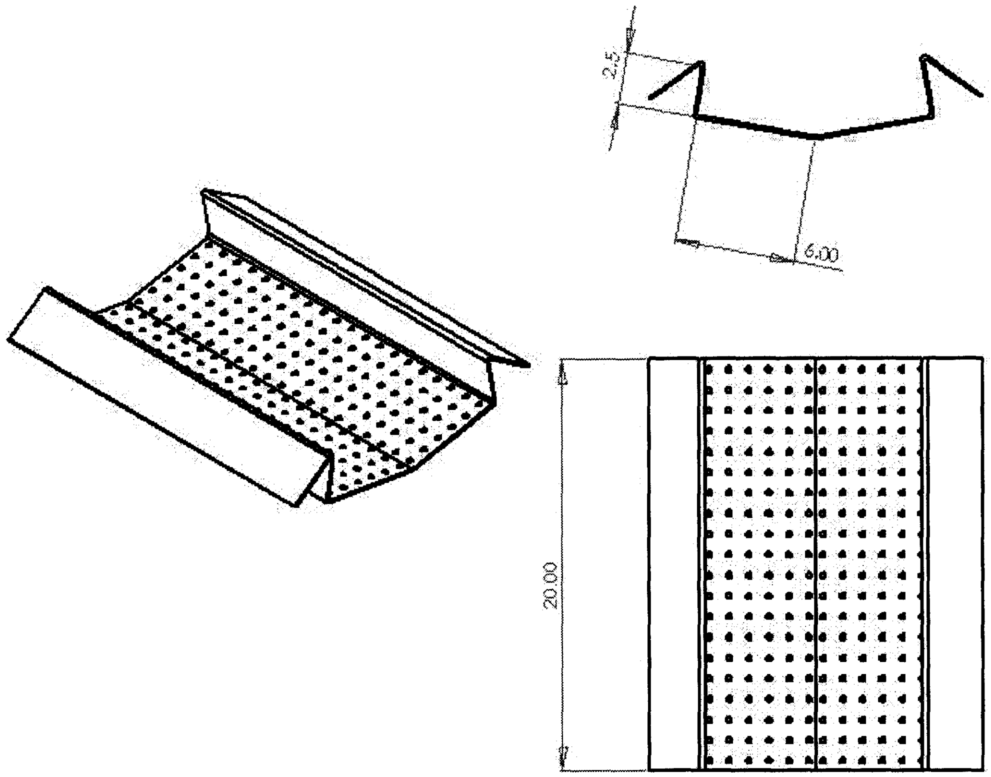


Figure 6-5: Side panel geometry

strong and flexible, and the panels can deform elastically to a significant extent. Some amount of pre-tension is desirable, as it keeps the panels in place during assembly. For this purpose the profile should be under-bent by 20-25 degrees along their central axis relative to their final shape when mounted on the drum.

The panels need to have perforations in order to drain the water from the clothing at the end of the wash cycle. A 3/16" hole pattern, with a rough spacing of 2 in between holes, is sufficient to perform this function, meaning that each panel should have 100 perforations. Drilling these holes during the central manufacturing would add an extra step to the manufacturing process, and likely result in a significant production cost increase. Instead, they can be performed on site during assembly, which should not add significantly to assembly cost and time.

The end caps are easily manufactured from ABS sheet, cut to be slightly larger than the profile of the assembled drum. During the drum assembly process, holes will be drilled based on exact dimensions of the frame. The end caps are held in place by threading the horizontal support beams through these holes. The shape and dimensions of the end caps are shown in Figure 6-6.

In order to ensure that the ABS panels do not fall come loose from the metal frame,

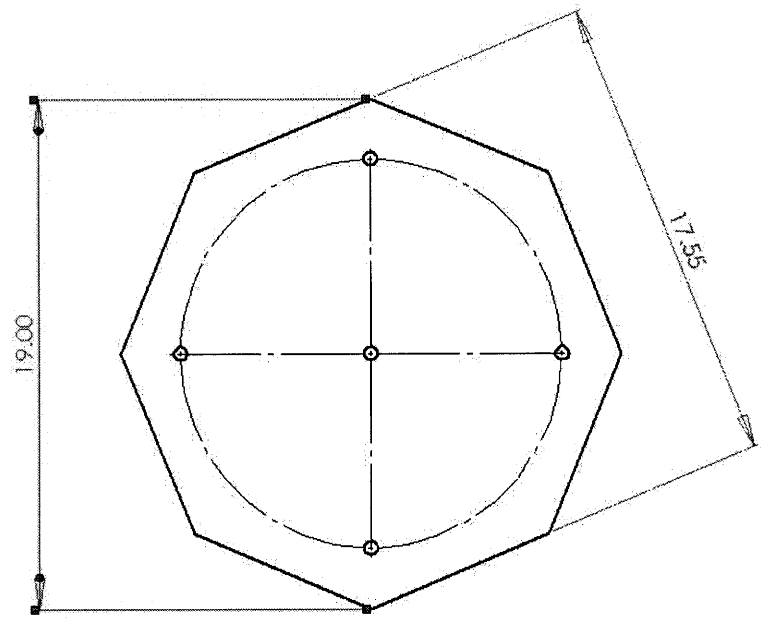


Figure 6-6: End cap geometry

they should be glued or fastened to each other during local assembly. For target areas where no appropriate fastening solution can be locally sourced, non-metal fasteners or an appropriate adhesive (such as ABS cement) should be distributed along with the panels.

6.1.2 Bearings and Drive Shaft

In order to simplify local construction, matched bearings and shaft sections are also distributed in the kit. Oil-impregnated bronze sleeve bearings are inexpensive, strong and require little maintenance, and as such are an ideal choice for this application. A pillow block unit is easy to mount, and can be found in self-aligning packages which significantly simplify construction.

Two short sections of precision diameter, thick-walled steel tubing can serve aptly as a shaft for the drum. A one foot section is included in the package, and it can be cut in two lengths for assembly as required. A length of nylon tubing, matched in size with the shaft, serves as a spacer between the frame and the bearings, preventing lateral motion of the shaft. This design eliminates the need for precision machining operation. The nylon tubing also serves to protect the shaft during transportation. Figure 6-7 shows the bearing and shaft assembly used on the prototype.

The diameter of the shaft and bearings can be changed as long as the shaft is strong enough to support the load. The prototype uses 1 3/8" diameter, 0.12" wall

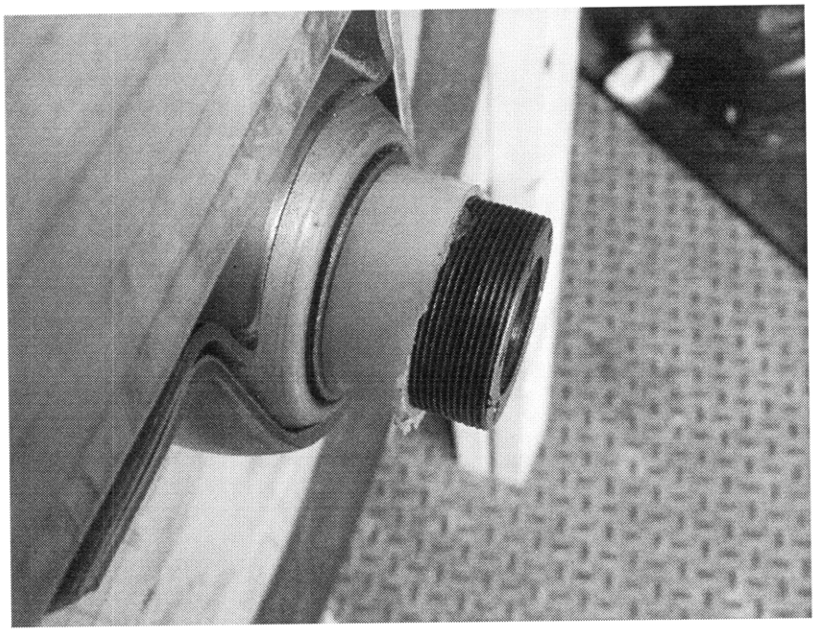


Figure 6-7: Bearing and shaft assembly

thickness 4130 steel tubing as a shaft, which provided ample strength and was easy to weld. The 1 3/8" dimension neatly matches with the diameter of a freewheel thread mount, which makes the assembly of a pedal power drive significantly easier. Further discussion of drive options is presented in Section 6.2.3.

6.2 Local Machine Assembly

This section will present a suggested method for assembling a complete machine. While alternative methods are suggested for some steps of the assembly, the author expects that local builders will adapt and improve the design significantly. The goal is to provide a reference assembly method that will be achievable throughout the rural areas of Guatemala. Specifically, the reference washer design requires the following manufacturing capabilities on site:

- metal drilling - the ability to drill 1/2" holes in mild steel bars;
- metal cutting - the ability to cut 1/2" construction steel bar and flat stock, easily accomplished with a hacksaw or angle grinder;
- mild steel welding - arc electrode (stick) or oxyacetylene welding equipment.

The following materials are also necessary to assemble a complete unit:

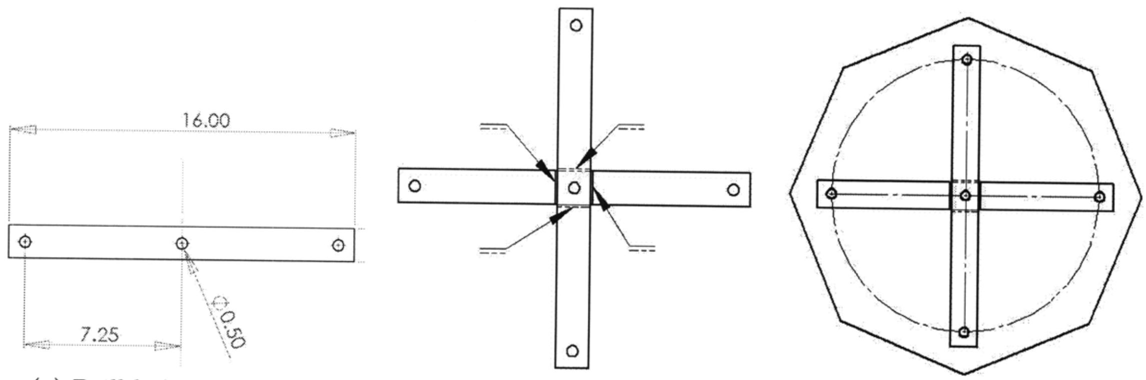
- 5 ft of 1.5"x1/8" mild steel bar, cut into four 15in lengths;
- 7 ft of #4 (1/2" diameter) construction re-bar, cut into four 21in sections;
- four 5" or longer pieces of threaded rod, or long machine screws, for mounting pillow block bearings;
- concrete mix - for the recommended design, a concrete basin must be poured at the final installation site;
- 6" or longer length of PVC tubing, and a matching faucet or valve to be used as a drain.

Additional components are required based on the choose for drive-train. The referenced pedal power drive, which only requires standard bicycle components, is described in Section 6.2.3.

6.2.1 Frame Construction

The frame forms the load bearing element of the inner drum. The construction steps, also illustrated in Figures 6-8 and 6-9, are as follows:

1. Holes are drilled in the steel bar the appropriate locations.
2. Each pair of flat stock bars is welded perpendicularly. The center holes can be used for alignment.
3. Matching holes are drilled into the end cap sheets.
4. Two sections of shaft are cut at the required lengths, and are aligned and welded to the flat stock assemblies.
5. Re-bar is cut 2" longer than the length of the ABS side panels, and threaded through the end caps and the flat stock assemblies. The whole assembly is aligned and the re-bar members are welded to the flat stock. Using another piece of re-bar through the middle of the assembly helps maintain the axis aligned. If this step is done with the assembly mounted on the bearings, rotating the frame will allow for visual inspection of the alignment. Adjustments can be made by bending individual members. After welding, the steel parts should be thoroughly cleaned and painted with a waterproof, rust protecting paint.
6. Side panels are snapped on.

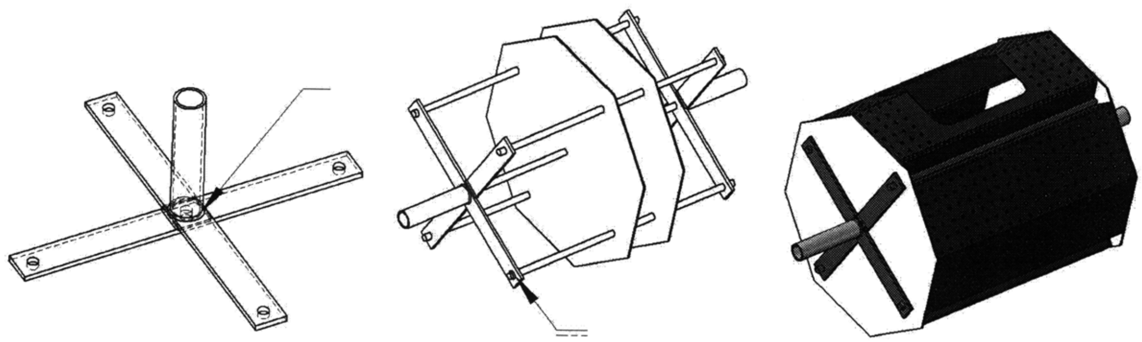


(a) Drill holes in steel bars

(b) Weld bars in perpendicular orientation

(c) Drill matching holes into end caps

Figure 6-8: Frame assembly steps 1-3



(a) Weld shaft sections

(b) Align and weld re-bar members

(c) Snap on side panels

Figure 6-9: Frame assembly steps 4-6

The prototype unit uses threaded rod instead of re-bar, which allows for rapid assembly, dissasebly and adjustment. This solution could be used in the field as well.

Once the frame is constructed, with the end caps captive, the side panels can be snapped onto the frame. The overlapping sections of the side panels are joined using mechanical fasteners, ABS cement, or another adhesive, to prevent them from becoming separated and falling away from the frame. The sliding access door should be in place before any permanent fastening is done.

6.2.2 Outer Drum or Basin

The requirements for the outer drum are minimal: it must hold water, be larger than the inner drum, and allow access to the inner drum. As such, there are a large number of design options from which the local builder can choose.

An outer drum that is closely matched in size with the inner drum will result in increased water economy. A simple construction can use a shortened 55 gallon drum, since the inner drum is sized to properly inside a standard 22" diameter barrel.

The preferred option for a permanent installation is a cast concrete basin. Aside from deterring theft, the concrete structure also serves as a structural frame for the machine, and virtually eliminates vibration issues experienced by a lighter machine. The form for the concrete basin should be simple to construct on site, and a section of a 55gal drum can be used to shape the basin to the correct dimensions. Threaded rod members embedded in the cast structure can be used as mounts for the pillow block bearings. A length of PVC pipe connecting the the bottom of the basin cavity serves as a drain once the basin is completed.

The sample design for the basin shown in Figure 6-10 has a concrete volume of 8.7 cu.ft, and if constructed using the standard 1:2:3:1/2 concrete formulation, would require twelve 100lbs bags of cement to construct as shown. Incorporating mounts for the drain and bearing supports when casting the basin makes the final installation much easier.

6.2.3 Drive Mechanism

The recommended solution for powering the washer is a pedal powered drive train utilizing bicycle components. This solution is very appropriate in Guatemala, where bicycle components are locally available at affordable prices.

The adjustable cup from a traditional cup-and-cone bicycle bottom bracket is welded to one end of the shaft. This allows a standard bicycle freewheel to be threaded

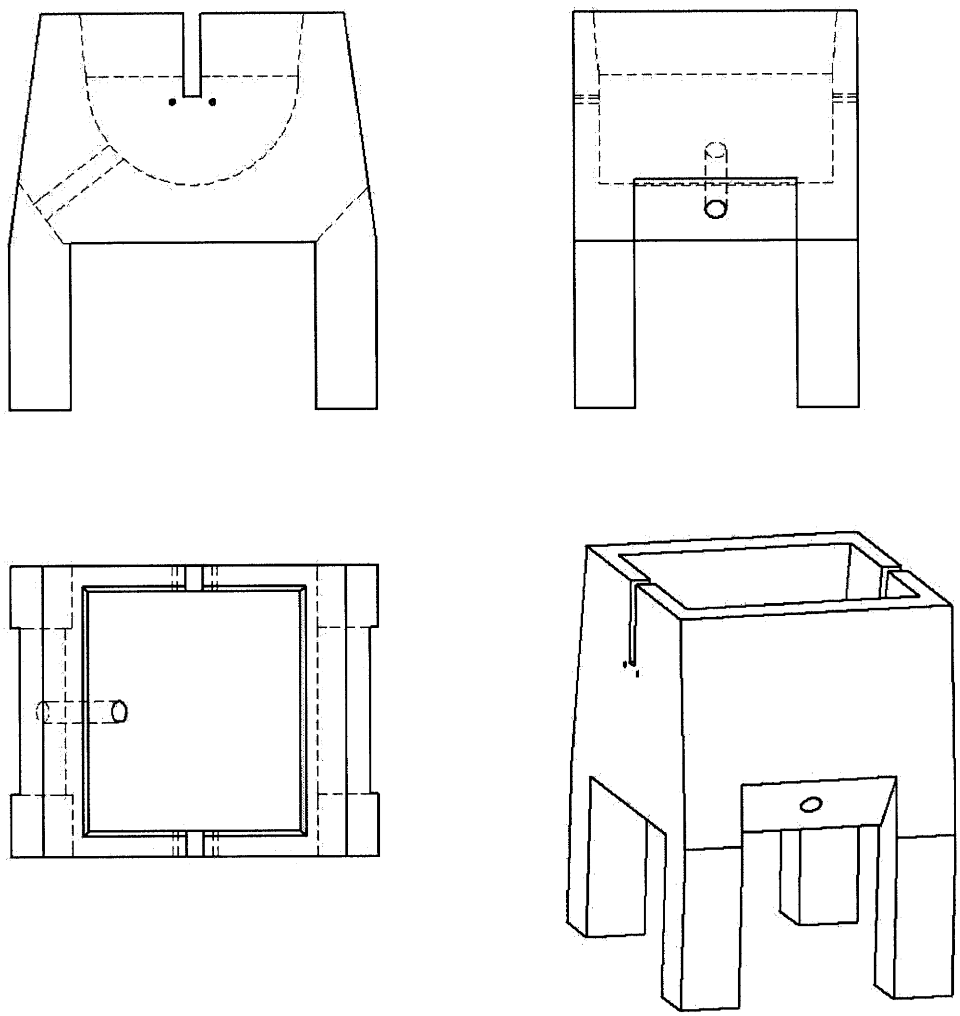


Figure 6-10: Sample design for concrete basin

on and drive the inner drum. A multi-speed freewheel cassette, when used in conjunction with a derailleur, allows for the gearing ratio to be varied between a 1:1 ratio optimal during the wash cycle, and a higher gear ratio which is desirable for spin drying.

An alternate design for areas where bicycle components are not readily available could make use of a custom pedal assembly, with belts and pulleys used for power transmission. Although it would be less mechanically efficient than a bicycle chain drive, a belt driven system can be designed to allow higher gearing ratio, which would improve the spin drying capacity of the unit.

Other options for powering the machine are certainly possible: using a simple hand crank welded to the drive shaft would still result in a machine that is more comfortable than washing each item of laundry by hand. However, if hand power is all that is available, a simpler washer design might be more appropriate.

At the other extreme of complexity and cost is a small electric motor, which could be powered by the grid where it is available and affordable, or by a bank of batteries charged by a wind turbine or solar array. While the cost of such a system ($250 for a 1/4hp electric motor and $400 for a 60W solar array, battery, charge controller and inverter) might seem prohibitive, 10 families might decide that paying $75 each is an acceptable cost if they can be freed from the drudgery of hand washing laundry.

6.3 Operation

The operation cycle of the machine is simple, and entirely controlled by the user. The guideline below was found to do a good job at washing a medium of mildly soiled clothing, but the times should be adjusted for the amount of clothing to be washed and the soiling level.

If using a drive-train that provides adjustable gearing, two separate settings should be available and easy to change between:

Wash mode: in wash mode, the drum should rotate at a speed of roughly 60rpm, resulting in a vigorous tumbling action. For a pedal powered drive train, this is comfortably obtained at a 1:1 gear ratio. This mode requires 60-100W of power, depending on the amount of clothing.

Spin mode: spin drying the clothing requires high speed, the higher the better. While structural integrity should be considered, most low-cost gearing solutions will not allow the user to induce speeds that are high enough to damage the washer. For the purpose of a human powered unit, the highest available gearing ratio should be used.

The suggested operation cycle for the machine is as follows:

1. Optional - dirty laundry should be soaked in warm water with detergent for 30 minutes or more. A quick tumble at the end of the soaking period will dislodge any dirt that has come loose. The dirty water should be drained at this point.

2. For the wash cycle, the drum should be filled 1/3 of the way with warm water and detergent should be added. The water from a previous load's rinse cycle can be reused for this purpose.

3. The main wash cycle requires 10-20 minutes of tumbling, depending on the quantity of clothing and soiling level. Tumbling direction should be alternated every 2-3 minutes to prevent tangling. A bicycle drive-train containing a free-wheel does not allow driving in reverse, and in this case the drum should be allowed to come to rest every 1-2 minutes before resuming pedaling.

4. The dirty water should be drained. This water is generally too dirty to be reused. If a biodegradable detergent is used, the water can be safely used for watering crops.

5. A 3-5 minute high speed spin removes even more dirty water from the clothing

6. For the rinse cycle, the drum should be filled with clean water and no detergent should be added. Tumbling the clothing dislodges the soap and any remaining dirt from the clothing.

7. The rinse water should be drained out, and saved for the next wash.

8. The clothing should be spun at the highest speed available until no more water is extracted, generally 3-5 minutes.

9. Optional - if the rinse water was dirty and very soapy, an additional rinse and spin may be required

The typical wash time, including the time required to load the laundry, fill and drain the tank, ranges between 30 and 50 minutes, based on the the quantity of clothing and soil level, as well as the temperature of the water and effectiveness of the detergent used.

6.4 Maintenance

The washer should be maintained in the field in order to ensure long life and safe operation. The following operations should be performed periodically:

- The drive train, including the bearings and any other bicycle components, should be cleaned and lubricated with the appropriate products.
- The metal frame of the inner drum should be inspected for rust, and the paint coat refreshed if necessary. Note that accessing the steel frame this might be difficult if the side panels are permanently glued to each other. If this is the case, any opportunity to gain access, such as the need to replace one of the panels, should be used to investigate the need for repainting.
- The ABS panels should be inspected for cracks, rips, deep gouges, and warping due to extreme heat or solvents. If any damage is found, the panel should be replaced to avoid potentially hazardous failures that might occur during operation. If spinning is limited to low speeds, and the cost or availability of replacement panels makes replacement impossible, contained damage can be mended locally by backing the damaged section with a large enough piece of ABS, glued using ABS cement.

6.5 Installed Cost Estimate

This section aims to estimate the total costs of an installed machine for a user in the central area of Guatemala. The total cost is a combination of the local purchase cost of the kit, and the cost of locally sourced materials and labor.

The cost of the distributed components can be estimated fairly accurately. A 50% distribution charge is a worst-case scenario, assuming no partnerships can be made to defray these costs. Co-distribution and co-promotion efforts with a detergent manufacturer would hopefully reduce or even eliminate dissemination costs.

The ABS panels are the most expensive part of the kit. Assuming production in large enough quantities, the panel costs will be mainly determined by the cost of the resin itself. In sheet form, ABS retails for $1.25 per sq. ft. for 1/8" thickness sheet, while 1/16" sheet costs half as much, at 65¢ per sq.ft.

The four side panels are manufactured from an equivalent 2.5 sq.ft of 1/8" ABS sheet, which is valued at $3.10. While profile extrusion means no material losses, the custom profile manufacturing process could add a 25-30% cost premium when

Item	Unit	Unit cost	Qty	Total
ABS side panel	ea	$4	4	$16
ABS end panel	ea	$2	2	$4
Thick wall steel tubing (shaft)	ft	$8	1	$8
Nylon tubing	ft	$2	1	$2
			Total materials	$30
			Retail cost (including 50% S&H)	$45

Table 6.1: Total washer kit cost - unsubsidized

compared to flat sheets. Assuming no volume discounts can be achieved, the cost of a side panel can be estimated at $4.

The end caps are cut from 1/16" flat sheet, utilizing roughly a 19in diameter circular area. A standard 4ft x 8ft would thus fit 10 pieces in the worst case scenario, or 14 end caps properly nested. The cost is thus $1.5 per end cap when nesting is possible, or $2 for the straight cut scenario. This includes the material cut losses.

Thus in the worst case scenario, the cost of the ABS components would total approximately $20. The oil impregnated bronze bearings typically retail for $5 each, although they can likely be sourced at a lower cost in large volumes. Thick walled precision diameter steel tubing of the required dimensions retails at $8 per linear foot, and thin walled nylon tubing can be obtained for $2 per foot.

The worst case scenario would thus yield a $45 cost to the final user, including shipping and distribution costs. Even with the most unfavorable assumptions, we were able to meet the $75 purchase cost design requirement. A more optimistic scenario, in which the component price can be reduced by 15% through volume manufacturing and purchases, and where the distribution is subsidized through co-distribution, results in a cost of $25 for the kit, which is a third of the target cost.

Arguably, the bare-bones kit can hardly be deemed a "washing solution" without the substantial amount of manufacturing and assembly to be done on site. The cost of the locally sourced materials and labor are harder to estimate, and will likely vary from region to region. A quick estimate based on the material and operating costs for Maya Pedal, which operates in the Chimaltenango department of Guatemala, is shown in Table 6.2.

The final machine cost estimate of $133 meets the target design goal, and is affordable when the shared by 4 or more families.

Item	Unit	Unit cost	Qty	Total
Flat steel bar	ft	$1	5	$5
#4 (1/2 in dia) steel re-bar	ft	$0.25	7	$2
Concrete mix	100 lbs	$3	12	$36
Bicycle drive train components	ea.	$20	1	$20
Labor and workshop operating costs	day	$25	1	$25
		Total assembly cost		$88

Table 6.2: Local assembly costs in Chimaltenango, Guatemala

Chapter 7

Future Work and Conclusion

Although the completion of an appropriate design for a low-cost washer that can be disseminated widely marks the end of this thesis, the task of providing a solution that can help women in rural Guatemala with the task of washing clothing is far from being complete. The design presented in this thesis brings the ambitious goal of disseminating 1 million washers in Guatemala within reach, but the successful implementation of such a project remains an ambitious task.

While the similar Bicilavadora prototype has recieved good reviews from Maya Pedal[1], the particular design presented in this thesis has yet to be validated in the field. Therefore the next step for the project is an extensive field study, which will point to any necessary design changes from both the manufacturing and the end-user perspective.

Another important step in achieving the dissemination goal will be developing a set of manufacturing instructions to be included with the kit, that will be informative enough to allow a small metal shop to assemble a complete machine.

The WHIRLWIND WHEELCHAIRS organization started by Ralf Hotchkiss uses an open source production manual[2] to manufacture wheelchairs in developing countries. Their step-by-step instructions guide the reader through the manufacturing stages, successfully using engineering drawings and diagrams to eliminate the use of written instructions, making them universally applicable without requiring translation. The approach was also used to help disseminate a design for a bicycle ambulance in Zambia by Vechakul [10].

A similar illustration-based approach, used for both the production and the end-user washer manuals, will render them applicable throughout Guatemala without

[1] see Section 2.2

[2] available at `http://www.whirlwindwheelchair.org/open.htm`

translation into the native Mayan languages used troughout the country, which could be costly and time consuming. An univerally accessible manual makes dissemination to other countries easier down the road.

The reference design presented in this thesis, which is human powered and uses a bicycle component drive train, is an appropriate solution for much of rural Guatemala. Alternative designs for the drive system should be developed for areas where bicycle components are not available.

Because of the simplicity of the final design, the conversion of the machine to a fully-automated washer is feasible, requiring only the addition of an electric motor and associated drive, actuated valves, a pump for emptying the drum, and a simple a timing control system. Such a conversion would be much less expensive for the end user than purchasing an new commercial machine, and also allows for individual components to be serviced and replaced as needed. Note, however, that at the level of cost anticipated for a complete system using this approach, a different wash-drum design might be warranted, one that has a higher upfront cost but provides longer life without additional any maintenance.

This thesis project has achieved its goal of delivering a washer design that is appropriate, inexpensive, and easy to disseminate to rural areas of developing countries in general, and Guatemala in particular. The design process also provided valuable insights into the particular challenge of designing a product for large-scale dissemination, and the design approach used in this thesis can easily be applied for other product design projects with similar dissemination goals.

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Appendix A

Structural Analysis of Inner Drum Panels

A numerical analysis was perfomed for the stress distribution in the inner drum side panels, using the CosmosWorks Finite Element Analysis (FEA) package, in order to validate the suitability of the shape, size and material choice for the component. The ABS material property values built into CosmosWorks were used, and are shown in Table A.1.

The initial panel geometry is shown in Figure A-1. Note that this shape varies from the panel shape shown in the product description, as the manufactured panel is underbent to provide a level of pretension when mounted on the frame to aid during assembly. The bend angle in the manufatured panel is 8-10 degrees. When the panel is installed on the frame, the central bend angle extends to 45 degrees.

The highest loading scenario occurs when the drum contains the maximum weight of wet clothing - in our case, 45 lbs of wet cotton. Rotating at the maximum spin drying speed of 240 rpm, which for our drum size results in a 10g centripetal acceleration, the clothing will subject the drum walls to a force of 450 lbf. Assuming uniform weight distribution over the inner drum walls, the pressure loading is 0.36 psi on the

Property	Value
Elastic Modulus	290,075 lbs/in^2
Poissons Ratio	0.394
Shear Modulus	46,252 lbs/in^2
Density	0.037 lbs/in^3
Tensile Strength	4351lbs/in^2

Table A.1: ABS material properties used for FEA stress calculations

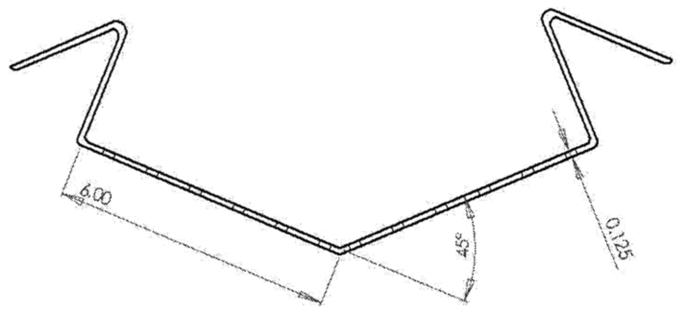

Figure A-1: Initial side panel geometry

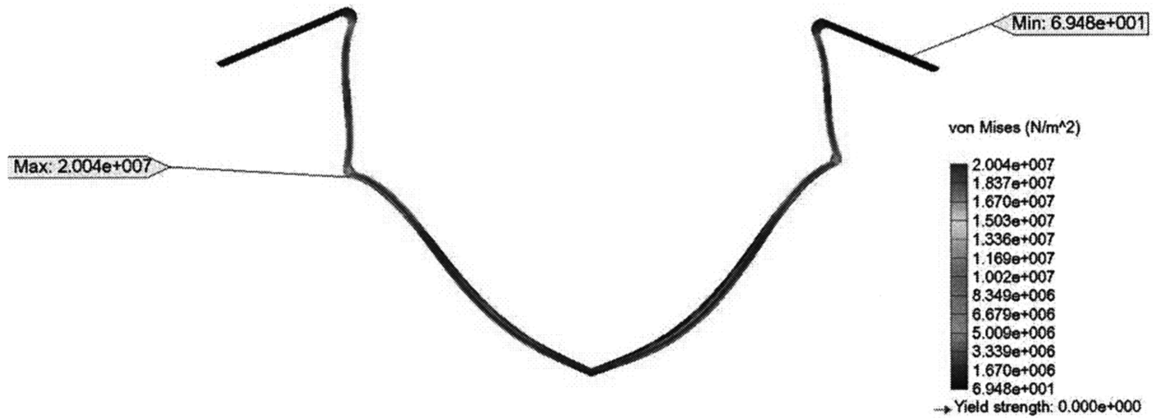

Figure A-2: FEA results for stress distribution for loaded side panel

inside of each panel.

In order to perform the simulation, the inner part of the rib of the panel, where it would meet with the frame, was fixed. The inner panel surfaces were loaded at 1 psi, for a safety factor of almost 3. The resulting stress distribution is shown in Figure A-2. Note that the deformation is exagerated by the CosmosWorks package by scaling the maximum deformation to a factor of 10% of the box of the part. The actual calculated displacement is shown in Figure A-3.

The maximum calculated von Mises stress loading at 3 times the nominal loading is 20 MPa, which is below the yield stress of generic ABS blends even at 70C [5]. The panels can therefore be trusted to safely carry the loads encountered during normal operation of the washer.

Because the maximum stress point occurs along the rib bend, the design of the part can be further improved by increasing the bend radius at this location.

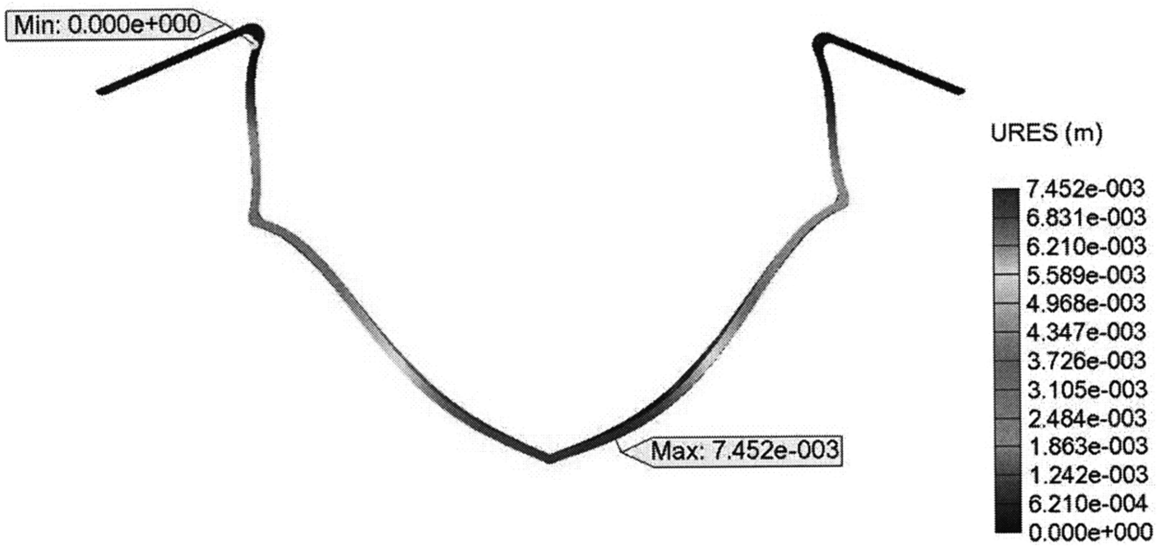

Figure A-3: FEA results for displacement for loaded side panel