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Considering Social Impact when Engineering for Global Development

Hans Jorgen Ottosson
Brigham Young University

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Hans Jörgen Ottosson

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Doctor of Philosophy

Christopher A. Mattson, Chair
Spencer P. Magleby
David T. Fullwood
John L. Salmon
Eric C. Dahlin

Department of Mechanical Engineering

Brigham Young University

ABSTRACT

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Hans Jörgen Ottosson
Department of Mechanical Engineering, BYU
Doctor of Philosophy

Every manufactured product has an environmental impact, a social impact, and an economic impact. As engineers, we should do our best to understand how our design decisions influence these impacts (the three pillars of sustainability), and at the same time make decisions that collectively lead to maximum positive impacts, or minimum negative impacts on the economy, environment, and society. Many times, engineers show interest and want to design for all three pillars of sustainability but are often constrained to focus on the environmental and economic aspects, leaving out social sustainability due to lack of understanding and resources.

In practice, this leaves the social dimension of sustainability out of sight and reach for many engineers. So to assist engineers to consider and improve the social impacts of their products, we have created two methods. The first method is focused on meeting customers' unmet needs through the use of collaborative products (a product created by temporarily combining physical components from two or more products to perform new tasks) and the second method is to be used throughout the product development process in order to increase the potential social impacts of the product being designed. It will assist engineers to become aware of social impact categories sometimes overlooked, especially when designing for global engineering.

If engineers are able to focus on all three pillars of sustainability early in the design process, including social sustainability, they can add social impact indicators along with technical performance measurements during the product development process and design a product that better meets the requirements for environment, economic, *and* social sustainability. This is why it is important for engineers to know how to handle the complexity and uncertainty associated with design parameters when creating products for social impacts aimed at global development.

In this dissertation, the two methods are outlined and explained. The demonstration of the first method showed that by using the method of collaborative product design to create a brick press, the task-per-cost ratio was improved by 30%. The demonstration of the second method showed that a redesign of the cup seal in the India Mark II/III hand pump system (a product used by approximately 10% of the world's population) could extend the service interval with 12% by replacing the cup seals.

Lastly, conclusions related to improving social impacts when engineering for global development and suggestions for future research are outlined.

Keywords: social impact, product development, global engineering, robustness, sustainable design, collaborative products, optimization, wear, India Mark

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The things which are impossible with men are possible with God - Luke 18:27

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CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

Of the world's population of 7.55 billion people, 6.29 billion live in less developed countries and out of those, one billion people are living in the least developed countries, surviving on less than 2 USD per day [4]. The projection for the world's population in 2050 is that the less developed population will have increased by 35%, the least developed population by 92%, while the developed world population is only projected to have a 3.2% increase (see Figure 1.1) [4].

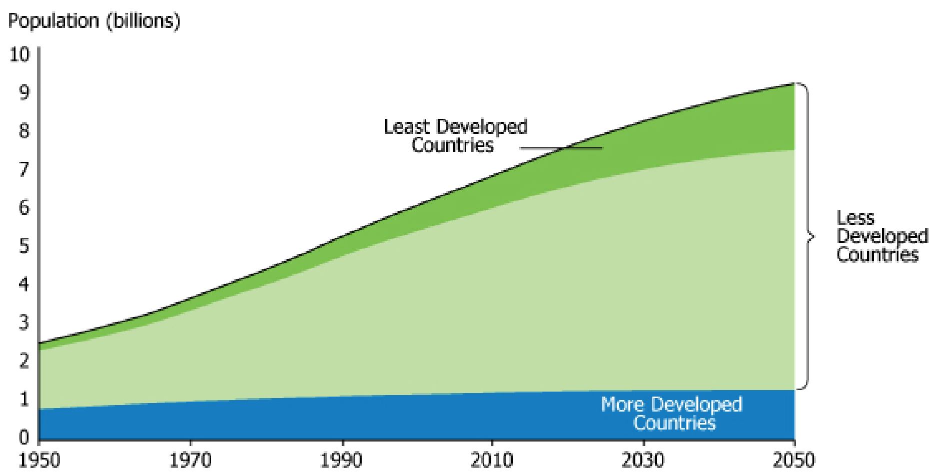

Figure 1.1: Projected global population growth [4]

As the less developed market size increases, there will be no shortage of needs to be met, nor opportunities to be had [14–17]. According to Prahalad, the bottom-of-the-pyramid (BOP) market and its demand for products engineered for less developed countries will increase, and that profit will be in sheer sales volume instead of individual sales price [18]. Polak points out that for success in this market, we have to "treat poor people as customers for goods and services instead of as recipients of charity" [19]. Resources such as technology transfer, new sustainable technologies

(3D printing etc.), and artificial intelligence could be used to better help these markets on their own terms, especially in the least developed countries (LDCs) [20]. See Figure 1.2 for map showing the LDCs.

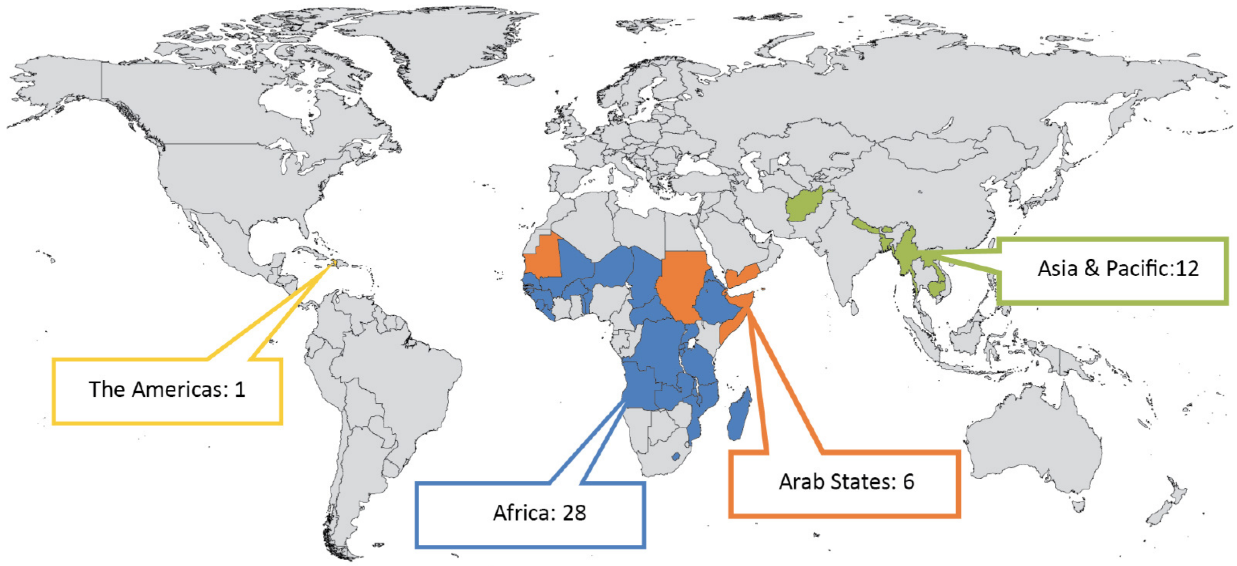

Figure 1.2: Map highlighting the least developed countries (1 in the Americas (Haiti), 28 in Africa, 6 among the Arab states, and 12 in the Asia-Pacific region [5]

However, there is a shortage in understanding how to effectively design products for this market [21]. Many have attempted to design products for global engineering, but few products have had the positive and widespread impact intended [21,22]. In the developed world, the success rate of introducing new products is one in seven, but in the developing countries it is only one in forty-six [23]. This makes the developing countries a complex and risky area to work in with much uncertainty. But even though it is a complex area filled with uncertainties, it is a market that is rapidly growing [4], a market that many people believe deserves engineering attention [24].

To help countries meet their needs on their own terms, designers working in the area of engineering for global development are striving to create products that are economically, environmentally, and socially sustainable, which is often referred to as the three pillars of sustainability [25]. While the former two pillars have garnered a great deal of attention, social sustainability or social impacts remain understudied. One reason is that the social environment of engineered products is often complex and uncertain.

To be clear, the following definitions have been adopted for this research:

Social impact: The impact of engineered products on the day-to-day lives of persons or communities [26].

Three pillars of sustainability: The three pillars of sustainability refer to environmental, social, and economic sustainability [25].

Engineering for global development: Engineering for Global Development (EGD) aims to improve the quality of life worldwide through the design and delivery of technology-based solutions [27]

Complexity: The complexity caused by combining the processes and structures of different systems, such as technical, social, political, and cultural into one [28].

Uncertainty: "Being any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system" [29].

There are frameworks set in place for dealing with the complexity and challenges of product development, but they are mostly geared towards the familiar markets of the developed countries [19, 30]. So even though some tools for assessing social impacts already exist [31–34], it is clear that engineers will need to be trained in order to design with social impact in mind [35, 36]. This has shown to be true time and again as customers fail to buy the products companies hope they will [37]. Such failures are often due to a misunderstanding by companies of what the true customer needs and wants are [35, 38]. This is also magnified when companies are physically removed from the customers and have a lack of understanding for the local culture [39].

In a survey carried out by Nonprofit Technology Network (NTEN), it was found that only half of the organizations that responded collected data on end-user impact [40], and another study reported that more than 70% of those giving grants to non-governmental organizations (NGOs) stated that the foundations did not have the necessary data to measure their impact [31]. Could the absence of success when working in the area of global development be because we lack the know-how to assess and predict the impacts of our products?

1.2 Gaps in Current Research

Most engineers design for the purpose of creating value and improving lives and while so doing, they often seek efficient ways to turn the Earth's resources into meaningful and impactful objects. *Explicit* in the engineer's modern product development process are the many quality assessments that are carried out during the product development process, (shown in Figure 1.3). Assessments are done to assess technical feasibility, financial value, the environmental cost, and more [41]. *Implicit* to the process, however, is the evaluation of social value created, or social impact – an area seldom discussed in literature [31]. Together, these are often referred to as the three pillars of sustainability–environmental, social, and economic sustainability [42].

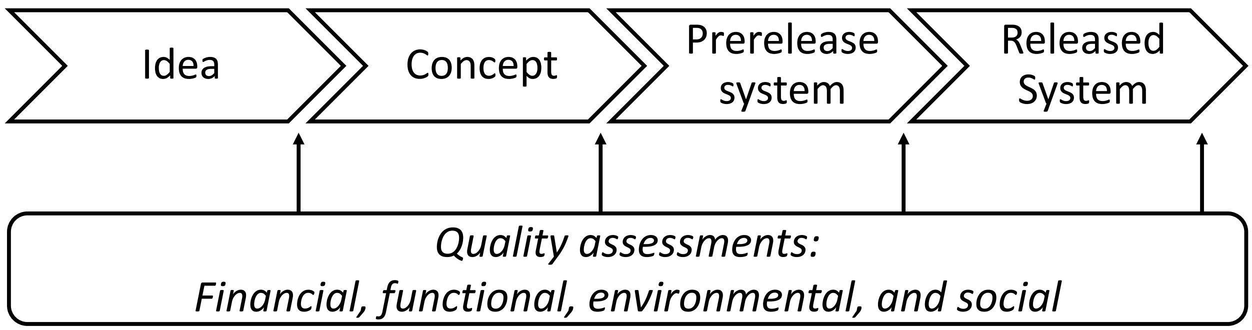

Figure 1.3: Basic product development process

Every manufactured product has an environmental impact, a social impact, and an economic impact [43,44]. As engineers, we should do our best to understand how our design decisions influence these impacts, (the three pillars of sustainability), and at the same time make decisions that collectively lead to maximum positive impact, or minimum negative impact on the economy, environment, and society. This is not a new concept among engineering professionals, with our code of ethics already embracing the practice to "hold paramount the safety, health, and welfare of the public" [45], the charge "to comply with the principles of sustainable development" [46], and the consideration of "the consequences of [our engineering] work and societal issues pertinent to it" [47]. Despite the wide acceptance of these canons of professional conduct, we unfortunately fall short of characterizing the social impacts our products can have beyond the basic engineering principles of mechanical and structural safety.

Many times, engineers show interest and want to design for all three pillars of sustainability but are often constrained to focus on the environmental and economic aspects, leaving out social sustainability due to lack of understanding and resources [8]. If engineers are able to focus on all three pillars of sustainability early in the design process, including social sustainability, they can add social impact indicators along with technical performance measurements during the product development process and design a product that better meets the requirements for environment, economic, *and* social sustainability [48]. This is why it is important for engineers to know how to handle the complexity and uncertainty associated with design parameters when creating products for social impact aimed at global development [35].

Since much of the research associated with product development is derived from technical, organizational, and environmental aspects based on the developed world [28, 49, 50], it is missing many of the local aspects of product development in the developing world [38]. Research has also shown that engineering students need to go beyond the notion of simply caring about who is affected by their engineering work, but instead be trained to willingly accept responsibility for how their work impacts society [35, 51]. At times, companies have developed products with the LDCs in mind but with all engineering work taking place in the developed world, their products often miss the mark, leading to products that fail to meet the local needs [52].

In practice, this leaves the social dimension of sustainability out of sight and reach for many engineers. So to assist engineers in knowing what to look for when considering social impacts of products, we researched different types of social impacts a product can have, how to measure and predict impacts, and how to improve impacts. During this research, the BYU Design Exploration Research group developed a list of eleven social impact categories, derived through a literature review (published by another team member) [1]. These categories can be seen in Table 1.1. The eleven categories became the framework for evaluating the social impacts a product can have. See Section 3.3.1 for more in-depth definitions and examples for each of the eleven categories.

Table 1.1: Social impact categories derived from literature (separated into three groups) [1]

Well-being and Inequality	**Demographics**	**Interaction and Identity**
1. Health and Safety	5. Education	9. Conflict and Crime
2. Paid Work	6. Family	10. Social Networks and Communication
3. Stratification	7. Gender	11. Cultural Identity/Heritage
4. Human Rights	8. Population Change	

As stated earlier, not all pillars of sustainability are equally assessed during the product development process [53,54]. The assessment of social impacts is a fundamental part of sustainable global development and is necessary in order to create and evaluate impacts, but it has been proven to be difficult to perform [55].

1.3 Objectives

The purpose of this dissertation is to address the following question: What practices can designers follow when engineering for global development in order to increase the social impacts of products in the lives of persons or communities? This dissertation develops an approach, which is explained, analyzed, and demonstrated in the subsequent chapters of this dissertation. The specific dissertation objectives are:

1. Develop and demonstrate a new technique or strategy to use domain knowledge from a mature area of engineering and apply it to the area of engineering for global development (see Chapter 2).

2. Analyse the perceived social impacts existing products can have, and show how this can be applied to new product development focused on engineering for global development (See Chapter 3).

3. Demonstrate how the method in Chapter 3 can be used to evaluate a product in order to explore design improvements that can increase its social impacts (see Chapters 4 and 5).

1.4 Research Findings

The following sections lists the research findings as they relate to the objectives. For more in-depth results, see Chapters 2 through 5.

1.4.1 Application of Domain Knowledge from Areas Outside of Engineering for Global Development

In Chapter 2, we use modular product design and multi-objective optimization to create collaborative products to benefit people in poverty (published in *Development Engineering* [56]). A collaborative product is created by temporarily combining physical components from two or more products to perform a task that the individual products are incapable of performing alone [6].

Our incentive is to create income-generating products for use by individuals or communities and to make products available that are currently unaffordable for someone living in poverty. It is done by evaluating products and decomposing them into sub-products that by themselves are both useful and affordable as stand-alone products. We then use multi-objective optimization to resolve the competing needs of each sub-product to find the most effective solution. See Section 2.3 for more information on the method for collaborative products.

In Section 2.4, a collaborative brick press is designed to demonstrate the method. The result of this example is that by purchasing a collaborative product instead of separate products, there is a 30% improvement to the task-per-cost ratio, showing great promise for engineering-based poverty alleviation. The individual and collaborative products can be seen in Figure 1.4.

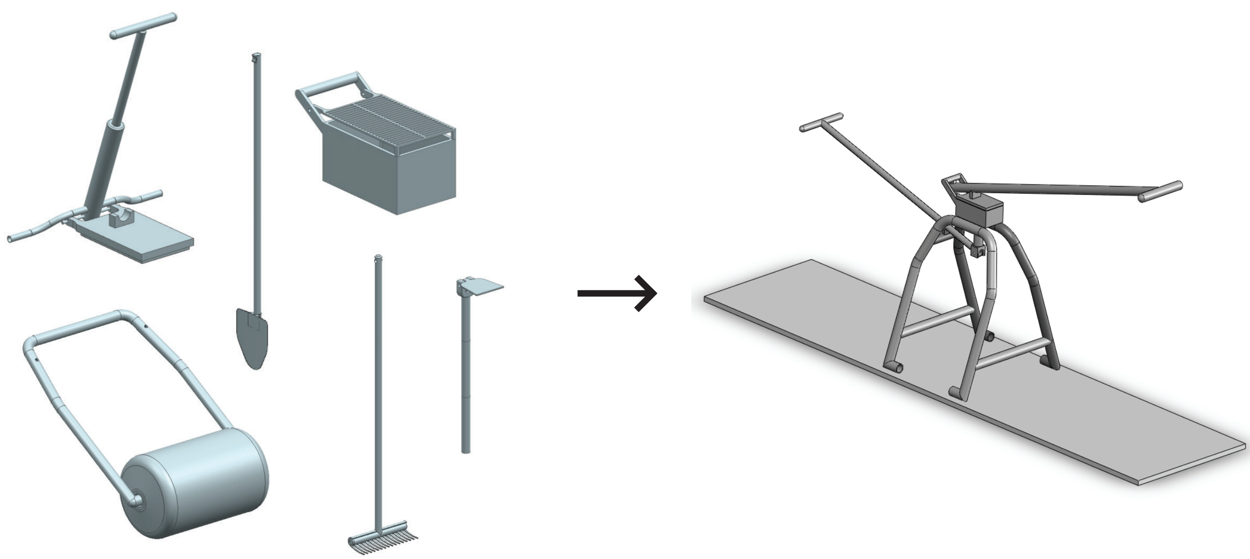

Figure 1.4: Individual and collaborative products used in Chapter 2

This method is developed by using domain knowledge from a mature area and applied it to the area of engineering for global development and demonstrated by designing a collaborate product (a brick press). It is a tool that can be used to design collaborative products for poverty alleviation–products that are able to perform new tasks beyond those of the combined products by themselves, negating the need to buy new products.

Even though the results show promise for alleviating poverty, this part of the research revealed the need for further focus on evaluation of social impacts since the main focus was on the product, and not on the users.

1.4.2 Analysis of Perceived Social Impacts in Existing Products

In Chapter 3, we create a method to be used by designers that want to increase the social impacts of the products they engineer (published in *Journal of Mechanical Design* [57]). It is created by reviewing 150 products designed for social impact and linking them to the 11 social impact categories mentioned earlier (see Table 1.1). By reviewing these products, the probability of social impact for each of the 11 categories to be present in a product is found together with the co-presence of other social impacts (see Section 3.6).

To prevent engineers from making decisions based on social norms and feelings that are out of context (which can lead to the creation of products with less social impacts than intended [58]), we suggest the use of our method. This method is to be used throughout the product development stages as indicated in Figure 1.5.

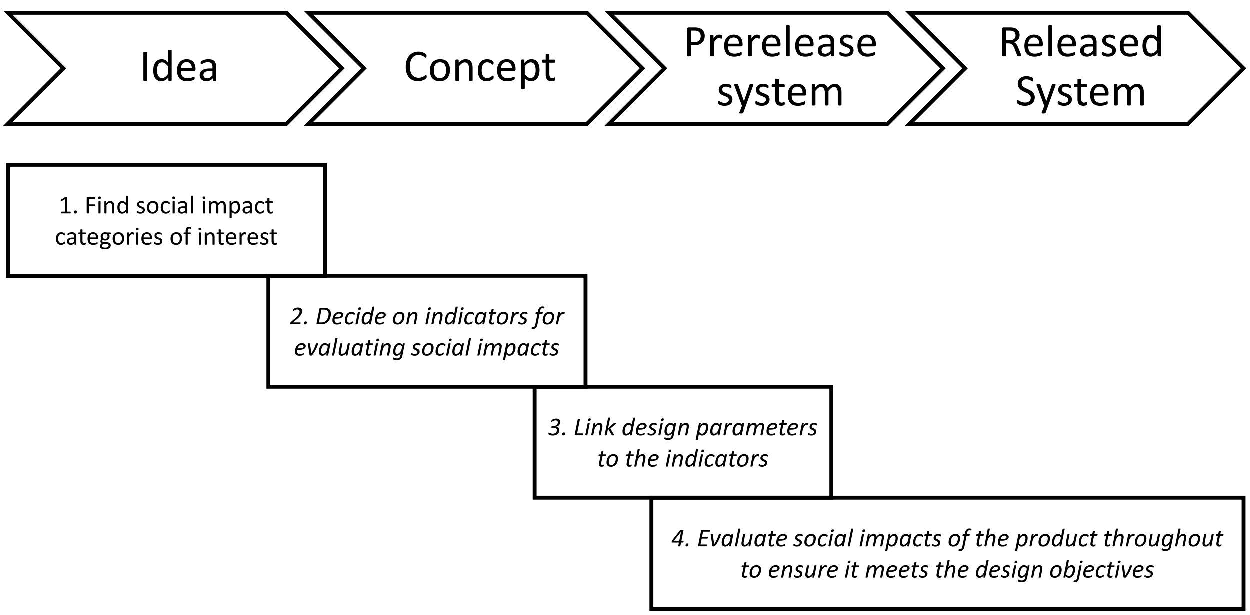

Figure 1.5: Method for improving social impacts of products during product development

Below are the steps to our method for increasing the potential social impact of engineered products:

1. *Find Social Impact Categories of Interest:*
   After having decided on a product to design or redesign, look at the 11 social impact categories found in Table 1.1 and identify one or more obvious social impact categories to be included. After choosing the main social impact categories, look at Table 1.2 to learn the probability of other social impact categories to be co-present by finding the row for each main category and then reading the probability of having impact in other categories. Select additional categories to be included.

2. *Decide on Indicators for Evaluating Social Impacts:*
   Decide which indicators to use in order to evaluate the social impacts of the product throughout the stages of product development.

3. *Link Design Parameters to the Indicators:*
   Link design parameters to the indicators and add them to the design objectives/requirements.

4. *Evaluate Social Impacts:*
   Evaluate social impacts of the product throughout the stages of development to ensure that it meets the design objectives. Also consider if the design negatively affects any of the social impact categories.

When considering social impacts early, there is a greater potential for added social impacts [8]. By following these steps, an engineer can be made aware of social impact categories that could otherwise be overlooked and now broaden the design to include additional social impact objectives, thus achieving a design with an increased impact in the original category together with additional impacts in other categories.

For this part of the research, we choose to analyse products designed for social impacts to find the co-presence of social impacts in products (see Table 1.2). From this, a method for increasing the social impacts of products is created. This method can be used during product development to increase the potential social impacts of the product being designed. See Chapter 3 for more information on how the 11 social impact categories are co-present in products.

Table 1.2: Observed conditional probability of impact when one category is known, table to be read row by row

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	**1**	0.427	0.066	0.293	0.183	0.185	0.173	0.104	0.127	0.259	0.169
Paid Work	0.867	**1**	0.076	0.340	0.211	0.292	0.214	0.170	0.154	0.471	0.278
Stratification	0.841	0.478	**1**	0.377	0.391	0.261	0.261	0.319	0.304	0.420	0.333
Human Rights	0.629	0.361	0.063	**1**	0.361	0.124	0.132	0.129	0.285	0.171	0.312
Education	0.592	0.338	0.099	0.544	1.000	0.081	0.099	0.184	0.349	0.232	0.301
Family	0.911	0.709	0.101	0.285	0.123	**1**	0.201	0.184	0.117	0.436	0.223
Gender	0.869	0.528	0.102	0.307	0.153	0.205	**1**	0.102	0.074	0.301	0.205
Population Change	0.829	0.667	0.198	0.477	0.450	0.297	0.162	**1**	0.414	0.315	0.414
Conflict and Crime	0.560	0.335	0.105	0.585	0.475	0.105	0.065	0.230	**1**	0.175	0.320
Social Networks and Communication	0.870	0.782	0.111	0.267	0.240	0.298	0.202	0.134	0.134	**1**	0.271
Cultural Identity/Heritage	0.703	0.571	0.108	0.604	0.387	0.189	0.170	0.217	0.302	0.335	**1**

1.4.3 Demonstration of Method Created in Chapter 3

The method created in Chapter 3 is now used to better understand how the India Mark II/III hand pump system impacts the lives of its users. We chose this product since it is the most common hand pump in use across the world, with more than 4 million installations and a track record of over 40 years [59, 60]. It is estimated that 10% of the world's population is using one of these pumps on a daily basis [61], and to our knowledge it has had no major updates or engineering analyses published for it.

Our hypothesis is that if we can improve the longevity of the pump, its perceived and actual social impacts will improve. We find this to be true by following the 4 steps of the method created in Chapter 3. See Chapters 4 and 5 for the engineering analyses and social impact analysis. Chapter 4 is published in *Developing Engineering* and most parts of Chapter 5 are under review in the same journal.

1.4.4 New Methods for Meeting Customer Needs and Improving Social Impacts of Products

The new methods created in this dissertation can assist engineers in meeting unmet customer needs and improving social impacts of products. They can help engineers to become aware of social impact categories sometimes overlooked, especially when designing for global engineering.

1.5 Description of Dissertation Layout

The remaining chapters of this dissertation are organized in the following manner. Chapter 2 contains a method were domain knowledge from consumer product design and other related fields are applied in the area of global development. Specifically, the method we created uses modular product design together with multi-objective optimization to benefit people living in poverty. An example on how to use this method is included. Chapter 2 is published in *Development Engineering* [56]. In Chapter 3, we show the probability of co-presence of social impact categories in products designed for social impact. We then present a method to be used throughout product development in order to increase the potential social impacts of products being designed. Chapter 3 is published in *Journal of Mechanical Design* [57].

In the next two chapters (Chapters 4 and 5), we explore design improvements to the cup seal in the India Mark II/III hand pump system in order to improve the pump's potential social impacts. We start by performing a baseline study of the cup seal in the India Mark II/III hand pump system (see Chapter 4). Chapter 4 is published in *Development Engineering* [62]. We then use the method created in Chapter 3 as we demonstrate how improved social impacts can be achieved by considering them throughout the redesign of the pump system. The steps are followed and engineering tools are used to explore design improvements to the cup seal found in the India Mark II/III hand pump system while considering the 11 social impact categories found in Section 3.3.1 (see Chapter 5). The main parts of Chapter 5 is under review in *Development Engineering*.

The last chapter, (Chapter 6) presents the conclusions and suggestions for future research. Appendix A contains the information collected during our research trip to Uganda, Africa.

CHAPTER 2. EXPERIMENTING WITH CONCEPTS FROM MODULAR PRODUCT DESIGN AND MULTI-OBJECTIVE OPTIMIZATION TO BENEFIT PEOPLE LIVING IN POVERTY

2.1 Chapter Overview

Every discipline has its own specific knowledge that has been accumulated and refined over time. In the aerospace industry, for example, the domain knowledge of multidisciplinary optimization has grown and matured. The same has happened with domain knowledge related to modularity in the consumer product design industry. Knowledge from these domains has carried over to other domains such as automotive, medical, and defense, and has enabled advances in these disciplines. One domain that has been underserved by the advanced engineering methodologies coming from other disciplines is the domain of *design for the developing world*. Exploring the use of engineering domain knowledge to alleviate poverty is a valuable study that will open opportunities to use engineering to benefit resource poor individuals. This chapter explores the domain knowledge of modularity and multi-objective optimization and applies it to the domain of design for the developing world by introducing the concept of collaborative products to assist the resource poor individuals. Can knowledge from one domain be used in a new domain, and if so, what would it look like? In this chapter, a general methodology is presented, followed by a simple example to illustrate the design of a collaborative product for the developing world. We suggest that by using domain knowledge from a non-related domain paired with the method presented, products can be designed and optimized for collaborative performance with potential to both generate new income and save money for the end customers.

2.2 Introduction

This chapter uses domain knowledge from one or more areas of engineering and applies it in the area of design for the developing world. We are motivated to do and report on this because we believe that many different areas of engineering expertise can be re-imagined and lead to new poverty alleviating products. In this chapter we build on our own expertise in modular-product design and multi-objective optimization to create a new product category created specifically for issues faced by those in poverty. The new category is called collaborative products, which are created when physical components from two or more products are brought together to form a **different** product capable of performing additional tasks **that could not have been done with the individual products alone** [6]. The goal of the method introduced herein is to design products that generate income, and appeal to a greater number of individuals due to affordability.

Modular product design is an essential part of the design of collaborative products since it involves joining together multiple products. In the literature, this type of design is known as *Type II modularity*. It is defined as the design of interfaces with modules that can only be attached to other specific modules through a unique interface, effectively reducing the complexity of the products [63,64]. Research has recently been aimed at bringing domain knowledge from the design of modular/reconfigurable products to the domain of design for the developing world [6, 65–67].

Collaborative products have the potential to significantly influence the impact that income-generating products can have on poverty alleviation efforts by reducing the cost of a set of products capable of performing a specified set of tasks. This is accomplished by increasing the task-per-cost ratio of a set of products [6] so as to reduce the number of products needed to perform a set of tasks. It is this ability to perform a set of tasks with fewer products that effectively lowers the financial risk for the user and increases his or her likelihood of purchasing and benefiting from these products.

The basic strategy surrounding the notion of collaborative products is this: Designers begin by identifying a relatively complex product that is currently unaffordable for someone living in poverty. That product is then decomposed into sub-products that are designed to be useful and affordable as stand-alone products. Individuals living in poverty could then share the purchase of the complex product with others in their community by having each person buy independently useful portions (or sub-products) of the complex product. In some cases the sub-products may be used to generate income to support the purchase of additional sub-products, thus working toward the complex product, alone or as a community. Although not the focus of this chapter, it is important to recognize that to be an effective strategy, the design, marketing, and sale of the collaborative products would need to be carefully planned so that users would know which sub-products work together and how they should be assembled.

The method presented here for designing collaborative products also involves many changing and competing needs that must be addressed to successfully design a product. One way to meet these demands and resolve the competing nature of both present and future needs of a set of products is through multi-objective optimization [68–70]. This technique serves as a fundamental foundation to the design method presented in this chapter. Multi-objective optimization characterizes the trade-offs between design objectives by identifying a Pareto frontier or a set of non-dominated optimal solutions. These Pareto solutions are of importance because they show that design objectives have been improved to their full potential without sacrificing the performance of objectives in other areas [65, 68–71].

A set of optimal solutions belonging to a Pareto frontier can be found through the following generic multi-objective optimization problem presented as *Problem 1* (P1):

$$\min_{x} \; \{\mu_1(x,p),\; \mu_2(x,p),\; \ldots,\; \mu_{n_\mu}(x,p)\} \quad (n_\mu \geq 2) \tag{2.1}$$

subject to:

$$g_q(x,p) \leq 0 \qquad \forall\, q \in \{1,\ldots,n_g\} \tag{2.2}$$

$$h_k(x,p) = 0 \qquad \forall\, k \in \{1,\ldots,n_h\} \tag{2.3}$$

$$x_{jl} \leq x_j \leq x_{ju} \qquad \forall\, j \in \{1,\ldots,n_x\} \tag{2.4}$$

where μ_i denotes the i-th generic design objective to be minimized (e.g., cost or size of a product); x is a vector of design variables that define the design of a product (e.g., length, width, height); p is a vector of design parameters (e.g., material yield strength, modulus of elasticity) that will be treated as constants in the optimization; x_u and x_l define the upper and lower bounds of the j-th design variable; g is a set of inequality constraints; and h is a set of equality constraints. Note that the objectives and constraints are functions of both x and p, and that the objectives will be minimized by changing the values of x.

Aside from the developing world context, collaborative products can also be applied in the *developed* world. Many individuals within the United States suffer from poverty, living in small dwellings with limited storage space [72]. Money is also limited for these individuals, and collaborative products are a way to help maximize available storage space while providing a set of product functions that are extremely affordable. Other identified areas that could benefit from collaborative products may include payload conscious industries such as aerospace and backpacking [6].

Morrise et al. have developed a method for designing collaborative products, consisting of an eight-step process [6]. While this method serves as a basic foundation to the design of collaborative products, we propose a revised method that builds upon and strengthens this existing process. Again, the goal behind the method is to increase the earning potential and simultaneously decrease the financial risk for the user. By buying **all the products included** in the Collaborative Product System, a new previously unattainable income generating task can be performed. By having a system of products that can perform **one task** as a collaborative product and where each product can perform **individual tasks**, the task-per-cost ratio is increased and the potential for income generation is also increased. The steps of the new method will be further explained in Section 2.3 of this chapter.

The remainder of this chapter is organized as follows: The theory for designing products for optimal individual and collaborative performance is found in Sec. 2.3. In Sec. 2.4, the design of a simple collaborative brick press demonstrates implementation of the presented method, followed by concluding remarks in Sec. 2.5.

2.3 Method of Designing Products for Optimal Collaborative Performance

This section presents a method that seeks to understand customer needs and meet them through the use of individual and collaborative products. The method consists of a nine-step process which can be abbreviated as follows: (1) Understand customer needs, (2) Identify a product that satisfies a need, (3) Decompose the identified product, (4) Use the decomposed components to satisfy additional needs, (5) Identify the product interfaces (6) Characterize the collaborative design space, (7) Define the areas of Pareto offset, (8) Identify the designs that fall within the offset areas, and (9) Identify the optimal product designs.

2.3.1 Step 1: Understand broad customer needs

The first step of the method is to seek out the broad customer needs that exist in society. This involves the study of groups and people as they go about their everyday lives. Research is carried out by immersing oneself in the culture and gathering information from individuals and potential customers of that society [73]. Other traditional methods used to gather this information include interviews, surveys, and observations [74, 75]. When it is not possible for the designer to be on site, a complementor can be used to gather the needed information [76]. Some other aspects to consider when developing products for the developing world is to have local knowledge and include on the design team the individuals that will be using the product [38, 77]. By using one or multiple of these methods the designer is able to gather statements from the customer and translate them into customer needs. It is essential to have a clear understanding of the customer needs to determine how to best meet them.

One way to focus the efforts of gathering customer needs is to select and work within a need category. Examples of categories when designing for the developing world might include: farming, hunting, tools, education, housing, cooking, health care, transportation, etc. The goal is to find an area that would benefit from a task-to-cost ratio increase–an area where new opportunities for income generation may be found [78]. For individuals in the developing world, the financial risk is lowered as this ratio increases. As this ratio and the chance of income generation are increased, people living in poverty will have more financial resources, which can lead to a better life [18]. If products can be affordable combined to complete a greater number of valuable tasks, the user will benefit from a lower cost. The end result of completing this step is to come to know the customer on a deeper level in order to gain an understanding of what could be done to benefit their lives.

2.3.2 Step 2: Create/select a product that satisfies one of the broad needs

After the customer needs have been sufficiently understood, the designer identifies a product that satisfies one or more of those needs. It can be a product that already exists in a society or one that is to be developed. Many design processes exist for creating new products, one of which consists of a five-step process [74]. The steps of this method are: (1) explore, (2) ideate and select, (3) engineer, testing and refinement, and (4) production ramp-up.

The explore step encompasses a wide range of activities including understanding the customer needs from Step 1 and defining the problem to be solved. The ideate and select step allows the designer to formulate new ideas based upon customer needs, evaluate those ideas, narrow them down, and ultimately select the most promising concept for further development. During the engineering of an idea, detail design commences. The selected concept is proven from an engineering design standpoint by defining part geometry, material type, and manufacturing steps. The selected design is then tested for weaknesses and refined as necessary. Design changes are implemented as needed to ensure the product satisfies the key customer needs. Production ramp-up will likely take place at the end of the collaborative product design process, rather than at this point in the method. It is a crucial step in the design process, but should be considered when all details of the collaborative product design have been established.

We note that it is here, in Step 2, that many of the design characteristics that cannot be quantified are chosen by the designer. Generally speaking, these characteristics will remain a fundamental part of the design even after the optimization search algorithm is used in Step 6 to fine tune the design parameters that define the characteristics chosen here.

The resulting product from Step 2, whether newly designed or already existing, will serve as the starting point to the creation of a collaborative product. This product typically will have the following qualities: be comprised of multiple if not many components; is desirable but generally not purchased by a customer due to its high cost, weight, or size; and is generally used less frequently than typical, everyday products. A product that is generally used less frequent tend to be a good candidate for becoming a collaborative product since the components used (other products), are unusable while they are configured into a collaborative product [6].

2.3.3 Step 3: Decompose the selected product into components

Step 3 requires the designer to decompose the selected product into its individual components. This step is necessary to begin learning about what products will make up the collaborative product and be able to satisfy additional customer needs. Generally, the selected product is decomposed only into the components required to perform an intended function. In other words, the decomposition will not include secondary components such as fasteners [6].

This type of product is decomposed three ways–structurally, functionally, and by physical characteristics. From a structural standpoint, the product is decomposed where the resulting components make up the primary structure of the product. Functionally, the product is decomposed by identifying the primary function of each component identified in structural decomposition. Lastly, decomposition by physical characteristics is completed by identifying the relevant characteristics such as size, shape, and color of each component identified during structural decomposition.

An example of a bicycle wheel decomposition, provided by Morrise et al., helps to illustrate the decomposition process [6]. This example demonstrates the need for three types of decomposition and how each type brings clarity to the collaborative design process. See Figure 2.1 for the bicycle wheel decomposition based upon structural, functional, and physical characteristics. If only structural decomposition was carried out, then a bicycle wheel would be viewed based on its structure alone. In other words, a bicycle wheel would only relate to other wheels and would not have any known relationship based on function. Decomposition to this extent allows the designer to better understand the components and characteristics that a selected product contains.

2.3.4 Step 4: Determine what other products can be created from the components to meet different broad customer needs, while if desired, adding missing secondary components

In this step, additional broad customer needs are studied to determine other products that can be made from the decomposed product components. Tools such as concept combination tables, recombination tables, and morphological matrices can be used to assist in this step [75, 79]. Needs are considered and thought is given to each decomposed product to determine how to best meet each additional need. The designer must be cautious of multiple products that may require concurrent use since the collaborative product will require use of all its components to function. Therefore, it may be best to select products that meet needs in different categories, activities, or seasons to prevent this from happening. If needs be, the designer can also add secondary components to complete a secondary design. Like Step 2, Step 4 is also centered on qualitative elements of the design that will simply be fine-tuned as part of the numerical search carried out in Step 6.

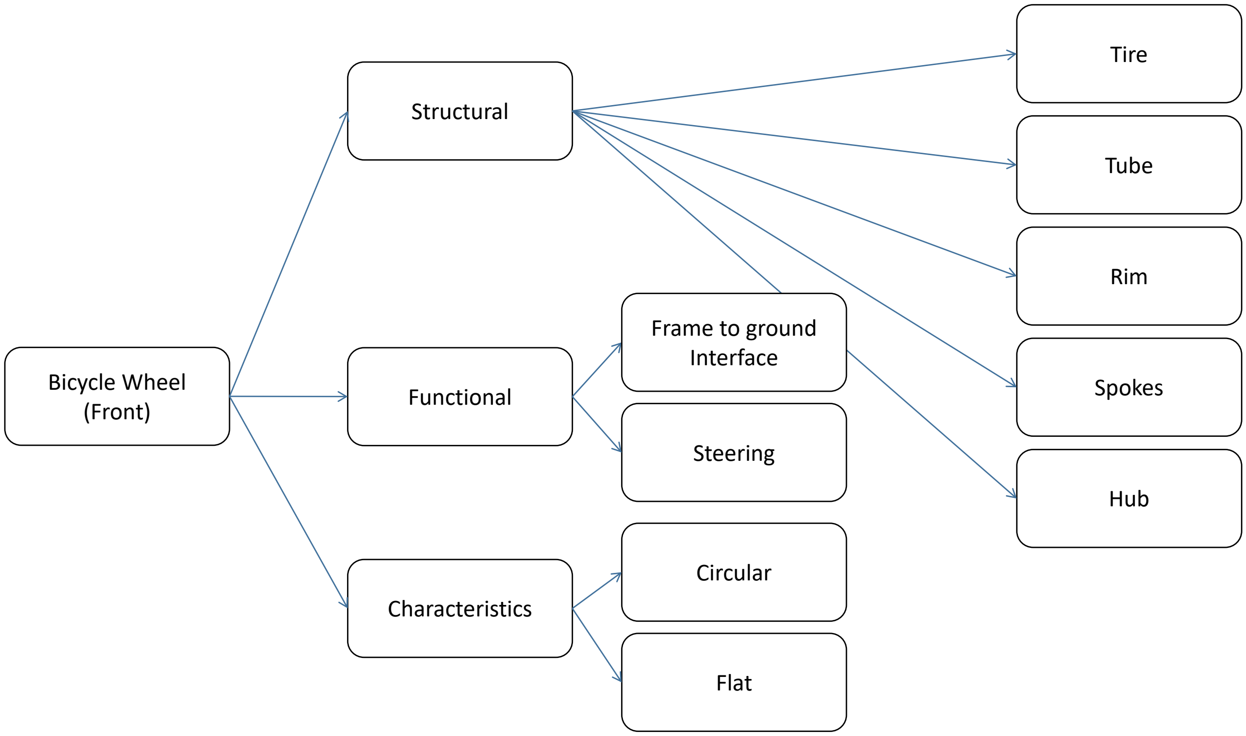

Figure 2.1: Bicycle wheel decomposition adapted from Morrise et al. [6]

2.3.5 Step 5: Identify the interfaces between components

Once all products have been chosen and the most important needs have been met, the designer must identify the interfaces between components. The addition of interfaces to the product may introduce weaknesses. However, it is because of these interfaces that the task-per-cost ratio is able to increase. As was stated in Section 2.2, this ratio is important to individuals in the developing world, as it defines the number of tasks a product can perform based on its cost. The higher this ratio is, the lower the financial risk will be for the end user. These interfaces are crucial to the functionality and reliability of the collaborative product as well as the safety of the user. They will determine how positive the user experience is and its usefulness as a collaborative product. Especially to reduce the onus placed on the end user regarding the complexity of knowing what and how to assemble the collaborative product, designers should focus on improving the user friendliness of transitioning between individual and collaborative product use. A detailed process for designing interfaces will not be discussed in this chapter since sufficient methods already exist in the literature [80, 81].

2.3.6 Step 6: Characterize the collaborative design space of the product set and collaborative product

When designing a product that will be part of a collaborative product, optimal design for each component can not always be achieved. This step must therefore start with the gathering of the knowledge of the product set and the corresponding collaborative product. Thus, the impact of design changes of both individual and collaborative product performance must be considered. All objective values must therefore be accounted for when performing a multi-objective optimization. The points along the Pareto frontier (graphically illustrated in Figure 2.2) represent the best possible trade-offs between the selected design objectives of each product. Although a design is located on the Pareto frontier of an individual product, the corresponding performance of the collaborative product, and the other products in the set, are not guaranteed to be Pareto optimal in each product's objective space. Because of this, the collaborative performance of a product correlates to the measured offset of its design from the corresponding Pareto frontier. By maximizing the collaborative performance of each product simultaneously, a product set is defined with optimal collaborative performance. Like all mathematically assisted design methods, the designer must be aware of the fidelity of the mathematics involved and use judgment as to if the mathematics sufficiently capture the designer's intent.

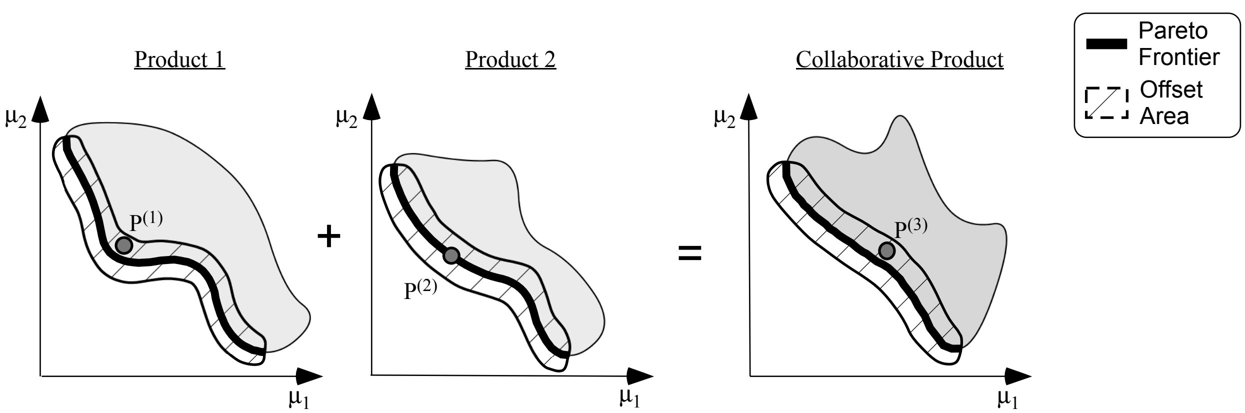

Figure 2.2: Graphical summary of the intent of the method presented in Section 2.3, illustrating the feasible bi-objective design spaces for a theoretical product set and corresponding collaborative product. The Pareto frontier (bold line) defines the most desirable set of solutions in each design space. The designs selected for each product are identified as points $P^{(1)}$, $P^{(2)}$, $P^{(3)}$. Note that the selected designs are within identified areas of acceptable Pareto offset.

Recognizing the inherent trade-offs and compromises in collaborative performance that must be explored, the purpose of steps 6-9 is to implement an optimization-based approach to mitigating these trade-offs. Figure 2.2 graphically represents the intent of balancing these trade-offs using the method presented in this section for two products that are combined to create a third product. Although the presented method is not limited to the simple case presented in Figure 2.2, a limited number of products are used for simplicity of visualization purposes. From Figure 2.2 it can be observed that the presented optimization routines select designs for each product that fall within identified offset areas within each objective space. In order to enable the use of optimization methods to explore possible design solutions, objectives for each of the products in the set and the collaborative product are identified, and models of these objectives are created that incorporate the intended product interfaces. Using the developed models, the design space of each product is determined by a multi-objective optimization problem similar to (P1).

To define each product and identify the variables that couple the design of each product in the set to the collaborative product, the design variables for each product are divided into three groups: interface variables (x_{I}), collaborative variables (x_{C}) and unshared (x_{U}) variables. The interface or platform variables are shared throughout the product set and define the connecting interface between each product. The collaborative variables are those connected to the elements of a product that are used to create the collaborative product. The unshared or unique variables are those connected to the elements of a product that are unique to each product in the product set. The characterization of the multi-objective design space for the i-th product in the set, and the collaborative product ($i = n_p + 1$), in terms of identifying the corresponding Pareto frontier (see Figure 2.2) is presented as *Problem 2* (P2):

$$\min_{\hat{x}^{(i)}} \left\{ \mu_1^{(i)}(\hat{x}^{(i)}, p^{(i)}),\ \ldots,\ \mu_{n_\mu^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) \right\} \quad (n_\mu^{(i)} \geq 2) \tag{2.5}$$

subject to:

$$g_{q^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) \leq 0 \quad \forall\, q^{(i)} \in \{1, \ldots, n_g^{(i)}\} \tag{2.6}$$

$$h_{k^{(i)}}^{(i)}(\hat{x}^{(i)}, p^{(i)}) = 0 \quad \forall\, k^{(i)} \in \{1, \ldots, n_h^{(i)}\} \tag{2.7}$$

$$\hat{x}_{jl}^{(i)} \leq \hat{x}_j^{(i)} \leq \hat{x}_{ju}^{(i)} \quad \forall\, j \in \{1, \ldots, n_{\hat{x}}^{(i)}\} \tag{2.8}$$

$$\hat{x}^{(i)} = \begin{bmatrix} x_{\mathrm{I},1},\ x_{\mathrm{I},2},\ \ldots,\ x_{\mathrm{I},n_{x_I}},\ x^{(i)}_{\mathrm{C},1},\ x^{(i)}_{\mathrm{C},2}, \\ \ldots,\ x^{(i)}_{\mathrm{C},n^{(i)}_{x_\mathrm{C}}},\ x^{(i)}_{\mathrm{U},1},\ x^{(i)}_{\mathrm{U},2},\ \ldots,\ x^{(i)}_{\mathrm{U},n^{(i)}_{x_\mathrm{U}}} \end{bmatrix} \tag{2.9}$$

$$x_\mathrm{C}^{(n_p+1)} = \left[x^{(i)}_{\mathrm{C},1},\ x^{(i)}_{\mathrm{C},2},\ \ldots,\ x^{(i)}_{\mathrm{C},n^{(i)}_{x_\mathrm{C}}}\right]\ \forall i \in \{1,2,\ldots,n_p\} \tag{2.10}$$

$$\hat{x}^{(n_p+1)} = \left[x^{(i)}_{\mathrm{U},1},\ x^{(i)}_{\mathrm{U},2},\ \ldots,\ x^{(i)}_{\mathrm{U},n^{(i)}_{x_\mathrm{U}}}\right]\ \forall i \in \{1,2,\ldots,n_p\} \tag{2.11}$$

where $\hat{x}^{(i)}$ is a vector of design variables containing the interface (x_I), collaborative (x_C), and unshared (x_U) variables for the i-th product in the set. The design parameters are also represented for the i-th product in the set by the term $p^{(i)}$. The Pareto frontier of each product is obtained by evaluating (P2) $\forall i \in \{1,2,\ldots,n_p+1\}$.

In Eq. 2.9, all variables that are included in the collaborate product ($i = n_p + 1$) contains all the collaborative variables from the product set. This coupling of the product set to the collaborative product design space is important since it illustrates to the designer the current collaborative nature of the product set.

2.3.7 Step 7: Define the areas of acceptable Pareto offset

In looking at the formulation of (P2), the resulting Pareto frontier for each product represents the best possible solutions for each of the products without considering the interaction between each product. As the number of products being combined increases, it becomes less likely that the designs capable of creating a collaborative product all fall on the Pareto frontier of the corresponding product. This is because the number of objectives and constraints to be satisfied, along with the complexities of the interactions between the products, increases with each additional product. As more interactions and trade-offs become apparent, the harder it is to meet all of the demands between products. In order to facilitate the selection of designs that will minimize the offset from these Pareto frontiers of the entire product set, the next step in the method is to use these Pareto frontiers to define areas of acceptable Pareto offset for each product (see Figure 2.2).

This process is carried out by defining a single offset value (β) for each product that will limit subsequent optimization routines to only consider designs with offsets from the Pareto frontier that are less than β. In the case of a two dimensional model, the values of β would be equivalent to defining a circle of radius β around each identified Pareto point from Step 1. In n-dimensional cases, the value of β represents the maximum allowable length of an n-dimensional vector between a design option and the closest Pareto point. This value is determined by the designer based upon the extent to which he or she wishes to limit the search space and focus optimization searches to the identified offset areas.

2.3.8 Step 8: Identify the designs that collaboratively fall within the areas of acceptable Pareto offset

In order to identify the designs, a multi-dimensional design space is created using axes represented by the predicted Pareto offsets for each product in the set as well as the collaborative product. This design space represents a combination of feasible designs in terms of the individual products and the collaborative product. In the case illustrated in Figure 2.2, these offset points would represent a three dimensional Pareto surface consisting of points from the offset area of each product. The offset space Pareto frontier is determined by a multi-objective problem statement presented as *Problem 3* (P3):

$$\min_{\hat{x}} \left\{ O^{(1)},\ O^{(2)},\ \ldots,\ O^{(n_p+1)} \right\} \tag{2.12}$$

subject to Equations 2.6–2.9 and:

$$O^{(i)}_{q^{(i)}} \leq \beta \qquad \forall\, q^{(i)} \in \{1, \ldots, n_g^{(i)}\} \tag{2.13}$$

where $O^{(i)}$ is the n-dimensional offset length of a design of the i-th product from the corresponding Pareto frontier of that product.

The Pareto surface is constructed by adjusting the interface, collaborative, and adjustable variables. The interface and collaborative variables are shared between the optimized products and the collaborative product, while the adjustable variables are unique to each optimized product, but shared with the collaborative product. It should be noted that in cases were there are no more than two products being combined to create a collaborative product, the result of *(P3)* is a Pareto surface. For product sets greater than two, the graphical representation of this offset space can no longer be provided for all products simultaneously. Fortunately, a graphical representation is not necessary for this method to be useful.

2.3.9 Step 9: Identify/select the optimal product designs

Since the goal of the method is to select the optimal design of each product while balancing the trade-offs required to create the collaborative product, this final step of the method uses the results of (P3) to select a single set of product designs. Under ideal circumstances, the selected designs are represented by a single Pareto point on the Pareto frontier of each product (i.e., the offset of each product is zero). One method of accomplishing this selection is through the use of an aggregate objective function (J) that represents the preferences and needs of the designer. If an aggregate objective function is used, one way of reducing the computation expenses related to the optimization problem evaluations, would be to replace Eq. 2.12 with an equation of the form of Eq. 2.14.

$$\min_{\hat{x}} J(O^{(1)},\ O^{(2)},\ \ldots,\ O^{(n_p+1)}) \tag{2.14}$$

At the conclusion of the design process presented in Section 2.3, the designer will have an understanding of the customer needs and a way to meet those needs with individual products and a collaborative product. Through the multi-objective optimization theory presented in Steps 6-9, the designer is able to simultaneously and numerically evaluate the performance of multiple designs in multiple design spaces. These computations would be near impossible without the use of computer aided calculations. This evaluation allows the designer to optimize the products to ensure they operate efficiently in both the individual and collaborative product states to effectively lower the financial risk for the end user.

2.4 Example: Collaborative Brick Press Design

This section demonstrates the implementation of the method presented in Section 2.3 through the design of a collaborative brick press. The concept for a collaborative brick press has been provided by Morrise et al. [6]. This design collaboratively uses the following six basic products to create the brick press: shovel, hoe, rake, water transportation roller, water pump, and a small cook stove. It is assumed these are potential products that a person living in poverty would be interested in purchasing as a way to improve his or her life situation. The ability to combine them together into an additional product would give individuals the potential to maximize their use and potentially increase their likelihood of purchasing these products. It should be noted that the intent of this example is not to show the feasibility and necessary logistics of implementing the collaborative brick press developed herein. Rather, the intent is to demonstrate the effectiveness of the method presented in Section 2.3 in identifying the optimal designs of a given collaborative product set.

The example is useful in illustrating this method because (i) it solves a challenging engineering design problem, (ii) it shows the use of complex interfaces between products and how they are addressed, (iii) it incorporates the use of actual products used or found in developing countries, and (iv) it demonstrates the use of a multi-objective optimization problem to deal with competing objectives from each product. Figure 2.3 illustrates the conceptual design and decomposition of each product in the identified product set, and Figure 2.4 shows how the products are assembled into the collaborative brick press.

2.4.1 Example Step 1: Understand broad customer needs

To understand the needs of the customer is the first step and in this example the following needs where included: cooking, home building, gathering food, transportation, and access to clean water.

2.4.2 Example Step 2: Create/select a product that satisfies one of the broad needs

The list of customer needs from step 1 was evaluated and the area of home building was chosen. A brick press was selected as a product that would be able to meet one customer need. A brick press serves as an ideal collaborative product candidate since it contains a large number of components, is desirable but typically not purchased due to its high cost, and is used less frequently than other typical, everyday products.

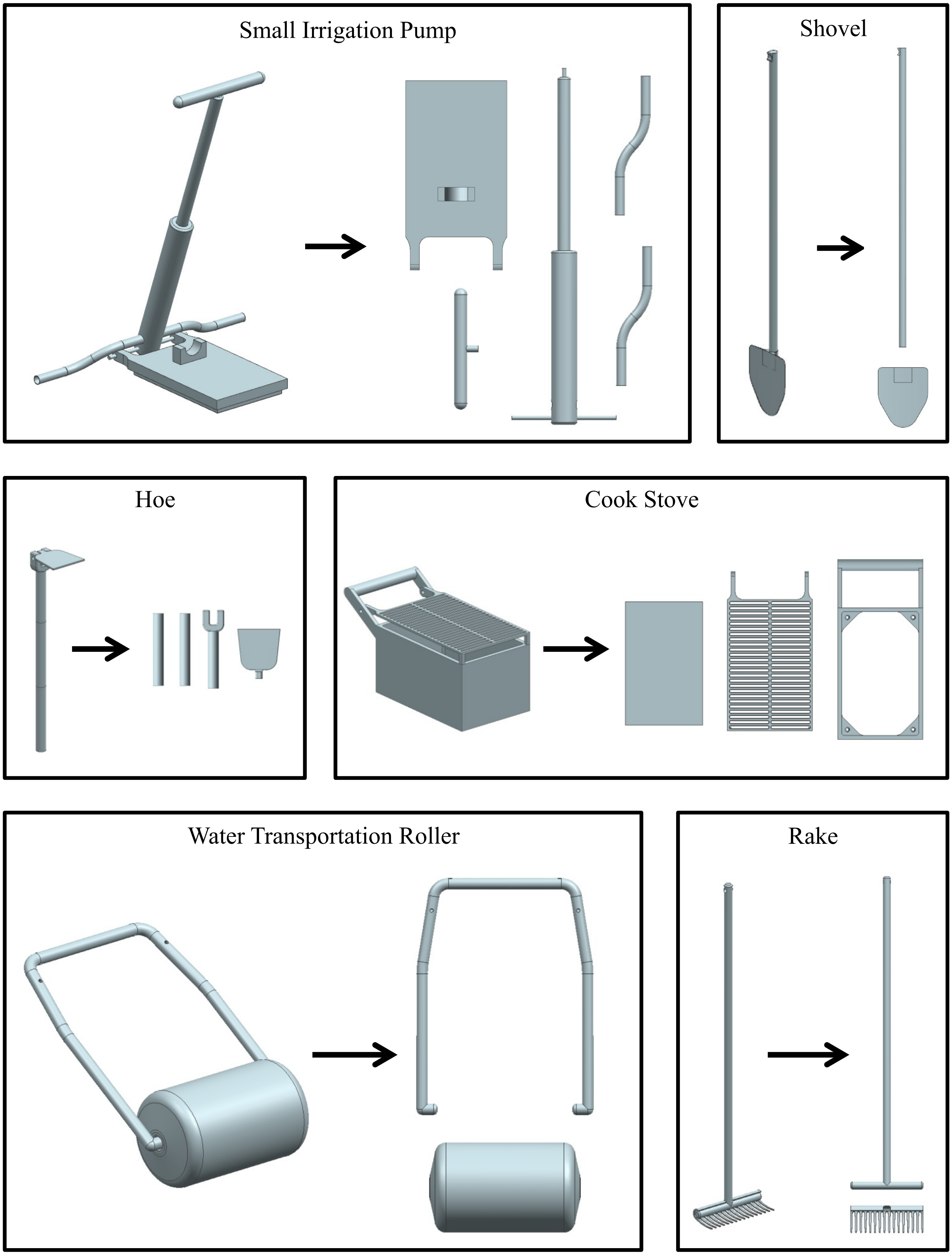

Figure 2.3: Decomposition of each product in the identified product set to create a brick press

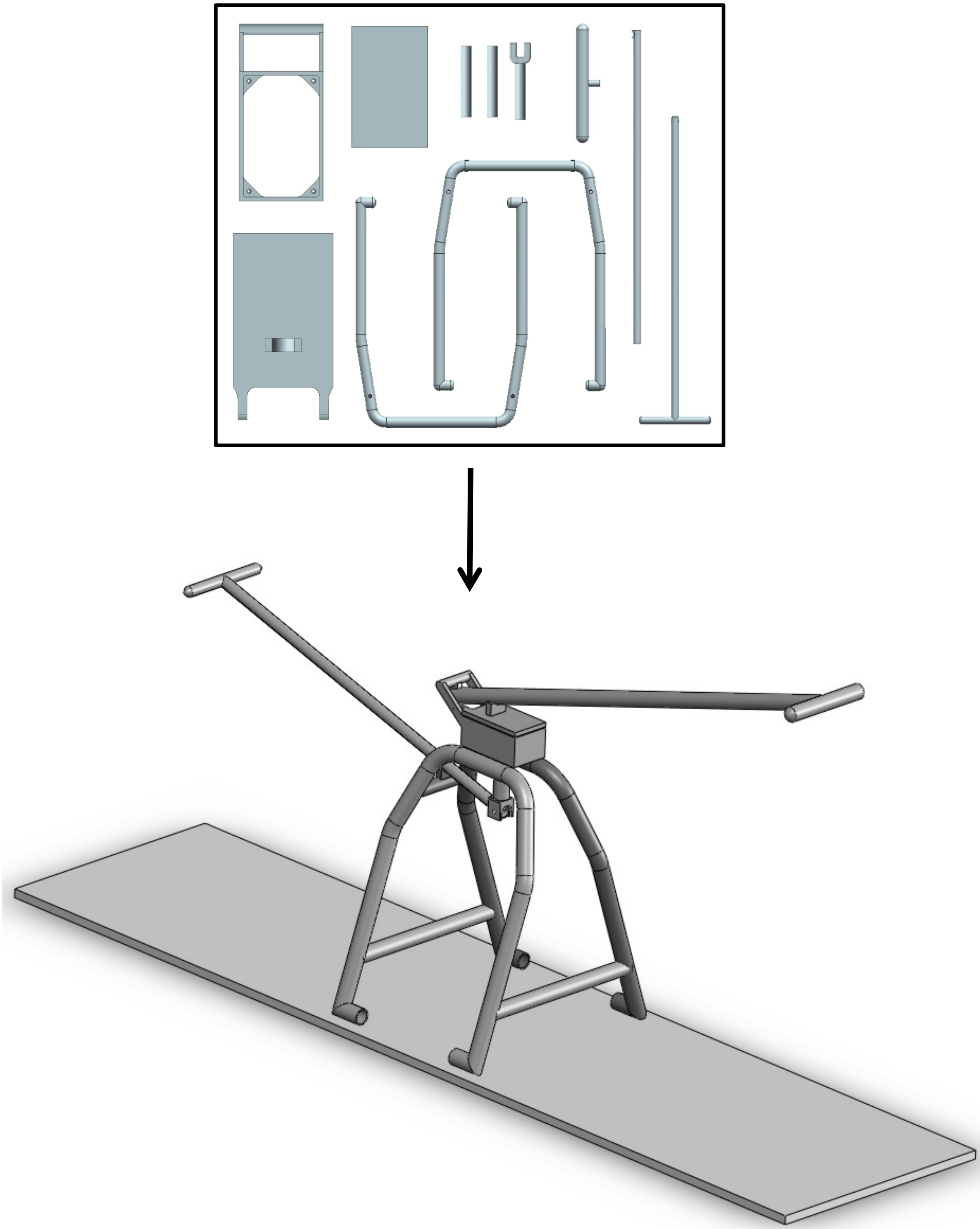

Figure 2.4: Illustration of the recombination of the components from the product set in Figure 2.3

2.4.3 Example Step 3: Decompose the selected product into components

A decomposition process was carried out after selecting the brick press to determine the component make-up. As is presented in Section 2.3.3, the product is to be decomposed by structure, function, and characteristics. See Table 2.1 for the completed decomposition of the brick press.

Table 2.1: Brick press decomposition

Component	Structural	Functional	Characteristic
Press Mold	Mold	Hold Material	Rectangular Basin
Legs	Long Handles	Press to ground interface	Cylindrical Tubes
Long Posts	Long Handles	Leverage	Cylindrical Tubes
Handles	Short Handles	Human to press interface	Cylindrical Tubes
Mold Cover	Cover	Pressure Plate	Rectangular Plate
Eject Plate	Plate	Brick Ejector	Rectangular Plate

The decomposition allows the designer to easily see the make-up of the selected product and begin identifying components that can solve different broad customer needs.

2.4.4 Example Step 4: Determine what other products can be created from the components to fulfill different broad customer needs, while if desired, adding missing secondary components

During this step the other broad customer needs identified in Section 2.4.1 were reviewed. This was done by determining what other products could be created from the components to fulfill these needs. In this example, components that make up the brick press were identified and it was determined how these components fulfilled other broad customer needs. The identified needs and the corresponding products used to fulfill each need can be found in Table 2.2. Also note that necessary secondary components were added to complete the design of each product in the table.

2.4.5 Example Step 5: Identify interfaces between components

To complete the collaborative design process, interfaces are then added to ensure complete usability of the products. The brick press will experience large forces during operation and will

Table 2.2: Other products created to fulfill different customer needs

Need	Component(s)	Product	Secondary Component(s)
Cooking	Press Mold, Eject Plate	Cook Stove	Cook Surface
Water Transportation	Legs	Water Roller	2 Water Barrels
Fresh Water	Press Cover	Water Pump Base	Pump, Hoses
Farming	Long Handle 1	Shovel	Blade
Farming	Long Handle 2	Rake	Tines
Farming	Short Handles	Hoe	Blade

therefore require interfaces that ensure a robust design. It is important to identify interfaces that allow high functionality of the brick press in its collaborative state as well as in its individual state, but also achieve the lowest possible cost. As was stated in Section 2.3, these interface design methods exist in the literature [80, 81].

2.4.6 Example Step 6: Characterize the collaborative design space of the product set and collaborative product

Once the collaborative product has been sufficiently developed, the designer then characterizes the collaborative design space of the six basic products as discussed in Step 6 of the presented method (see Section 2.3.6). This is carried out by constructing mathematical models of each product in the product set. It is important to construct robust models that accurately represent each product to ensure that they hold up to the optimization under realistic conditions. Table 2.3 summarizes the objectives ($\uparrow$ = maximize, $\downarrow$ = minimize) that were selected to characterize the performance of each product. Definitions of the objectives presented in Table 2.3 are as follows: (i) for the shovel, rake, and hoe the objective μ_1 represents the maximum bending stress in the product's handle; (ii) for the water roller and brick press, μ_1 represents the maximum bending, shear, and buckling stress that each product could experience; (iii) for the cook stove, μ_1 represents the available area for cooking food; (iv) for the water pump, μ_1 represents the rate at which the pump can pump water; and (v) the objective μ_2 represents the cost to purchase each product.

Once the collaborative product has been sufficiently developed, the designer then characterizes the collaborative design space of the six basic products as discussed in Step 6 of the presented method (see Section 2.3.6). This is carried out by constructing mathematical models of each product in the product set. It is important to construct robust models that accurately represent

each product to ensure that they hold up to the optimization under realistic conditions. Table 2.3 summarizes the objectives (↑ = maximize, ↓ = minimize) that were selected to characterize the performance of each product. Definitions of the objectives presented in Table 2.3 are as follows: (i) for the shovel, rake, and hoe the objective μ_1 represents the maximum bending stress in the product's handle; (ii) for the water roller and brick press, μ_1 represents the maximum bending, shear, and buckling stress that each product could experience; (iii) for the cook stove, μ_1 represents the available area for cooking food; (iv) for the water pump, μ_1 represents the rate at which the pump can pump water; and (v) the objective μ_2 represents the cost to purchase each product.

Table 2.3: Summary of the objectives that were selected for each product in the product set and collaborative product

	↑ / ↓	μ_1	↑ / ↓	μ_2
Shovel	↓	Stress (psi)	↓	Cost ($)
Rake	↓	Stress (psi)	↓	Cost ($)
Hoe	↓	Stress (psi)	↓	Cost ($)
Water Roller	↓	Stress (psi)	↓	Cost ($)
Cook Stove	↑	Cook Area (in^2)	↓	Cost ($)
Water Pump	↑	Flow Rate (L/s)	↓	Cost ($)
Brick Press	↓	Stress (psi)	↓	Cost ($)

From the models and their corresponding functions, design variables, and design objectives a multi-objective optimization problem was constructed in the form of *(P2)* in Section 2.3.1. From this optimization problem, the design spaces for each product was then defined with their corresponding Pareto frontiers (See Figure 2.5).

2.4.7 Example Step 7: Define the areas of acceptable Pareto offset

In this step, the area of acceptable Pareto offsets was defined. Since there are two objectives for each product in the product set and collaborative product, the value of β is equivalent to defining a circle of radius β around each identified Pareto point from Step 1. For these two-dimensional cases, the value of β represents the maximum allowable length of a two-dimensional

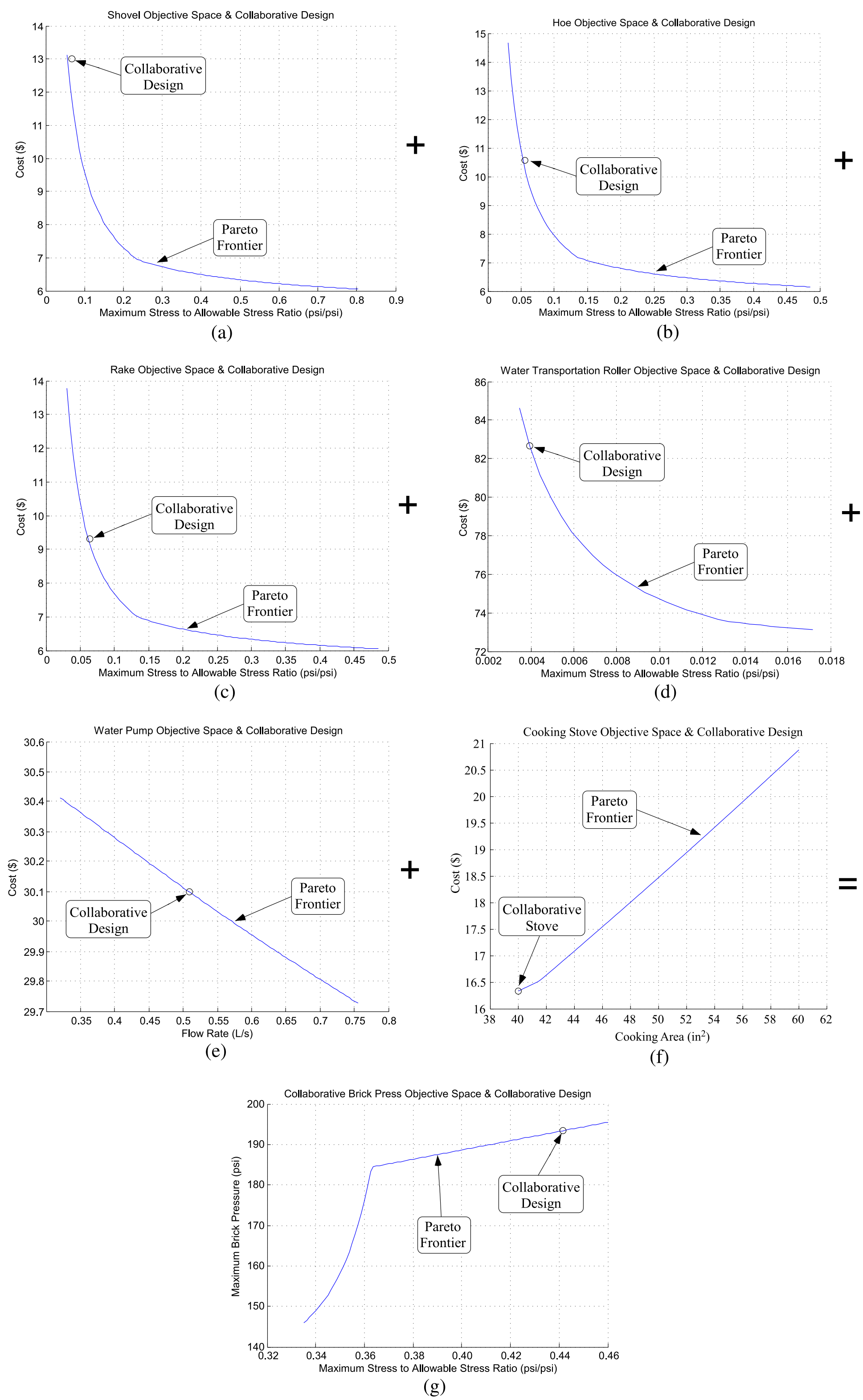

Figure 2.5: Graphical illustration of the Pareto frontiers for each product obtained through Step 1 of the method, and the optimal collaborative design of each product identified in Step 4 of the method.

vector between a design option and the closest Pareto point. For our example, the β offset values were defined as shown in Table 2.4 for each product.

Table 2.4: Defined acceptable offset values (β) for the normalized objectives of each product

	β Value
Shovel	0.5
Rake	0.1
Hoe	0.1
Water Roller	0.1
Cook Stove	0.1
Water Pump	0.1
Brick Press	0.1

2.4.8 Example Step 8: Identify the designs that collaboratively fall within the areas of acceptable Pareto offset

Once the offset areas were defined, the combinations of designs that fall in each offset area were identified using a multi-objective problem statement of the form of *(P3)* (see Section 2.3.3). Because it is a multi-objective optimization problem, a graphical representation of the results of evaluating this formulation carries no visualization value due to its dimensionality.

2.4.9 Example Step 9: Identify/select the optimal product designs

As was mentioned in Section 2.3.4, an aggregate objective function was used to select the optimal combination of product designs. In this example a weighted sum of offsets was used with all weights equal to one except for the brick press, which was equal to 10. The weights were selected with the goal of minimizing the offset of the collaborative product (brick press) from the corresponding Pareto frontier. The resulting design selection using these weights is illustrated in Figure 2.5.

From the results presented in Figure 2.5 it can be observed that the identified design for each product is located on the Pareto frontier of the corresponding product objective space. Although the selected aggregate objective function and weights were successful in identifying designs on or near the Pareto frontier of each product, the majority of these designs are located near the boundaries of the Pareto frontiers. If solutions are more desirable in a particular region of the identified Pareto frontiers, additional constraints or alternative aggregate objective functions would need to be explored.

Illustrated in this example, the task-per-cost ratio of the collaborative brick press has increased. More specifically, and assuming that the calculated total cost of all components making up the newly designed brick press are $160 and are capable of completing seven different tasks, the ratio will be 0.043. For comparison, a comparable brick press, cook stove, small irrigation pump, shovel, rake, hoe, and water transportation rollers approximately cost a total of $200 with a ratio of 0.030. This illustrates that the task-per-cost ratio has improved by 30% from 0.030 to 0.043 through the use of this method [6].

2.5 Conclusions

This chapter has presented a method by taking domain knowledge and using the information when designing products for optimal collaborative performance with application to engineering-based poverty alleviation. The primary result of this method is the ability to optimize the collaborative performance of a set of products while dealing with the various, and often complex, performance interactions between the products and the collaborative product. To reiterate, all products are being simultaneously optimized not only on an individual level, but on a collaborative level. Through the optimization, the collaborative performance is optimized while dealing with the various trade-offs between the products and the collaborative product.

As described in the introduction, the task-per-cost ratio can be observed to more fully understand the potential impact a collaborative product may have on alleviating poverty. The method presented in this chapter is an optimization-based strategy for selecting designs of a given collaborative product set. The ability of this method to optimize based on objectives like cost and task performance, enables the task-per-cost ratio of the product set to increase. As such, the resulting collaborative product would have a higher potential impact and application within the developing world. To illustrate application of this method, a collaborative brick press created by combining a shovel, hoe, rake, water transportation roller, water pump, and a small cook stove was provided. As stated earlier, we do not suggest that this brick press should go into production but that it is used to show that knowledge from one domain can be used when creating a collaborative product in another domain.

From the example, and the presented results, the authors believe that the presented method has the potential to be an effective tool for designing products for optimal collaborative performance. We recognize however that this chapter simply explores the idea that domain knowledge from modularity and multi-objective optimization can be applied to developing world situations. The potential benefit that collaborative products can have on poverty alleviation by reducing the cost, weight, and size of a set of products was presented as motivation for this work. Opportunities for future work that build on this method includes: (i) addition of design objectives and constraints that will ensure that the identified product designs embody these goals of reducing the cost, weight, and size of a set of products; (ii) further research in the correlation of the task-per-cost ratio to the impact and implementation of a collaborative product; and (iii) explore additional indicators, such as income generation-to-cost ratio, to better understand the impact that collaborative products will have on poverty alleviation.

CHAPTER 3. ANALYSIS OF PERCEIVED SOCIAL IMPACT OF EXISTING PRODUCTS DESIGNED FOR THE DEVELOPING WORLD, WITH IMPLICATIONS FOR NEW PRODUCT DEVELOPMENT

3.1 Chapter Overview

Engineered products often have more social impacts than are realized. A product review was conducted to bring this to light. In this chapter, we show the extent to which different social impacts in 11 impact categories are co-present in 150 products, and how this can help engineers and others during the product development process. Specifically, we show how social impact categories not previously considered can be identified. The product review resulted in 13,200 data points that were divided into two data sets, one with 8,800 data points from which a social impact probability table was created. The remaining data points were then used to validate the table. All data points were then combined to create a final social impact probability table. This table provides insight for how various social impact categories correlate and can assist engineers in expanding their views to include additional social impact objectives and thus achieve a design with broader social impact or a design with minimized unwanted negative social impact. A simple method for predicting social impact is also created in order to assist engineers when developing products with social impacts in mind.

3.2 Introduction

Most engineers design for the purpose of creating value and improving lives. While so doing, engineers transform and combine raw materials into potentially meaningful products. To be sustainable, different processes are often put in place, aimed at making efficient use of materials, energy, and financial resources. This is referred to as the three pillars of sustainability: environmental, social, and economic sustainability [25, 82, 83]. Of these three, the least understood from an engineering design perspective is social sustainability. Social sustainability is defined as positive social impact of a product over time [84]. To better understand a product's social impact over time, we and other researchers have sought to understand how current products impact society [82]. We have done this to inform social impact modeling of new products. In this way the prediction of social impact is a necessary step toward designing for long-term social impact – or social sustainability.

Tools for assessing the environmental and economic sustainability exist today [85] but the evaluation of social sustainability is seldom discussed in literature [31, 86]. This chapter is suggesting that instead of evaluating social sustainability after the fact, a predictive method should be used - just as with economical and environmental sustainability. This would ensure that resources that are being spent on developing products will have greater potential impact.

To help deepen the understanding of social sustainability, its impact, and how it can be implemented, we have carried out a three-tier approach aimed at a deeper understanding on how engineered products impact society. The first two tiers, a literature review to understand the different areas of social impact [1], and an industry review on practices for how social impact is considered and measured during product development [7, 8] have already been published by the authors. The third tier is the focus of this chapter; what we can learn from the social impacts of existing products, how different social impact categories are correlated, and how we might use that information to anticipate the social impact of new products.

We believe that understanding the social impact of existing products and the extent to which the social impact categories found in literature [1] correlate one to another will allow us to better anticipate the social impacts of a product during the product development process, leading to the creation of products with greater social impact.

3.3 Evaluating Social Impact

To be clear, the definition of social impact used in this chapter is the impact that engineered products have on the day-to-day lives of persons or communities [26]. The day-to-day impact on people is important since it is what creates a lasting effect for everyone–a positive improvement in the quality of life of those who come in contact with the products. In our review of industry practice [7, 8], we have found that many engineers lack the tools they need to be able to design for and measure social impact of their products during and after the development process.

Table 3.1: Social impact categories [1]

Well-being and Inequality	Demographics	Interaction and Identity
Impact 1. Health and Safety	*Impact 5. Education*	*Impact 9. Conflict and Crime*
Safety and security (real and perceived), activity/exercise, mental and physical health, mortality, improvement of life/health from product	Education, skills, empowerment	Potential conflicts, crimes, increased or decreased substance abuse, potential of assault
Impact 2. Paid Work	*Impact 6. Family*	*Impact 10. Social Networks and Communication*
Earning potential, industrial diversification/change in economic focus	Alteration in family roles, structure, violence, stressors, ties and role in society	Impaired or improved personal relations, network's reliance on participation in decision making process
Impact 3. Stratification	*Impact 7. Gender*	*Impact 11. Cultural Identity/Heritage*
Social capital, inequality, introduction of new classes, social status, social mixing	Gender roles, violence, stressors, inequality	Weakening/strengthening of values, norms, and beliefs, cultural intolerance, personality traits
Impact 4. Human Rights	*Impact 8. Population Change*	
Human rights, respect for indigenous and minority rights, democracy/decision making participation	Transiency of population, age structure, presence of seasonal population	

3.3.1 Tier 1: Literature Review

As a first step to increasing the social impact of a product, it is helpful to become familiar with the different types of social impacts a product can have. To facilitate this, we refer to Rainock et al. [1] where they gathered categories of social impact from both sociology and engineering literature. These categories were identified for the purpose of helping to better understand the social impacts of products designed but also for the purpose of discovering and assessing such impacts. We do not claim that the social impact categories herein to be exhaustive, but use them as a standard found in the literature to compare the 150 products against.

For visual simplicity, we have summarized the data into the form shown in Table 3.1. This table has three major impact categories, shown as columns, and multiple sub-categories shown as rows. Note that there is no implied importance or other meaning to the order of the columns or rows. We have numbered each sub-category to simplify referencing.

To familiarize the readers with these categories, and subcategories, the following sections provide brief definitions and further explanations of each category beyond that which is given in the Rainock et al. paper. We do this in order to show how these findings apply to engineering. To clarify them further, we have also included brief examples of actual products from our review of 150 products with names in parenthesis. It is important to note that these examples can also have other social impacts beyond those that are listed here. For example, the GRIT Leveraged Freedom Chair have impacts in Health and Safety, Paid Work, Stratification, Human Rights, Education, Family, and Social Networks and Communication and Contraceptives have impacts in Health and Safety, Stratification, Human Rights, Family, Gender, and Population Change. A brief description and source for each of the 150 products can be found in Table 3.2.

Impact 1: Health and Safety. Health is said to be "a state of well-being" [87]. This state of well-being can be impacted by the products an individual is surrounded by. Examples of products that impact health are jaundice treatment lights for newborns (BlueRay Phototherapy), adjustable flues that reduce smoke in biofuel cooking (Cocina Veloz), products enabling family planning (Contraceptives), and products that promotes an active lifestyle (DIY Soccer Ball and the GRIT Leveraged Freedom Chair). Safe housing (UtiYurt), collection device for used needles (Antivirus), and a shield that absorbs shock waves from land-mines (Spider Boot) are examples of products that impact safety.

It is also valuable to consider the ways in which products affect *Health and Safety* even when they are not obviously a health or safety product such as flashlights (BOGO Light) or informational games (Freedom HIV/AIDS) [88, 89].

Impact 2: Paid Work. Paid work refers to employment opportunities that can be found within a community that are available to individuals. It also refers to changes in employment rates and economic focus within a company or product portfolio [88]. While some products can increase the amount of available jobs in a region, other products can simplify work tasks and thus have a negative impact on the amount of jobs in a community and thus impact the local and personal economy [90–92]. Successfully gaining employment often has a great impact on the worker's self-esteem and leads to other positive outcomes such as greater ability to afford food and shelter [93, 94].

The following products are examples that can create job opportunities: Vehicles that can be used as taxis or to transport goods (Basic Utility Vehicle), devices that can charge electrical devices (SolarRolls), and products that can refine grains and other goods (Burr Mill). Other products, like a wheelchair, can make it possible for a person to get to work (GRIT Leveraged Freedom Chair). These, and products like them, impact employment or can be used to generate income.

Impact 3: Stratification. Stratification refers to social class and the formation of social status [95]. Its purpose is to place people in a social rank according to their contribution to, and their worth in society, resulting in inequalities [87,96]. Products that enable education and learning (eGranary Pocket Library), provide internet in rural areas (AMD Personal Internet Communicator), and enable near-instant translation of languages (Pilot) are examples of products that can enable people to cross over into new stratification layers and give them opportunities that lead to a higher social ranking. Products that enable people to choose when and how to contribute to society will also impact this category (GRIT Leveraged Freedom Chair and Contraceptives).

Impact 4: Human Rights. Human rights "are those liberties, immunities and benefits which, by accepted contemporary values, all human being should be able to claim 'as of right' of the society in which they live" [97]. Since a product can have both a positive and a negative impact on human rights, these rights must be taken into consideration and must be protected and justified by everyone [1]. These rights are the embodiment of the collective conscience of a society [87]. Examples of products impacting this area are those that enable the blind the basic right of reading (Tack-Tiles Braille System), kits for newborns, making sure their inherent right to be safely born and cared for in their first moments of life is fulfilled (Shishu), and shelters for refugees (Global Village Shelter). Other examples are wheelchairs that give back mobility (GRIT Leveraged Freedom Chair) and contraceptives that provide people greater freedom relative to the complexities of family planning versus health/financial/career planning.

Impact 5: Education. Education is the opportunity to learn or the process for gaining new knowledge and capabilities. It can be acquired formally or informally [88, 89]. Access to education has almost universally great social impact and improves the lives of those involved [98, 99]. It can also empower the students by changing their engagement in the community [88]. Products that give light in the home (The Solar Home Lighting System), those that can provide information and curriculum to students (One Laptop Per Child), give close access to water, eliminating time spent carrying water far distances (Village Drill, providing access to groundwater), and that enable students to go to school (GRIT Leveraged Freedom Chair) creates impact in this area.

Impact 6: Family. Family is a close domestic group bounded by blood or legal ties. This union is traditionally for raising children and supporting each others' survival [95, 100]. Products can create stronger bonds within the family unit, reduce quality family time, and also cause a change in how each member perceives their individual role by changing how routine tasks are performed [1]. Products providing basic needs such as cooking (Ecocina Cookstove), maximizing the use of family resources by preventing food from spoiling (Pot-in-Pot Cooler), enables family planning, and help facilitate family members to carry out their roles (GRIT Leveraged Freedom Chair) are examples of products that have impact on the family.

Impact 7: Gender. Gender refers to the social and cultural norms associated with identifying as masculine or feminine as well as the social roles enacted by men and women. Although products typically do not affect one's gender identity directly, a product can impact or reinforce gender roles, gender inequality, and gender-based violence [95]. These impacts can be manifest within a family, the workplace, or other social settings [101, 102]. Self-defense products (Subtle Safety Ring), postpartum kits (Janani), and birth control products (Contraceptives), all of which can empower women are examples of products that have impact in this area.

Impact 8: Population Change. Population change is a measure that accounts for the deaths, births, and the move-ins/move-outs of a population [87]. Population change can be linked to products [92]. One example is a product that influences a population in such a way that it causes move-ins/move-outs of the population [92] – such as irrigation (iDE Sprinkler Irrigation) or a sanitation system (Daily Dump) being added to a community, thus increasing the desirability of that community. Another class of products that impacts this area is shelter (A Better Shelter). Lastly, products that help manage family size will also impact this category (Contraceptives).

Impact 9: Conflict and Crime. Conflicts are activities that go against the social establishment. The impacts can be both positive and negative. On the one hand, conflict can strengthen a group's purpose and identity. But, on the other hand, conflict can cause groups to fracture and break up [87]. Crime is defined as a violation of set laws [95]. Conflicts are usually punished by the social network while crimes are punished by set laws [87]. Products can be used to reduce the probability of, but also to perpetrate a crime. An example of a product that can reduce the probability of crime is the street light (Starsight Project). Mobile phones can be used when perpetrating drug and gang crimes (Nokia 1100). Temporary housing for refugees (Rapid Deployable System) can ease the negative impact of conflict.

Impact 10: Social Networks and Communication. A social network is "a finite set of actors and the relation or relations defined on them" [103]. Social networks can be divided into three units: Micro level (small groups), meso level (organizations or fields), and macro level (cities or nations). These levels can have no connections, weak connections, or strong connections between them [87]. Product impacts can make network connections within a level stronger or weaker, even to the point of dissolving them [98, 102, 104]. Bicycles (Calfee Bamboo Bike), wheelchairs (GRIT Leveraged Freedom Chair), and other vehicles that create mobility impact the size of networks and lead to an increase of interactions between people.

Communication is the "process by which messages are transferred from a source to a receiver" [105]. It is found in every social situation and can be broken up into five different types of communication: Conversation with self, face-to-face interactions, group communication, mass communication, and non-human communication (communication with machines and computers). The type of communication that is carried out and the effectiveness of it can impact social systems because of how a message can be interpreted or understood [95]. Clearly, products can change how communication is done [102]. Mobile phones (Nokia 1100), Wi-Fi hotspots (Internet Village

Motoman), and translation devices (Pilot) are some examples of products in this area.

Impact 11: Cultural Identity/Heritage. "Cultural heritage is an expression of the ways of living, developed by a community and passed on from generation to generation, including customs, practices, places, objects, artistic expressions and values" [106]. Products can influence the ways that cultural heritage is passed on from generation to generation and thus change the identity and heritage of a culture over time [89,104,107]. Products that can utilize local skill sets and crafts (The Portable Light Project) and provide enlightenment on cultural behavior and stigmas by showing correlation between HIV in infants and cultural practices [108] (DFA POC Diagnostics: Nucleic Acid Detection) are examples that impact cultural identity and heritage.

3.3.2 Tier 2: Industry Review

In the industry review conducted by Pack et al. [7, 8], the 11 social impact categories introduced in [1] and discussed in the previous section were used to understand to what extent these impacts were being considered by professional engineers in industry. Interviews were conducted with 46 industry professionals to glean insights regarding processes, metrics, and general perspectives relating to the social impact categories. In the study, it was found that not all impact categories are considered equally when designing a product (see Figure 3.1). Additionally, it was found that very few processes exist to predict and quantify the social impact of a product.

Pack et al. conclude from the industry review that engineers lack sufficient tools to assist them in their work to consider social impact holistically and that they rely heavily on intuition to inform many of their product decisions that affect social impact [7, 8].

3.3.3 Tier 3: Product Review

Recall that the purpose of this three tier approach, is to help deepen the understanding of what social impact is and how engineered products impact society. With this, we hope to shift engineering decisions relative to social impacts from being intuition based to instead being information based. To assist with this, we conducted a review of 150 existing products to find the extent to which the social impact categories discussed in Section 3.3.1 appear together in engi-

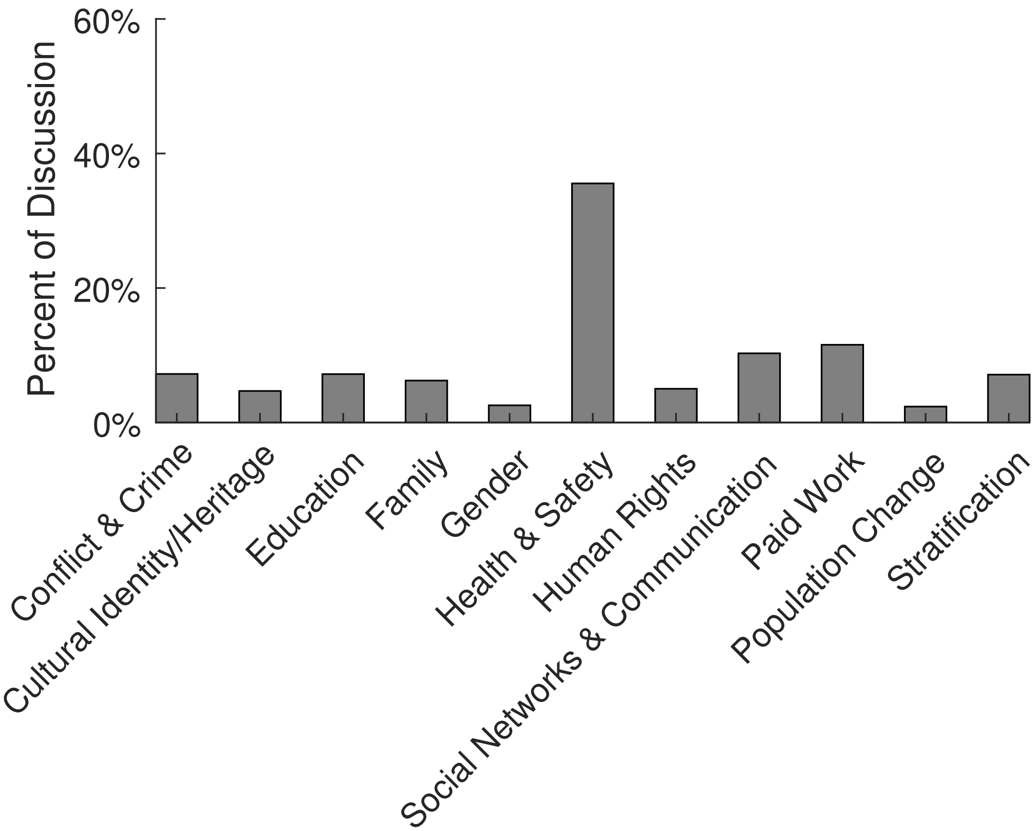

Figure 3.1: Percent of social impact considerations in each social impact category [7, 8]

neered products. As will be shown, this review lays the foundation for predicting social impacts of products.

The next section will discuss the research approach, followed by a results section. These results will then be discussed and a method for predicting social impact will be presented.

3.4 Research Approach

The product review was carried out by a multidisciplinary team which choose a set of products to be included in the product review, they then evaluated each product related to social impact categories found in Section 3.3.1. The correlation between the different social impact categories was then discovered and a probability chart was developed. Below is an overview of how the product review was carried out:

1. Choose team (Section 3.4.1),

2. Select criteria for including products (Section 3.4.2),
3. Create product review instrument (Section 3.4.3),
4. Distribute instrument (Section 3.4.3),
5. Evaluate instrument data (Section 3.4.4), and
6. Evaluate the results (Section 3.5).

The results from the product review, the correlation of social categories, and a social impact probability table can be found in Section 3.5.

3.4.1 Research Team

Being cognizant that we cannot fully eliminate research bias, the product review and evaluation were carried out by a team of people from both sociology and engineering disciplines. The team consisted of three females and one male social scientists, and two female and two male engineers. Age, home country, and educational level were also considered when choosing the respondents. Three had an age above 35, two grew up and received university degrees outside the US (Europe and Asia) and three had graduate degrees. (See Section 3.5.1 for the intraclass correlation coefficient for the respondents).

3.4.2 Selection Criteria for Products

The following questions were used as selection criteria for the products that were included in the review. Products for which 'yes' was the answer for all questions were included.

1. Is the product designed specifically for social impact?
2. Can we learn something about social impact from this product?
3. Does the product have the potential to better the life of a person using it?

The products included in the analysis were selected from our own findings, conference proceedings by Troxell and Kim [109], and from two books, one by Pilloton [110] and the other by Smith [111].

One hundred fifty products were chosen to be included in the product review. These products can be found in Figure 3.2 with their names, descriptions, and sources in Table 3.2. While many if these products were designed for the developing world, the findings in this chapter may also benefit any product that is designed with a specific social impact in mind, regardless of its intended market. For example, while the GRIT Leveraged Freedom Chair is designed for a foreign market and has impacts in categories 1, 2, 3, 4, 5, 6, and 10, the GRIT Freedom Chair is its domestic counterpart that also has social impacts, but in slightly different categories; impacts 1, 3, 4, and 5. From this, we observe that products can be designed for social impact regardless of whether it targets the developing world, the developed world, or both simultaneously. We acknowledge that the review of products in this chapter is not exhaustive. We also acknowledge that the impact assessed is "perceived impact" and in light of this we chose the best set of respondents we could.

Table 3.2: Products included in the analysis

	Product name	**Product description**	**Source**
1	Adaptive Eyecare	Corrective eyeglasses with adjustable prescription	[110]
2	Afridev pump	Lever action hand pump for water	[112]
3	Air X (wind turbine)	Efficient small wind turbine for low energy needs	[110]
4	Air2Water Dolphin 2/Dragonfly M18 (atmospheric water generator)	Atmospheric water generator that collects and purifies water from the surrounding air	[110]
5	Alcohol Stove	Alcohol stove made with locally sources materials	[110]
6	Alive and Kicking (soccer ball)	Soccer ball with educational messages printed on the ball for developing countries	[110]
7	AMD Personal Internet Communicator	Device to allow people in less developed countries access to internet	[111]
8	Antivirus (needle canister)	Cap that turns a regular soda can into a safe needle disposal	[110]
9	Aquacube Containerized Water Treatment Plants	Mobile water-treatment plant, all in a shipping container	[110]
10	Aquaduct (water filtration)	Bicycle that stores and filter water during transport	[110]
11	AquaPak	Portable bag for pasteurization of water by the use of sunlight	[110]
12	Aquastar Flow Through	System that treats water in large batches, enough to generate income	[111]
13	Aquastar Plus!	Portable UV water treatment system in a bottle	[111]
14	Bamboo Treadle Pump	Affordable water pump for irrigation	[111]

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Table 3.2 – continued from previous page

	Product name	Product description	Source
15	Basic Utility Vehicle (BUV)	Economic vehicle to transport goods and people	[110]
16	BCK Solar Cooker	Solar powered food cooker	[110]
17	Berkeley Darfur Stove	Fuel-efficient stove with low emissions	[113]
18	Better Shelter	Innovative housing solutions for displaced people	[114]
19	Big Boda Load-carrying Bicycle	Affordable bike built for carrying heavy loads	[111]
20	BioLite HomeStove	Clean burning stove with the ability to charge USB powered devices	[115]
21	BioSand Water Filter	Household water filter	[116]
22	BlueRay Phototherapy	Affordable infant phototherapy device with long-lasting LED lights	[110]
23	BOGO Light	Long lasting solar LED flashlight	[110]
24	BRCK	Durable mobile WiFi hotspot, providing internet in rural areas	[117]
25	Burr Mill	Economic and reliable crop mill	[110]
26	Calfee Bamboo Bike	Bike with frame made of bamboo	[110]
27	Clay Water Filters	DIY clay water filter	[110]
28	Cocina Veloz (pot skirts)	Pot skirts that improve most stoves thermal efficiency and reduces required fuel	[118]
29	Community Cooker (kitchen)	Communal cooker/oven that uses trash for fuel	[119]
30	Contraceptives	Device or drug that prevents pregnancy	[120]
31	Cyclean (washing machine)	Pedal-powered washing machine	[110]
32	D.Light A1 Solar Lantern	Affordable, portable solar lantern	[121]
33	Daily Dump (compost system)	Pot compost system	[110]
34	Day Labor Station	Employment hiring center	[111]
35	DFA POC Diagnostics: Immunity	Low-cost diagnostic tool to test for successful vaccination against tetanus and measles	[122]
36	DFA POC Diagnostics: Liver Function	Low-cost liver function test	[123]
37	DFA POC Diagnostics: Nucleic Acid Detection	Device for early diagnosis of HIV in infants	[124]
38	DFA POC Diagnostics: Small Farmer Support	Heat test for cows for minimally-trained technicians	[125]
39	DIY Biodiesel and Strait Vegetable Oil (SVO) Fuel	Eco friendly biodiesel	[110]
40	DIY Soccer Ball	Stitched soccer ball casings sold by AIDS victims	[110]

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Table 3.2 – continued from previous page

	Product name	Product description	Source
41	DREV Low-cost Microscope	Low-cost microscope	[126]
42	DREV ReMotion Knee	Affordable high-performance knee joint for amputees	[127]
43	DTM Firefly Phototherapy	Jaundice treatment in newborns	[128]
44	DTM NeoNurture Newborn Incubator	Low-cost newborn incubator	[128]
45	DTM Otter Newborn Warmer	Affordable solution to prevent hypothermia for premature newborns	[128]
46	DTM Pelican Pulse Oximeter	Portable pulse oximeter to diagnose pneumonia in newborns	[128]
47	Ecocina Cookstove	Mini Ecosystem that uses fauna and bacteria to treat water and sewage	[129]
48	Eco-Machines (mini ecosystem)	Cookstove that reduces fuel consumption and pollutants	[110]
49	eGranary Pocket Library	Database with educational materials stored on a microchip	[130]
50	Envirolet FlushSmart VF	Low-flush, vacuum toilet that composts the waste	[110]
51	EyeNetra NETRA Autorefractor	Smartphone powered mobile eye diagnostic and vision screening	[131]
52	EyeNetra Netrometer Lensometer	Smartphone-based netrometer	[132]
53	EyeNetra Netropter Handheld Phoropter	Affordable and portable phoropter	[133]
54	FairWater BluePump	Hand pump for water wells	[134]
55	Freedom HIV/AIDS (game)	Game to increase awareness for HIV/AIDS	[110]
56	Freeplay Encore Radio	Rechargeable world radio with ability to charge USB devices	[135]
57	GCS Bicycle Phone Charger	Phone charger integrated on a bicycle	[136]
58	GE Vscan Portable Ultrasound	Portable ultrasound device	[137]
59	Global Village Shelter (housing)	Low cost emergency shelters	[111]
60	Grameen Danone	Affordable yogurt that compensates for nutritional deficiencies	[110]
61	Green Cell (battery dispenser system)	Universal battery dispenser system	[110]
62	GreenFire Technology Stoves	Economic, fuel-efficient cookstove	[110]

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Table 3.2 – continued from previous page

	Product name	Product description	Source
63	GRIT Leveraged Freedom Chair	Wheelchair for use in rough terrain	[138]
64	GROW	Hybrid device to collect solar and wind power	[110]
65	Hippo Roller	Economic water transportation	[110]
66	HYmini	Solar or wind powered charger	[110]
67	iDE Ceramic Water Filter	Simple filter for cleaning water	[139]
68	iDE Drip Irrigation	Economic irrigation system	[111]
69	iDE Multiple Use Water Storage Systems	Water resource management that taps and stores water for households and small communities	[140]
70	iDE Rope Pump	Low-cost hand pump	[140]
71	iDE Sprinkler Irrigation	Efficient irrigation system	[140]
72	iDE Treadle Pump	Human-powered suction pump for irrigation	[140]
73	iDE Water Storage Systems	Stores water captured in monsoon rains for use during dry season	[111]
74	IKEA SUNNAN Solar Lamp	Solar powered lamp for off the grid households	[141]
75	Inclusive Edge Canopy	Canopy providing a gathering place	[111]
76	India Mark II/III pump	Lever action hand pump for water	[142]
77	IntelMobile Clinical Assistant	Assists healthcare professionals by compiling medical information	[110]
78	Internet Village Motoman	Internet for rural villages	[111]
79	Jaipur Foot Prosthetic	Low-cost foot prosthetic	[110]
80	Janani	Postpartum care kit for women	[143]
81	Janma	Clean birth kits sold in a stylish purse	[143]
82	Kanya	Menstrual hygiene kit	[143]
83	Kenya Ceramic Jiko	Fuel efficient charcoal stove	[111]
84	KickStart Domed Pit Latrine Slab Kit	Slab to seal off human waste in refugee camps	[111]
85	KickStart Moneymaker Block Press	Block press for making durable bricks	[111]
86	KickStart Moneymaker Hip Pump	Lightweight pressure irrigation pump	[111]
87	KickStart Super Moneymaker Treadle Pump	Manual treadle irrigation pump	[111]
88	Kiln	Small natural gas kiln to fire pottery	[144]
89	Kinkajou Microfilm Projector and Portable Library	Low-cost literacy library with solar-powered projector	[110]
90	Lampen	Self electrifying pen that provides light	[145]
91	Laveo	Portable, self-contained toilet that requires no water	[146]

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	Product name	Product description	Source
92	Learning Landscape (playground)	Playground that teaches math through games	[110]
93	LIFESAVER Bottle	Bottle with built in water filtration cartridge	[110]
94	LifeStraw	Water filter for individual use	[110]
95	LifeStraw Family	High-capacity water purifier for families	[110]
96	Low-cost Water Testing	Economical water testing	[110]
97	M2E Technology	Battery charger powered by kinetic energy	[110]
98	Mad Housers Hut (housing)	Secure temporary shelters for displaced people	[111]
99	MakaPads	Cheap disposable sanitary pads for women	[147]
100	Maya Pedal	Repurposes bicycles to create pedal-powered machines	[110]
101	Mechanical Advantage Tourniquet	Self administered tourniquet to stop bleeding	[110]
102	Menstrual Cups	Washable silicon cup to collect menstrual fluids	[148]
103	MIT Lab Sugarcane Charcoal Press	Creates fuel from sugarcane waste	[110]
104	Montessori Toys	Toys to facilitate learning through exploration	[110]
105	Nokia 1100 (mobile phone)	Low-cost and reliable mobile phone	[149]
106	One Laptop Per Child	Laptop for the developing world	[110]
107	OneDollarGlasses	Frames made locally by hand with supplied lenses	[150]
108	PermaNet	Long-lasting insecticidal net for malaria prevention	[151]
109	Pilot (translation device)	Earphones that translates languages in real time	[152]
110	Plumpy'nut	Food bar with high nutritional value	[110]
111	Portable Light Project	Local handcraft with solar panel and LED lights and batteries	[111]
112	Pot-in-Pot Cooler	Simple refrigeration system to preserve crop	[111]
113	Q Drum	Economic water transportation	[111]
114	Rainwater Catchment Systems	System to catch potable rain water	[110]
115	Rapid Deployable System (RDS)	Durable and portable shelter	[110]
116	ReadyPay	Pay-as-you-go solar charger	[153]
117	Roundabout PlayPump	Pumps water from well into a tank by having children play on a merry-go-round	[154]
118	ROVAI Rope Pump	Water pump for the developing world	[110]
119	SAFE AGUA Water System	System for distributing water inside a household	[155]
120	Shishu	Essential kit for newborns	[143]

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Table 3.2 – continued from previous page

	Product name	Product description	Source
121	Single Cell Battery Charger for Portable Electronic Devices	Replaces disposable batteries with rechargeable batteries	[156]
122	Small-scale Photovoltaic-powered Reverse Osmosis (PVRO) Desalination Plants	Produces potable water for remote locations	[157]
123	sOccket	Soccer ball that generates electricity	[158]
124	SODIS	DIY technique to disinfect water with the help of the sun	[110]
125	Solar Aid (hearing aid)	Solar-powered hearing aid charger	[111]
126	Solar Dish Kitchen	Communal solar-powered kitchen	[111]
127	Solar Home Lighting System	Wireless solar-power lighting	[111]
128	SolarRolls	Solar panel charger	[110]
129	Solidarites International Garden-in-a-Sack	Grow produce in a sack	[159]
130	Solio Classic Universal Hybrid Charger	Device to charge electronics using the sun	[110]
131	Spark (computer)	Mobile learning tool for children worldwide	[110]
132	Spider Boot	Boot platform with deflector-shell that absorbs shock waves of land-mines	[110]
133	Starsight Project	Reliable solar lighting to keep public areas lit and to provide internet	[110]
134	Subtle Safety Ring	Ring with sharp point to be used in self defense	[110]
135	Sudanese Refugee Cookware	Easy to transport cookware for refugees	[110]
136	Sugarcane Charcoal	Wood and smoke free cooking fuel	[110]
137	Tack-Tiles Braille System	Interactive braille block learning system	[110]
138	Tessera (game)	Interactive educational game for refugees	[110]
139	UGASTOVE	Stove project that empowers women and creates income generating business opportunities	[110]
140	UtiYurt (housing)	Economic and durable shelter	[160]
141	Vaccine Patch - Transcutaneous Immunization	Needle-free alternative for immunization	[110]
142	Village Drill	Durable, simple, and affordable hand-powered bore-hole drill	[161]
143	Weza Portable Energy Source	Foot powered device to generate energy	[110]
144	Whirlwind RoughRider	Rugged, affordable wheelchair	[110]
145	Windbelt	Utilizes vibrations to generate energy	[110]

Continued on next page

Table 3.2 – continued from previous page

	Product name	Product description	Source
146	World Cart	Cheap transportation solution for developing countries	[162]
147	Worldbike Prototype	High capacity bike	[111]
148	Zambulance	Stretcher on two wheels that can connect to a bicycle or motorcycle	[163]
149	ZeroFly Screen	Screen with incorporated insecticide for livestock	[164]
150	ZeroFly Storage Bag	Food grade storage bag with incorporated insecticide	[165]

3.4.3 Product Review and Distribution

To extract the social impacts of products, a review instrument was created to collect and compare the social impacts as perceived by both social scientists and engineers. We know that the best impact to measure is real-life impact. This however is not easily done since we are looking at long-term, comprehensive impact and actual impact can only be known with data spanning over a large extended period of time (potentially decades). This is why we chose to extract *perceived* impact. This choice is supported by Expert Systems where a knowledge-base is used to make informed decisions [166, 167].

A Qualtrics online survey platform was used to create the review instrument [168]. The review consisted of 1650 questions where 150 products were evaluated relative to each of the 11 social impact categories. Each of the eight respondents evaluated all 1650 questions resulting in 13,200 data points. For each product, the respondent ranked the 11 social impact categories on a Likert scale[1] from *Fundamentally Related* to *Not Related* for the product under evaluation (see Figure 3.3).

To further minimize reviewer bias, the survey platform randomized the order the social impact categories were displayed each time a new product was introduced. The order of the products was also randomized for each respondent. Due to the high number of questions in the survey, the respondents were able to pause and resume the survey to prevent respondent burnout. This resulted in an total average working-time of approximately three hours answering survey questions, spread out over a longer period of time ranging from half a day to several days.

[1]"A scaled response continuum measured from extreme positive to extreme negative (or vice versa) in five, seven, or nine categories" [169].

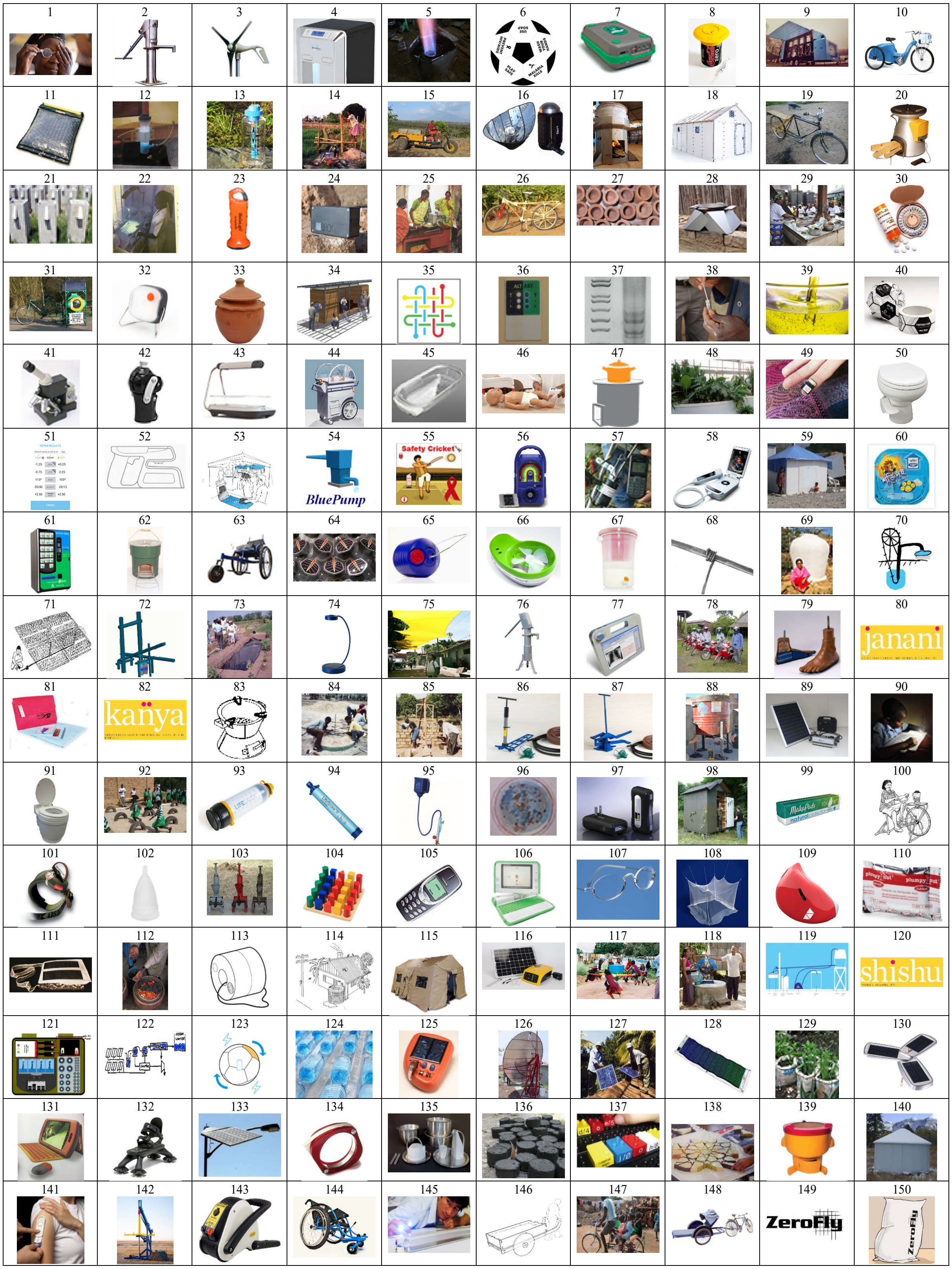
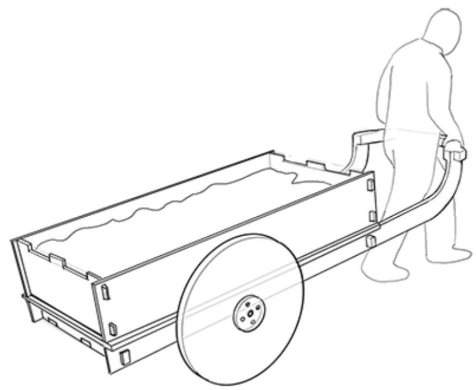


Figure 3.2: Reviewed products. Product names and sources are provided in Table 3.2

Consider the people that need a way to transport goods. In what categories would the World Cart impact their lives?

World Cart



A cheap transportation solution for developing countries.

	Fundamentally Related	Likely Related	Possible Related	Extremely Unlikely Related	Not Related
Impact on Education	○	○	○	○	○
Impact on Family	○	○	○	○	○
Impact on Networks and Communication	○	○	○	○	○
Impact on Human Rights	○	○	○	○	○
Impact on Conflict and Crime	○	○	○	○	○
Impact on Population Change	○	○	○	○	○
Impact on Gender	○	○	○	○	○
Impact on Health and Safety	○	○	○	○	○
Impact on Stratification	○	○	○	○	○
Impact on Cultural Identity/Heritage	○	○	○	○	○
Impact on Paid Work	○	○	○	○	○

Figure 3.3: Example of one question set in the product review instrument

The product review was distributed to the research team discussed earlier in Section 3.4.1. Before starting the review, the respondents were asked to read an instruction sheet and familiarize themselves with the impact categories. The instruction sheet also showed how the review instrument was laid out.

3.4.4 Evaluation of Instrument Data

Statistical tools were used to evaluate the review data and to ensure that it had statistical significance and that there was agreement among the respondents (see Section 3.5.1). The experimental probabilities (based on observations) were then calculated for each social impact category. The co-presence of impacts in two categories were also calculated. Equations 3.1 and 3.2 are for general probabilities, Equation 3.3 is for joint probabilities, and Equations 3.4 through 3.6 are for calculating conditional probabilities (both experimental and theoretical probability are calculated the same way) [170–172]. All analyses were done considering dependent events.

General probabilities:

$$P(A) = \frac{n_{\mathrm{A}}}{n} \tag{3.1}$$

$$P(B) = \frac{n_{\mathrm{B}}}{n} \tag{3.2}$$

Joint probabilities:

$$P(A \cap B) = \frac{n_{\mathrm{AB}}}{n} \tag{3.3}$$

Conditional probabilities:

$$P(A \mid A) = \frac{n_{\mathrm{A}}}{n_{\mathrm{A}}} = 1 \tag{3.4}$$

$$P(B \mid A) = \frac{P(A \cap B)}{P(A)} = \frac{n_{\mathrm{AB}}}{n_{\mathrm{A}}} \tag{3.5}$$

Chain rule of conditional probabilities:

$$P(C_1 \cap \ldots \cap C_k) = P(C_1)P(C_2 | C_1) \ldots P(C_k | C_1 \cap \ldots \cap C_{k-1}) \quad (3.6)$$

where

A, B, and C_i are different events

n_A = Occurrence of event A

n_B = Occurrence of event B

n_{AB} = Occurrence of event A *and* B

n = Number of total sample

Figure 3.4(a) shows the general probability for an event, Figure 3.4(b) shows the joint probability for two events, and Figure 3.4(c) shows the conditional probability for two events.

3.5 Results

The product review produced a total of 13,200 data points from eight respondents. SPSS [173] was used to analyze the consistency of the review responses.

After the agreement of the respondents was analyzed, the data set was separated into two sets in order to use one for validation. The probability of social impacts being associated with the product set was calculated using Equations 3.1-3.3, creating Table 3.5. This table was then validated with the second data set (see Tables 3.6 and 3.7). After the validation, the two data sets were combined to create a probability table that can be used for future design work (see Table 3.8). Equations 3.4 and 3.5 were then used to calculate the conditional probability, capturing the condition when one impact is known to exist and the designer wants to know the probability of other impacts existing concurrently (see rows in Table 3.9).

3.5.1 Respondent Agreement Analysis

The agreement analysis was carried out using SPSS. The intraclass correlation coefficient (ICC) was calculated in a mixed mode to find the agreement between the respondents [2,174].

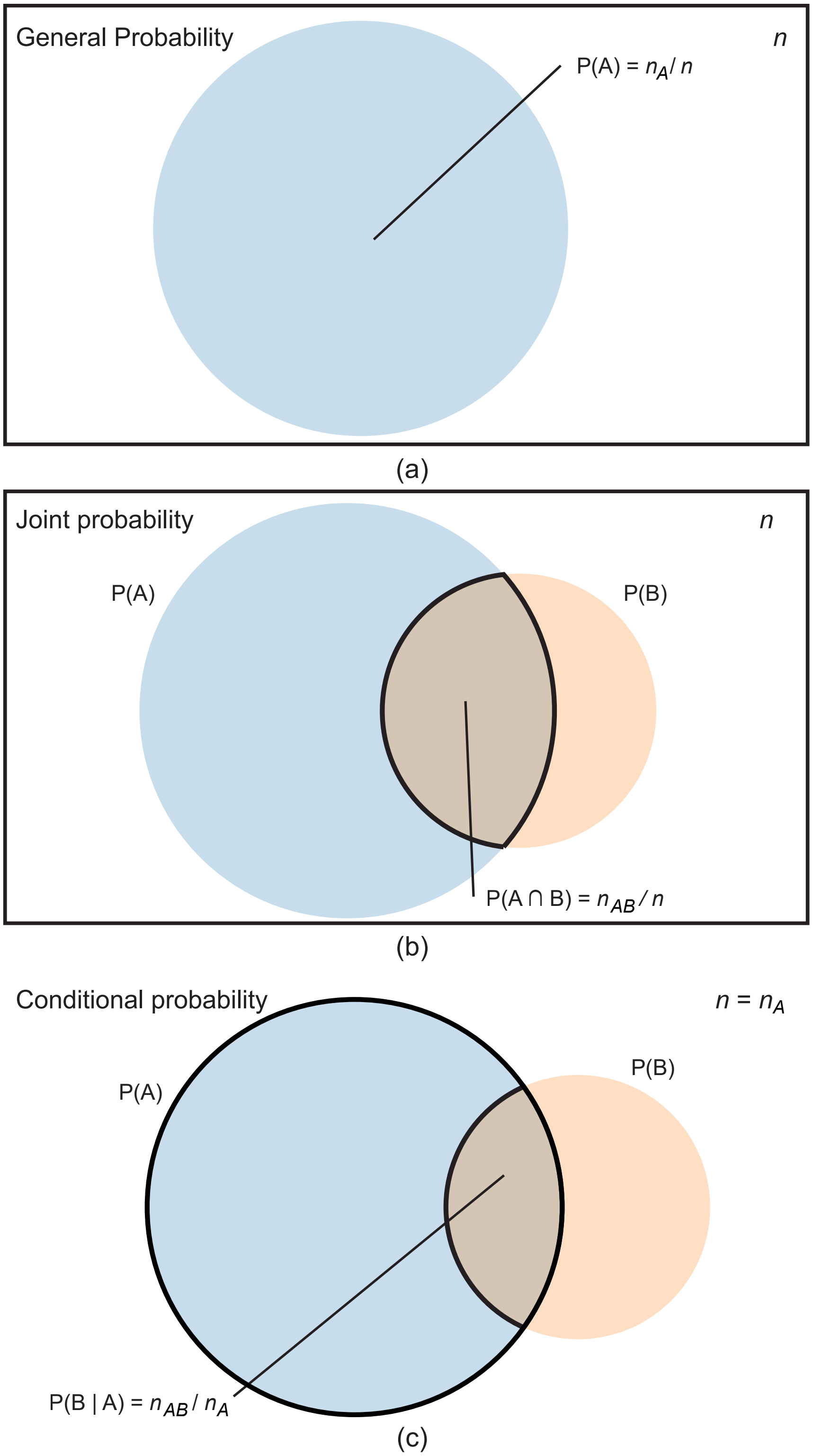


Figure 3.4: Venn diagrams showing general probability for an event (a), joint probability for two events (b), and conditional probability for two events

The ICC was found to be 0.855 with a significance value of 0.00, indicating that there was good level of agreement between the respondents [175]. See Table 3.3 for the ICC results and Table 3.4 for the commonly accepted ICC reliability levels [2]. Because of the good level of agreement between the respondents, we are confident that the expert respondents reviewed the 150 products in such a way that statistically reliable data was produced.

Table 3.3: Intraclass correlation coefficient

	Intraclass Correlation	95% Confidence Interval		F Test
		Lower Bound	Upper Bound	Significance
Average Measures	0.855	0.831	0.875	0.00

Table 3.4: Intraclass correlation coefficient (ICC) reliability chart [2]

ICC value	**Reliability**
0 - 0.5	Poor
0.5 - 0.75	Moderate
0.75 - 0.9	Good
0.9 - 1	Excellent

3.5.2 Probability Samples

Out of the sample of 150 products, 100 products were selected as one data set. It was done randomly to "ensure constant and independent probabilities" [176]. The remaining 50 products were put into a separate data set to be used to validate the first set [169].

Figure 3.5 shows the impact between two categories. In order for a correlation between two impact categories to be considered related, the responses must be either Fundamentally Related or Likely Related as shown in the box in Figure 3.5. It can also be seen in the figure that the majority of the responses for *Health and Safety* are *Fundamentally Related* while for *Population Change* the majority of the responses are *Not Related*.

The remaining correlations can be found in Figure 3.6 were trends can be found in a similar fashion. Most clearly, the category of *Health and Safety* has the majority of the responses in the row/column for *Fundamentally Related* while the category of *Conflict and Crime* has a majority of responses in the row/column for *Not Related*.

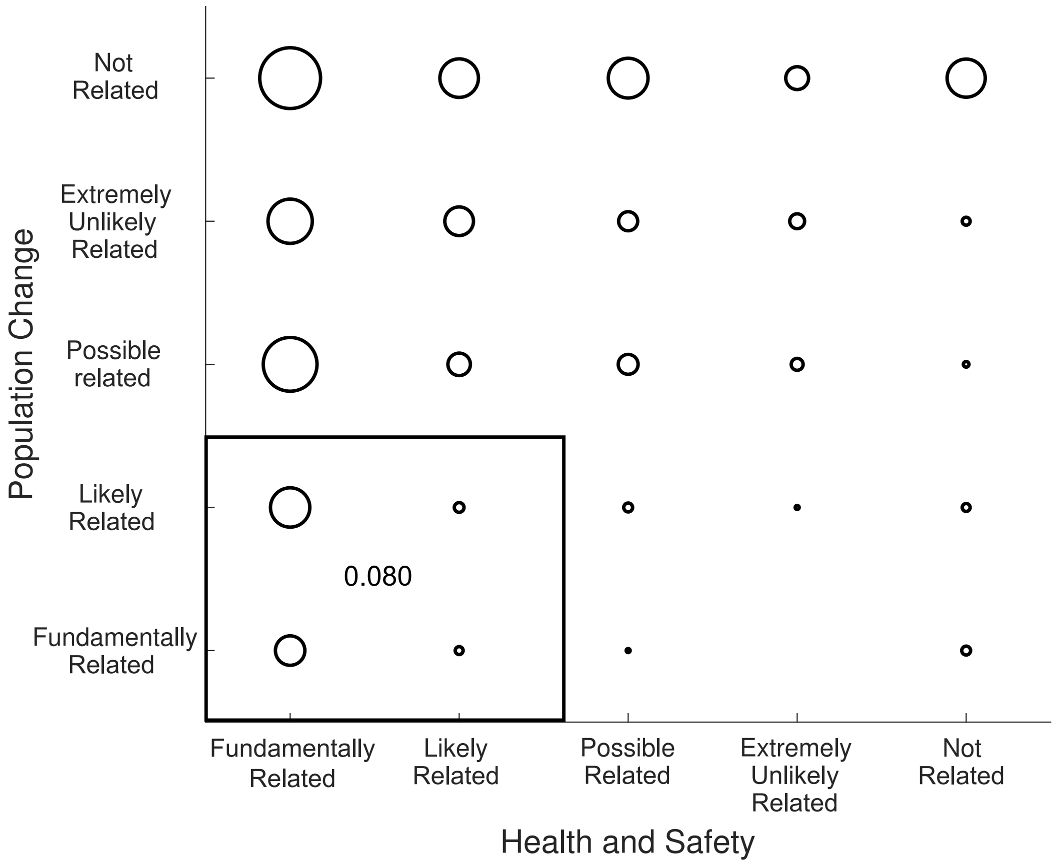


Figure 3.5: Scatterplot showing the correlation between *Health and Safety* and *Population Change* where the size of the circles indicates the number of times the respondents gave the particular rating. The value of the probability for *Fundamentally* and *Likely Related* is also shown (see box in lower left corner of figure). The data from the 100 randomly selected products were used for creating this scatterplot.

3.5.3 Probability Table and Prediction

The data set with 100 products was then analyzed using Matlab and STATA [177] to learn how the different social impact categories correlate. The respondents answers were calculated into probabilities and put into Table 3.5 where the shaded cells are for the general probability for one

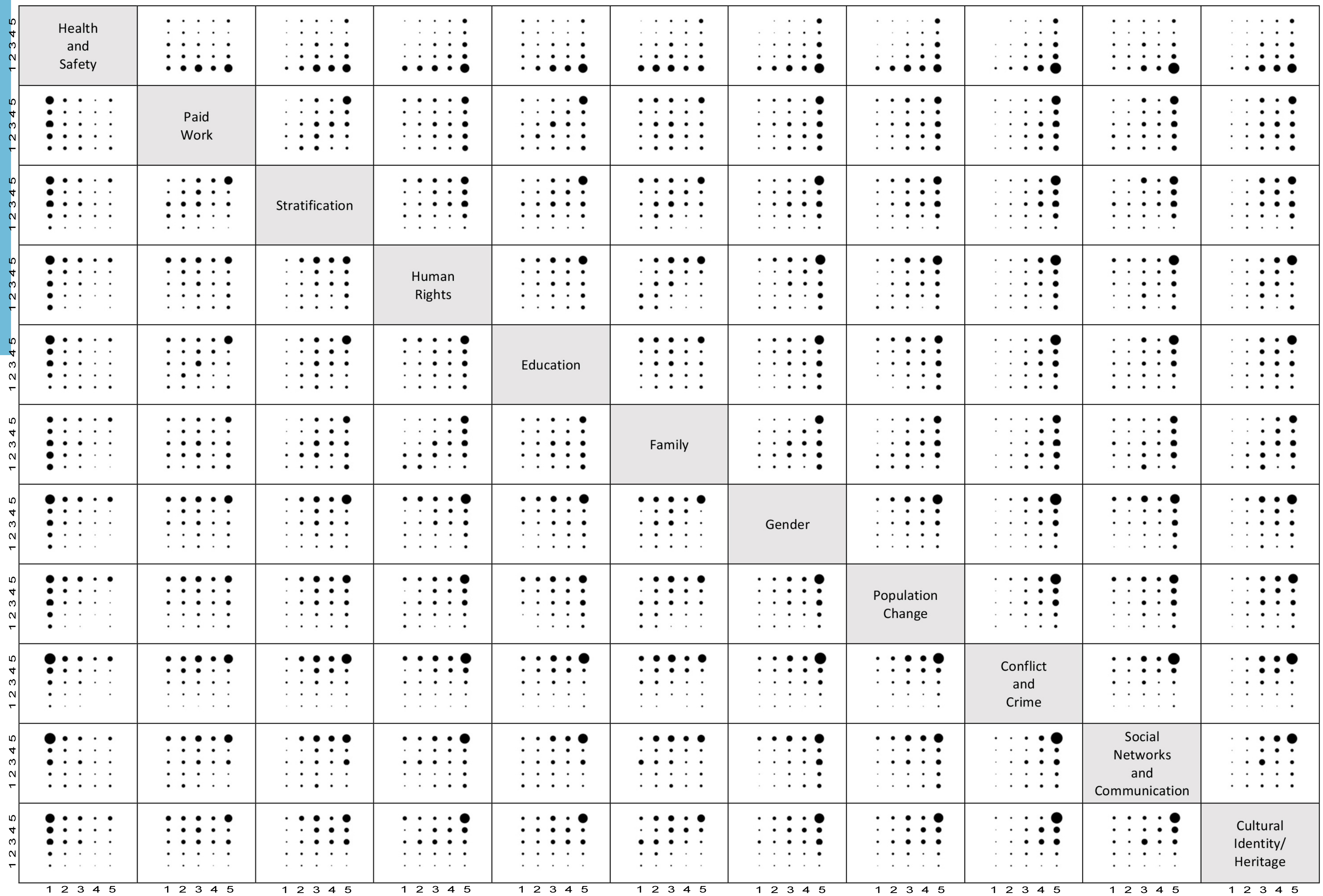


Figure 3.6: Scatterplots showing the correlation between the different social impact categories where the size of the dots indicates the number of occurrences for the correlation and where 1=*Fundamentally Related*, 2=*Likely Related*, 3= *Possible Related*, 4=*Extremely Unlikely Related*, and 5=*Not Related*. See Figure 3.5 for a correlation scatterplot in more detail. The data from all 150 products were used for creating these scatterplots.

impact to occur (using Equations 3.1 and 3.2), and the non-shaded cells show joint probability for two impacts occurring (using Equation 3.3).

This table was then used to predict social impact for 50 random products (products that would fulfill the requirements for product selection found in Section 3.4.2). This prediction can be seen in Table 3.6.

3.5.4 Validation of Probability Table

The remaining 50 products were then evaluated and the observed impact for all categories together with their joint impacts were counted and put into Table 3.7. This was done in order to validate the probability table created earlier (Table 3.5).

An analysis for statistical significance of the predicted and observed values for 50 products (found in Tables 3.6 and 3.7) was carried out in Matlab. The coefficient came to 0.9683 with a significance value of 0.00 indicating that there is a strong relationship between the two tables and we therefore draw the conclusion that the values did not happen by chance, that the data is statistically significant, and the probability table is validated (Table 3.5).

3.5.5 Final Probability Table

After the validation of the probability table, the observations from all 150 products were combined and Table 3.8 was created using Equations 3.1 - 3.3, where the shaded cells show the general probability for an impact to occur and the non-shaded cells show the joint probability of two impacts to occur. For example, by looking in Table 3.8 we find that the probability for impact in *Education* is 0.227 and the joint probability for both *Paid Work* and *Human Rights* to occur is 0.123.

Suggestions for how to use this table in a product development setting can be found in Section 3.6.

3.5.6 Conditional Probability Table

Using the properties of conditional probabilities, Table 3.9 was created using Equations 3.4 and 3.5 together with the values in Table 3.8. Table 3.9 shows the probability for a second social

Table 3.5: General probability (shaded cells) and joint probability (non-shaded cells) for when there is no known impact, observed from 100 randomly selected products

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	**0.746**	0.318	0.046	0.213	0.121	0.144	0.138	0.080	0.095	0.190	0.116
Paid Work	0.318	**0.368**	0.028	0.119	0.064	0.109	0.081	0.054	0.056	0.173	0.093
Stratification	0.046	0.028	**0.055**	0.023	0.020	0.018	0.014	0.019	0.019	0.024	0.018
Human Rights	0.213	0.119	0.023	**0.329**	0.105	0.045	0.044	0.044	0.091	0.053	0.091
Education	0.121	0.064	0.020	0.105	**0.189**	0.020	0.019	0.034	0.065	0.038	0.049
Family	0.144	0.109	0.018	0.045	0.020	**0.159**	0.034	0.029	0.016	0.066	0.034
Gender	0.138	0.081	0.014	0.044	0.019	0.034	**0.153**	0.016	0.013	0.048	0.033
Population Change	0.080	0.054	0.019	0.044	0.034	0.029	0.016	**0.096**	0.044	0.024	0.031
Conflict and Crime	0.095	0.056	0.019	0.091	0.065	0.016	0.013	0.044	**0.156**	0.023	0.043
Social Networks and Communication	0.190	0.173	0.024	0.053	0.038	0.066	0.048	0.024	0.023	**0.209**	0.053
Cultural Identity/Heritage	0.116	0.093	0.018	0.091	0.049	0.034	0.033	0.031	0.043	0.053	**0.155**

Table 3.6: Showing the number of predictions for each social impact category (out of 50 products) using the probabilities in Table 3.5

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	37	16	2	11	6	7	7	4	5	10	6
Paid Work	16	18	1	6	3	5	4	3	3	9	5
Stratification	2	1	3	1	1	1	1	1	1	1	1
Human Rights	11	6	1	16	5	2	2	2	5	3	5
Education	6	3	1	5	9	1	1	2	3	2	2
Family	7	5	1	2	1	8	2	1	1	3	2
Gender	7	4	1	2	1	2	8	1	1	2	2
Population Change	4	3	1	2	2	1	1	5	2	1	2
Conflict and Crime	5	3	1	5	3	1	1	2	8	1	2
Social Networks and Communication	10	9	1	3	2	3	2	1	1	10	3
Cultural Identity/Heritage	6	5	1	5	2	2	2	2	2	3	8

Table 3.7: Showing the number of observations for each social impact category out of the remaining 50 observed products

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	36	15	3	11	8	6	5	4	5	10	7
Paid Work	15	18	1	7	5	5	4	4	3	8	6
Stratification	3	1	3	1	1	1	1	1	1	1	1
Human Rights	11	7	1	18	8	2	2	2	6	4	7
Education	8	5	1	8	15	1	2	3	5	4	5
Family	6	5	1	2	1	7	1	1	1	3	2
Gender	5	4	1	2	2	1	7	1	0	2	1
Population Change	4	4	1	2	3	1	1	4	1	2	3
Conflict and Crime	5	3	1	6	5	1	0	1	9	2	4
Social Networks and Communication	10	8	1	4	4	3	2	2	2	12	4
Cultural Identity/Heritage	7	6	1	7	5	2	1	3	4	4	11

Table 3.8: Observed probability (shaded cells) and observed joint probability (non-shaded cells) for when there is no known impact, observed from all 150 products

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	**0.735**	0.314	0.048	0.215	0.134	0.136	0.128	0.077	0.093	0.190	0.124
Paid Work	0.314	**0.363**	0.028	0.123	0.077	0.106	0.078	0.062	0.056	0.171	0.101
Stratification	0.048	0.028	**0.058**	0.022	0.023	0.015	0.015	0.018	0.018	0.024	0.019
Human Rights	0.215	0.123	0.022	**0.342**	0.123	0.043	0.045	0.044	0.098	0.058	0.107
Education	0.134	0.077	0.023	0.123	**0.227**	0.018	0.023	0.042	0.079	0.053	0.068
Family	0.136	0.106	0.015	0.043	0.018	**0.149**	0.030	0.028	0.018	0.065	0.033
Gender	0.128	0.078	0.015	0.045	0.023	0.030	**0.147**	0.015	0.011	0.044	0.030
Population Change	0.077	0.062	0.018	0.044	0.042	0.028	0.015	**0.093**	0.038	0.029	0.038
Conflict and Crime	0.093	0.056	0.018	0.098	0.079	0.018	0.011	0.038	**0.167**	0.029	0.053
Social Networks and Communication	0.190	0.171	0.024	0.058	0.053	0.065	0.044	0.029	0.029	**0.218**	0.059
Cultural Identity/Heritage	0.124	0.101	0.019	0.107	0.068	0.033	0.030	0.038	0.053	0.059	**0.177**

Table 3.9: Observed conditional probability of impact when one category is known, table to be read left to right

	Health and Safety	Paid Work	Stratification	Human Rights	Education	Family	Gender	Population Change	Conflict and Crime	Social Networks and Communication	Cultural Identity/ Heritage
Health and Safety	**1**	0.427	0.066	0.293	0.183	0.185	0.173	0.104	0.127	0.259	0.169
Paid Work	0.867	**1**	0.076	0.340	0.211	0.292	0.214	0.170	0.154	0.471	0.278
Stratification	0.841	0.478	**1**	0.377	0.391	0.261	0.261	0.319	0.304	0.420	0.333
Human Rights	0.629	0.361	0.063	**1**	0.361	0.124	0.132	0.129	0.285	0.171	0.312
Education	0.592	0.338	0.099	0.544	1.000	0.081	0.099	0.184	0.349	0.232	0.301
Family	0.911	0.709	0.101	0.285	0.123	**1**	0.201	0.184	0.117	0.436	0.223
Gender	0.869	0.528	0.102	0.307	0.153	0.205	**1**	0.102	0.074	0.301	0.205
Population Change	0.829	0.667	0.198	0.477	0.450	0.297	0.162	**1**	0.414	0.315	0.414
Conflict and Crime	0.560	0.335	0.105	0.585	0.475	0.105	0.065	0.230	**1**	0.175	0.320
Social Networks and Communication	0.870	0.782	0.111	0.267	0.240	0.298	0.202	0.134	0.134	**1**	0.271
Cultural Identity/Heritage	0.703	0.571	0.108	0.604	0.387	0.189	0.170	0.217	0.302	0.335	**1**

impact category to occur if one category is known. For example, if we know that there is impact in *Family*, then there is a probability of 0.201 that there is also impact in the category of *Gender* compared to a probability of 0.030 (value from Table 3.8) if no impacts are known.

Similarly, if there is known impact in one category, the probability of impact for multiple categories can be found. This can be done using the values found in Tables 3.8 and 3.9 together with Equation 3.6 to find the probability for several categories occurring.

3.6 How to Apply the Findings

Engineers sometimes make decisions based on social norms, feelings, and experiences [58]. We believe that this can lead to the creation of products with less social impact than intended.

One way to overcome this is for engineers to use Table 3.8 and 3.9 that show how social impact categories are correlated in order to find additional impact categories of interest and to use this throughout the product development process.

Below is our method for increasing the potential social impact of engineered products:

1. *Find Social Impact Categories of Interest:*

   After having decided on a product to design or redesign, look at the 11 social impact categories found in Table 3.1 and identify one or more obvious social impact categories to be included. After choosing the main social impact categories, look at Table 3.9 to learn the probability of other social impact categories to be co-present by finding the row for each main category and then reading the probability of having impact in other categories. Select additional categories to be included.

2. *Decide on Indicators for Evaluating Social Impacts:*

   Decide which indicators to use in order to evaluate the social impacts of the product throughout the stages of product development.

3. *Link Design Parameters to the Indicators:*

   Link design parameters to the indicators and add them to the design objectives/requirements.

4. *Evaluate Social Impacts:*

   Evaluate social impacts of the product throughout the stages of development to ensure that it meets the design objectives. Also consider if the design negatively affects any of the social impact categories.

By following these steps, an engineer can be made aware of social impact categories that could otherwise be overlooked and now broaden the design to include additional social impact objectives, thus achieving a design with an increased impact in the original category together with additional impacts in other categories.

When looking at the shaded cells in Table 3.8 it is observed that not all social impact categories have the same probability. This falls in line with the findings in the second tier, the Industry Review [7, 8] where it is clear that the *Health and Safety* category is over-represented. This shows that there is a potential for work to be done and products to be developed that focus on the categories with low probabilities.

By looking at the different correlations between social impact categories, engineers may be inspired to extend their focus to include additional inputs to extend their product's potential social impact. This consideration can lead to products with greater social impacts than if the correlation had not been considered.

3.7 Conclusions

In this chapter we have reviewed 150 products and linked them to social impact categories found in literature. We then discovered how the impact categories manifest themselves in the 150 products. We did this to allow us to better anticipate the social impacts of products and to understand how engineered products impact society.

A review instrument was created to help us know how different social impact categories are co-present in products. We then showed how the results from the product review gives us the probability of social impacts. A table for predicting social impact was created using two thirds of the 13,200 data points collected and then validated by using the remaining one third. After the validation, the whole data set was used to create the final prediction table. This table shows the general probability and the joint probability for social impacts to occur, and is also part of the method to be used for improving the social impacts of products.

When using this method, the initial design objective can be widened to include related social impact categories and thus achieve additional impacts in both the original social impact category and in other related categories not previously considered. By using this method, we believe better informed engineering decisions can be made throughout the product development process.

The presented material is limited in the following important ways. Some of the 11 impact categories overlap and we have not explored what implications that has for engineers (e.g. family and gender impacts). While the social impact categories presented are based on an extensive literature survey [1], the review of products is not extensive nor exhaustive. While we believe that all products have a social impact, and thus an exhaustive survey is not possible, we do believe that the extent of the review can be expanded. The time it took each respondent to complete the product reviews was another limitation, creating a risk of respondent burnout. To combat this when using similar surveys in future research, we would possibly include a greater number of respondents, all of whom would complete only a subset of the survey, thus avoid the risk of burnout for any one respondent. Another limitation that has not been discussed is the relationship between perceived impact of a product and the actual impact. Lastly, the more pertinent limitation is that for the probability table to be accurate, any product that is evaluated must fulfill the selection criteria set up in Section 3.4.2.

Ultimately, we believe that the contribution of this chapter lies in the linking of existing products to published social impact categories and how these categories correlate statistically. As such it alerts the engineer to various social impact areas that are not commonly considered during the product development process. Thus, by expanding the views to include related social impact categories, the products that are designed can have a broader social impact.

CHAPTER 4. NITRILE CUP SEAL ROBUSTNESS IN THE INDIA MARK II/III HAND PUMP SYSTEM

4.1 Chapter Overview

Accessing clean water is a persistent and life-threatening challenge for millions of people in the world. Each hour, 400 children under the age of five die because of the lack of clean water. To help people get access to clean ground water, mechanical hand pumps are often used. Among the most ubiquitous is the India Mark II/III hand pump system, of which there are more than 4 million installed across the world. These are estimated to serve between 600 million and 1 billion people. But as with most mechanical systems, they degrade over time–leading to pumps becoming dysfunctional due to lack of required service. The pump's nitrile cup seals are the most common cause of dysfunctionality. The purpose of this chapter is to analyze the robustness of the cup seals in the India Mark II/III hand pump system. In this chapter, 110 off-the-shelf nitrile cup seals purchased by the authors in Uganda were tested and characterized. Leak and pump performance tests were performed in both static and dynamic settings and the correlations between performance and geometry and material properties of the cup seals were determined. This important baseline evaluation for the seals supports our future work to improve the longevity and robustness of the India Mark II/III hand pump system, with a focus on the cup seals. We believe that by finding the baseline of a product, engineers and designers will be able to improve its performance

4.2 Introduction

The world's need for clean drinking water cannot be overstated, as diarrhea kills more children than malaria, measles, and AIDS combined (see Figure 4.1) [9]. Each hour, 400 children under the age of five die due to the lack of access to clean water [178]. The lack of clean water also causes 19.5 million people per year to be infected with roundworm and whipworm [179]. These parasites retard children's physical development and prevent education. If they had access to clean water, poverty would be reduced, suffering would decrease, and more children would be able to go to school [180].

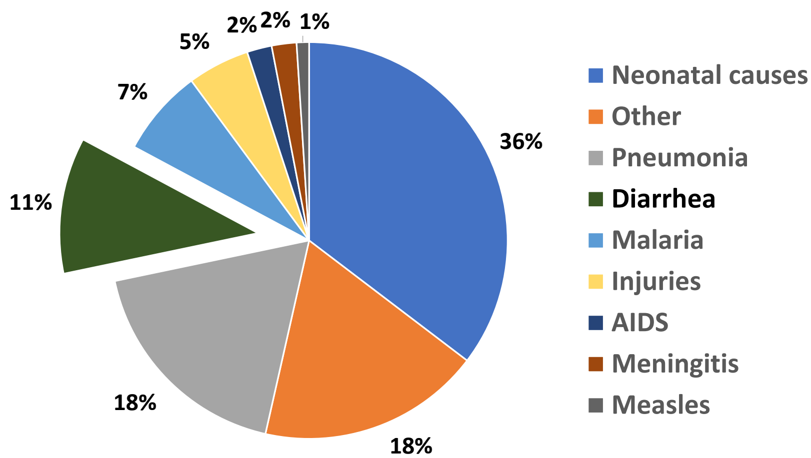


Figure 4.1: Cause of death for children under 5 (worldwide) [9]

Mechanical hand pumps have a long history of helping people access clean ground water for drinking and daily use. Ground water is a good source of clean water since it is naturally filtered through layers of soil [178, 181]. It is estimated that at least 1 billion people get their drinking and daily usage water from hand pumps across the world [61] and that at over 4 million hand pumps have been installed in Africa, Asia, and India over the last 20 years [59, 60]. Although ownership models vary across these continents, mechanical hand pumps are often community owned and maintained in countries such as Uganda. A hand pump is often within 500 meters of one's dwelling, and is shared by approximately 150-250 people (known through interviews by the authors with water officials in Uganda and through literature) [59]. One of the most commonly manufactured mechanical hand pump systems is the India Mark II hand pump, shown in Figure 5.1. It was developed by UNICEF in 1978 [182]. The India Mark II hand pump is now used across the globe. In India alone, it is estimated that over 2.6 million India Mark hand pump systems are operating [59].

As expected, it is common for mechanical hand pumps to become dysfunctional over time, owing largely to the degradation of items such as seals, bushings, and bearings. Not uncommon is the dysfunction stemming from theft and vandalism [183]. Other times hand pumps fail after aid agencies and donors turn over their projects to local villages, leaving them without resources

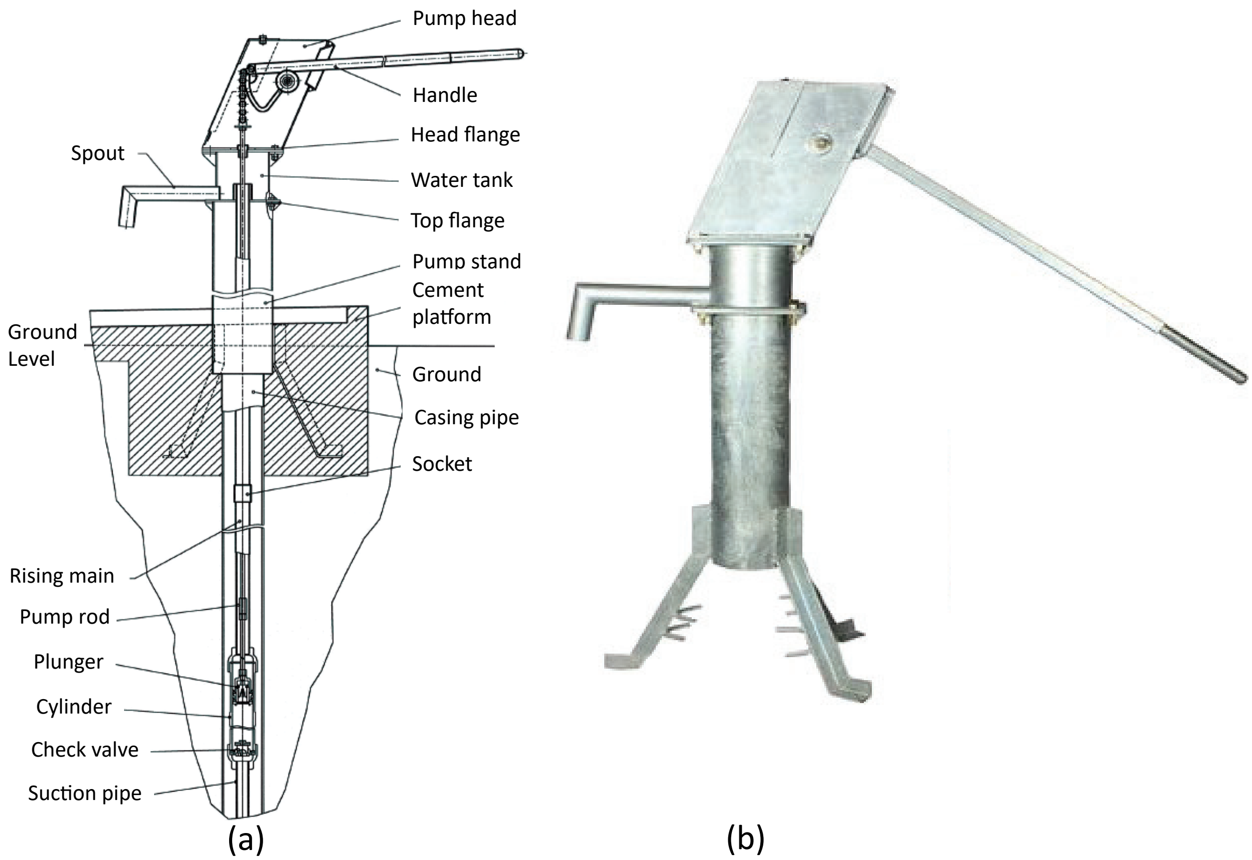


Figure 4.2: (a) India Mark II hand pump system schematic and (b) image of an India Mark II hand pump [10]

for upkeep and repairs [184]. This is a reoccurring problem with many aid-based projects due to culture, lack of training, infrastructure, finance, public consultation, political backing, and other related challenges [185, 186]. Also, some pumps remain functional but fail to support local communities when water tables change or become contaminated [183, 187]. It is estimated that 15% of India Mark II hand pumps are currently dysfunctional or otherwise not supporting the needs of local communities [59]. Of those, approximately 70% are dysfunctional due to hardware problems that could be repaired [183]. Additionally, as a pump system ages, its functionality goes down due to lack of maintenance, leaving more people without direct access to clean water (see Figure 4.3) [11, 188]. One reason for lack of maintenance is often the associated cost (see Appendix A) [187]. Another reason for infrequent service visits in Uganda was because the service personnel were overwhelmed with the number of pumps they needed to service (see Appendix A). Unfortunately, repair times can be expected to be between 1 and 5 weeks for any type of failure [59]. As a pump becomes dysfunctional, the people relying on its water are often forced to use unimproved water sources [183]. It was found in a study by Hunter et al. that even a few days of using unimproved water sources can be sufficient to offset the benefits from normally having clean water, leading to serious sickness and/or death [189]. For the 1 billion people using hand pumps for daily access to clean water, their health is directly related to the reliability of the pump system they use [184].

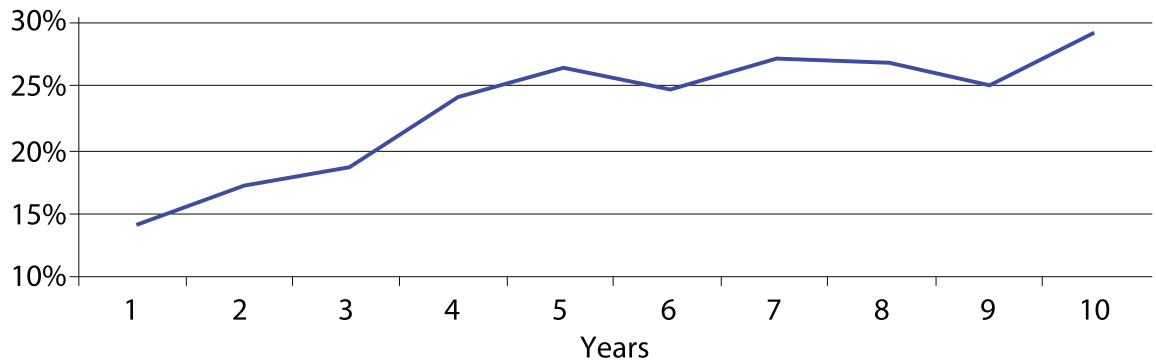


Figure 4.3: Percent of hand pump water sources non-functional by age [11]

The social impact of loosing access to clean water is significant: When a local water source becomes non-functional, users walk to another more distant source, preventing them from performing other tasks and activities such as work, school, tending to the family, etc.

The gender impacts of loosing a water source are also significant as the burden of collecting water is typically borne by women and girls [59, 190]. Having a nearby functional hand pump has a greater impact on women than men since they are principally responsible for taking care of the family in terms of health, food, and water [191]. Women also bear the extra burden of water-related diseases (diarrhoea, dysentery, typhoid, giardiasis, dracunculiasis, shigellosis, etc) as they more often care for the sick [59]. Another impact of a mechanical pump with poor reliability is that communities loose confidence and patience with the water source and ultimately abandon it [192].

Research shows that pump malfunction is most often due to hardware problems [183] and that the cup seals degrade and cause the pump efficiency to go down [59, 183]. Figure 4.4 shows common points of failures for the India Mark II/III pump system with the cup seal as the biggest point of failure [12].

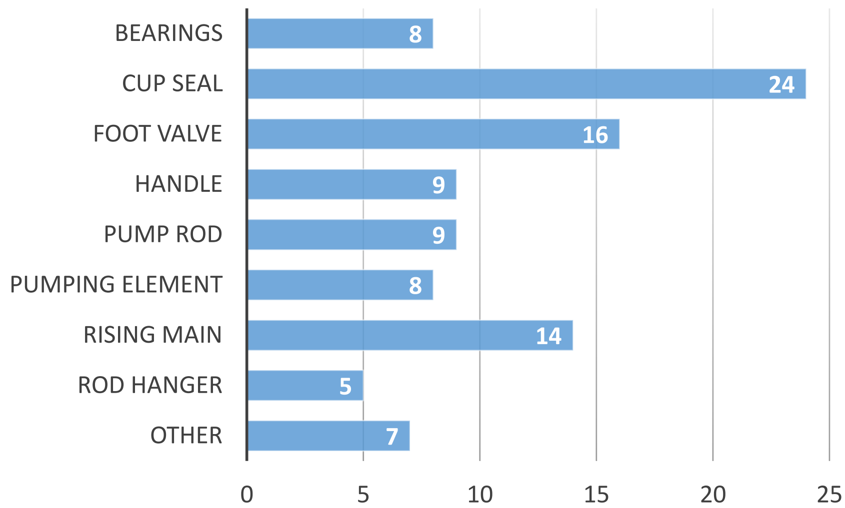


Figure 4.4: Points of failure for the India Mark II/III hand pump system (percent of total failures) [12]

The purpose of this chapter is to quantify baseline performance for the nitrile cup seal used in the India Mark hand pump system and to create the foundation for the next step in a larger study to understand – mechanically and socially – how hand pumps perform, degrade, get repaired, and ultimately meet human needs. The findings presented here will be incorporated into our larger research where we have used field sensor data to capture pump usage scenarios, and machine learning techniques to begin mapping engineering design parameters, such as those presented in this chapter, to the social impacts of an engineered product (see Appendix A) [193, 194].

The remainder of the chapter is organized as follows: In Section 4.3, we present technical preliminaries related to seal configuration and performance. We then present a short synopsis of the approach, limitations of the current study, followed by the methods and results of gathering geometric, material, leak, and pump data. This is followed by a conclusion with suggestions for future work.

4.3 Technical Preliminaries

The India Mark II/III hand pump has three sets of seals as shown in Figure 4.5. The seals that are the focus of this chapter are the cup seals (two in each pump installed in the plunger assembly). The other seals are flat seals that are part of check valves. This configuration is a common setup for reciprocating hand pumps [182]. The large majority of cup seals are molded in India according to the dimensioned drawing shown in Figure 4.6 [10, 195]. Such seals are sold in small and large shops throughout the world in units of one or thousands. Typically, a pump repair person will purchase one or a few seals at a time depending on the maintenance jobs in the queue. When purchasing in these quantities seals cost the buyer approximately 0.50 USD in Uganda (purchased in Uganda by authors in 2018). Due possibly to the low profit margins, vastly differing environmental conditions (throughout the developing world) and manner in which seals are stored, there are significant variations in new seal geometry and material properties, as will be shown in this chapter.

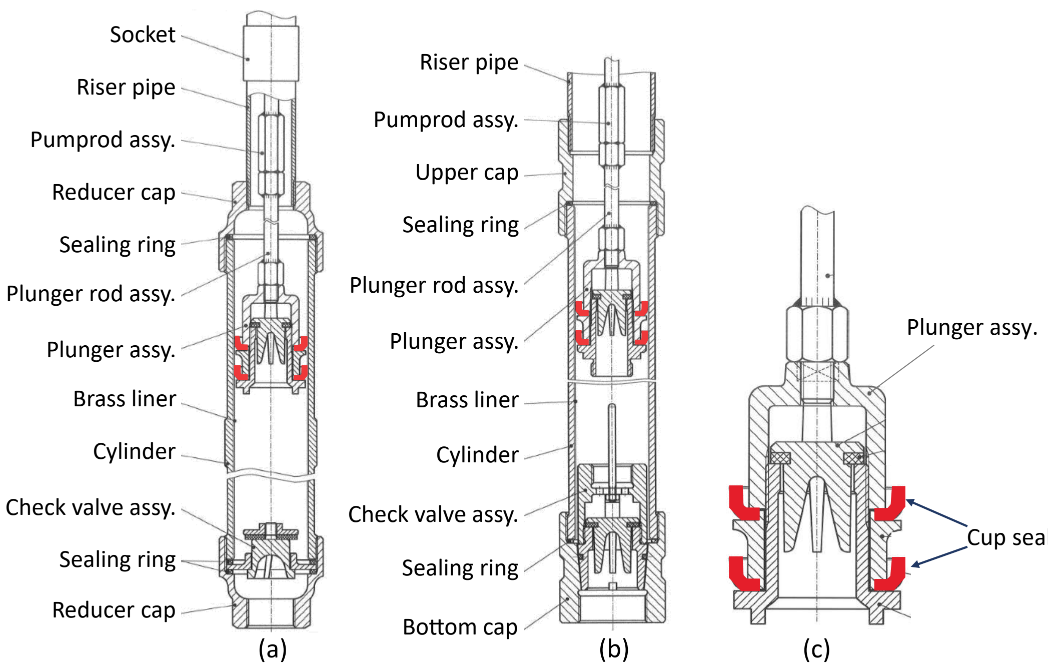


Figure 4.5: (a) Schematics of the India Mark II and (b) India Mark III pump cylinders, together with (c) the plunger assembly (cup seals highlighted)

Basic Functionality: Conceptually the seal functions at its peak when there is a column of water in the riser pipe that acts downward on the seal causing the seal to flex radially outward thus making greater contact with the surrounding cylinder wall. In east Africa, a common well depth is 42 m [196], producing a hydrostatic pressure of 412 kPa acting on the first seal in the seal set. The

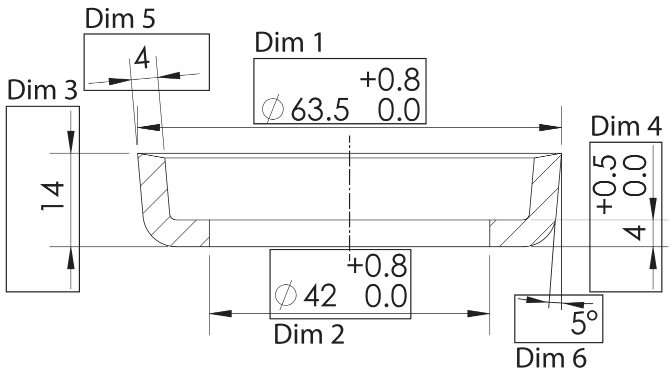


Figure 4.6: Specified cup seal dimensions (mm) [10]

cup seal performance, together with stroke length, determines how much of the column of water is lifted during each pump stroke and exits the spigot at the surface.

Seals for machinery in general have been well-studied and are well-documented in the literature. Earlier works include fundamental principles of seal performance [197, 198], while new research continues to seek for improvements in seals [199, 200]. It is important to recognize that while the nature of seals are relatively well known as a whole, no work has been published on characterizing the seal performance of the India Mark II/III cup seals, possibly due to the harsh realistic operating conditions, and how these seals are made, distributed, and sold. Because millions of people are affected by the performance of the cup seals in the India Mark II/III, we are motivated to present findings that lay the ground work for engineering an improved seal and pump that could increase access to clean water.

With a better understanding of the cup seal mechanics and its performance sensitivity to real geometric and material variations, we can examine the potential to engineer a more robust, longer lasting, and possibly more easily maintained seal.

Installation and Maintenance: In order to better help governments and NGO's install and manage hand pumps and to provide clean water to more people (159 million people still collect their drinking water directly from surface water sources [201]), an initiative to create a set of guidelines for hand pumps was created in the early 1980's. It was called the *Village Level Operation and Management of maintenance project* (VLOM) [202]. See textbox below for VLOM project guidelines. With this came a need to have a hand pump system suitable for the VLOM directives. After the introduction of the VLOM initiative and the India Mark II hand pump, the hand pump failure rates in India went from about 70% in the 1970's to about 20% in the 1980's [182].

The Village Level Operation and Management of maintenance (VLOM) project guidelines [59, 182, 202]: • Easily maintained by a villager caretaker, requiring minimal skills and few tools; • Manufactured in-country, primarily to ensure the availability of spare parts; • Robust and reliable under field conditions; • Cost effective; • Community choice of when to service pumps; • Community choice of who will service pump; and • Direct payment to repairers by the community.

In order to better comply with the VLOM guidelines, the India Mark II hand pump system was improved. The main objectives for the redesign was to increase the Meantime Before Failure (MTBF) and to simplify maintenance [59]. This resulted in the India Mark III hand pump system where the serviceability of the seals was greatly improved. The redesign enabled the seals to be changed without having to remove the riser pipes (which are wider in the India Mark III), making it both easier and faster to service the pump (see Figure 4.5(b) for the India Mark III pump cylinder). The cup seal configuration remained the same [203].

A Pump Redesign: A notable non-UNICEF commisioned redesign of the traditional hand pump increased the MTBF significantly by removing the need for cup seals completely. The redesigned pump was developed by Fairwater Foundation together with Oxfam and is called the BluePump [134, 204]. The BluePump has proven to be a more reliable pump than the India Mark II/III hand pump system [134] but adoption rates have been very low due to its significantly higher initial price, lack of part standardization, and regulations across Africa [205].

4.4 Approach and Limitations of the Current Study

We have taken a multifaceted approach to better understand the nature of the failures of the India Mark II/III hand pump system. While there are many potential points of failure, this chapter focuses on just one – the eventual failure of the cup seals. Prioritizing the cup seals is motivated by both literature research [12, 180, 206] and our interviews with hand pump technicians and suppliers in Uganda (see Appendix A). This will then be used as a baseline for a future study where we will develop a wear model for the cup seal to predict degradation over time.

For the present chapter, we have done the following:

1. Searched literature for understanding of hand pump failures
2. Acquired multiple India Mark hand pumps for use in the laboratory
3. Visited multiple pumps sites, observing pump usage at each site
4. Interviewed water district officials in multiple locations
5. Acquired district managers' water reports
6. Interviewed pump mechanics and water source caretakers
7. Purchased 110 seals from local markets in multiple locations (see Figure 4.7)
8. Tested seals in field and laboratory settings
9. Analyzed the findings

The primary limitation of this study is that the dynamic performance test of the cup seal is limited to a laboratory setting with a pump depth of 0.6 m instead of using the well depth of 42 m commonly found in east Africa (greater borehole depth increases the hydrostatic pressure on the cup seal caused by the water column in the rising main, causing a potential performance difference for the cup seal). This is not a limitation for the static performance test, which used increased water pressure to simulate actual well-depths. Another limitation of the study is that our field work was performed in one country. But after reading other research on hand pumps across many developing countries throughout the world [182, 205–208], we conclude that the findings in this chapter can also be meaningful for someone researching hand pumps in other developing countries with similar conditions to those in Uganda (such as humidity and temperature). It is also important to note that the India Mark hand pump systems and their spare parts are almost exclusively manufactured in India due to price and quality [195]. Despite these limitations, this chapter will characterize:

1. Geometric variation of off-the-shelf seals
2. Material variation of off-the-shelf seals
3. Static zero-cycle leak performance of off-the-shelf seals
4. Dynamic zero-cycle pump performance of off-the-shelf seals
5. Statistical correlations between Geometric and Material variation to zero-cycle performance

Figure 4.7: The different locations in Uganda where seals were purchased

4.5 Quantification of Geometric and Material Variation of Off-the-Shelf Seals

In order to better understand the workings of the India Mark hand pump system and how seal degradation occurs, the authors traveled to Uganda and interviewed local pump users, caretakers, technicians, part store owners, and water officials. Uganda was chosen for two reasons: first, through our existing relationship with WHOlives [209] we could utilize their network of contacts. Second, the Ugandan government has regulations in place, limiting the number of hand pump systems across the country (India Mark II being the most prevalent system) [205]. Data on pump usage, spare part availability, and interviews were collected. New and used seals (see Figure 4.8) and other spare parts were also purchased for evaluation. It was found during the field visits and interviews that the cup seal was indeed a significant point of failure.

Figure 4.8: New cup seal (left) and a used cup seal (right) for the India Mark II/III hand pump system

To find cup seals and other spare parts, we went to three different towns across Uganda: Kampala, Jinja, and Gulu (see Figure 4.7). For each town, we visited multiple local markets and stores. It was found that of the stores visited, all had only a small supply of cup seals except for one store in Kampala. To not interrupt the local supply of seals, only a small number of seals were purchased from each store. There was no indication to how long the cup seals had been in the stores before we purchased them. This resulted in a total of 110 cup seals purchased. No set price was found in any of the stores we visited. This always led to a discussion between our local team members and the shop owners. The cost of a seal did not vary much between each store (approximately 0.50 USD per cup seal).

Multiple methods were used to assess the geometric and material variations in the seals. The weight, volume, density, hardness, and geometry of each seal were measured and recorded. These measurements were performed in Uganda directly after purchase to ensure that the measurements reflected the local environment and weren't changed due to changes in climate or prolonged storage. The same procedures and testing equipment were used to measure all seals. These measurements were performed to evaluate whether the seals met the manufacturing specifications (see Figure 4.6).

A test fixture was used to simultaneously take a top, right and left side photo of each seal. These images were then processed with Matlab image processing software [210] for dimensions 1, 2, and 6 (see Figure 4.9). For dimensions 3, 4, and 5, a digimatic indicator with an accuracy of 0.02 mm, (Mitotoyo 575-123) was used. The Sartorius AY303 scale was used to measure seal weight, with 0.001 g readability, repeatability 0.005 g, and linearity 0.005 g. The water displacement method was used to measure seal volume. To measure volume, the seal was held by a steadying rod and a seal basket to keep the seal from touching the side and bottom of the vessel. The Sartorius scale was also used for this test. Density was then calculated by using the weight and volume results. The hardness of each seal were measured by using a Starrett Handheld Digital Durometer (H, Shore A Scale). This durometer is capable of a resolution of 0.5 H, deviation $<1\%$ in the 20-90 HSA range.

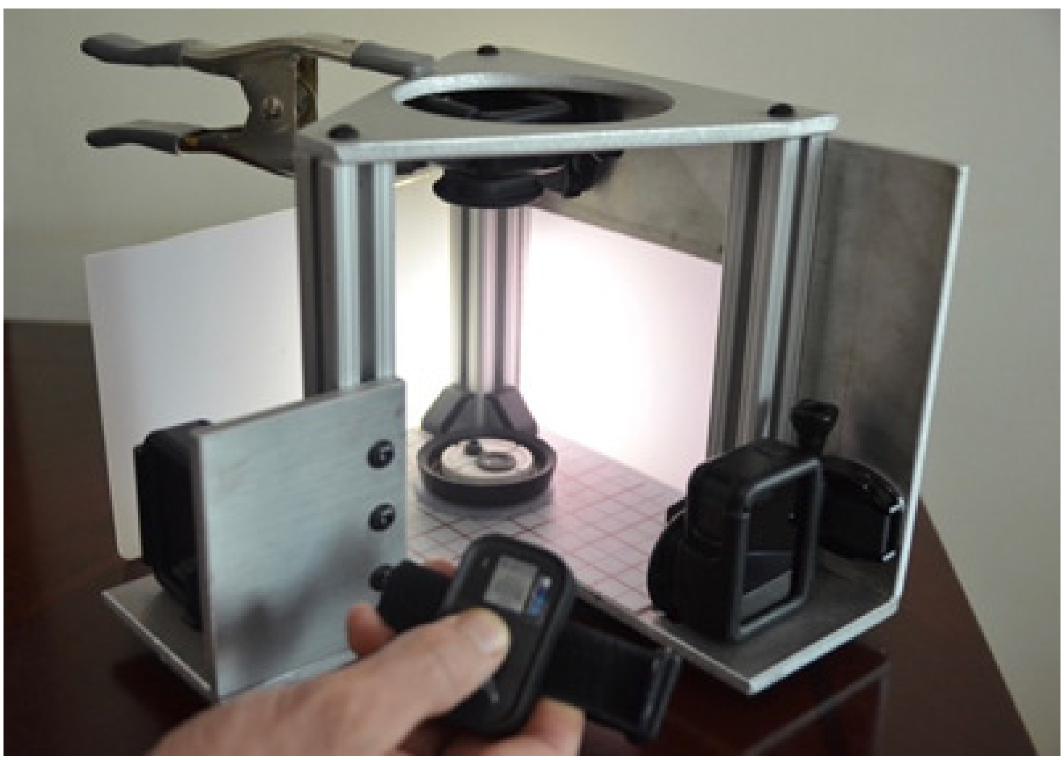


Figure 4.9: Test rig used for recording pictures of each seal

All data was gathered and Matlab was used to calculate statistical significance and variations. The average values and variations can be seen in Table 4.1.

It was found that the mean for three of the six dimensions and the seal hardness fell outside the specified tolerance. Since the material was only specified as "*Nitrile-Butadien Rubber (NBR) conforming to BS 2751*" [10] without mentioning a specific density interval, the specification for weight and density are left blank [10]. The volume was calculated from a 3D CAD file of the cup seal downloaded from the Rural Water Supply Network [211]. These results create the baseline for the seal performance in our study.

Table 4.1: Measurement results from the 110 seals acquired in Uganda, shaded cells indicate where mean is outside tolerance (see Figure 4.6 for drawing of cup seal with dimensions)

	Dim 1 (mm)	**Dim 2** (mm)	**Dim 3** (mm)	**Dim 4** (mm)	**Dim 5** (mm)	**Dim 6** $(degrees)$	**Weight** (g)	**Volume** (cm^3)	**Density** (g/cm^3)	**Hardness** $(ShoreA)$
Spec	63.5	42	14	4	4	5	-	12.91	-	75-85
Spec Min	63.5	42	13.5	4	3.5	4.5	-	-	-	75
Spec Max	64.3	42.8	14.5	4.5	4.5	5.5	-	-	-	85
Mean	64.27	41.87	12.40	4.23	4.17	7.53	17.589	12.410	1.417	86.05
Stdev	0.53	0.23	0.43	0.18	0.18	2.22	1.333	0.450	0.0842	3.44
Min	62.86	41.42	11.36	3.75	3.76	1.57	14.685	11.718	1.250	75.75
Max	65.68	42.71	13.15	4.77	4.62	12.50	23.142	13.812	1.677	96.75
Range	2.82	1.29	1.79	1.02	0.86	10.93	8.457	2.094	0.427	21
Median	64.26	41.85	12.46	4.24	4.16	7.48	17.541	12.386	1.392	85.63

4.5.1 Error Analysis for the Geometric and Material Measurement System

An error analysis was done on the measuring system. The purpose of this analysis is to characterize the uncertainty associated with the measurement methods themselves. We are interested in this uncertainty because it cannot be attributed to part variation, and therefore must be discovered in order to more fully characterize a part's actual variation. There is potential error in the measurements of geometry, weight, volume, and hardness.

The geometry, weight, volume, and hardness of a single seal was measured at least 30 times. In all cases except the hardness tests and the wall angle test (Dim 6), the percent error was less than 1%. For these two tests, a larger uncertainty is expected because they were not fully automated.

Note that the units for the amount shown for Stdev are the native units for the item being evaluated. E.g., for weight it is *grams*, for volume it is g/cm^3, etc. The result of the analysis can be seen in Table 4.2.

Table 4.2: Coefficient of variation (CV), the % error, mean, standard deviation, 3*standard deviation, min, max, range, and median (110 seals)

Test	Dim 1 (*mm*)	Dim 2 (*mm*)	Dim 3 (*mm*)	Dim 4 (*mm*)	Dim 5 (*mm*)	Dim 6 (*degrees*)	Weight (*g*)	Volume (cm^3)	Hardness (*ShoreA*)
CV	0.0049	0.0025	0.0025	0.0030	0.0088	0.0165	0.0002	0.0011	0.0337
% error	0.49%	0.25%	0.25%	0.30%	0.88%	1.65%	0.02%	0.11%	3.37%
Mean	64.1069	41.7731	11.8606	4.1809	4.0973	10.7038	16.7579	12.0292	86.1743
Stdev	0.3146	0.1029	0.0296	0.0124	0.0359	0.1770	0.0028	0.0130	2.9058
3*Stdev	0.9438	0.3087	0.0888	0.0372	0.1077	0.531	0.0084	0.039	8.7174
Min	63.4890	41.4879	11.79	4.1625	4.0800	10.3048	16.7500	12.0040	79.625
Max	64.7374	41.9869	11.9150	4.2050	4.2950	11.0035	16.7640	12.0560	91.00
Range	1.2484	0.4990	0.1250	0.0425	0.2150	0.6987	0.0140	0.0520	11.375
Median	64.0707	41.7781	11.8650	4.1800	4.0925	10.7073	16.7580	12.0260	86.125

4.6 Static Zero-Cycle Leak Performance of Off-the-Shelf Seals

To find the leak rate of each purchased seal, a static seal leak-rate test rig was built at Brigham Young University (see Figure 4.10). It consisted of a pump cylinder from an India Mark III hand pump system complete with a plunger. Attached to the pump cylinder was a high pressure water source, an adjustable regulator, and a gauge. Different well depths could be simulated by adjusting the pressure of the water entering the pump cylinder. Each seal was tested individually and the data collected and evaluated. The seal being tested was placed in the lower seal position of the plunger (see Figure 4.5(c)).

The 110 seals that were tested came from seven different stores in Uganda. Out of those, five seals leaked (4.5%). The results can be seen in Table 4.3. Interesting to note is the information in the last row of Table 4.3, showing the number of seals outside specifications. To ensure that leakage was not due to improper installation, each seal that leaked was removed, re-installed, and tested five times.

The data suggest that installation could have been a factor in seal leakage since only one out of five seals leaked again (see Table 4.4). The seal that leaked multiple times was then tested

Figure 4.10: Test setup for determining cup seal leak rate

Table 4.3: Leak test results (shaded cells indicate where the value is outside of tolerance)

Seal number	**Leak rate** (mL/min)	**Dim 1** (mm)	**Dim 2** (mm)	**Dim 3** (mm)	**Dim 4** (mm)	**Dim 5** (mm)	**Dim 6** ($degrees$)	**Hardness** ($ShoreA$)
1B-027	10.27	64.13	41.75	12.90	3.99	4.19	11.31	92.38
5B-017	0.30	64.12	42.08	11.81	4.16	4.03	7.40	80
5B-018	0.01	65.46	41.81	11.76	4.33	4.00	9.72	85.63
5B-023	1.39	64.44	41.66	11.93	4.06	3.89	8.50	86.38
6-019	0.69	64.18	42.31	12.83	4.13	4.09	8.13	96.75
Number of seals that fall outside the tolerance	-	58/110	81/110	110/110	13/110	3/110	95/110	67/110

further to study the variation of seal performance due to installation. After testing the seal ten times and comparing the leak rates, it can be seen that the installation did affect the seal's leak performance (see Table 4.5).

Table 4.4: Additional tests of seals that failed during initial testing

	Leak test (mL/min)				
Seal	**1**	**2**	**3**	**4**	**5**
1B-027	10.27	140.69	No leak	60.11	120.86
5B-017	0.30	No leak	No leak	No leak	No leak
5B-018	0.01	No leak	No leak	No leak	No leak
5B-023	1.39	No leak	No leak	No leak	No leak
6-016	0.69	No leak	No leak	No leak	No leak

Table 4.5: Variation of seal performance due to installation

Seal 1B-027	
Test	**Leak rate** (mL/min)
1	10.27
2	140.69
3	No leak
4	60.11
5	120.86
6	No leak
7	6.53
8	70.36
9	42.60
10	No leak

A two-level full factorial design of experiments was generated with angle and insertion position as the parameters to further quantify the effect of installation on seal performance. The two angles were 0° and 1.51° (the maximum angle that can be imposed before the connecting rod impinges on the surrounding cylinder) and the two positions were related by a 90° axial rotation from each other. The process parameters for the experiment can be seen in Table 4.6. Each experimental condition was replicated five times. To ensure that leak would occur, the seal that leaked multiple times was used.

Table 4.6: Process parameters for the design of experiment

Process parameters	Labels	Low level	High level
Angle	A	0°	1.51°
Insertion position	P	1	2

The results from the design of experiments can be seen in Table 4.7. The change in position had a greater influence on leak rate than the change in angle (see Figure 4.11). This can also be seen in Figure 4.12 where the second box plot is taller than the other box plots.

Table 4.7: Design layout of the experiment with response values and averages

DOE trial #	Angle	Insertion position	Leak rate (mL/min)					
			Test 1	Test 2	Test 3	Test 4	Test 5	Average
1	0°	1	0.003	24.247	0	0	2.310	5.312
2	0°	2	50.382	154.059	115.649	116.739	14.312	90.228
3	1.51°	1	0	0	0	11.230	42.951	10.836
4	1.51°	2	39.188	0	4.601	48.709	82.056	34.911

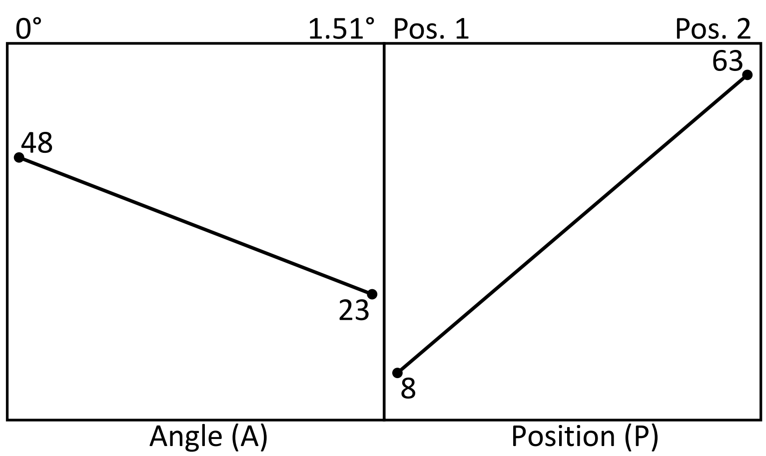


Figure 4.11: Main effects plot for the design of experiment

To quantify what an acceptable leak rate for a new seal is, old seals that had been removed during pump maintenance visits in both Uganda and Haiti were installed in the leak-rate test rig (see right seal in Figure 4.8 for an example of an old seal). The logic behind this approach is that if the seal had been replaced during a maintenance visit, its performance was likely to be

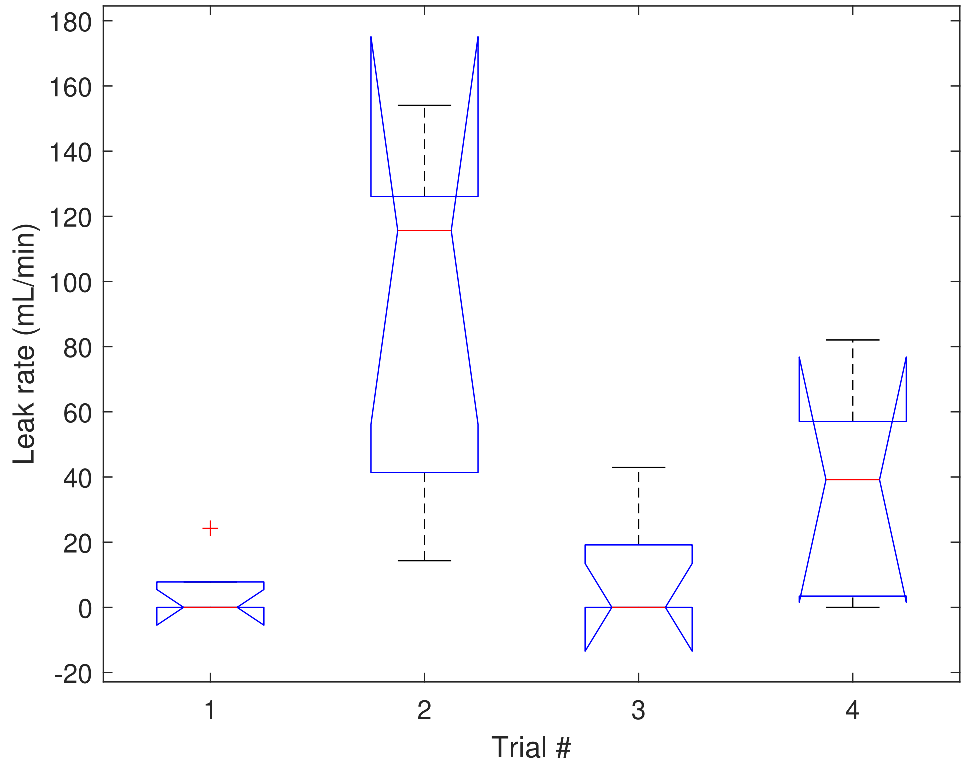


Figure 4.12: Box plots showing the different trials for the design of experiment

unacceptable. Consequently, the leak rate for these decommissioned seals provides an estimate of what is an unacceptable leak rate.

The used seals from Uganda were purchased by the authors and the seals from Haiti were acquired by WHOlives [209]. The average measured leak rate for the decommissioned seals were 35,000 mL/min, many times higher than the leak rates measured during the tests with new seals (see Tables 4.3-4.5, and 4.7, and Figure 4.12).

Based on the leak rate of the decommissioned seals, we conclude that none of the 110 new seals violates the leak rate acceptable limit. This suggests that the observed geometric and material variations, together with the variability introduced by installation, have a negligible impact on static zero-cycle pump performance.

4.6.1 Error Analysis for the Leak Test

The seal leak test was analyzed by performing three different self studies with one seal randomly selected from the 110 seals. The first self study was to find variations due to the test-rig.

The second was to find variations due to the mating between the pump cylinder and the plunger assembly. And the third was to find variations due to disassembly and assembly of the plunger assembly. Each self study was repeated 30 times for the single seal.

No leaks were found in the first self study. For the second self study (variation due to the mating between the pump cylinder and the plunger assembly), one test out of thirty produced a measurable leak rate. This corresponds to a probability of 3.3% of leaks happening due to installation of the plunger assembly into the cylinder. No leaks were found in the third self study.

4.7 Dynamic Zero-Cycle Pump Performance of Off-the-Shelf Seals

To find how each seal performed off-the-shelf, a dynamic test-rig was built at Brigham Young University (see Figure 4.13). An India Mark II pump cylinder complete with a plunger assembly was connected to a water tank (see schematic on the left side in Figure 5.1) from an India Mark III. A water tank from the India Mark III was used in order to enable the removal of the plunger assembly without dismantling the rising main. Then a motor-powered crank-slider mechanism was built to simulate the movement of the pump handle. The pump cylinder was immersed in a barrel of water. A National Instruments controller and LabView [212] were used to start and stop the motor to ensure a cycle time of one minute. The crank-slider mechanism pumped 42 full strokes per minute. Each seal was tested individually by being placed in the lower seal position of the plunger assembly, leaving the upper position empty (see Figure 4.5(c)). A scale was used to measure the water output (Mango Spot portable scale). The test setup was created to match the discharge test performed in the field at the time of cup seal/pump cylinder installation (see text box). This is done to ensure that the pump cylinder is tight and that the cup seals are functioning properly.

Discharge Test [10]:
The cylinder shall be primed and testing shall start after a continuous flow of water through the spout has been obtained. The water shall then be collected in a container for 40 continuous full strokes of the plunger. This test shall be completed in one minute and the discharge thus measured shall not be less than 15 liters.

Because the in-field discharge test is done with two cup seals and the in-lab pump performance test setup employed only one cup seal, it was necessary to determine the equivalent acceptable output for a single-seal pump configuration. To determine the acceptable level of output, two seals were placed in the plunger assembly and the test was performed. The same test was then repeated with only one seal to compare the output. The discharge test was repeated with several different seal configurations and a model was created to calculate the output of one seal that would corresponding to the output using two seals. The output was reduced by 4.24%. Therefore, an output of 14.36 liters/min was deemed acceptable (95.76% of 15 liters/min).

The dynamic test was then performed for all 110 seals. The range of the output was 6.425 to 16.36 liters/min with an average of 14.188 liters/min, σ = 2.2477. 60 of the 110 seals had an output above 14.36 liters/min (55%). It was noted that the seals from store 4 and 5 performed better overall compared to seals from the other stores (see Figure 4.14).

Based on the pump performance test, we can conclude that 45% of the seals would have failed a field discharge test. This suggests that the observed geometric and material variations and how the seals were stored before purchase affected the dynamic pump performance to the degree that one in four seals would not perform satisfactory at time of installation.

4.7.1 Error Analysis for the Pump Performance Test

The dynamic test setup was analyzed by performing two self studies with one seal randomly selected from the 110 seals. The first self study was to find the variation in output due to the mechanical pump system and the second was to find the variation in measuring the weight of the water output. Each self study was repeated 30 times for the single seal.

In the first self study, the results of the output ranged from 15.90 to 16.03 liters/min with an average of 16.00 liters/min, σ = 0.02331. For the second self study, a 13.66 kg weight was used to find the variation of measurements for the scale. No variation was found for the scale.

4.8 Statistical Correlations Between Geometric and Material Variations to Zero-Cycle Performance

Principal component analyzes were done to determine if there were correlations between geometric and material parameters and leak and pump performance that could not be observed naturally. This type of analysis is helpful for researchers and engineers to aid in determining which

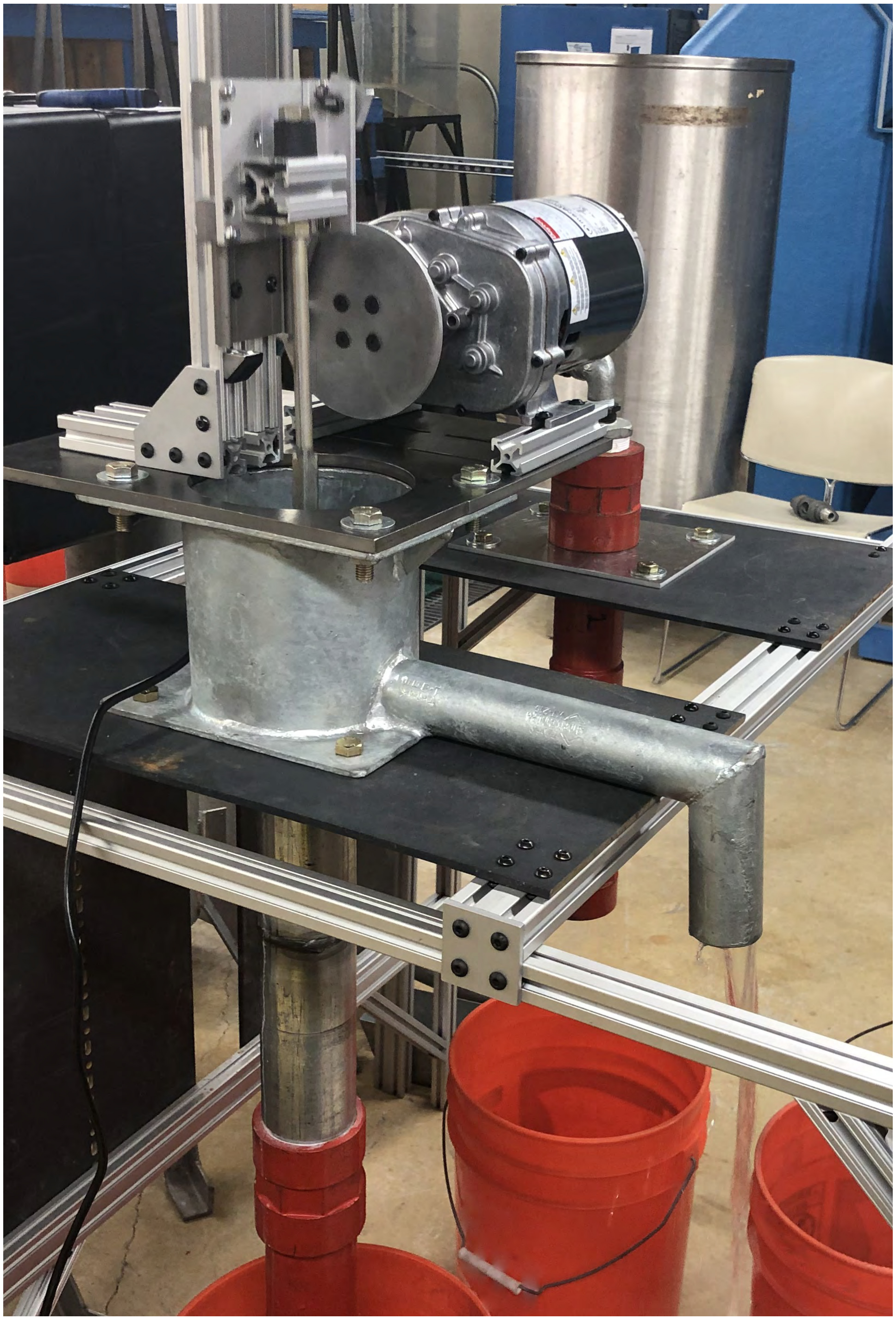


Figure 4.13: Dynamic test rig for determining cup seal performance

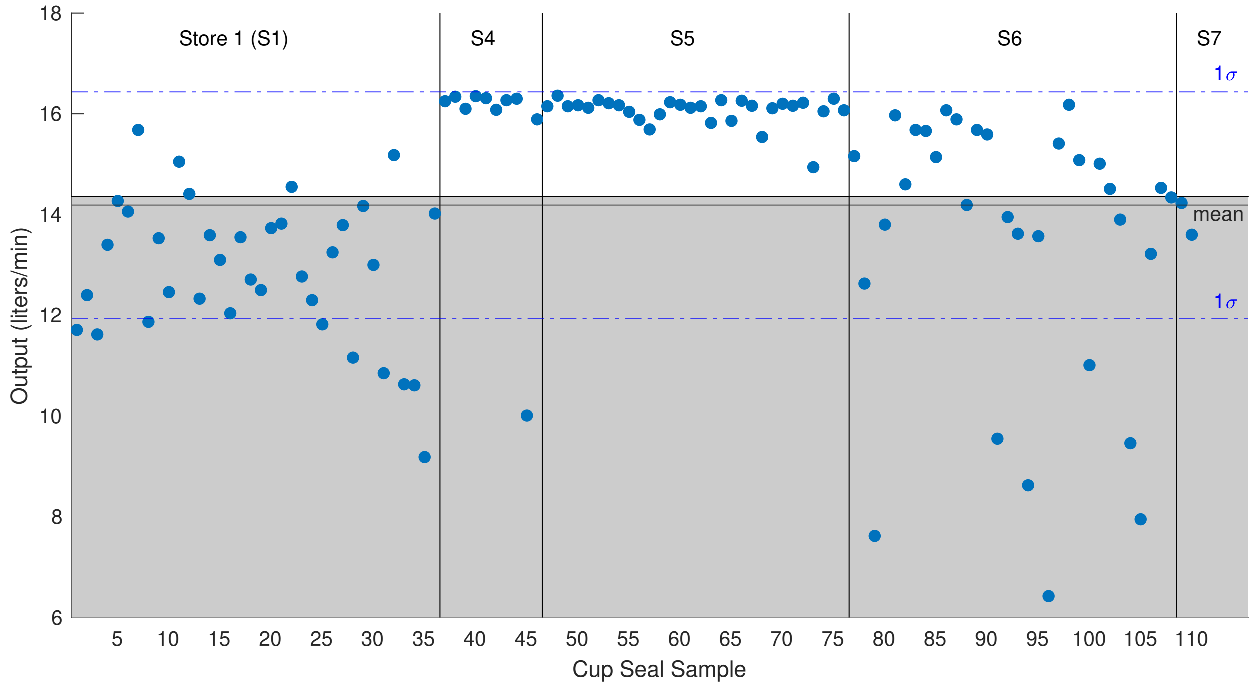


Figure 4.14: Seal output for the zero-cycle pump performance test, values in the grey area are outside of specification (displayed in same order as tested)

parameters should be prioritized throughout the design process. Principal component analysis (PCA) is a dimensionality reduction technique used to identify a small number of mutually orthogonal composite variables (principal components), that are linear combinations of the original variables, and which better explain the variance in the observed data [213–215].

It was found that many of the parameters were highly correlated with each other, meaning that they are partially redundant (see Sections 4.8.1 and 4.8.2). These findings will guide us in our future work to improve the seal.

4.8.1 Geometric Variations

The variables included in the PCA for the geometric variations were the six different dimensions seen in Figure 4.6. The PCA showed that much of the geometric variability in both the static leak and dynamic pump performance tests could be accounted for by height (Dim 3) and base thickness (Dim 4) as seen in column PC 1 of Table 4.8, (even though all six geometric parameters would have to be included to fully represent the total system variability due to geometry). This agrees with the results found when evaluating a free body diagram of the seal, where it can be seen that the height and base thickness affected the seal performance. From Table 4.8 we can also see that four parameters account for half of the variance (the two first principal components). Also, see Figure 4.15. To verify the results, we analyzed the measurement data for the seal height (Dim 3) in relation to the pump water output and found that there is a linear relationship. We believe that extra focus on these four parameters could lead to improvements of pump performance when considering a redesign of seal geometry.

Table 4.8: Geometric parameters affecting each principal component for the zero-cycle performance tests (PC 1-6)

Parameter	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Outer diameter (Dim 1)	-0.134	**0.696**	0.129	0.036	**0.613**	-0.323
Inner diameter (Dim 2)	0.279	-0.384	**0.466**	**0.611**	0.416	0.102
Height (Dim 3)	**0.694**	0.007	-0.159	0.047	-0.182	**-0.677**
Base thickness (Dim 4)	**0.490**	0.388	-0.440	0.209	0.067	**0.607**
Wall thickness (Dim 5)	0.427	-0.016	**0.465**	**-0.719**	0.177	0.231
Wall angle (Dim 6)	0.026	**0.467**	**0.575**	0.250	**-0.618**	0.080
Variance explained by each principal component	26.9%	22.9%	20.1%	13.1%	10.9%	6.1%

4.8.2 Material Variations

The variables included in the PCA for the material variations were weight, volume, density, and hardness. The PCA showed that more than half of the material variability in both the static leak and dynamic pump performance tests could be accounted for by weight and density as seen in column PC 1 (first principal component) of Table 4.9, (even though all four material parameters would have to be included to fully represent the total system variability due to material). Since these two parameters affect how dense the material is, it is in agreement with our physical models. Also, see Figure 4.16. We believe that extra focus on weight and density could lead to improvements of pump performance when considering a redesign of seal material.

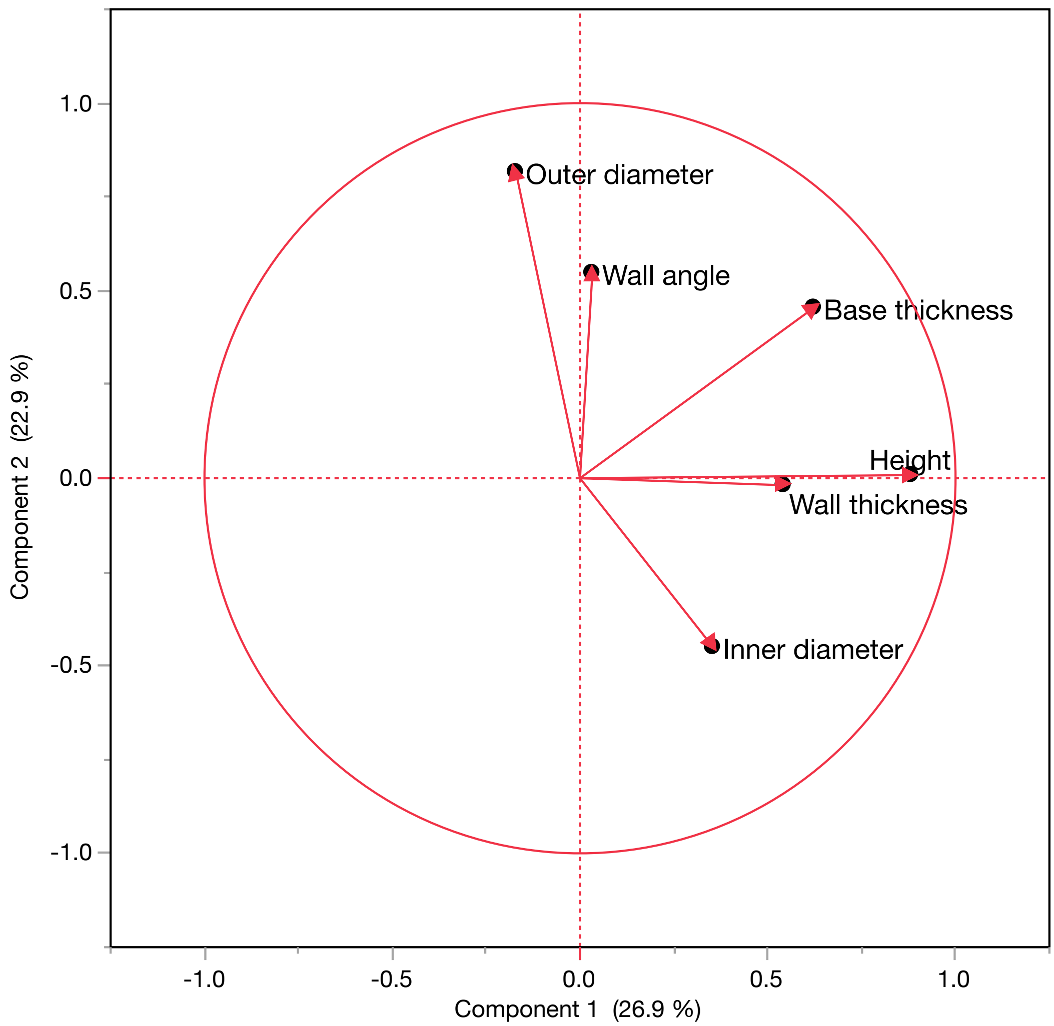


Figure 4.15: Principal component analysis (PCA) plot showing the geometric parameters for the performance tests projected in the first two principal components

Table 4.9: Material parameters affecting each principal component for the zero-cycle performance tests (PC 1-4)

Parameter	PC 1	PC 2	PC 3	PC 4
Weight	**0.683**	-0.040	-0.067	**-0.726**
Volume	0.422	**-0.545**	**0.622**	0.370
Density	**0.586**	0.296	-0.483	**0.579**
Hardness (durometer)	0.107	**0.783**	**0.612**	0.02
Variance explained by each principal component	53.3%	28.8%	17.9%	0.003%

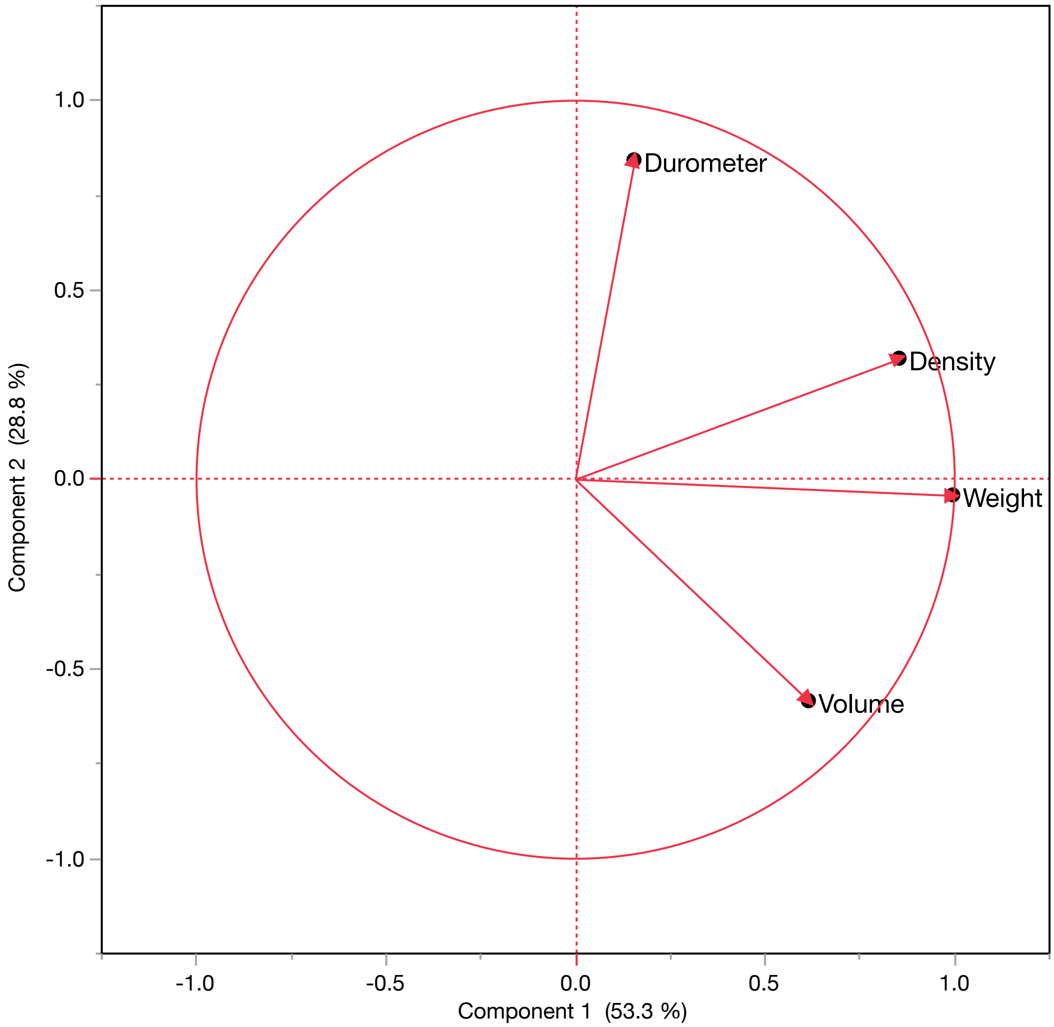


Figure 4.16: Principal component analysis (PCA) plot showing the material parameters for the performance tests projected in the first two principal components

4.8.3 Cup Seal Manufacturer

Out of the 110 cup seals purchased in Uganda, seven different manufacturers were identified and their performance analyzed and compared.

No difference was found for the static leak performance test, but for the dynamic pump performance test it was found that the output varied greatly between manufacturers (see Figure 4.17). This explains in part why the seals from store 4 and 5 performed so well (see Figure 4.14) since they were principally manufactured by AOV. By comparing the measurements and material properties of the seals from each manufacturer, it was found that the seals from AOV have a higher percent of their seals within specifications for base thickness (Dim 4), wall angle (Dim 6), and hardness compared with the other manufacturers. Different manufacturing processes and material blends can also be factors affecting performance (not part of this research).

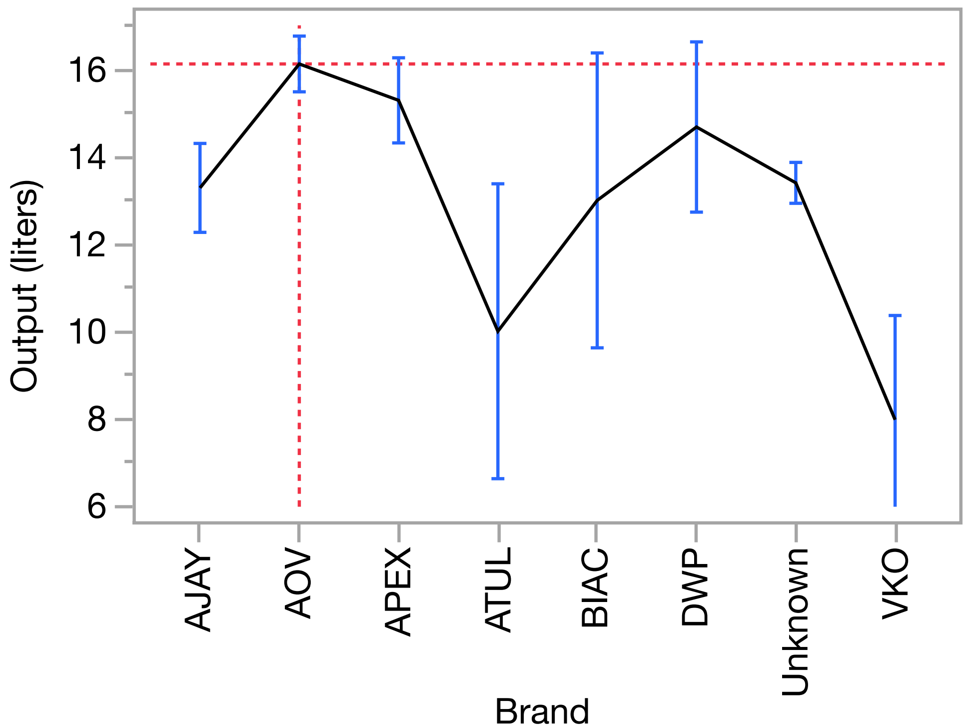


Figure 4.17: The effect of different manufacturers on water output (best performing seal manufacturer highlighted

4.9 Discussion

This section displays the test results and discusses the robustness of the cup seal. For convenience, a summary of the test results can be found in Table 4.10.

Characterization of the Robustness of a New Cup Seal in the India Mark II/III Hand Pump System:

In the static zero-cycle leak performance test (Section 4.6) we found that 95.5% of the seals functioned correctly at a simulated depth of 42 m. Important to note is that for the seals that did leak, the leak rate was 140 mL/min or lower. When considering the fact that there are always two seals installed in the plunger assembly, a leak at this rate will have a negligible impact on pump performance.

Table 4.10: Summary of cup seal tests

Test	Result
Geometry variation (Section 4.5)	3 out of 6 dimensions had mean and median outside of specifications. See Table 4.1 for all results.
Material variation (Section 4.5)	Both the mean and median for the hardness were outside of specification. See Table 4.1 for all results.
Static leak test (Section 4.6)	Geometric and material variations had minimal or no effect on leak at time of cup seal installation.
Dynamic pump test (Section 4.7)	The average output for the zero-cycle test was 14.188 liters/min with an output range between 6.425 and 16.36 liters/min. 60 out of the 110 seals had an output above 14.36 liters/min (55%).

The dynamic zero-cycle pump performance test (Section 4.7) was done in laboratory settings where the pump depth was only 0.6 m instead of the average depth of 42 m. This could have influenced the water output due to a shorter water column above the plunger assembly, causing less pressure between the cup seal and the pump cylinder. The average water output was 14.188 liters/min. Out of the 110 seals, 60 had an acceptable output above 14.36 liters/min. It was found that for the seals that performed poorly, many of their parameters were out of specification. If the seals had been tested at 42 m, it is probable that the increased pressure would have improved seal performance. Figure 4.14 displays the output for the 110 seals.

Variation in how the cup seals were stored by vendors (sometimes hanging on a string, piled in a bucket or on a counter with average temperature 28.9°C and relative humidity 47.8%), together with variations in geometry and material properties did not affect the static leak performance once seals were installed. For the dynamic pump performance test, 50 seals (45%) performed below specification.

The geometry and material parameters that had the greatest impact on pump performance were height (Dim 3), base thickness (Dim 4), weight, and density. When comparing the different cup seal manufacturers, it was found that AOV and APEX performed better and more consistently over all.

4.10 Conclusions

Our focus for this chapter has been on the cup seal of the India Mark II/III hand pump system. This was because the cup seal is the part of the pump system that caused the most dysfunction [12, 180, 206]. In this chapter we have examined off-the-shelf nitrile seals for the India Mark II/III mechanical hand pump, which is the most ubiquitous pump for accessing ground water in the developing world. We examined four facets of the cup seals (i) the geometric variation present in the off-the-shelf components, (ii) the material variation present in the off-the-shelf components, (iii) the leak performance in a static test simulating 42 m well depth, and (iv) the pump performance of the cup seals in a dynamic test. Measurement error was evaluated and analyses were performed to extract meaningful relationships and findings. This robustness study was carried out since it can be used to improve a product's design as shown in other research [216, 217].

The results show wide geometric and material variation to be present in the off-the-shelf cup seals. Surprisingly, the leak performance was shown to be incredibly robust to these geometric and material variations, yielding acceptable performance for the static zero-cycle leak test for all tested seals. However, in the dynamic zero-cycle test, only 55% of the seals yielded an output above the 14.36 liters/min threshold, leaving room for improvement.

With a track record of over 40 years, the cup seal design has proven to be a robust design that is well suited for low cost production and small sales margins. These characteristics, together with the findings in this chapter, make the cup seal well suited for global development, and as such, a candidate for geometry and material updates to become even more robust.

Why the baseline performance matters: From a scientific point-of-view, and a design point-of-view, it doesn't matter what the baseline performance is as long as it is known. Knowing the baseline is essential, so that observed performance can be compared to baseline performance and a change in performance can be declared. We believe that this is a process engineers and designers can use as they work on improving the performance of existing products. In this chapter, we have established that wide variations in geometric and material properties produce little to no leakage for off-the-shelf cup seals tested statically but that for the dynamic pump performance test it was found that only 55% of the tested seals passed, leaving room for improvement.

Our future work is to understand how and to what degree seals can be improved in terms of both material and geometry by developing a wear model for the cup seal. We will also link the performance of the India Mark II/III to social impact categories found in literature [1] and to UN's sustainable development goals [218].

CHAPTER 5. DEMONSTRATION OF THE SOCIAL IMPACT METHOD CREATED IN CHAPTER 3

5.1 Chapter Overview

This chapter contains a demonstration of the method created in Chapter 3. It shows how the social impact of the India Mark II/III hand pump system could be increased by considering the 11 social impact categories discussed in Section 3.3.1 during a redesign of its cup seal. As part of the method, the changes in social impacts of the India Mark II/III hand pump system were analyzed.

5.2 Introduction

Many engineered products are designed to impact the lives of users. Mechanical hand pumps for accessing ground water are part of a group of products with particularly large impacts. These hand pumps, with the India Mark II/III hand pump system being the most prevalent (see Figure 5.1), are used worldwide to supply clean water to at least 1 billion people in developing countries [61].

Hand pumps typically provide clean water, adding to the health and well-being of the community. The need for clean water is paramount, since water-borne diseases often lead to diarrhea, which kills more children than malaria, measles, and AIDS combined [9]. As stated in Section 4.2, when a pump becomes dysfunctional, the people relying on its water are often forced to use unimproved water sources [183] and that even a few days of so doing can be sufficient to offset the benefits from normally having clean water, leading to serious sickness and/or death [189]. For the 1 billion people using hand pumps for daily access to clean water, their health is directly related to the reliability of the pump system they use [184]. Importantly, a functional hand pump does not only provide clean water. It is well known that pumps (which typically serve 150 to 250 people [59]) act as a hub of the village by creating space for social gatherings and meetings to take place [219]. As a pump becomes derelict, conflict often arise among the pump users [180]. Failure of the hand pump can increase the use of unimproved water sources which leads to disease [189], it can cause loss of income due to sickness or time lost due to the gathering of water [180], it can cause education gaps since time has to be spent getting water or from recovering from illness caused by using unsafe water [219], and it can also cause an increase in crime against women and children since assault and rape is prevalent as they travel further distances and later at night to gather water [180].

Failure of India Mark II/III hand pump systems are extremely common, as would be expected for any mechanical system. It is estimated that 15% of India Mark II/III hand pumps are currently dysfunctional or otherwise not supporting the needs of local communities [59]. Of those, approximately 70% are dysfunctional due to hardware problems that could be repaired [183]. Additionally, as a pump system ages, its functionality degrades due to lack of maintenance, leaving more people without direct access to clean water [11, 188]. Unfortunately, repair times can be expected to be between 1 and 5 weeks for any type of failure [59].

We believe that decreasing the number of dysfunctional hand pumps and/or increasing their longevity, will result in an increase in positive social impacts.

With over 4 million installations of the India Mark II/III hand pump system, it is estimated that 10% of the world's population is using one on a daily basis [59, 60]. It is rare that a single product affects such a large portion of the world's population and this acts as a great motivation for us to find improvements to the India Mark II/III hand pump system. For this reason, it was selected for a redesign, using the 4 step method presented in Chapter 3.

5.3 Redesign of the India Mark II/III hand pump system while Considering Social Impacts

The method in Section 3.6 was used while redesigning the India Mark II/III hand pump system in order to increase its potential for positive social impacts while at the same time minimize negative impacts. The following sections describe the design decisions that were made and the reasoning that drove those decisions for this developing world product. These decisions are provided as an illustration of using the 4-step method.

Figure 5.1: India Mark II hand pump (photo by the authors)

5.3.1 Design Objectives and Constraints

Given that this redesign project was specifically for a developing world product, important objectives and constraints were discovered and articulated early in the design process. To be clear, the driving objective, which centers on improving the longevity of the pump, is to (i) increase the mean time between pump failures, (ii) decrease the amount of pumping time required of users, and (iii) decrease the cost of pump repair. It is assumed that if mean time between failure is decreased, the overall downtime of a pump, over its life, will be decreased, thus having a positive social impact. Likewise it is assumed that if pumping time is reduced, and pump repair costs are reduced, these will have a positive social impact. More details regarding the specific impacts are provided in Section 5.3.2.

An essential design consideration is that regulations in many countries across Africa that prohibit the introduction of new pump systems [205]. Therefore we constrain the design to keep the current hand pump system mostly intact in order to minimize the negative impact of large design changes on manufacturers and distributors. This also minimizes the need for training pump users and mechanics on a new pump system (many pump mechanics already feel overwhelmed, see Appendix A).

Another constraint was to develop a *culturally sensitive* design. This was sought by considering positive and negative impacts for multiple stakeholders (pump users, pump mechanics, and pump manufactures) during the design process.

5.3.2 Step 1 – Find Social Impact Categories of Interest

For the first step (as presented in Section 3.6), after selecting the India Mark II/III hand pump system, we examined its main function to find obvious social impacts. Being that the India Mark II/III hand pump system supplies daily water for millions of people, we chose the obvious impact category of *Health and Safety* from Table 3.1.

Knowing that pumps impact *Health and Safety*, we then looked at the conditional probability table (Table 3.9) to find other social impact categories with high probability of co-presence. After studying the table, some less-obvious social impact categories with high probability of impact were selected for inclusion: *Paid Work*, *Human Rights*, and *Social Networks and Communication*. To be clear, the table helped consider the ways in which the pump affects paid work, for example. It affects paid work in multiple ways: When a pump breaks down and a user needs to drink water from unclean sources, sickness such as diarrhea can occur, impacting employment. When pump users need to travel to more distant functional pumps, time and energy are used to gather water. That loss of time and energy can also affect employment [180]. Further, the United Nations General Assembly has recognized the right to have water within 30 minutes of one's home as a *Human Right* [220]. A not too distant functional pump allows for this to happen. The pump often becomes the heart of the village by creating a natural meeting point for the pump users [219]. When the pump functionality goes down, there will be more tension among the pump users, causing a negative social impact in the category of *Social Networks and Communication* [180].

Considering that the burden of collecting water is typically borne by women and girls [59, 190], *Education*, *Family*, *Gender*, and *Conflict and Crime* were also considered and added to the social impact categories of interest. When a pump stops working or is abandoned because of extended pumping time, users will have to travel farther distances for their water. This puts women and girls at greater risk of harassment, sexual assault, or other abuse (negative impact in

Family, *Gender*, and *Conflict and Crime*) [180, 221]. Dysfunctional pumps can also lead to longer time needed for gathering water and higher risk of contracting diseases, both of which can prevent pump users from going to school (negative impact in *Education*).

How a redesign specifically affects these social impact categories will be discussed further in Step 4, after a new design emerges from Steps 2 and 3.

5.3.3 Step 2 – Decide on Indicators for Evaluating Social Impacts

As part of this step, we examine the social impacts identified in Step 1 and choose product-centric indicators that influence the social impacts. We chose to include indicators that a design engineer would have control over, as opposed to indicators s/he does not, such as density of pumps in a municipality, or speed of pump mechanics responding to a maintenance request. We first chose to include *Meantime Between Failure* and *Pumping Time* for evaluating social impacts because decreasing one or both of these improves the negative effects of dysfunctional pumps on *Health and Safety*, *Paid Work*, *Human Rights*, *Education*, *Family*, *Gender*, *Conflict and Crime*, and *Social Networks and Communication* as described earlier in this chapter. Also chosen as an indicator was *Cost*. When considered in the context of all three stakeholders (users, mechanics, and manufactures) it is clear that a redesign can affect each one financially, positively or negatively (see Section 5.3.1).

Note that although we used Mean Time Between Failure, Pumping Time, and Cost of Pump Repair earlier in this chapter to show specifically how pump longevity affects society, it was indeed in this step, Step 2, that those three indicators were chosen as the link between social impact categories (Step 1) and engineering design parameters (Step 2).

5.3.4 Step 3 – Link Design Parameters to Indicators

This step brings the engineering more fully into focus as engineering design parameters for the pump are connected to the three indicators chosen in Step 2. Considering the objectives and constraints of this developing world product, we considered each part of the India Mark II/III hand pump and focused solely on the wear items to be consistent with governmental regulations to not introduce new pump systems. Literature revealed that the cup seals in the India Mark II/III hand pump systems were the most frequently occurring failure in the field [12]. We found this literature to be consistent with dominant failure modes described by WHOlives [188]. The cup seal can be seen in Figure 5.2.

Figure 5.2: New, off-the-shelf India Mark II/III cup seal

The cup seals were, therefore, chosen as the single component that would be parameterized and linked to the indicators chosen in Step 2. The dimensions of the cup seal can be seen in Figure 5.3. Note that it is not necessary for this step that only one component be selected. It is however valuable to the pump ecosystem to achieve improvement with minimal changes that affect manufacturing, assembly, repair, and use.

Choosing the seal as the only component for redesign would allow us to (i) pursue improvement without violating governmental regulations, (ii) pursue improvement that would be unlikely to require new maintenance training, (iii) pursue improvement that would most likely be consistent with existing manufacturing and supply chains, and (iv) it would allow the user interaction with the pump to be imperceptibly different than the current pumps, namely that the stroke length and stroke force would be imperceptibly different.

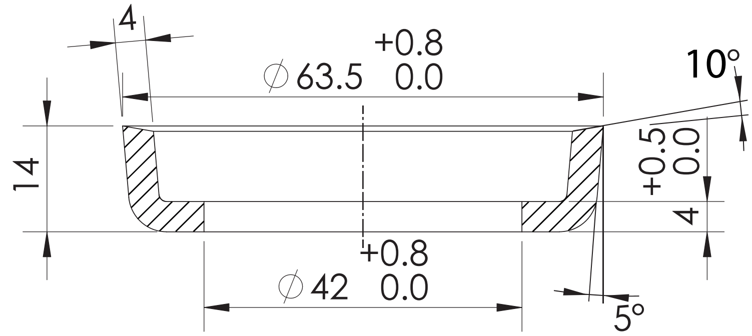


Figure 5.3: Specified cup seal dimensions (mm) [10]

To be clear, the cup seal has a direct impact on pump longevity. When the seal lasts longer, the mean time between pump failures is reduced. The performance of the cup seal also determines how much water is lifted during each pump stroke, therefore the cup seal also has a direct affect on pumping time required of users. Finally, we recognize that seals will always need to be replaced and that decreasing the frequency of seal replacement, reduces maintenance costs. We also recognize that design changes to the seal could result in seal unit costs that negate or override the reduced maintenance costs for the users. Considering the three stakeholders (user, maintenance worker, and manufacturer), it is clear that changes to the seal's geometry or specified material may impact costs of repair, maintenance, and manufacturing. For this study, it was determined for each stakeholder if an increase in each indicator would result in positive or negative change in social impacts (see Table 5.1).

The remainder of this section is dedicated to creating the formal link between the cup seal parameters to the indicators chosen in Step 2.

Performance Prediction of Current Cup Seal Design

To be able to link seal parameters to indicators and predict the performance of the current cup seal design, seals were purchased in Uganda by the authors. A dynamic test rig was designed and built to test the performance of each seal in terms of water output. A seal degradation test was then performed to find how well the cup seals behaved as their geometric values changed. The data was then analysed and used to create a model to predict water output with cup seal geometry data as input.

As shown in the upcoming sections, these models were then linked to a long term dynamic wear study, which allowed us to model degradation over time based on geometric properties of the seal. As will be shown, this model allows us to assess mean time between failure and pumping time for any seal geometry within the parameterization.

Dynamic Pump Test Rig

To measure how each seal performed off-the-shelf and over time, a dynamic test rig was created (see Figure 5.4). The reciprocating movement of the pump was done by a crank-slider

Table 5.1: Expected changes in social impacts for the India Mark II/III hand pump system after a cup seal redesign

Social impact category	**Conditional probability for social impact**	**Meantime between failure (users)**	**Meantime between failure (mechanics)**	**Meantime between failure (manufacturers)**	**Reduction in pumping time (users)**	**Reduction in monthly cost for service (users)**	**Manufacturing cost (manufacturers)**
Health and safety	1	↗	n/a	n/a	↗	n/a	n/a
Paid work	0.427	↗	↘	↘	↘	↗	↘
Stratification	0.066	n/a	n/a	n/a	n/a	n/a	n/a
Human rights	0.293	n/a	n/a	n/a	↗	n/a	n/a
Education	0.183	n/a	n/a	n/a	↗	n/a	n/a
Family	0.185	n/a	n/a	n/a	↗	n/a	n/a
Gender	0.173	n/a	n/a	n/a	↗	n/a	n/a
Population change	0.104	n/a	n/a	n/a	n/a	n/a	n/a
Conflict and crime	0.127	n/a	n/a	n/a	↗	n/a	n/a
Social networks and communication	0.259	n/a	n/a	n/a	↗	n/a	n/a
Cultural identity/heritage	0.169	n/a	n/a	n/a	n/a	n/a	n/a

mechanism as seen in Figure 5.4, simulating the up-and-down linear pump motion done by a human. Consistent with hand pump usage, the mechanism operated at a speed of 42 full pump strokes per minute (see Appendix A).

For the test, a seal was inserted in the lower placement in the piston assembly (see Figure 4.5) and tested alone. The test setup was created to match a volumetric discharge test done in the field at time of cup seal/pump cylinder installation [10]. A scale was used to measure the water output (Mango Spot portable scale).

The primary limitations of this test rig is that the experimentation of *dynamic* performance of the cup seal is limited to a laboratory setting with a pump depth of 0.6 m (greater borehole depth increases the hydrostatic pressure on the cup seal applied by the water in the rising main).

Error Analysis for the Pump Test Rig

The dynamic test setup was analysed by performing two self studies with one randomly selected cup seal. The first self study was to find the variation in output due to the mechanical pump system and the second was to find the variation in scale readings for the same water output. Each self study was repeated 30 times for a single seal.

In the first self study, the results of the output ranged from 15.90 to 16.03 liters with an average of 16.00 liters and a standard deviation of 0.02331. For the second test, a set of calibrated weights were used to ensure that the scale was accurate. A combined mass within the range of normal water output for one minute was chosen (13.66 kg) to find the variation of measurements for the scale. Variation was not detected for the scale at a resolution of +/-0.01 kg.

These tests show that there are minimal or no variation in pump output due to the test rig, drawing the conclusion that the uncertainty in the pump output for the test rig is negligible.

Seal Degradation Test

In order to better understand how the seals perform over time, a seal degradation test was created where a seal was worn, measured, and tested repeatedly using the dynamic test rig until it failed to lift the minimum amount of required water. The pump was considered non-functional

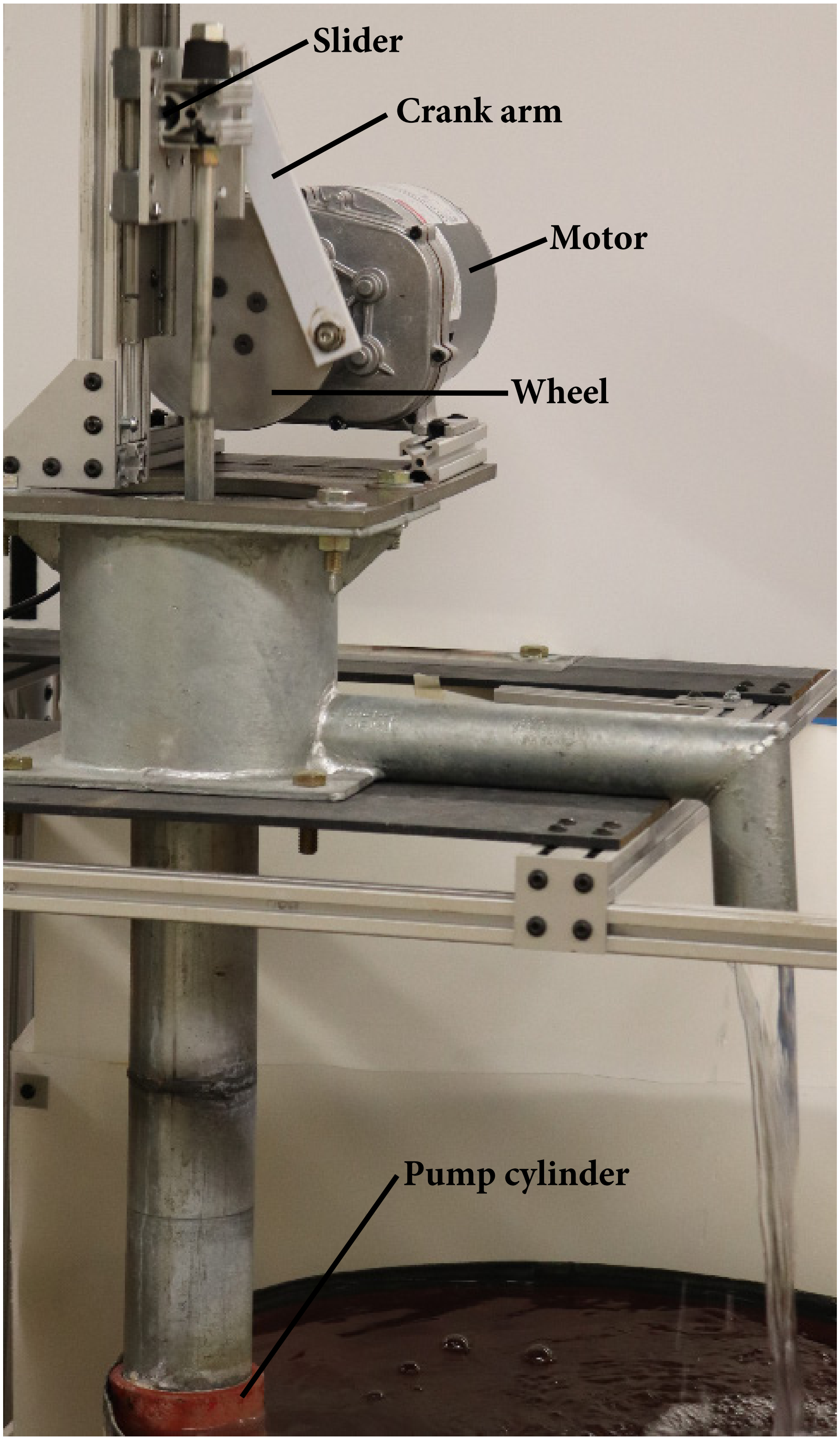


Figure 5.4: Dynamic test rig for determining cup seal performance complete with a crank-slider mechanism, (motor, wheel, crank arm, and a slider)

when the output was less than one liter/minute. Figure 5.5 shows a 3D plot of the seal degradation test results. Fifty-five seals were used for this test.

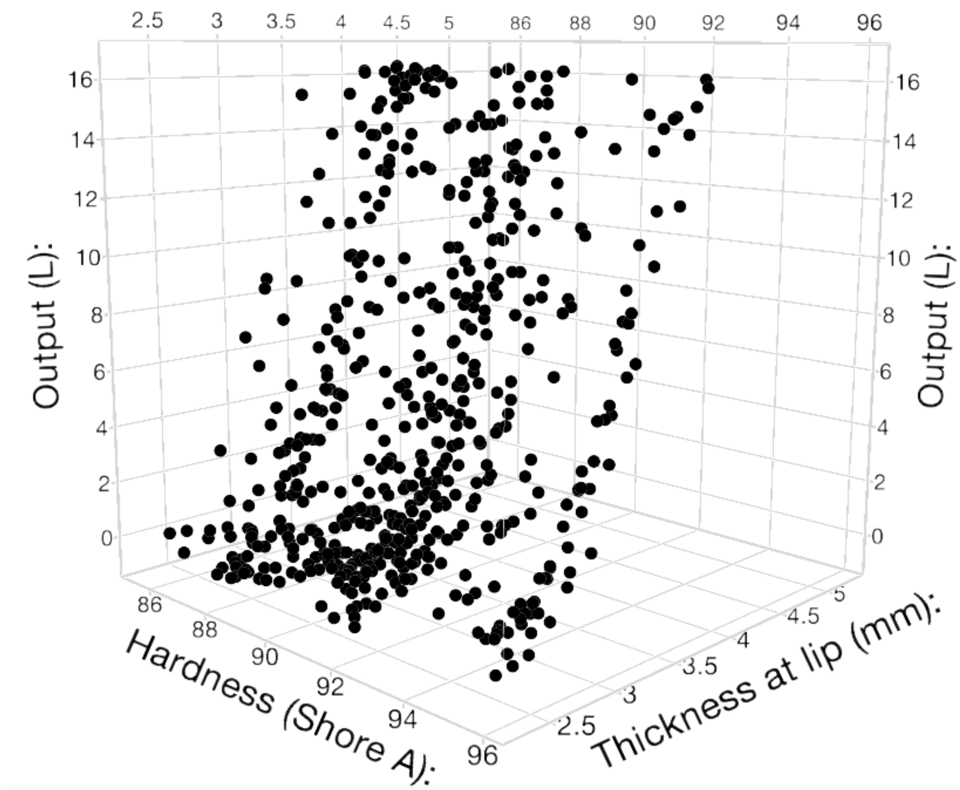


Figure 5.5: Results from the seal degradation test

Seal Performance Model

A pump performance model, with the cup seal parameters as input, was derived from the collected data using JMP Pro 15 statistical software [222]. Only terms with p-values less than 0.05 were included. The seal volume parameter was also excluded since it would be hard to measure it in the field. The predicted water output is found by entering the seal outer diameter, wall thickness, and weight values (see Equation 5.1). A plot showing predicted versus actual output can be seen in Figure 5.6.

$$O_P = -328.18 + 1.3434 \cdot T_W + 5.2627 \cdot D_O$$
$$+ 51.088 \cdot T_W \cdot W - 655.37 \cdot D_O \cdot W$$
$$+ 4,365.2 \cdot {D_O}^2 \tag{5.1}$$

where

O_P is the projected water output (l)

T_W is the seal wall thickness (mm)

D_O is the seal outer diameter (mm)

W is the seal weight (g)

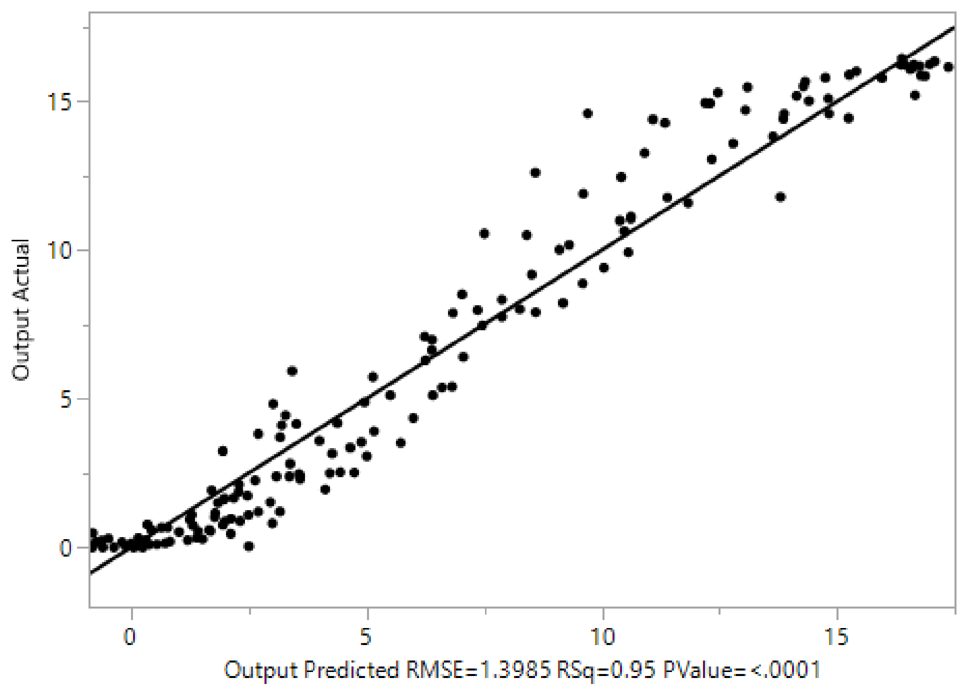


Figure 5.6: Predicted output (solid line) versus actual output (points)

Wear Prediction

To develop a wear model for the cup seal, Archard's wear equation was used (Equation 5.2) [223]. Archard's wear equation is often used as a universal wear volume predictor [224, 225]. It works well for polymer-metal contacts [226], as is the case for the India Mark II/III hand pump.

$$V = K \cdot F_N \cdot s \tag{5.2}$$

where

V is the wear volume (m^2)

K is the wear coefficient (m^2/N)

F_N is the normal load (N)

s is the sliding distance (m)

Wear Coefficient

To find the wear coefficient (K), a long-term wear experiment was performed with a new cup seal placed in the lower position in the piston (see Figure 4.5) with the intention to find the change of wall thickness due to wear over time [227, 228]. Measurement of the cup seal was performed throughout the experiment by removing the cup seal and measuring its lip thickness, weight, and volume. The test was done over a period of one year in the same test rig that was used for the dynamic tests.

The wear results can be seen in Figure 5.7. The data corresponds well with the theoretical wear curve (unsteady/steady state of wear) [229]. Equation 5.3 was then used to calculate the wear coefficient (derived from Equation 5.2). The value of F_N was calculated through the use of the test rig. The value of K was found to be 2.41E-8 and in line with tribology literature (see Table 5.2) [3, 228].

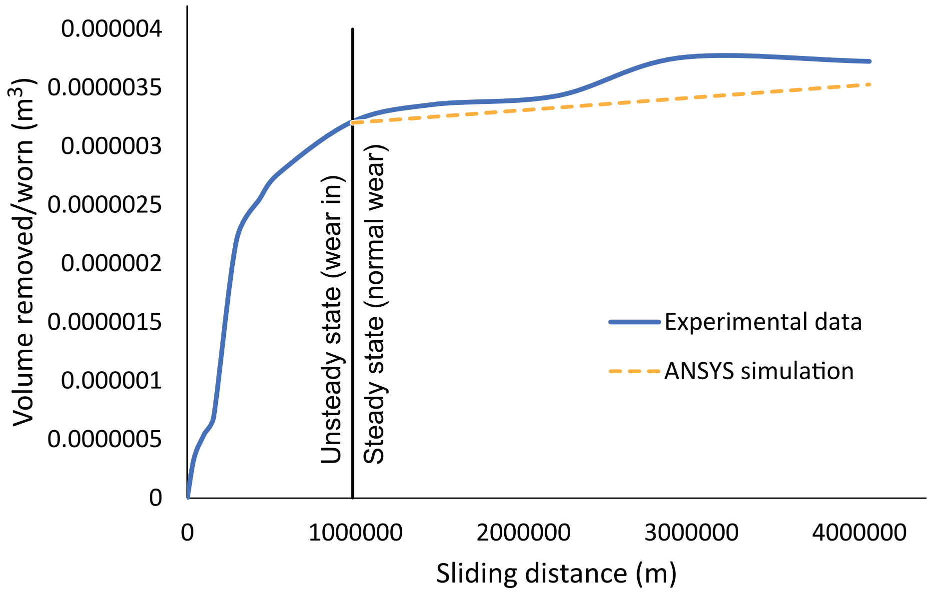


Figure 5.7: Wear curve showing the wear experiment and ANSYS simulation

$$K = \frac{V}{F_N \cdot s} \tag{5.3}$$

Table 5.2: Typical values of wear coefficient (K) for non-metal on metal under different degrees of lubrication [3]

Condition	K (m^2/N)
No or poor lubrication	1.5E-6
Average lubrication	3E-7
Excellent lubrication	3E-8

Wear Prediction Model

ANSYS [230] was used to create a wear prediction model for the cup seal wear. We chose to use ANSYS over hand calculations to be able to explore a larger design space, since some geometries would need to be simplified to carry out hand calculations. A more thorough exploration was particularly important for this developing world product, because even the slightest improvement in pump performance can have noticeable impact in the lives of those depending on these pumps as their only source of drinking water. A 2D model was created in ANSYS with asymmetric contact (only simulates the wear of the seal). Nitrile Rubber/Acrylonitrile butadiene copolymer (NBR), a Mooney-Rivlin 2-parameter material supplied with ANSYS was used for the simulations. This material is a nearly incompressive hyper-elastic material often used in rubber analyses [231–233]. The density was determined to be 1420 kg/m^3 by taking the mean value of the density of 110 nitrile cup seals purchased in Uganda by the authors (see Appendix A). The setup of the model geometry, the mesh, and the constraints and loading of the cup seal can be seen in Figure 5.8. For the finite element mesh, the PLANE182 elements were used and the contact was modeled between the seal and pump cylinder by overlaying the surfaces with contact elements CONTA172 and target elements TARGE169. The mesh element size for the seal was set to 0.2 mm with the refinement option for the outer and lower seal edge (see Figure 5.8). The *Nonlinear Adaptive Region* option in ANSYS was also applied to the seal body.

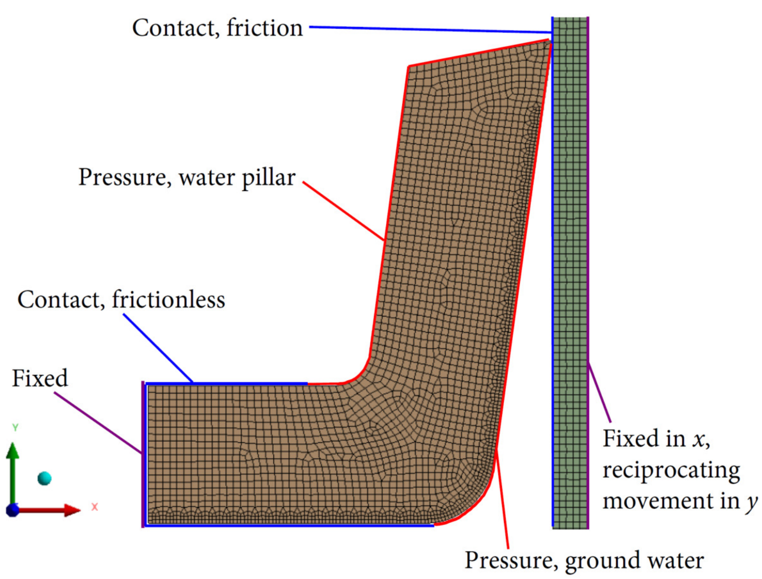


Figure 5.8: Model for the ANSYS simulation with the cup seal on the left and pump cylinder on the right

The model was constrained by preventing movement in the x-direction of the left side of the seal and the three sides of the seal that are in contact with the piston were set as a "Frictionless" contact type. The piston was fully constrained and the pump cylinder was prevented to move in the x-direction and set to move in a reciprocating motion in the y-direction. The contact pair between the seal and the pump cylinder was set to "Frictional" with a frictional coefficient of 0.15 (see Figure 5.8). The frictional coefficient was calculated from experiments using the test rig. It falls within the range found for nitrile in literature [3, 234, 235].

A pressure was then applied to the top of the seal to simulate the pillar of water. The deformation of the seal can be seen in Figure 5.9. A lower pressure was also applied to the bottom side of the seal, representing the pressure from the ground water. The right, vertical part of the seal in Figure 5.9 is where the seal is in contact with the pump cylinder.

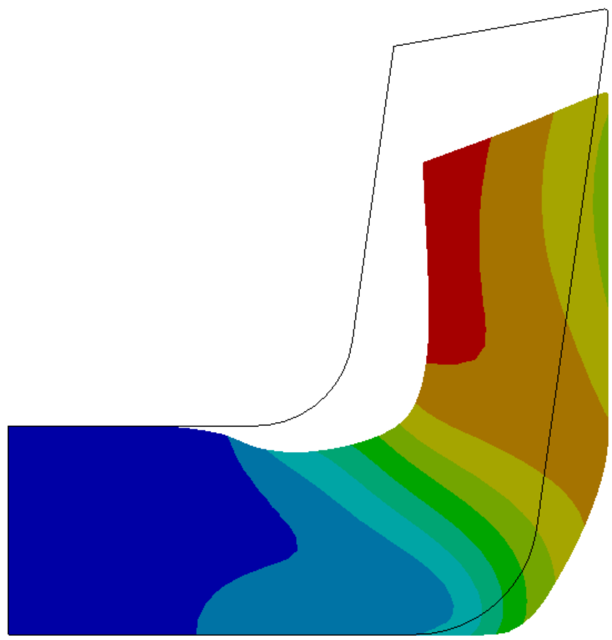


Figure 5.9: Seal deformation due to a simulated water depth of 42 m. Right side of the cup seal is in contact with the pump cylinder as shown in Figure 5.8)

Mesh Validation

To validate the mesh, different mesh sizes were tested with the same setup and the results compared. As the results converged, the mesh size was decided [236]. Through this process, the mesh size for the seal was set to 0.2 mm. The mesh size for the pump cylinder was also set to 0.2 mm.

Wear Results for a Depth of 0.6 m

The ANSYS wear simulation was extended to find the seal wear over time. The wear experiment and ANSYS results can be seen in Figure 5.7. Agreement was observed between the steady-state segment of the experimental and simulated results (no wear-in regime was done in ANSYS).

Wear Results for a Depth of 42 m

After finding correspondence between the seal degradation test and the FEA analysis for a depth of 0.6 m, a wear analysis was performed for a simulated depth of 42 m (the average well depth in Uganda, see Appendix A). Two used nitrile seals acquired in Uganda that had previously been replaced due to wear were measured and the average worn-off material was found to be 1.324×10^{-6} m^3. The wear rate from the ANSYS simulation for a depth of 42 m was used and it was determined that it would take 12.4 months for the ANSYS model to reach the same amount of wear.

This corresponds well with findings during field studies in Uganda and with what is found in literature where the cup seal is to be replaced each year [237, 238].

Potential Geometric Improvements to the Cup Seal

Using an ANSYS wear model for predicting cup seal wear life is a useful tool in evaluating different geometric variations [239, 240]. Design parameters can quickly be changed in ANSYS, and after each simulation, the different scenarios can be compared. Real-world tests can then be performed with promising geometry.

Seal Lip Geometry

Since the lip design of a seal impacts performance and wear rates [241], FEA software can be used to model and evaluate different geometric designs of the lip. A knife-edge or straight lip design provides good scraping properties but also reduces sealing performance. They are often used in sealing applications where there are high fluid contamination [13]. Figure 5.10 displays suggestions for different lip geometries as found in a piston seal design consideration guide from American High Performance Seals [13]. A squeeze seal design (spring loaded) was also considered but discarded due to its added cost and complexity (not suited for low-cost production).

Figure 5.10: Different lip geometries [13]

FEA Comparison Between Different Lip Geometries

ANSYS was used to compare the effect different lip geometries could have on wear. The different lip designs suggested by American High Performance Seals were considered together with two variances of the rounded design (the convex and concave designs). The comparison of the results can be found in Table 5.3 where the original design is used as a base line. The analyses show different wear rates for the different lip designs, indicating that the way the lip is designed affects the wear and should be considered during a redesign of the seal. The different lip geometries can be seen in Figure 5.11. The FEA simulations for this comparison was for a depth of 42 m.

Table 5.3: ANSYS FEA results at a simulated depth of 42 m for different seal lip designs (numbers less than 1 corresponds to less wear)

Edge design	**Seal wear base line**
Original design	1
Concave edge	0.99
Convex edge	1.00
Knife edge	0.97
Straight edge	1.02
Beveled edge	1.05
Rounded edge	1.05
Optimized design (geometry)	0.88

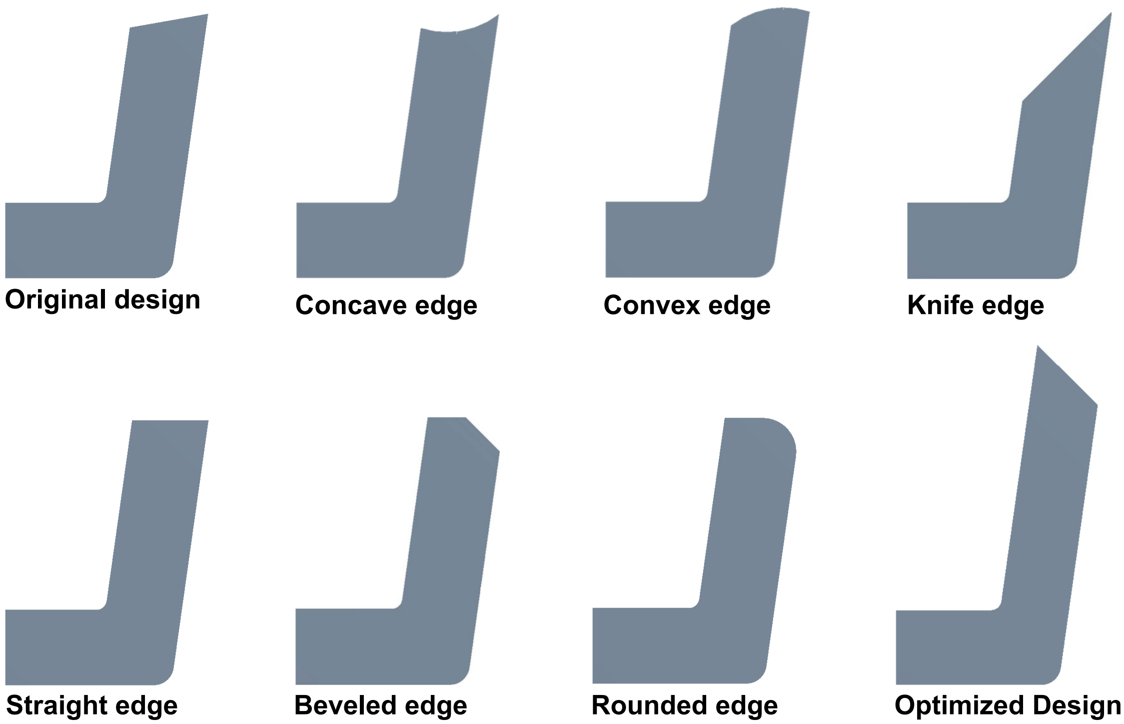


Figure 5.11: Different seal designs used for wear comparison

Using ANSYS as a Design Exploration Tool

After running the ANSYS simulation for the current cup seal design, the model was parameterized and ANSYS DesignXplorer was used to apply DOE algorithms to the cup seal in order to better understand its design space. Since the *Knife edge design* showed promise for reduced wear, the *Original design* was paired with the *Knife edge design* for the DOE. The DOE table of design points was then solved in batch mode. ANSYS and JMP were used to evaluate the results.

The correlations between seal height, thickness, and top angle in relation to wear were found (see Figures 5.12, 5.13, and 5.14 where dark blue denotes less wear). These correlations can now be used during a redesign of the cup seal.

Seal Wear Model

A seal wear model with seal parameters as input, was derived from the ANSYS simulation data using JMP. The predicted seal wear is found by entering the seal wall thickness, height and

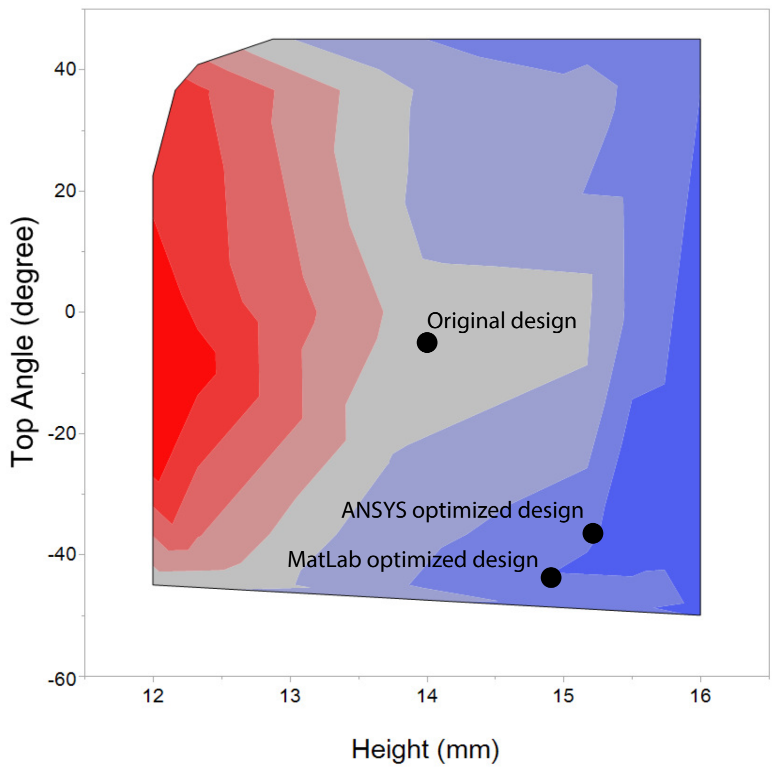


Figure 5.12: How wear is affected by seal height and top angle (dark blue denotes less wear)

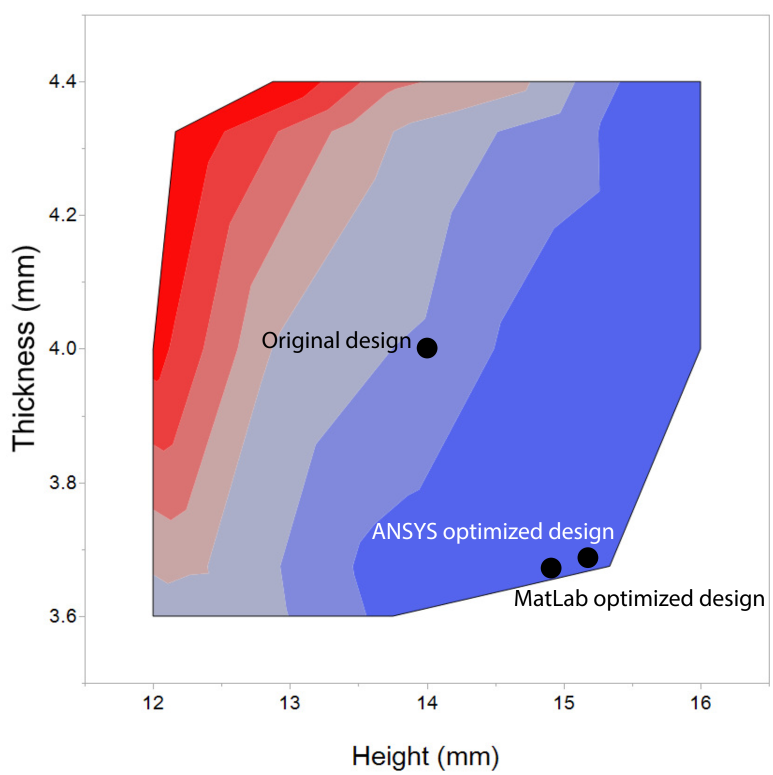


Figure 5.13: How wear is affected by seal height and thickness (dark blue denotes less wear)

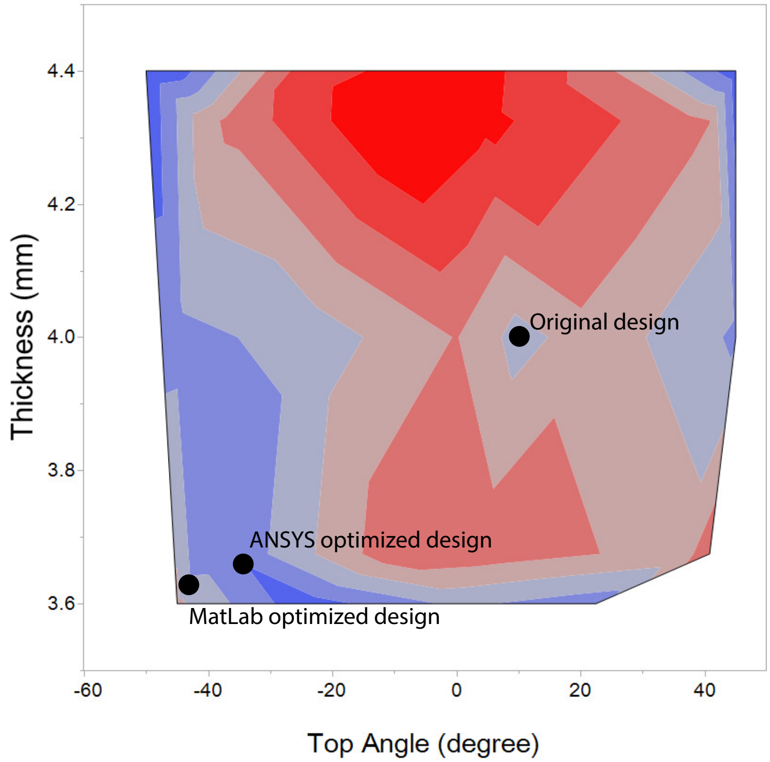


Figure 5.14: How wear is affected by seal thickness and top angle (dark blue denotes less wear)

top angle (see Equation 5.4). A plot showing predicted versus simulated wear can be seen in Figure 5.15.

$$
\begin{aligned}
V_P = 9.707\text{E-}13 - 4.3\text{E-}14 \cdot S_H \\
+ 1.039\text{E-}13 \cdot T_W + 2.331\text{E-}16 \cdot \alpha \\
+ 8.257\text{E-}15 \cdot (S_H - 13.6148)^2 \\
- 2.7\text{E-}14 \cdot (S_H - 13.6148) \cdot (T_W - 4.03408) \\
- 4.09\text{E-}16 \cdot (T_W - 4.03408) \cdot (\alpha + 1.45431) \\
- 2.17\text{E-}17 \cdot (\alpha + 1.45431)^2
\end{aligned} \tag{5.4}
$$

where

V_P is the projected seal wear (m^3)

T_W is the seal wall thickness (mm)

S_H is the seal height (mm)

α is the seal top angle (°)

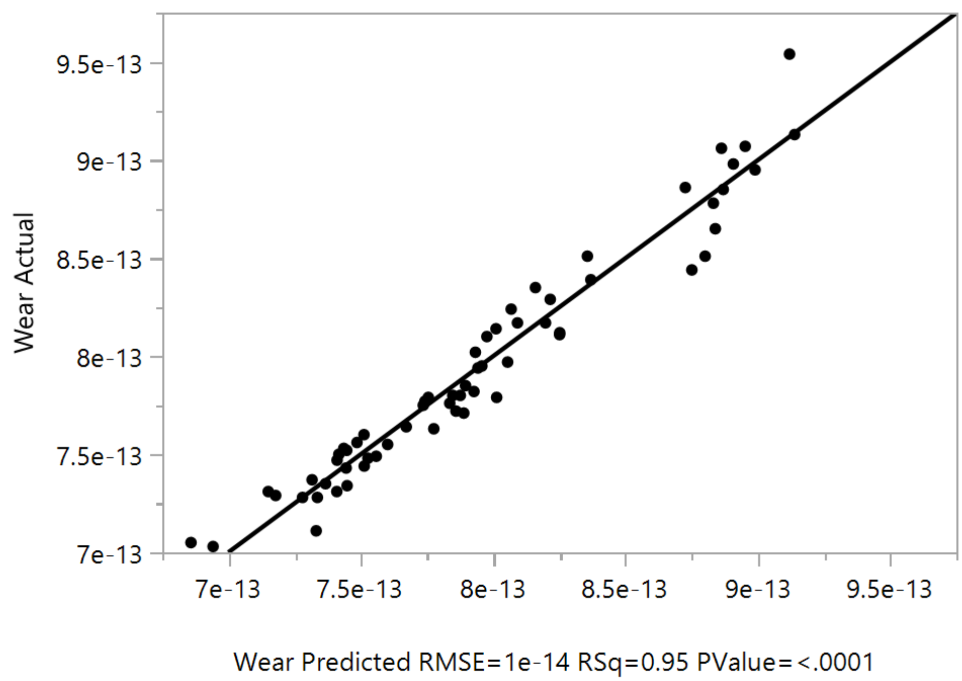


Figure 5.15: Predicted wear (solid line) versus simulated wear (points)

Using MATLAB to Further Optimize and Improve the Cup Seal Design

Since optimization is often used to find improved designs [242], we used MATLAB [210] to minimize the predicted wear equation found from the ANSYS simulations (see Equation 5.4). This was done in order to evaluate the indicators *Meantime between Failure* and *Cost*.

This gives us the optimization problem seen in Equation 5.5 with seal design parameters as inputs (as can be seen in Figure 5.16). MATLAB was used for the optimization calculations. In establishing the optimization formulation, we chose the optimization objective, the variables that the optimizer would change, and the constraints that limit the optimization search space. We chose to minimize the seal wear because it directly affects meantime to failure, pumping time, and maintenance cost as described earlier in this chapter. We chose the parameters T_W, S_H, and α (see Figure 5.16) as the optimization variables because these have potential to improve wear as indicated by the American High Performance Seals guide [13], and demonstrated by the design of experiments carried out using ANSYS. When establishing constraints, we had a deliberate choice to make; to constrain the seal volume to be identical to the existing seal, thus keeping the manufacturers from having to reconsider the profit model, or to allow the parameters to change such that greater seal volumes would be allowable. We chose to allow the latter in favor of maximizing impacts to users. To not negatively affect the manufactures profit model, we chose to allow the optimizer to find seals of greater volume, with a planned for post-optimization evaluation of the cost. As will be shown, the manufacturers' increased cost is passed on to the user, while still lowering the overall maintenance cost for the user. In these ways social impacts were an important and integrated part of searching for an optimal seal geometry.

$$\underset{T_W,\, S_H,\, \alpha}{\text{minimize}}\ V_P \tag{5.5}$$

subject to

$3.6 < T_W < 4.4$

$12 < S_H < 15.5$

$-45^\circ < \alpha < 45^\circ$

where

V_P is the projected seal wear (m^3)

T_W is the seal wall thickness (mm)

S_H is the seal height (mm)

α is the seal top angle (°)

Since the performance functions have many local minimum points, a Monte Carlo approach was used to find 1,000 initial starting values of the seal parameters to be used for the MATLAB

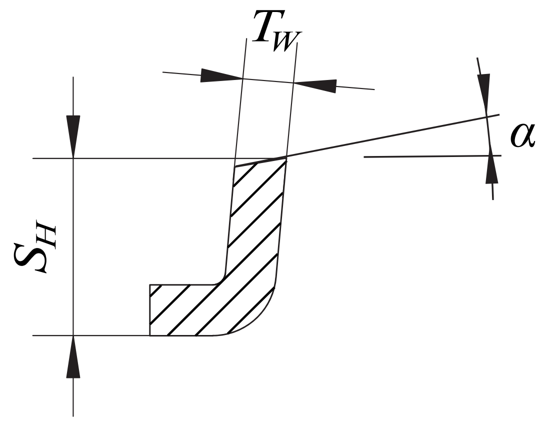


Figure 5.16: Seal parameters used in the MATLAB optimization

optimizations. The results from each run were then compared and values for the seal parameters were derived for minimal wear.

The optimized design can be seen in Figure 5.17. The seal height increased to 14.9 mm and the seal wall thickness decreased to 3.63 mm. The top of the seal is now leaning outwards instead of inwards at an angle of -44.8°. Note that with any optimization analysis, the result is not necessary the most optimal or final solution since there is always additional exploration that can be done.

Important to note is that once an optimized design has been determined through the use of analyses, a physical prototype should be made and tested to ensure that all product requirements can be met. Also, to have a lip design with this angle is traditionally not advised in high speed, high pressure machinery due to possible collection of debris at the lip (K. Paulson, personal communication, May 21, 2021). Future research will determine if this will affect the low speed application of the cup seal negatively, which it may not. Our suggestion would be to make a seal with a height of 15 mm, a thickness of 3.6 mm, and an angle of -45° due to variation in manufacturing, and then run physical tests.

Material Considerations

It was found through the testing of the 110 nitrile cup seals purchased by the authors in Uganda, that hardness affected the cup seal performance (they varied from 75 to 97 Shore A, see

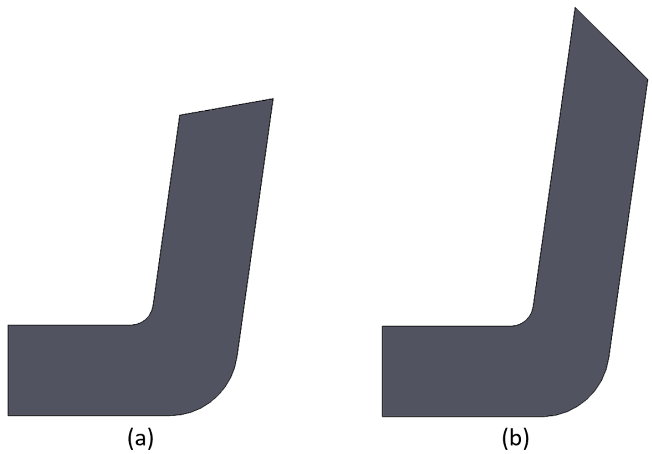


Figure 5.17: Profiles of (a) the original and (b) optimized cup seal designs

Appendix A). This indicates that even if the base material is the same, additives and/or environmental parameters affect pump performance.

As indicated earlier, many new materials for seals are now commonplace in developed nations. Some of these material are potential candidates for the cup seal, though they may not be practical in this developing world setting due to current manufacturing practice and supply chains in developed countries.

To evaluate a potential material for the cup seal, a wear test should be performed to find the wear rate coefficient for that material. This coefficient can then be used in ANSYS or other FEA software to calculate wear rates. In this way, different materials can be tested and compared for the cup seal. Materials that are promising can then be used to make cup seals for field testing and evaluated against the current nitrile cup seal.

Some additional materials to consider are those being used for similar applications mentioned in handbooks and design guides, such as [241, 243, 244]:

- Hydrogenated Nitrile (HNBR)
- Polyurethane (AU, EU)
- Carboxylated Nitrile (XNBR)
- Propylene
- Urethane

By finding the wear rate coefficient for different materials and then using them in FEA software, the materials can be ranked and expensive testing of unsuitable materials can be avoided, leading to lower development cost and faster implementation. The considerations of which materials are available for production in developing world countries should also be taken into consideration.

Results from the Cup Seal Redesign Study

Throughout the engineering work carried out in the analysis, the focus was on improving the longevity of the cup seal while concurrently considering its social impacts. Social impact considerations were incorporated via the design constraints and for each design iteration, the seal wear was evaluated to ensure that the design objectives would be met (improved longevity of the India Mark II/III hand pump system and improved social impacts), by ensuring that the wear resistance of the cup seal had increased.

We believe that wear can be reduced further when material parameters are added to the optimization (the wear rate for each material of interest must first be found through wear tests).

We found that the optimized design had better resistance to wear when compared to the original design by 12%. The wear simulation results for this improved design can be seen in Table 5.3 and the design can be seen in Figure 5.17.

5.3.5 Step 4 – Evaluate Social Impacts

As the final step in the process, the social impacts for each stakeholder are evaluated for the design that emerged from Step 3. This evaluation brings the focus out of the engineering and back to the social impacts that drove the redesign.

After finding an optimal design of the cup seal, the social impacts of the India Mark II/III hand pump system were evaluated. The following sections break down the social impact analysis per stakeholder.

5.3.6 Pump Users

Meantime Between Failure

Positive social impact in *Health and Safety*: As the cup seal wears down and the pump becomes dysfunctional, it affects the pump users in the category of *Health and Safety* as they are forced to use unimproved water sources [183]. It was found by Hunter et al. that even a few days of using unimproved water sources can be sufficient to offset the benefits from normally having clean water and that the probability for getting infected by E. coli goes from 0.001 to 0.128 when having one day of untreated water in a year [189]. By designing a cup seal that is more resistant to wear, the *Meantime between Failure* is extended, resulting in fewer days with unimproved water.

Positive social impact in *Paid Work*: Longer time between failures results in less time being spent retrieving water from sources further away and/or recovering from waterborne diseases. This leads to more time that can be allotted to paid work.

Reduction in Pumping Time

Positive social impact in *Health and Safety*: As pumping time decreases (or as they increase at a slower rate, compared to current pump systems), users will be less likely to use water from unimproved water sources, leading to fewer days with unimproved water sources [189].

Positive social impact in *Paid Work*: With less time spent pumping water, users will have more time to work [180].

Positive social impact in *Human Rights*: The United Nations General Assembly has recognized the right to have water as a human right and stated that it should not take longer than 30 minutes for anyone to gather their daily water [220]. Decreasing pumping time will allow for more people to access water from the same water source.

Positive social impact in *Education*: With less time spent pumping water, users will have more time to pursue education [180, 245].

Positive social impact in *Family*: With less time spent pumping water, users will have more time to fulfil family needs [180].

Positive social impact in *Gender*: As pumping time decreases, women and girls who are the primary gatherers of water will be able to find time for other tasks, such as work and education [180].

Positive social impact in *Conflict and Crime*: With less time required for gathering water, fewer users will abandon the pump due to wait time at the pump. This will avert the need to travel further distance to pump and also lessen the need for pumping water after dark, leading to lower risks for women and children to be harassed, sexually assaulted, or become victims for other crimes [180, 221].

Positive social impact in *Social Networks and Communication*: The hand pump is often considered the heart of a village, giving space for social gatherings and meetings to take place [219]. When pumping time is decreased, there will be less tension among the pump users, resulting in more positive interactions [180].

Cost

Positive social impact in *Paid Work*: Servicing cost for the cup seals for an India Mark II hand pump in Jinja, Uganda is approximately 56.50 USD including materials (see Appendix A). If this is done according to the suggested maintenance interval of one year [237], the monthly cost would be 4.71 USD. A 12% increase in cup seal life could extend the service interval to approximately 13.5 months. If the change in price of the cup seal reflected the added material and manufacturing cost as mentioned in Section 5.3.8, the price would only increase by 0.09 USD per seal but the monthly cost of service would decrease to 4.20 USD [246]. A saving of 6.05 USD per year, with over 4 million installations of India Mark II/III hand pump systems [59, 60] corresponds to 24.2 million USD per year saved in servicing costs in the weakest economy system in the world.

5.3.7 Pump Mechanics

Meantime Between Failure

Negative social impact in *Paid Work*: With fewer breakdowns due to better cup seals, the pump mechanics would receive less work. This could negatively affect their finances. For pump mechanics in Uganda, this would have minimal effect since they already feel overwhelmed due to their high work load (see Appendix A).

Reduction in Pumping Time

No change in social impacts: This indicator is perceived to only affect pump users.

Cost

No change in social impacts: Since the cost of the cup seals is passed on to pump users, we perceive no change in social impacts for pump mechanics for this indicator.

5.3.8 Pump Manufacturers

Meantime Between Failure

Negative social impact in *Paid Work*: With fewer breakdowns, there would be less demand for the purchase of new cup seals, which could affect pump manufacturers negatively.

Reduction in Pumping Time

No change in social impacts: This indicator is perceived to only affect pump users.

Cost

Negative social impact in *Paid Work*: Implementing a new cup seal design would require new tooling, leading to an increase in manufacturing cost. To compensate for this, we pass the tooling cost to the user.

With an estimated tooling cost of 4,000 USD and a volume of 500,000 cup seals, the added tooling cost per seal would be 0.008 USD. With the new seal volume, there would also be an increase in material cost of 0.004 USD per seal [246]. With the current price of 0.50 USD per cup seal (see Appendix A), the added material and manufacturing costs (if considering the same markup as for the original design), the new cup seal price would be 0.59 USD. With these small changes in seal price, the negative social impact in *Paid Work* for pump manufacturers could be considered minimal since the added cost of the seal will be passed on to pump users.

5.4 Discussion of Redesign

A redesign of the cup seal in the India Mark II/III hand pump system was carried out to improve its longevity. For this, the method in Section 3.6 was used. The redesign was carried out with pump users as the main stakeholder. Also, the new design had to account for any perceived changes in social impacts for pump mechanics and pump manufacturers (both positive and negative impacts) as described in Section 5.3. See Table 5.4 for a breakdown of the changes to the social impacts for the India Mark II/III hand pump system due to the cup seal redesign.

A redesign of the whole hand pump system was first considered, but to be both culturally sensitive and to not interrupt the supply chains and distribution networks, we chose to keep the India Mark II/III hand pump system mostly fixed during the redesign, only focusing on the cup seal. We also considered spring-loaded and doubled lipped seal designs (common in seal applications in the developed world [240]), but to keep the price low and to allow the same suppliers to continue delivering seals, the simplicity of the current cup seal was kept. This intentionally constrained the optimization analyses for the redesign and led to a new cup seal design with similar geometric characteristics as the original cup seal, but with improved resistance to wear.

As a final part of demonstrating the method, we list some choices we would have made differently if we were improving the longevity of the India Mark II/III hand pump system with the *developed* world market in mind. We would have:

- Considered a more expensive advanced material for the cup seal.
- Considered a spring-loaded seal design.
- Considered seal scrapers.
- Considered smart seals that alert users to impending failure so repair can be completed in advance.
- Considered redesigning the entire plunger assembly, if not the whole pump.

Table 5.4: Changes in social impacts for the India Mark II/III hand pump system after a cup seal redesign

Social impact categories	**Meantime between failure (users)**	**Meantime between failure (mechanics)**	**Meantime between failure (manufacturers)**	**Reduction in pumping time (users)**	**Reduction in monthly cost for service (users)**	**Manufacturing cost (manufacturers)**
Health and safety	Resulted in fewer days with unimproved water	n/a	n/a	Fewer days with unimproved water sources	n/a	n/a
Paid work	More time can be allotted to work	This could potentially hurt the mechanics financially due to less frequent service calls	This could potentially hurt manufacturers financially due to lower sales of cup seals	More time can be allotted to work	The monthly service cost for the pump will decrease	There will be a negative impact due to an increase in manufacturing cost
Stratification	n/a	n/a	n/a	n/a	n/a	n/a
Human rights	n/a	n/a	n/a	Decreased pumping time allows for more people to access water	n/a	n/a
Education	n/a	n/a	n/a	More time can be allotted to education	n/a	n/a
Family	n/a	n/a	n/a	More time to fulfil family needs	n/a	n/a
Gender	n/a	n/a	n/a	Reduction in pumping time will free up time for other tasks, such as work and education	n/a	n/a
Population change	n/a	n/a	n/a	n/a	n/a	n/a
Conflict and crime	n/a	n/a	n/a	Decrease in risk for women and girls to be harassed, sexually assaulted, or become victims of other crimes	n/a	n/a
Social networks and communication	n/a	n/a	n/a	There will be more time for socializing and less tension among pump users	n/a	n/a
Cultural identity/ heritage	n/a	n/a	n/a	n/a	n/a	n/a

While these considerations could be beneficial for one stakeholder, they would negatively affect others and cause major disruptions to the supply chain, and would therefore be impractical in the pump's developing world setting. Even though the new design can negatively affect pump mechanics and pump manufacturers, our records show that mechanics are already overwhelmed with their workload and that the estimated added cost for the manufacturers would be negligible, we perceive that there will be minimal or no negative impact for them. If we only approach the redesign from an engineering perspective, and not from a social perspective, we would just have designed a brand new pump, as was done by BluePump in 2008 [247]. This seal-less pump is prohibitively expensive, requires first world manufacturing, and significantly alters the user experience since the stroke length and force are undesirably different that that of the India Mark II/III pump system. Perhaps most restrictive is that the Blue Pump is not allowed in many countries as it violates governmental regulations by introducing a new pump system. The social impact categories and the conditional probabilities table 3.9 helped us consider how the India Mark II/III hand pump affected the employment of various people and that recognition influenced the design process.

Other areas for future consideration include the creation of prototypes for field testing, negotiating with current seal manufacturers in India to produce a seal with different material and geometric parameters, and performing wear tests with sediment in the water.

By using the method created in Chapter 3, we were able to show how the potential social impacts of the India Mark II/III hand pump system can be increased through an engineering redesign of the cup seal.

CHAPTER 6. CONCLUDING REMARKS

6.1 Chapter Overview

In this dissertation, we have provided methods that can be used by designers and engineers desiring to increase the social impacts their products can have, especially when working in the area of global development. This chapter contains the contributions and conclusions for the dissertation, together with suggestions for future research.

6.2 Contributions

As stated in Chapter 1, the question this dissertation seeks to answer was: What practices can designers follow when engineering for global development in order to increase the social impacts of products in the lives of persons or communities? This question was answered in the following ways:

1. We developed a method that uses domain knowledge from a mature area of engineering to be applied in the area of engineering for global development, in order to increase social impacts of products by meeting unmet customer needs. This method was demonstrated by designing a collaborative product (see Chapter 2). Chapter 2 is published in *Development Engineering* with the title "Experimenting with Concepts from Modular Product Design and Multi-Objective Optimization to Benefit People Living in Poverty" [56].

2. We analysed 150 products designed for social impacts and created a method to assist designers to consider additional categories of social impact during product development in order to increase the potential social impacts their product can have (see Chapter 3). In reviewing these products, the probability of social impact for each of the 11 categories to be present in a product were found together with the co-presence of other social impacts (see Section 3.6), which can alert design teams to impact areas worth considering. Chapter 3 is published in

Journal of Mechanical Design with the title "Analysis of Perceived Social Impact of Existing Products Designed for the Developing World, With Implications for New Product Development" [57].

3. We demonstrated the method created in Chapter 3 by evaluating the India Mark II/III hand pump system, a system with a proven track record of social impacts, to find areas of improvements. We found the cup seal to be a candidate for redesign (see Chapter 4). Chapter 4 is published in *Development Engineering* with the title "Nitrile Cup Seal Robustness in the India Mark II/III Hand Pump System" [62]. We then continued the steps of the method as we explored design improvements to the cup seal. This led to a new seal design with the potential to resist wear 12% better than the original seal (see Chapter 5). The main parts of Chapter 5 is under review in *Development Engineering* with the title "Use of Simulation and Wear Prediction to Explore Design Improvements to the Cup Seal in the India Mark II/III Hand Pump System." Lastly, the perceived social impacts of the India Mark II/III hand pump system were evaluated. With an improvement in seal life, the social impacts of the India Mark II/III hand pump system can increase in multiple areas for its users and their communities by more reliably providing clean water. (see Chapter 5).

6.3 Conclusions

The purpose of this research was to create methods for engineers to use in order to design products with greater social impacts when engineering for global development. We created these methods because we believe that when social impacts are considered early in the design of a product, it will allow engineers to increase the positive impacts their products can have in the lives of persons and their communities.

By using the first method, unmet needs can be addressed by designing collaborative products. This method was demonstrated in Section 2.4. And by using the second method, additional social impact categories can be considered in order to increase a products social impacts. The use of this method was demonstrated in Chapter 5.

As a result of this research, we now know:

- About the task-to-cost ratio and that it can be optimized.

- That different social impact categories coexist and that awareness to these categories during product development will increase the potential for the product to have positive social impacts.
- How sensitive the cup seal in the India Mark II/III is to variations in geometry and material properties.
- How the cup seal performance can be improved if optimized.
- That the potential social impact of a product can be increased by focusing on the different social impact categories throughout the product design process.

The following sections summarizes the conclusions from Chapters 2 through 5.

6.3.1 Experimenting with Concepts from Modular Product Design and Multi-Objective Optimization to Benefit People Living in Poverty (Chapter 2)

Chapter 2 presented a method were domain knowledge from a mature area of engineering was used to design products for optimal collaborative performance with application to engineering-based poverty alleviation. The primary result of this method was the ability to optimize the collaborative performance of a set of products while dealing with the various, and often complex, performance interactions between the products and the collaborative product. Through the optimization of the sub-products and the collaborative product, the collaborative performance was optimized while simultaneously dealing with the various trade-offs between the products and the collaborative product.

The method presented in Chapter 2 is an optimization-based strategy for selecting designs of a given collaborative product set. The ability of this method to optimize based on objectives such as cost and task performance, enables the task-per-cost ratio of the product set to increase. As such, the resulting collaborative product could have high potential social impacts and application within the developing world.

From the example, and the presented results, we see this method to have the prospect to be an effective tool for designing products for optimal collaborative performance and that the social impacts of the products will increase. Chapter 2 was published in *Development Engineering* [56].

6.3.2 Analysis of Perceived Social Impact of Existing Products Designed for the Developing World, With Implications for New Product Development (Chapter 3)

In Chapter 3, we reviewed 150 products and linked them to social impact categories found in literature. We then discovered how the impact categories manifest themselves in the 150 products. This was done to allow us to better anticipate the social impacts of products and to understand how engineered products impacts society.

A review instrument was created to help us know how different social impact categories are co-present in products. We then showed how the results from the product review gives us the probability of social impacts resulting from engineered products. Two tables for predicting social impacts were created and validated (one third of the data points were used for validation). These tables show the general probability, the joint probability, and the conditional probability for social impacts to occur. These tables are part of the method to be used for improving social impacts of products.

By using this method, the initial design objective can be widened to include related social impact categories and thus achieve additional impacts in both the original social impact category and in other related categories not previously considered, leading to better informed engineering decisions being made throughout the product development process. The steps of the method can be seen in Figure 6.1.

The contribution of Chapter 3 lies in the linking of existing products to published social impact categories and how these categories correlate statistically. As such it alerts the engineer to various social impact areas that are not commonly considered during the product development process. Thus, by expanding the views to include related social impact categories, the products that are designed can have broader social impacts. Chapter 3 was published in *Journal of Mechanical Design* [57].

6.3.3 Nitrile Cup Seal Robustness in the India Mark II/III Hand Pump System (Chapter 4)

In Chapter 4, we examined off-the-shelf nitrile seals for the India Mark II/III mechanical hand pump, which is the most ubiquitous pump for accessing ground water in the developing world, in order to find its baseline performance.

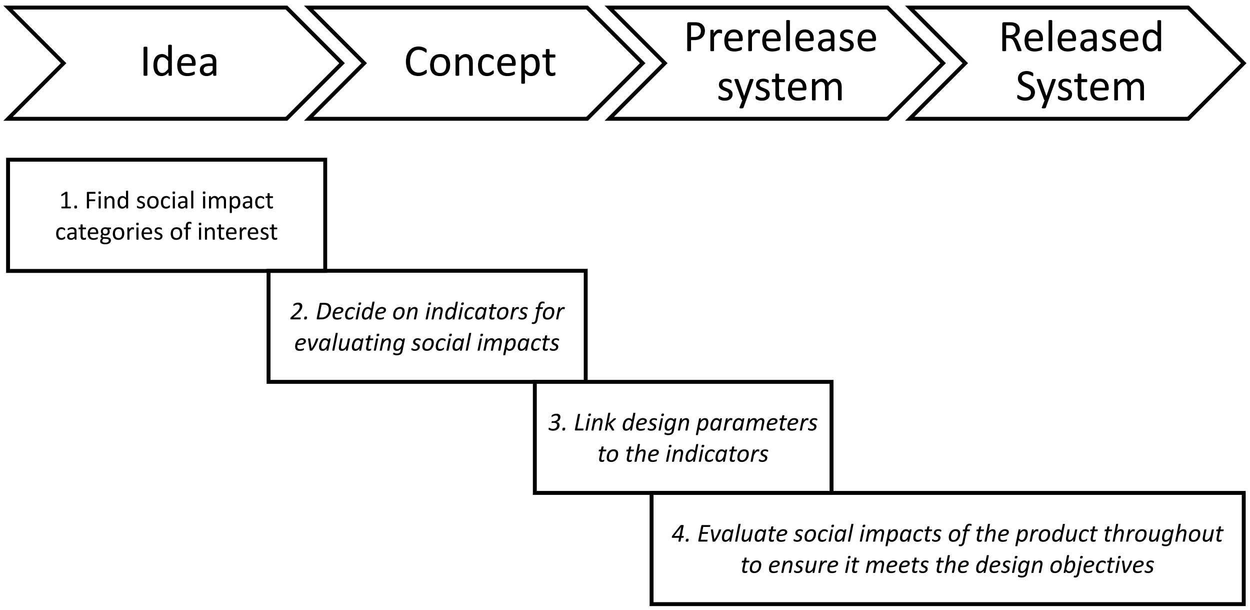


Figure 6.1: Method for improving social impacts of products during product development

The results showed wide geometric and material variation to be present in the off-the-shelf cup seals. Surprisingly, the leak performance was shown to be incredibly robust to these geometric and material variations, yielding acceptable performance for the static zero-cycle leak test for all tested seals. However, in the dynamic zero-cycle test, 45% of the seals yielded an output below the 14.36 liters/min threshold.

From a scientific point-of-view, and a design point-of-view, it doesn't matter what the baseline performance is as long as it is known. Knowing the baseline is essential, so that observed performance can be compared to baseline performance and a change in performance can be declared. This is a process engineers and designers can choose to use as they work on improving the performance of existing products.

In Chapter 4, we established that wide variations in geometric and material properties produce little to no leakage for off-the-shelf cup seals tested statically but that for the dynamic pump performance test it was found that only 55% of the tested seals passed, leaving room for improvement. Chapter 4 was published in *Development Engineering* [62].

6.3.4 Demonstration of the Social Impact Method Created in Chapter 3 (Chapter 5)

In Chapter 5, we demonstrated the method created in Chapter 3. For this demonstration, we improved the longevity of the India Mark II/III hand pump system by 12%, a hand pump system that is used on a daily basis by approximately 10% of the world's population. The baseline from Chapter 4 was used together with engineering analyses to derive a wear optimized cup seal design for the India Mark II/III hand pump system. By using the method created in Chapter 3, we demonstrated that by having a focus on social impacts while redesigning the India Mark II/III hand pump system, it led to greater perceived social impacts in the lives of pump users. It also showed how the design could negatively impact other stakeholders. Most parts of Chapter 5 are under review in *Development Engineering*.

6.4 Top Level Concluding Remarks

With the majority of engineers designing for the richest 10% of the world's population, most people are left without access to engineering [19]. We believe this is partly due to the fact that most engineers do not have the right exposure to the social impact areas or know what to do with them [35, 36]. As a result, we as engineers only develop and design products for a very small portion of the world's population.

We are in the dark, not just because this is not our context, but because our way of evaluating the quality of a design is based on efficiency, cost, manufacturing, etc. (all the principles we learned as engineers) and not on its social impacts. We found this to be true early on in our research as we created the collaborative product method (see Chapter 2), where we used optimization models to maximize function and the task-to-cost ratio, but not fully accounting for how the product would impact the users. This approach to engineering was from a "white man's perspective" which is a myopic financial view of the world where we suggested the user buy all products included in the collaborative product in order to have the extra function.

With most of our engineering thinking and methods focused on engineering principles, what can we do to move beyond the areas of comfort and extend engineering solutions that will create positive social impacts in the lives of people? It starts with awareness, which can lead to a genuine concern [35]. What we are trying to accomplish with this research is to go beyond awareness, and step back and look at our designs through a macro lens instead of through a magnifying glass, to find the true needs of the customers we want to serve, not just the needs that are reflected from our own society.

Our research is one approach to get to know the real needs and possible solutions to peoples everyday challenges. We also know that there are many other ways to learn and understand their difficulties and concerns. As a design community, we need to keep looking for different ways and angles to find and solve these needs and challenges.

We recognize that in this dissertation, by choice, we got very specific about certain things such as the pump, the seals, and seal improvements. We did this because we wanted to avoid being too abstract in our discussions and wanted to take steps forward in terms of giving some concrete new knowledge.

Having been very detailed and specific about these things, we now see the value of stepping back to see the bigger picture. As we did this, we could see the effects of our work in terms of both social impacts and engineering quality. We learned that engineering for global development has many complexities associated with it, and that they are not all technical. They are also about society, adoption rates, political issues, supply chains, etc. We also learned that the challenge is not in the technology, it is in choosing whether it should be design A or design B. For our demonstration of the method created in Chapter 3, it was between the choice of a full redesign of the hand pump versus a cup seal redesign.

We made the choice to redesign the cup seal instead of a full redesign not because of technical challenges, but because of non-technical challenges. Our choice was based on social impacts; not wanting to disrupt supply chains, not wanting to help one stakeholder and negatively affect others, and at the same time positively impact pump users.

There are, of course, many different ways to approach this choice, but we chose to approach it from a social impact perspective. As a whole, what we walk away with from this research and what we have observed in other research that has been done in the area of engineering for global development, is that we are getting a better sense of what is possible, which is exciting in a new field of research. We are just learning what the issues are and how we might approach them, and this is the current state of engineering for global development research right now.

6.5 Future Research

This dissertation has presented ways to consider social impacts when working in the area of engineering for global development. We acknowledge that there are many different ways to increase the potential social impacts our products can have. We also acknowledge that much more can, and must, be done to better understand how to successfully work in this area. Below are some of our suggestions for future research:

- There is opportunity to add additional objectives related to the social impact categories discussed in Section 3.3.1, together with a stakeholder analysis for the collaborative product method created in Chapter 2. We believe that this could further alleviate poverty and have the potential for increasing positive social impacts for multiple stakeholders.

- The sensitivity of the result tied to the Pareto offset values used during Step 7 in the collaborative product method could be better understood (see Section 2.3.7). We know that they influence the outcome of the optimization and believe that it would be beneficial to better understand how to choose them.

- The product review survey in Chapter 3 could be improved by using more respondents combined with smaller sub-sets of questions so that there is a lesser risk for respondent fatigue. With the original survey's 1650 questions, there was a high risk for respondent burnout (as discussed in Section 3.4.3). A survey tool could also be created for products that are not specifically designed for social impact (different selection criteria for products to be included).

- It is not clear if the different social impact categories are dependent or independent and since joint probability assumes independence of events, it would be of interest to learn if they are independent or somehow dependent on each other.

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APPENDIX A. INDIA MARK II AND INDIA MARK III BOREHOLE HAND PUMP VARIATION STUDY IN UGANDA

DOCUMENT REVISION HISTORY

Revision, Date	Comment
R1.0, 30 Jul 2018	Initial Document Creation
R3.0, 4 Aug 2018	Importing all Data for Artifacts 1-10
R3.1, 7 Aug 2018	Importing data for Artifacts 11 -25, sending out to team for review
R3.2, 7 Aug 2018	Added gender study, and internal measurement error, general document clean-up
R3.3, 8 Aug 2018	Updated Artifacts 7 – 15, and 17 – 24. Added Artifact A27
R3.4, 8 Aug 2018	Updated liter estimates, added Artifact 28
R3.4, 13 Aug 2018	Transitioned document to Microsoft word online for document sharing. Added contact information for Evelynn
R3.5, 15 Aug 2018	Added DOE surface plots, wave form images, water estimates, pump sensor information, and coefficient of variation
R3.6, 20 Aug 2018	Added Discharge test by Immy Irot (Artifact 29)
R3.7, 11 May 2021	Added images of pump sites and stores. Removed the “Water Particulate Count” placeholder artifact. Added Figure and table captions. Added the cost for servicing the cup seals.

India Mark II and India Mark III Borehole Hand Pump Variation Study in Uganda

Revision 3.7 | July 30, 2018 (Revised on May 11, 2021)

Field Study Data:
20 July 2018 – 03 August 2018
Kampala Uganda (July 20, 21, 22)
Jinja Uganda (July 23, 24, 25)
Masindi Uganda (July 26)
Murchison Park Uganda (July 27, 28)
Gulu Uganda (July 29, 30, 31)
Kampala Uganda (August 1, 2, 3)

Team Members:
Hans Ottosson (PhD Candidate)
Tom Naylor (Research Assistant)
James Mattson (Maintenance Specialist)
Christopher Mattson (Professor)

Department of Mechanical Engineering
Ira A. Fulton College of Engineering and Technology
Brigham Young University

Brief Overview of this Study

The purpose of this study is to characterize the variation in parameters associated with Ugandan borehole pump parts, usage, performance, and operating environment. Ultimately, we hope to use this and other information to design improved borehole pump parts that are robust to variation. Academically, this information will be used to explore the extent to which uncertainty quantification is possible and useful in an engineering for global development setting.

Purpose of this Report

The purpose of this report is to clearly convey the data collected during a BYU Design Exploration Research Group trip to Uganda in July-August 2018. This report provides our observations regarding the data, and also provides other observations regarding the Ugandan context, which while included here for completeness, we consider them valuable yet anecdotal.

The report exists in two main parts: The body, and the artifacts. The body is a few pages. Artifacts are small self-contained test reports. Together the artifacts take the vast majority of the space in this report.

Key Findings

For us that are used to having clean water readily available in our homes, it is important to realize that without these water hand pumps, many of the people we came in contact with would not have clean water. The local communities are dependent on functional pumps to get access to clean water daily.

Before the water officials installs a new water hand pump, the local village must set up a committee to ensure that the pump would be managed. The committee is in charge of taxing the local families so that when the pump needs service, they can readily call for repairs. Due to the lack of resources of the committee, a pump that fails would often go un-repaired for weeks or months before the committee could pay a private pump mechanic to start the repairs.

The local users and water officials were supportive of our work and would often ask us to share any findings with them.

We were able to find pump parts and supplies in each of the communities we visited. This study investigated the qualities of pump cup seals found in local retail shops in the study area.

By interviewing pump technicians, we found that pump performance could be improved with adherence to the preventive maintenance schedule outlined in the “Installation & Maintenance Manual for the India Mark II Handpump” Edition 2008 page 28-34 and Annexes 1-4.

We believe that the research we performed and the results we found in Uganda could and should be extended to areas around the world where the local population depends on hand pumps for their clean water supply. Additional research can and needs to be completed around improving the performance and longevity of borehole pumps around the world. Specifically, the systematic collection of data to determine failure conditions that have been reported during this research project. These failures include the pump subassemblies of; the handle, pump head, head flange, riser pipe, pump rod, cylinder, pump rod grommets, and Dynamic Water Table monitoring.

Methods used to Assess Variation

Multiple methods were used to assess the variation related to the India Mark II and India Mark II[1] borehole pump parts, usage, performance, and operating environment. The Table below summarizes the methods used and the results. Note the reference to specific artifacts for more detail. Also assessed is Internal Measurement Error, which characterizes the variation that exists when measuring the same sample many times.

Table 1. Summary of artifacts, methods, and results for the study.

Key Parameter	Method used to Test	Result	See Artifact
Cup Seal Weight (g)	Purchased 112 seals from 6 Ugandan stores. Measured each seal using precision scale. Calculated statistics.	Mean = 17.5891 Stdev = 1.33278 Spec value = none Spec tol. = none	A1
Cup Seal Volume (cm^3)	Purchased 112 seals from 6 Ugandan stores. Measured each seal using water displacement method with precision instruments. Calculated statistics.	Mean = 12.7056 Stdev = 0.245873 Spec value = none Spec tol. = none	A2
Cup Seal Density (g/cm^3)	Calculated density based on the measurement of seal weight and seal volume.	Mean = 1.41672 Stdev = 0.0841749 Spec value = none Spec tol. = none	A3
Cup Seal Durometer (Shore A)	Purchased 112 seals from 6 stores. Measured each using durometer. Four measurements were made per seal. Calculated statistics.	Mean = 86.0536 Stdev = 3.4368 Spec value = 80 Spec tol. = +/-5	A4
Cup Seal Geometry: Outer Diameter (DIM 1), (mm)	Purchased 112 seals from 6 stores, took precision photo of each. Measured each optically with MATLAB image processing. Calculated statistics.	Mean = 64.2653 Stdev = 0.530363 Spec value = 63.5 Spec tol. = +0.5	A5
Cup Seal Geometry: Inner Diameter (DIM 2), (mm)	Purchased 112 seals from 6 stores, took precision photo of each. Measured each optically with MATLAB image processing. Calculated statistics.	Mean = 41.8651 Stdev = 0.227975 Spec value = 42.5 Spec tol. = +0.8	A6
Cup Seal Geometry: Height (DIM 3), (mm)	Purchased 112 seals from 6 stores, used digimatic indicator to measure seal height at four places on the seal.	Mean = 12.4019 Stdev = 0.429384 Spec value = 14 Spec tol. = +/-0.5	A7

[1] Uganda-Modified pumps U2 and U3 are derivatives of India Mark II and India Mark III pumps.

Cup Seal Geometry: Base Thickness (DIM 4), (mm)	Purchased 112 seals from 6 stores, used digimatic indicator to measure seal thickness at four places on the seal base.	Mean = 4.22616 Stdev = 0.175371 Spec value = 4.0 Spec tol. = +0.5	A8
Cup Seal Geometry: Wall Thickness (DIM 5), (mm)	Purchased 112 seals from 6 stores, used digimatic indicator to measure wall thickness at eight places on the seal wall.	Mean = 4.1533 Stdev = 0.180924 Spec value = (4.0) ref Spec tol. = +.05	A9
Cup Seal Geometry: Wall Angle (DIM 6), deg)	Purchased 112 seals from 6 stores took precision photo of each. Measured each optically with MATLAB image processing. Calculated statistics.	Mean = 7.52808 Stdev = 2.22381 Spec value = 5 Spec tol. = none	A10
Locations of Stores and Boreholes	This artifact simply lists the names, contacts, and locations (GPS) of the stores and boreholes.	See artifact	A11
Operating Environment: Water pH Test	Water samples were taken at each borehole at various times throughout the day. pH test strips were used an matched to color scale.	See artifact	A12
Operating Environment: Water Hardness Test	Water samples were taken at each borehole at various times throughout the day. Water hardness test strips were used an matched to color scale.	See artifact	A13
Operating Environment: Water Salinity Test	Water samples were taken at each borehole at various times throughout the day. A salinity meter was used to measure salinity in PPT.	See artifact	A14
Operating Environment: Water Temperature Test	Water samples were taken at each borehole at various times throughout the day. A salinity tester also provided water temperature.	See artifact	A15
Pump Performance: Borehole 1	A design of experiments (DOE) was carried out varying stroke length and stroke frequency. The measured parameter was amount of water discharged.	See artifact	A16
Pump Performance: Borehole 2	A design of experiments (DOE) was carried out varying stroke length and stroke frequency. The measured parameter was amount of water discharged.	See artifact	A17
Pump Performance: Borehole 3	A design of experiments (DOE) was carried out varying stroke length and stroke frequency. The measured parameter was amount of water discharged.	See artifact	A18
Pump Performance: Borehole 4	A design of experiments (DOE) was carried out varying stroke length and stroke frequency. The measured parameter was amount of water discharged.	See artifact	A19
Pump Usage: Borehole 1	A custom sensor system was deployed and used to understand usage. A camera was also used to characterize gender balance.	See artifact	A20
Pump Usage: Borehole 2	A custom sensor system was deployed and used to understand usage. A camera was also used to characterize gender balance.	See artifact	A21
Pump Usage: Borehole 3	A custom sensor system was deployed and used to understand usage. A camera was also used to characterize gender balance.	See artifact	A22
Pump Usage: Borehole 4	A custom sensor system was deployed and used to understand usage. A camera was also used to characterize gender balance.	See artifact	A23
Field Trip Anecdotal Observations	n/a	See artifact	A24

Internal Measurement Error assessment	The same measurement methods described above were carried out on the same seal at least 33 times. The % error was calculated.	See artifact	A25
Water Coverage Reports	These were provided to us by the district. They are repeated here for completeness.	See artifact	A26
Uganda Contact List	n/a	See artifact	A27
Discharge test by Immy Irot	Discharge test done after we left Uganda	See artifact	A28

Discussion

There is evidence that entire communities depend on and benefit in many ways from functioning borehole pumps. This includes daily access to dependable, affordable clean water and social-behavioral traditions that may add to the stability of the community. The factors contributing to the breakdown and often slow repair of pumps is deeply rooted in the local culture and traditions of the community and should be studied.

Conclusions

See each individual Artifact (especially A24).

References

ERPF, K. (2007) ***India Mark Handpump Specifications***. (Revision 2-2007), v.2, RWSN/Skat, St Gallen, Switzerland

SKAT (2008) ***Installation & Maintenance Manual for the India Mark II Handpump***. (Edition 2008), Skat, Rural Water Supply Network, St Gallen, Switzerland

Artifacts

Table 2: Artifacts included in this report.

Artifact Number	Revision	Title
Artifact A1	1.1	Cup Seal Weight measurements
Artifact A2	1.1	Cup Seal Volume measurements
Artifact A3	1.0	Cup Seal Density calculations
Artifact A4	1.0	Cup Seal Durometer measurements
Artifact A5	1.0	Cup Seal DIM1 Outer Diameter measurements
Artifact A6	1.0	Cup Seal DIM2 Inner Diameter measurements
Artifact A7	1.0	Cup Seal DIM3 Height measurements
Artifact A8	1.0	Cup Seal DIM4 Base Thickness measurements
Artifact A9	1.0	Cup Seal DIM5 Wall Thickness measurements
Artifact A10	1.0	Cup Seal DIM6 Wall Angle measurements
Artifact A11	1.1	Locations of Stores and Boreholes
Artifact A12	1.0	Operating Environment: Water pH Test
Artifact A13	1.0	Operating Environment: Water Hardness Test
Artifact A14	1.0	Operating Environment: Water Salinity Test
Artifact A15	1.0	Operating Environment: Water Temperature Test
Artifact A16	1.1	Pump Performance: Borehole 1 (Jinja)
Artifact A17	1.1	Pump Performance: Borehole 2 (Jinja)
Artifact A18	1.1	Pump Performance: Borehole 3 (Gulu)
Artifact A19	1.1	Pump Performance: Borehole 4 (Gulu)
Artifact A20	1.1	Pump Usage: Borehole 1 (Jinja)
Artifact A21	1.1	Pump Usage: Borehole 2 (Jinja)
Artifact A22	1.1	Pump Usage: Borehole 3 (Gulu)
Artifact A23	1.1	Pump Usage: Borehole 4 (Gulu)
Artifact A24	1.1	Anecdotal Findings
Artifact A25	1.0	Internal Measurement Error Analysis
Artifact A26	1.0	Water Coverage Report (Gulu and Jinja)
Artifact A27	1.1	Uganda Contact List
Artifact A28	1.0	Discharge test by Immy Irot

Cup Seal Weight	Artifact A1

Artifact Prepared by: Tom Naylor and Christopher Mattson | Revision 1.1
Tests Performed by: Tom Naylor
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
Measure the weight in grams (g) of individual cup seals.

Summary of Test Results:

Summary of test results can be seen in Table A1.1.

Table A1.1. Summary of weight test results.

Spec (g)	Spec Min (g)	Spec Max (g)	Samples (count)	Mean (g)	Stdev (g)	Min (g)	Max (g)	Range (g)	Median (g)
None	None	None	112	17.5891	1.33278	14.685	23.142	8.457	17.5405

Test Equipment and Set up:
The Sartorius AY303 scale (see Figure A1.1) was used to measure seal weight with readability 0.001 g, repeatability 0.005 g, and linearity 0.005 g. The AY303 was powered using eight 1.5 V batteries to make the device portable. Before use, the scale was leveled using the adjustable legs and the built-in bubble level. Measures were taken to ensure that there was no airflow in the test environment, as the scale is sensitive enough to be affected by it. Also before use, the scale was able to sit for a short period of time while connected to the battery power supply (step 3 below). This resulted in a consistent readout.

Figure A1.1. Sartorius AY303 scale.

Test Procedure:

1. Balance scale using the built-in bubble level
2. Turn on scale and open lid
3. Wait for measured value to steady
4. Zero scale
5. Place seal on the center of the scale
6. Wait for measured value to steady
7. Record value
8. Remove seal
9. Repeat steps 3 – 8 (zeroing only when scale does not return to zero) until all measurements are taken

Test Results:
Figures A1.3 and A1.4 show the data, and Table A1.2 shows the raw data collected.

Observations and Conclusions:
Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

As can be seen in Figures A1.3 and A1.4, the weight of the seals from store 1 is noticeably more consistent than those of stores 6. Store 1 had a large box of seals from which they took these samples. No other store had as many seals for sale. This could be an indication that Store 1 is one of the larger suppliers in the area.

The seals from store 6 were noticeably dirtier at the time of purchase. Each seal was cleaned before it was measured. Figure A1.2 shows the state of the seals from store 6 at the time of purchase.

Figure A1.2. Dirty cup seals from store 6

Only 4 samples were purchased from store 7. With only 4 pieces of data, little can be said about any general trend for store 7.

There is no specification for the seal weight, so it cannot be stated if the variation in weight is acceptable or not.

Figure A1.4 shows 6 significant things for each store. The horizontal line below the box shows the small number in the data set (excluding outliers). The horizontal line above the box shows the large number in the data set (excluding outliers). The lower edge of the box is the 1st quartile line, and the upper edge is the 3rd quartile line. The line in the center of the box is the mean. Outliers in the data are represented by the "+" sign. The dashed horizontal line is the mean for all stores combined.

From the boxplots we can easily see that stores did not share the same mean nor the same variation, though stores 1 and 4 are the most similar. Store 1 was in Kampala, and store 4 in Jinja. The seals from store 4 where kept tied in a plastic bag in a bucket with other parts.

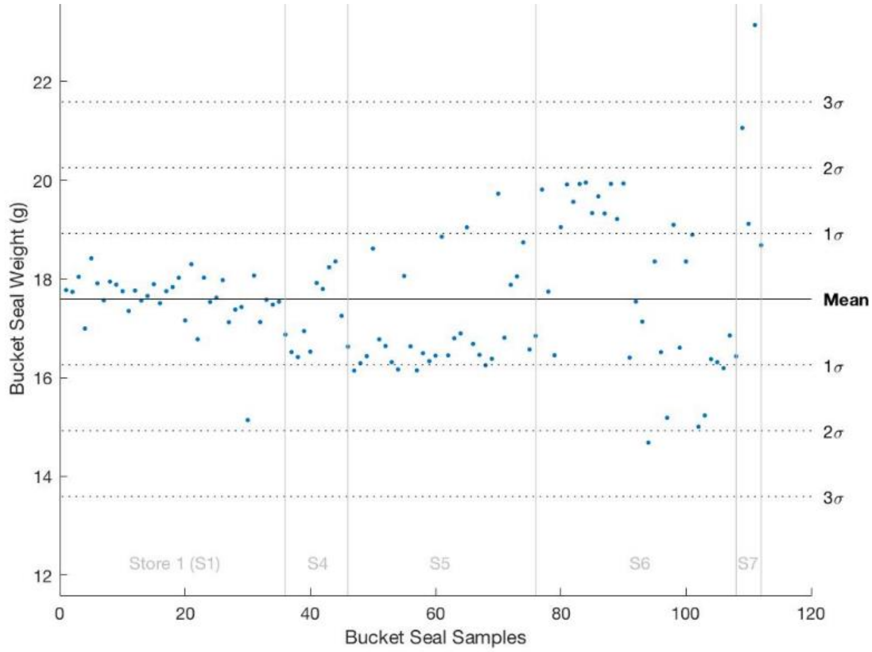

Figure A1.3. Cup seal weight. Ordered as tested.

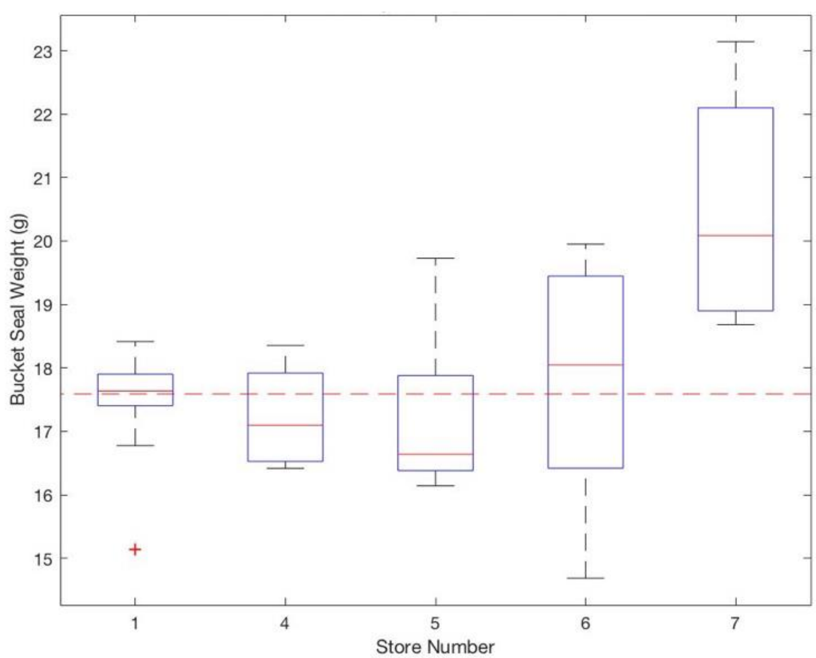

Figure A1.4. Cup seal weight. Boxplots for each store.

Table A1.2. Raw data for weight measurements. Units = grams.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	17.774	n/a	n/a	16.517	16.141	19.811	21.058
XX-002	17.738	n/a	n/a	16.418	16.292	17.743	19.116
XX-003	18.042	n/a	n/a	16.943	16.434	16.451	23.142
XX-004	16.993	n/a	n/a	16.526	18.616	19.047	18.683
XX-005	18.416	n/a	n/a	17.919	16.774	19.913	n/a
XX-006	17.912	n/a	n/a	17.795	16.642	19.562	n/a
XX-007	17.564	n/a	n/a	18.238	16.312	19.922	n/a
XX-008	17.944	n/a	n/a	18.353	16.166	19.953	n/a
XX-009	17.883	n/a	n/a	17.251	18.059	19.335	n/a
XX-010	17.751	n/a	n/a	16.628	16.634	19.672	n/a
XX-011	17.35	n/a	n/a	n/a	16.146	19.326	n/a
XX-012	17.765	n/a	n/a	n/a	16.496	19.925	n/a
XX-013	17.56	n/a	n/a	n/a	16.334	19.212	n/a
XX-014	17.655	n/a	n/a	n/a	16.445	19.932	n/a
XX-015	17.893	n/a	n/a	n/a	18.856	16.405	n/a
XX-016	17.508	n/a	n/a	n/a	16.45	17.541	n/a
XX-017	17.752	n/a	n/a	n/a	16.798	17.135	n/a
XX-018	17.836	n/a	n/a	n/a	16.897	14.685	n/a
XX-019	18.023	n/a	n/a	n/a	19.044	18.352	n/a
XX-020	17.157	n/a	n/a	n/a	16.682	16.516	n/a
XX-021	18.298	n/a	n/a	n/a	16.46	15.185	n/a
XX-022	16.777	n/a	n/a	n/a	16.252	19.096	n/a
XX-023	18.025	n/a	n/a	n/a	16.381	16.605	n/a
XX-024	17.533	n/a	n/a	n/a	19.728	18.352	n/a
XX-025	17.619	n/a	n/a	n/a	16.81	18.894	n/a
XX-026	17.976	n/a	n/a	n/a	17.88	15.007	n/a
XX-027	17.123	n/a	n/a	n/a	18.05	15.235	n/a
XX-028	17.38	n/a	n/a	n/a	18.738	16.373	n/a
XX-029	17.43	n/a	n/a	n/a	16.571	16.312	n/a
XX-030	15.141	n/a	n/a	n/a	16.845	16.193	n/a
XX-031	18.068	n/a	n/a	n/a	n/a	16.853	n/a
XX-032	17.127	n/a	n/a	n/a	n/a	16.433	n/a
XX-033	17.576	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	17.478	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	17.54	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	16.871	n/a	n/a	n/a	n/a	n/a	n/a
Mean	17.5688	n/a	n/a	17.2588	17.0644	17.843	20.4997
Stdev	0.561698	n/a	n/a	0.758023	1.02184	1.73068	2.04193
Min	15.141	n/a	n/a	16.418	16.141	14.685	18.683
Max	18.416	n/a	n/a	18.353	19.728	19.953	23.142
Range	3.275	n/a	n/a	1.935	3.587	5.268	4.459
Median	17.637	n/a	n/a	17.097	16.638	18.0475	20.087
CV[2]	0.0319713	n/a	n/a	0.0439210	0.0598814	0.0969949	0.996078

[2] CV stands for coefficient of variation, $C_v = \frac{\sigma}{\mu}$

Cup Seal Volume	Artifact A2

Artifact Prepared by: Tom Naylor and Christopher Mattson | Revision 1.1
Tests Performed by: Tom Naylor
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
Measure the volume (cm^3) of individual cup seals.

Summary of Test Results:

Summary of test results can be seen in Table A2.1.

Table A2.1. Summary of weight test results.

Spec (cm^3)	Spec Min (cm^3)	Spec Max (cm^3)	Samples (count)	Mean (cm^3)	Stdev (cm^3)	Min (cm^3)	Max (cm^3)	Range (cm^3)	Median (cm^3)
None	None	None	112	12.4099	0.449553	11.718	13.812	2.094	12.3865

Test Equipment and Set up:
The water displacement method was used to measure seal volume. The Sartorius AY303 scale (Figure A2.1) was used in the set up. See Artifact A1 (Cup Seal Weight) for scale specifications and setup. To measure volume, the seal was held by a steadying rod and a seal basket to keep the seal from touching the side and bottom of the vessel (see Figure A2.1).

Figure A2.1. Setup of seal volume test.

Test Procedure:

1. Balance scale using the built-in bubble level
2. Turn on scale and open lid
3. Fill container to the blue line with water (ensures the scale capacity is not exceeded)
4. Place container on scale and wait for the value to steady
5. Zero scale
6. Place seal in measuring basket
7. Hang basket on metal rod
8. Immerse seal into the water
9. Steady the rod and seal so it does not touch side or bottom of vessel
10. Wait for measured value to steady
11. Record number
12. Remove scale and zero scale as some water is removed along with the seal
13. Repeat steps 6 – 12 until all measurements are recorded

Test Results:
Figures A2.3 and A2.4 show the data, and Table A2.2 shows the raw data collected.

Observations and Conclusions:
Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

As can be seen in the box plots[3] (Figure A2.4), the seals from store 1 are the most consistent. Whether or not variations in seal volume affects seal performance is not known or speculated on in this report, other than to indicate how seal density varies (see Artifact A3).

Of the 4 samples that were purchased from store 7. It was found that two had a significantly different inner radius (see Figure A2.2). These seals were sold as replacement cup seals for the India Mark II. The figure below shows the two seal types purchased from the Store 7. With such an inner diameter difference, it is expected that two data points would be noticeably larger than the others, however this is not the case. The data shows only 1 seal with a noticeably larger volume than the others.

There is no specification for the seal volume, so it cannot be stated if the variation in volume is acceptable or not.

[3] Artifact 1 Cup Seal Weight provides a brief description about box plot interpretation.

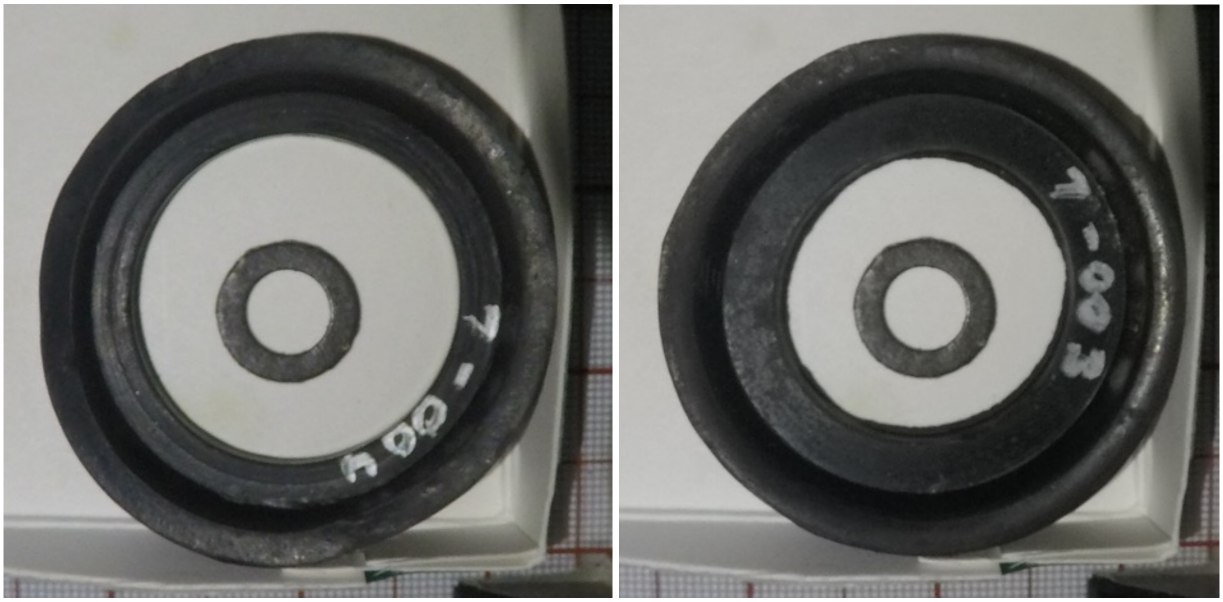

Figure A2.2. Differences for the inner diameter – seals purchased at store 7.

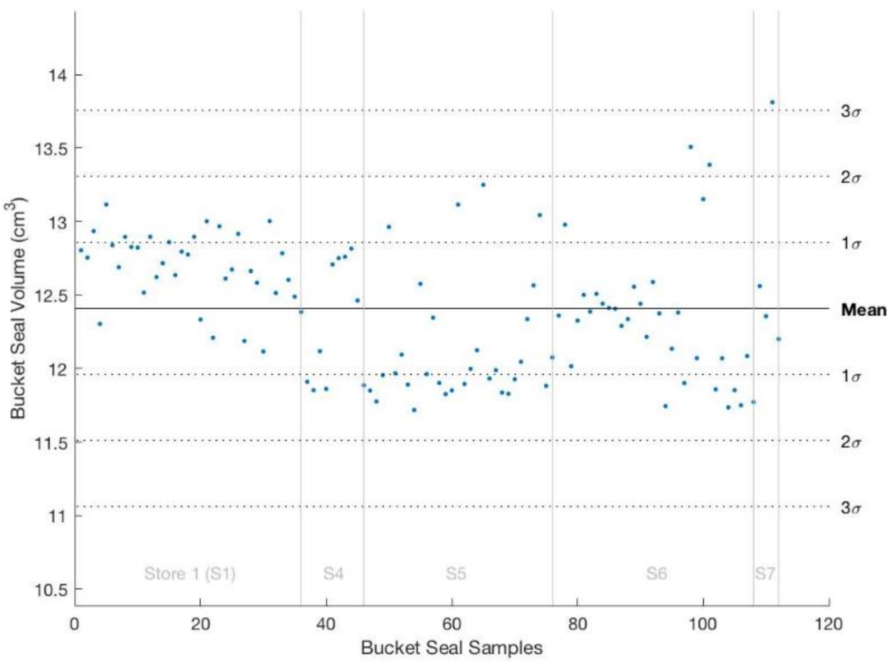

Figure A2.3. Cup seal volume. Ordered as tested.

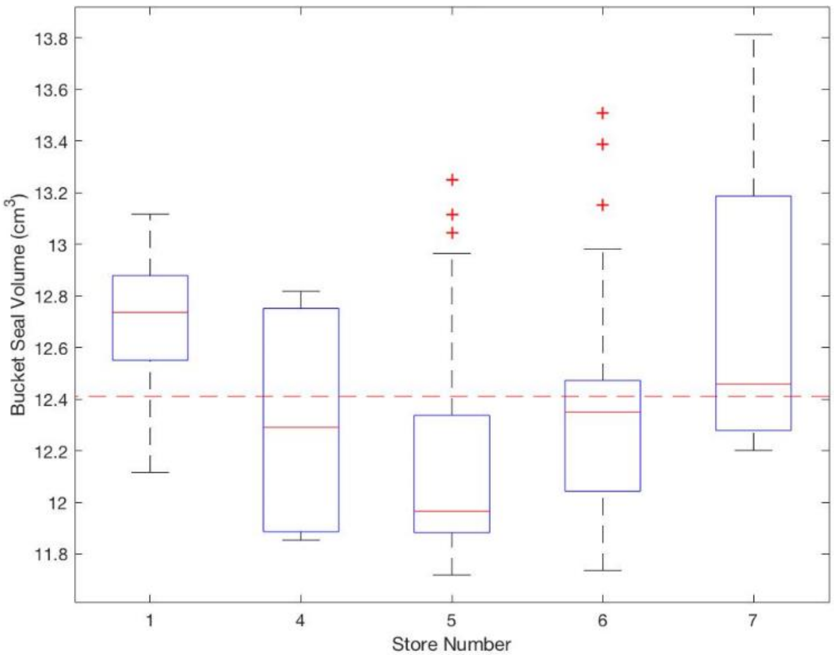

Figure A2.4. Cup seal volume. Boxplots for each store.

Table A2.2. Raw data for volume measurements. Units = cm^3.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	12.805	n/a	n/a	11.91	11.85	12.361	12.561
XX-002	12.755	n/a	n/a	11.853	11.776	12.98	12.356
XX-003	12.935	n/a	n/a	12.118	11.955	12.016	13.812
XX-004	12.304	n/a	n/a	11.862	12.964	12.326	12.201
XX-005	13.116	n/a	n/a	12.709	11.968	12.502	n/a
XX-006	12.84	n/a	n/a	12.751	12.095	12.388	n/a
XX-007	12.69	n/a	n/a	12.761	11.891	12.508	n/a
XX-008	12.896	n/a	n/a	12.817	11.718	12.442	n/a
XX-009	12.827	n/a	n/a	12.463	12.577	12.412	n/a
XX-010	12.823	n/a	n/a	11.886	11.963	12.407	n/a
XX-011	12.517	n/a	n/a	n/a	12.346	12.291	n/a
XX-012	12.897	n/a	n/a	n/a	11.902	12.337	n/a
XX-013	12.623	n/a	n/a	n/a	11.826	12.557	n/a
XX-014	12.717	n/a	n/a	n/a	11.851	12.441	n/a
XX-015	12.86	n/a	n/a	n/a	13.116	12.215	n/a
XX-016	12.636	n/a	n/a	n/a	11.895	12.588	n/a
XX-017	12.796	n/a	n/a	n/a	11.998	12.375	n/a
XX-018	12.776	n/a	n/a	n/a	12.125	11.744	n/a
XX-019	12.897	n/a	n/a	n/a	13.25	12.135	n/a
XX-020	12.334	n/a	n/a	n/a	11.932	12.381	n/a
XX-021	13.003	n/a	n/a	n/a	11.989	11.901	n/a
XX-022	12.21	n/a	n/a	n/a	11.837	13.509	n/a
XX-023	12.968	n/a	n/a	n/a	11.828	12.071	n/a
XX-024	12.612	n/a	n/a	n/a	11.927	13.153	n/a
XX-025	12.674	n/a	n/a	n/a	12.047	13.387	n/a
XX-026	12.917	n/a	n/a	n/a	12.337	11.859	n/a
XX-027	12.188	n/a	n/a	n/a	12.566	12.07	n/a
XX-028	12.664	n/a	n/a	n/a	13.044	11.736	n/a
XX-029	12.584	n/a	n/a	n/a	11.882	11.853	n/a
XX-030	12.116	n/a	n/a	n/a	12.076	11.75	n/a
XX-031	13.004	n/a	n/a	n/a	n/a	12.085	n/a
XX-032	12.514	n/a	n/a	n/a	n/a	11.772	n/a
XX-033	12.785	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	12.604	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	12.489	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	12.385	n/a	n/a	n/a	n/a	n/a	n/a
Mean	12.6878	n/a	n/a	12.313	12.151	12.3297	12.7325
Stdev	0.247475	n/a	n/a	0.424741	0.43087	0.445642	0.734615
Min	12.116	n/a	n/a	11.853	11.718	11.736	12.201
Max	13.116	n/a	n/a	12.817	13.25	13.509	13.812
Range	1	n/a	n/a	0.964	1.532	1.773	1.611
Median	12.736	n/a	n/a	12.2905	11.9655	12.349	12.4585
CV	0.0195050	n/a	n/a	0.0344953	0.0354596	0.0361438	0.0576961

Cup Seal Density	Artifact A3

Artifact Prepared by: Tom Naylor and Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Calculation:
To calculate the seal density from the measured seal weight and seal volume.

Summary of Test Results:

Summary of test results can be seen in Table A3.1.

Table A3.1. Summary of density test results.

Spec (g/cm^3)	Spec Min (g/cm^3)	Spec Max (g/cm^3)	Samples (count)	Mean (g/cm^3)	Stdev (g/cm^3)	Min (g/cm^3)	Max (g/cm^3)	Range (g/cm^3)	Median (g/cm^3)
none	none	none	112	1.41672	0.0841749	1.24967	1.67646	0.426789	1.39155

Test Equipment and Set up:
None needed for the density calculation.

Calculation Procedure:
Density is simply calculated as the measured weight (see Artifact A1) divided by the measured volume (see Artifact A2).

Test Results:
Figures A3.1 and A3.2 show the data, and Table A3.2 shows the calculated density.

Observations and Conclusions:
Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

As can be seen in the plots[4] (Figure A3.2), the seals from store 1 are remarkably consistent in their density. Those from stores 4 and 5, are less but similarly consistent. Interestingly stores 4 and 5 are both in the city of Jinja (a few hours east of Kampala). Both stores 1 and 5 have outliers. Store 6 is very inconsistent. Although there are only 4 samples from store 7, its mean is noticeably different than the other stores as shown in the box plots (see Figure A3.2). Both stores 6 and 7 were in the city of Gulu (which is many hours north of Kampala). The similarities in stores 4 and 5 and in stores 6 and 7 could be an indication of a particular supplier, or of different handling or environmental conditions in those cities.

[4] Artifact 1 Cup Seal Weight provides a brief description about box plot interpretation.

It is not yet known how seal density affects seal performance, though it is possible that it does.

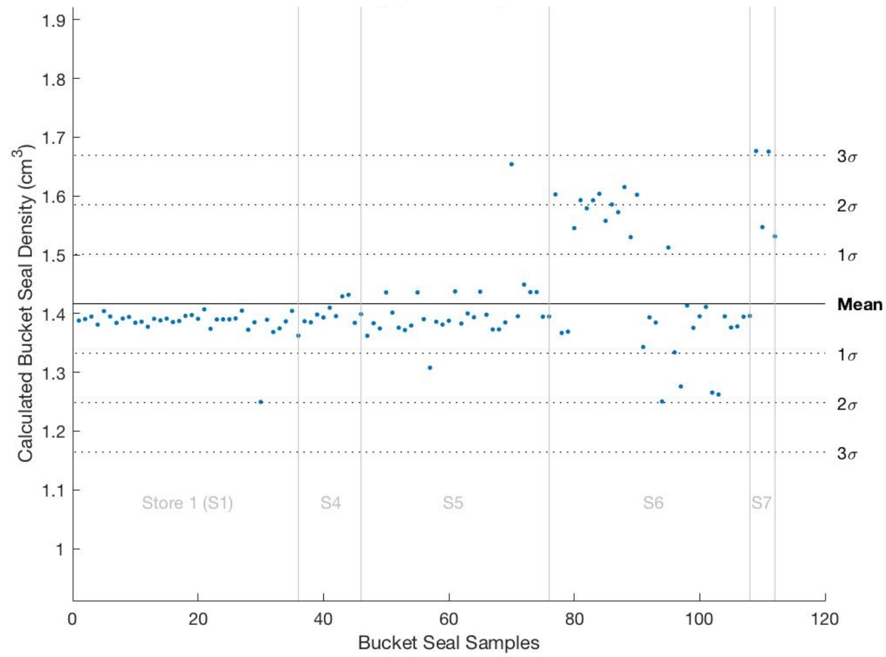

Figure A3.1. Cup seal density (calculated). Ordered as tested.

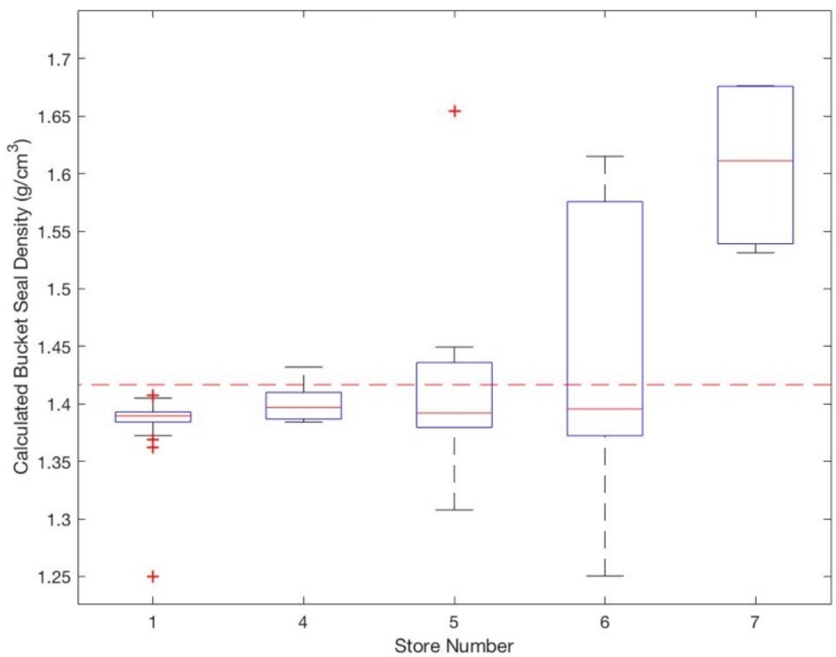

Figure A3.2. Cup seal density (calculated). Boxplots for each store.

Table A3.2. Raw data for density calculations. Units = g/cm^3.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	1.38805	n/a	n/a	1.38682	1.36211	1.6027	1.67646
XX-002	1.39067	n/a	n/a	1.38513	1.38349	1.36695	1.5471
XX-003	1.39482	n/a	n/a	1.39817	1.37465	1.36909	1.6755
XX-004	1.3811	n/a	n/a	1.39319	1.43598	1.54527	1.53127
XX-005	1.40409	n/a	n/a	1.40995	1.40157	1.59279	n/a
XX-006	1.39502	n/a	n/a	1.39558	1.37594	1.57911	n/a
XX-007	1.38408	n/a	n/a	1.4292	1.37179	1.59274	n/a
XX-008	1.39144	n/a	n/a	1.43193	1.37959	1.60368	n/a
XX-009	1.39417	n/a	n/a	1.38418	1.43588	1.55777	n/a
XX-010	1.38431	n/a	n/a	1.39896	1.39045	1.58556	n/a
XX-011	1.38611	n/a	n/a	n/a	1.30779	1.57237	n/a
XX-012	1.37745	n/a	n/a	n/a	1.38599	1.61506	n/a
XX-013	1.39111	n/a	n/a	n/a	1.38119	1.52998	n/a
XX-014	1.3883	n/a	n/a	n/a	1.38765	1.60212	n/a
XX-015	1.39137	n/a	n/a	n/a	1.43763	1.34302	n/a
XX-016	1.38557	n/a	n/a	n/a	1.38293	1.39347	n/a
XX-017	1.38731	n/a	n/a	n/a	1.40007	1.38465	n/a
XX-018	1.39606	n/a	n/a	n/a	1.39357	1.25043	n/a
XX-019	1.39746	n/a	n/a	n/a	1.43728	1.51232	n/a
XX-020	1.39103	n/a	n/a	n/a	1.39809	1.33398	n/a
XX-021	1.40721	n/a	n/a	n/a	1.37293	1.27594	n/a
XX-022	1.37404	n/a	n/a	n/a	1.37298	1.41358	n/a
XX-023	1.38996	n/a	n/a	n/a	1.38493	1.37561	n/a
XX-024	1.39018	n/a	n/a	n/a	1.65406	1.39527	n/a
XX-025	1.39017	n/a	n/a	n/a	1.39537	1.41137	n/a
XX-026	1.39165	n/a	n/a	n/a	1.4493	1.26545	n/a
XX-027	1.40491	n/a	n/a	n/a	1.43642	1.26222	n/a
XX-028	1.37239	n/a	n/a	n/a	1.43652	1.39511	n/a
XX-029	1.38509	n/a	n/a	n/a	1.39463	1.37619	n/a
XX-030	1.24967	n/a	n/a	n/a	1.39492	1.37813	n/a
XX-031	1.38942	n/a	n/a	n/a	n/a	1.39454	n/a
XX-032	1.36863	n/a	n/a	n/a	n/a	1.39594	n/a
XX-033	1.37474	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	1.3867	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	1.40444	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	1.36221	n/a	n/a	n/a	n/a	n/a	n/a
Mean	1.38447	n/a	n/a	1.40131	1.40386	1.44601	1.60758
Stdev	0.0251279	n/a	n/a	0.0172212	0.0557464	0.11843	0.0792431
Min	1.24967	n/a	n/a	1.38418	1.30779	1.25043	1.53127
Max	1.40721	n/a	n/a	1.43193	1.65406	1.61506	1.67646
Range	0.157544	n/a	n/a	0.0477492	0.34627	0.364635	0.145191
Median	1.38969	n/a	n/a	1.39687	1.39201	1.39561	1.6113
CV	0.0181498	n/a	n/a	0.0122894	0.0397094	0.0819012	0.0492934

Cup Seal Durometer	Artifact A4

Artifact Prepared by: Tom Naylor and Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To measure the durometer (rubber hardness) of the seals. To do this in four distinct places along the circumference of the seal.

Summary of Test Results:

Summary of test results can be seen in Table A4.1.

Table A4.1. Summary of durometer test results.

Spec (H)	Spec Min (H)	Spec Max (H)	Samples (count)	Mean (H)	Stdev (H)	Min (H)	Max (H)	Range (H)	Median (H)
75-85	75	85	112	86.0536	3.4368	75.75	96.75	21	85.625

Test Equipment and Set up:
The Starrett Handheld Digital Durometer (H, Shore A Scale) was used to measure the durometer as shown in the photos below. The durometer is capable of a resolution of 0.5 H, deviation <1% in the 20-90 HSA range.

Figure A4.1. Measurement of seal edge.

Test Procedure:
1. Set seal open face down on a hard flat surface
2. Turn on the durometer measurement device
3. If the device does not read zero, zero it
4. Place the pin on the outside round of the seal (pictured)
5. Press down and hold until the measurement is steady

6. Record value
7. Rotate seal 45 degrees and repeat steps 3 – 6 to measure hardness in different places
8. Take four measurements per seal following steps 3 – 7
9. Repeat steps 1-8 for each seal

Test Results:
Figures A4.2, A4.3, and A4.4 show the data, and Table A4.2 shows the raw data collected. Note that each point in the first scatter plot provided is the average of four durometer measurements for one seal. The variation of those four measurements is illustrated in Figure A4.4, showing lines representing the range with the mean value shown as a point.

Observations and Conclusions:
Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

As seen in the box plots[5] (Figure A4.3), the mean durometer is similar for every store. Given the outliers in measurements for store 1, it is difficult to conclude that anyone store is more consistent than another. Generally, from this data we can conclude that the durometer is relatively consistent at approximately 86 H (Shore A, or HSA). Nitrile is typically between 40-90 HSA, and the spec for this part is 85 HSA. Given the relatively large standard deviation, the measured values are at the high end of the expected Nitrile range. Roughly 15% of the sample tested had an average HSA above 90 HSA. To what extent this affects pump performance, it is not yet known. Also, it is worth noting that the internal measurement error (see Artifact A25) shows the durometer tests to have the largest amount of internal measurement error, at approximately 3.5%.

For the most part, the Cup Seal Durometer Variation plot shows wide variation within each sample (see Figure A4.4).

[5] Artifact 1 Cup Seal Weight provides a brief description about box plot interpretation.

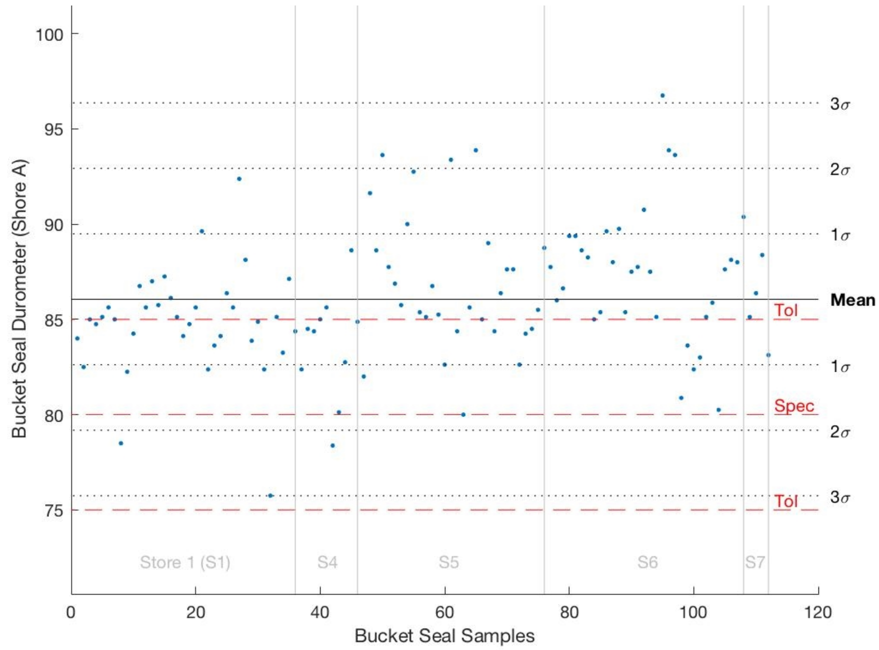

Figure A4.2. Cup seal durometer. Ordered as tested.

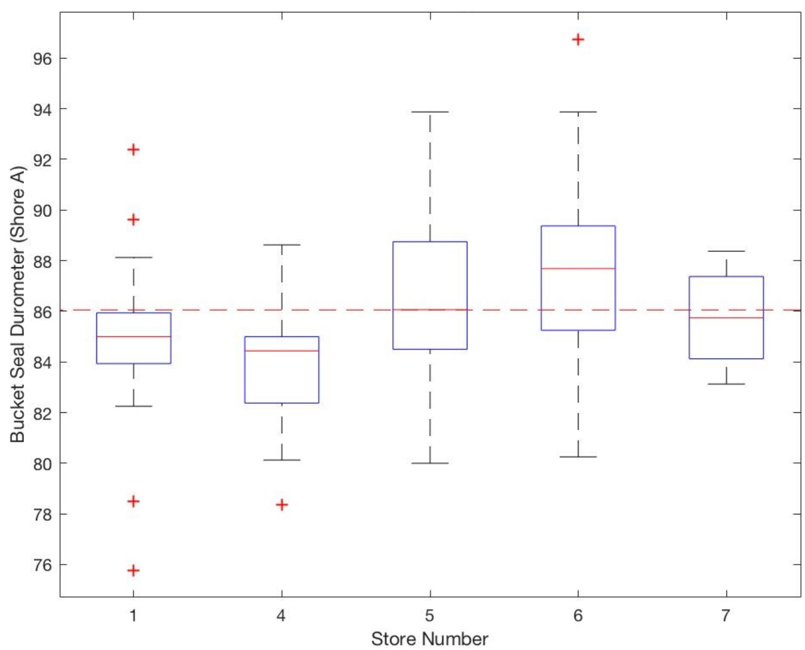

Figure A4.3. Cup seal durometer: Boxplot for each store.

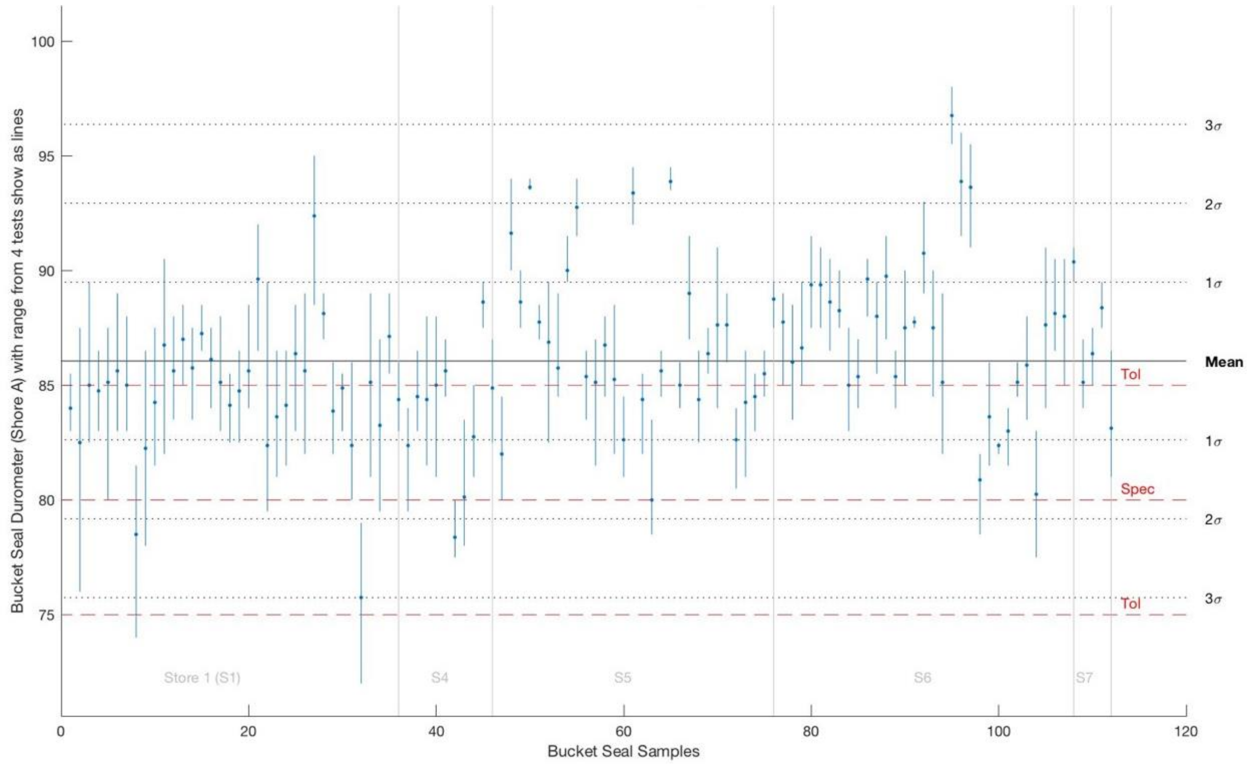

Figure A4.4. Cup seal durometer variation within sample. Four tests per sample.

Table A4.2. Raw data for durometer measurements. Units = Shore A.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	84	n/a	n/a	82.375	82	87.75	85.125
XX-002	82.5	n/a	n/a	84.5	91.625	86	86.375
XX-003	85	n/a	n/a	84.375	88.625	86.625	88.375
XX-004	84.75	n/a	n/a	85	93.625	89.375	83.125
XX-005	85.125	n/a	n/a	85.625	87.75	89.375	n/a
XX-006	85.625	n/a	n/a	78.375	86.875	88.625	n/a
XX-007	85	n/a	n/a	80.125	85.75	88.25	n/a
XX-008	78.5	n/a	n/a	82.75	90	85	n/a
XX-009	82.25	n/a	n/a	88.625	92.75	85.375	n/a
XX-010	84.25	n/a	n/a	84.875	85.375	89.625	n/a
XX-011	86.75	n/a	n/a	0	85.125	88	n/a
XX-012	85.625	n/a	n/a	0	86.75	89.75	n/a
XX-013	87	n/a	n/a	0	85.25	85.375	n/a
XX-014	85.75	n/a	n/a	0	82.625	87.5	n/a
XX-015	87.25	n/a	n/a	0	93.375	87.75	n/a
XX-016	86.125	n/a	n/a	0	84.375	90.75	n/a
XX-017	85.125	n/a	n/a	0	80	87.5	n/a
XX-018	84.125	n/a	n/a	0	85.625	85.125	n/a
XX-019	84.75	n/a	n/a	0	93.875	96.75	n/a
XX-020	85.625	n/a	n/a	0	85	93.875	n/a
XX-021	89.625	n/a	n/a	0	89	93.625	n/a
XX-022	82.375	n/a	n/a	0	84.375	80.875	n/a
XX-023	83.625	n/a	n/a	0	86.375	83.625	n/a
XX-024	84.125	n/a	n/a	0	87.625	82.375	n/a
XX-025	86.375	n/a	n/a	0	87.625	83	n/a
XX-026	85.625	n/a	n/a	0	82.625	85.125	n/a
XX-027	92.375	n/a	n/a	0	84.25	85.875	n/a
XX-028	88.125	n/a	n/a	0	84.5	80.25	n/a
XX-029	83.875	n/a	n/a	0	85.5	87.625	n/a
XX-030	84.875	n/a	n/a	0	88.75	88.125	n/a
XX-031	82.375	n/a	n/a	n/a	n/a	88	n/a
XX-032	75.75	n/a	n/a	n/a	n/a	90.375	n/a
XX-033	85.125	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	83.25	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	87.125	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	84.375	n/a	n/a	n/a	n/a	n/a	n/a
Mean	84.8368	n/a	n/a	83.6625	86.9	87.4141	85.75
Stdev	2.78674	n/a	n/a	2.90417	3.54898	3.55592	2.20322
Min	75.75	n/a	n/a	78.375	80	80.25	83.125
Max	92.375	n/a	n/a	88.625	93.875	96.75	88.375
Range	16.625	n/a	n/a	10.25	13.875	16.5	5.25
Median	85	n/a	n/a	84.4375	86.0625	87.6875	85.75
CV	0.0328482	n/a	n/a	0.0347129	0.0408398	0.0406790	0.0256935

Cup Seal Geometry: Outer Diameter (DIM 1)	Artifact A5

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.0
Tests Performed by: Christopher Mattson, and Hans Ottosson
Test Date: 31 July 2018 (photos taken on various days leading to analysis)
Test Location: Gulu, Uganda

Purpose:
The purpose of this artifact is to clearly describe how dimension 1 (DIM 1) was measured and the variation there of characterized. This artifact also, presents the resulting data and give reference to the necessary files to reproduce the results.

Purpose of the Test:
DIM 1 is the outer diameter of the cup seal for the India Mark II and India Mark III hand pumps for boreholes. To eventually be able to characterize pump performance as a function of geometric variation of the seals, key dimensions were measured on 112 cup seals purchased in Uganda. The cup seal is made of Nitrile, which is soft and prevents a hard measurement using a traditional measurement device (such as a pair of calipers). Therefore, an optical approach was taken. Key dimensions are shown in Figure A5.1.

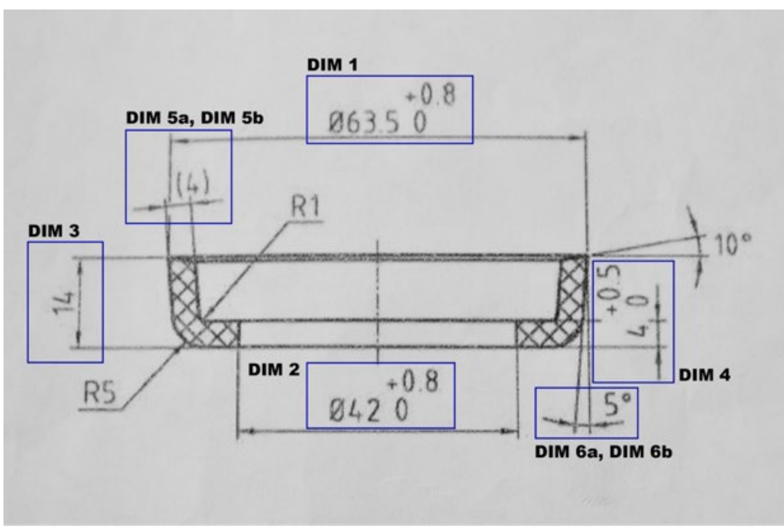

Figure A5.1. Cup seal dimensions.

Summary of Test Results:
Table A5.1 shows the summary statistics for all stores and all parts combined.

Table A5.1. Summary of test results.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
63.5	63.5	64.3	112	64.2653	0.530363	62.8561	65.6768	2.82072	64.2558

Test Equipment and Set up:
A test fixture was used to simultaneously take a top, right and left size photo of each seal. This was done for every seal as it was placed in the "bucket up position" (cup seal with the opening of the bucket upward), as shown in Figure A6.2. The seal was placed on a white centering fixture, which helped place the seal in the camera frame.

MATLAB's (R2017b) image processing software was used to best fit a circle to dimension of interest (DIM 1).

<u>Camera Settings:</u>

Camera = GoPro Hero 5
Trigger = GoPro Smart Remote (activates the shutter of all cameras simultaneously)
Macro Lens = 2x macro
Wide Angle Setting: Narrow
Resolution: 12 MP

<u>MATLAB Settings:</u>

Function =
```
[center2, radius2] = imfindcircles(RGBs,[Rmin …
    Rmax],'ObjectPolarity','dark','Sensitivity',.993);
```
Sensitivity = 0.993 (1.0 is max sensitivity)
File Resolution Adjustment = 50% reduction via `RGBs = imresize(RGBc, .5);`

<u>Reference:</u>

A black washer was used as a known (black circle) reference. Its diameter was measured at 18.7825 mm. This was used to scale MATLAB's pixel measurements to mm.

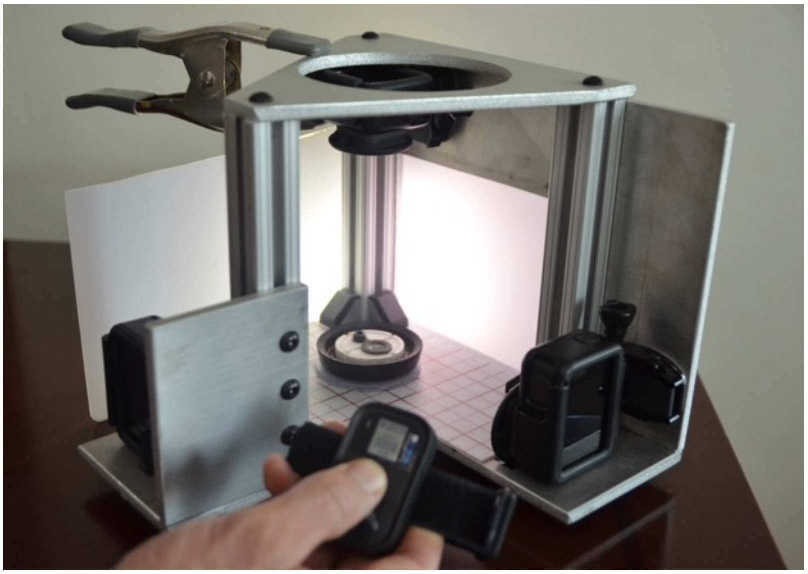

Figure A5.2. Photo test fixture.

Test Procedure:

1. Set test fixture on stable surface in a well-lit area.
2. Ensure that the cameras are turned on and connected to the GoPro Smart remote.
3. Place washer on the white centering fixture.
4. Place cup seal in the upward position (as seen in picture).
5. Take picture of the upper side with the remote.
6. Turn seal over.
7. Take picture with remote.
8. Replace seal with new seal and repeat until done, keeping track of the order of seals.
9. Once done, upload pictures to computer and rename files ('store number'-'seal number'-t-u for upper side and 'store number'-'seal number'-t-d for bottom side).
10. Run MATLAB script and save the results.

Test Results:

Figure A5.3 shows the visual output from the analysis of a seal. Figures of this type for each seal can be found in the DIM1_Results folder.

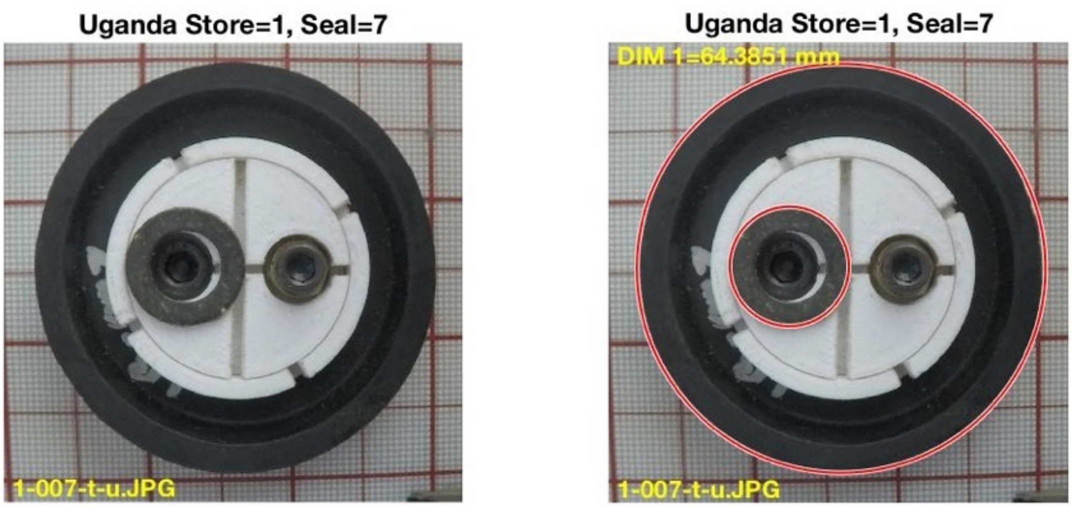

Figure A5.3. Visual output from cup seal analysis.

Table A5.2 is the complete set of collected data, with summary statistics.

Accounting for Internal Measurement Error:

A study of internal measurement error was carried out for this measurement set up. The result of this study is provided in Artifact A25. In that artifact it is shown that the error associated with this measurement device is less than one half percent. Nevertheless, this means that the measurements displayed in this artifact could be larger by 0.95 mm or smaller by 0.95 mm simply because of measurement error. This number is based on a 6 sigma analysis.

Observations and Conclusions:

Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

Perhaps the most significant thing to observe from the data is that many of the seals are out of specification, with many being larger than the upper tolerance limit. Even more interesting is that nearly all the seals from the town of Jinja (stores 4 and 5) are measured at above the upper tolerance limit. Worth noting is that very few <3% of the seals are below the lower specification limit (63.5 mm).

Also, worth noting is that the MATLAB image processing software places a circle as well as it can to the image. As shown in Figure A6.4, the image processing may actually be a better measure of how misshapen the seal is. As a note, this is one of just a few extreme misshapen seals.

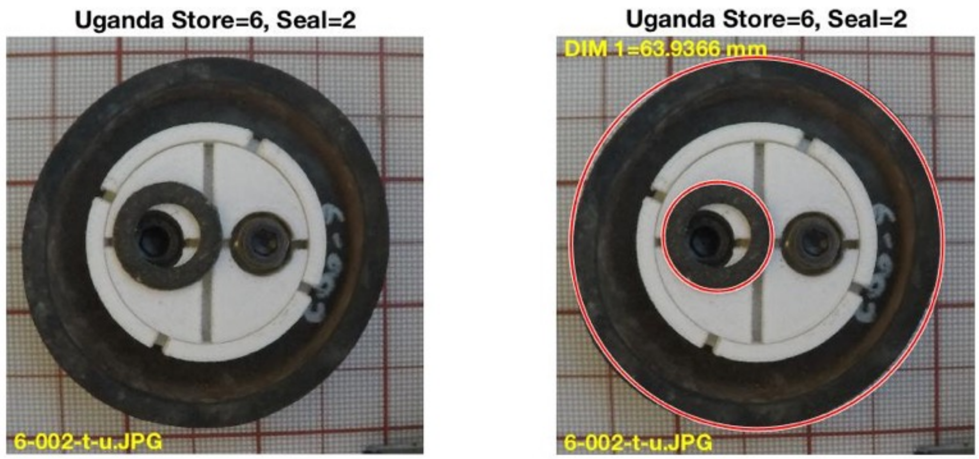

Figure A5.4. Example of output when seal shape is oval.

It is quite possible that a more sophisticated image processing method would yield different, possibly more accurate results.

Files Associated with this Artifact:
Within the archive the analysis associated with DIM can be found in the folder called "Bucket_Seal_Dimensional_Analysis/DIM1". The photos analyzed and the MATLAB code are included in the folder.

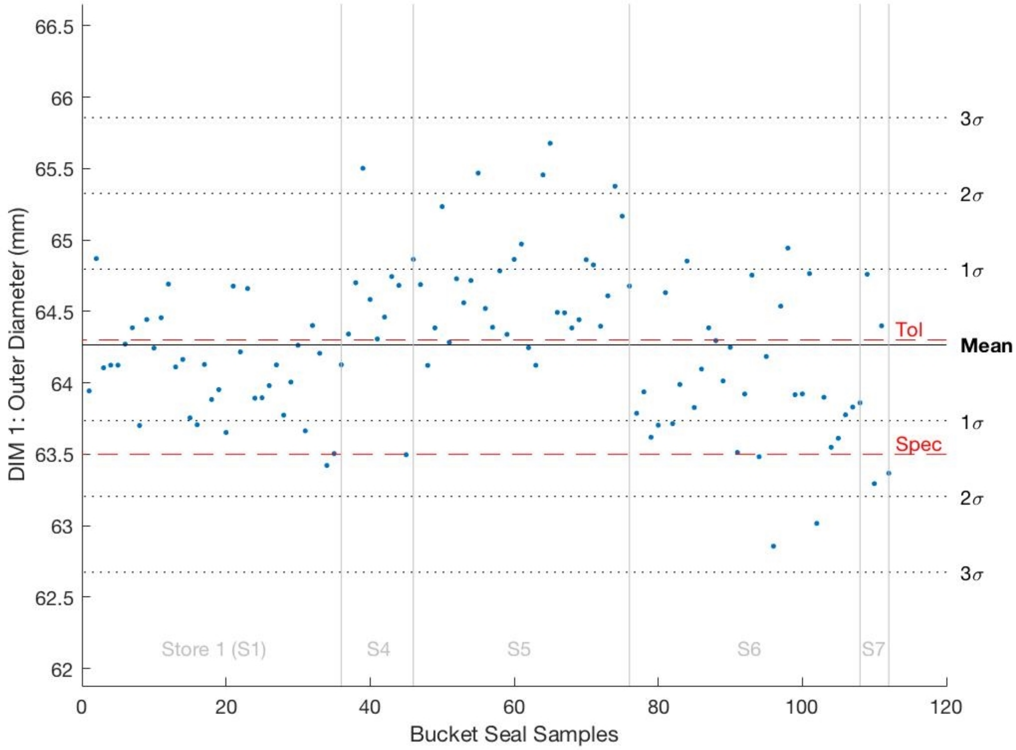

Figure A5.5. DIM 1: Outer diameter. Ordered as tested.

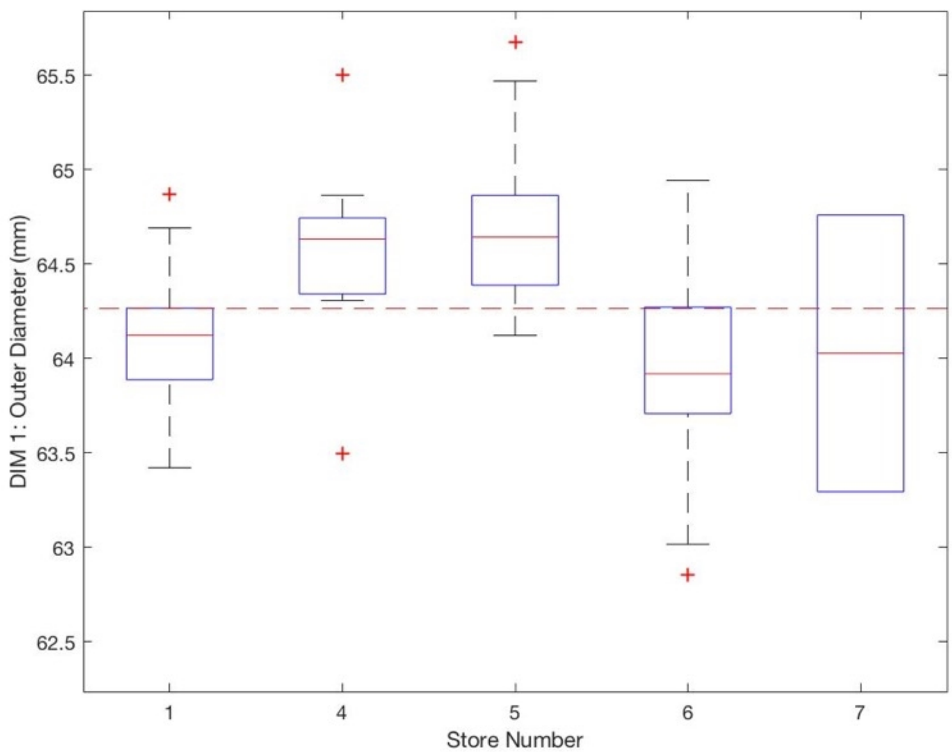

Figure A5.6. DIM 1: Outer Diameter. Boxplots for each store.

Table A5.2. Raw data for DIM1 (outer diameter) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	63.9433	n/a	n/a	64.3414	64.6879	63.7869	64.7598
XX-002	64.8693	n/a	n/a	64.7003	64.1217	63.9366	63.294
XX-003	64.1052	n/a	n/a	65.5016	64.3841	63.6188	64.3991
XX-004	64.1235	n/a	n/a	64.583	65.2337	63.7035	63.3669
XX-005	64.1231	n/a	n/a	64.3065	64.2839	64.6311	n/a
XX-006	64.2706	n/a	n/a	64.4599	64.7283	63.7138	n/a
XX-007	64.3851	n/a	n/a	64.744	64.5606	63.9886	n/a
XX-008	63.7007	n/a	n/a	64.6825	64.716	64.852	n/a
XX-009	64.4427	n/a	n/a	63.4963	65.4683	63.8271	n/a
XX-010	64.2433	n/a	n/a	64.8641	64.5204	64.0961	n/a
XX-011	64.4555	n/a	n/a	0	64.3885	64.3844	n/a
XX-012	64.691	n/a	n/a	0	64.7836	64.2951	n/a
XX-013	64.1105	n/a	n/a	0	64.3391	64.0128	n/a
XX-014	64.1632	n/a	n/a	0	64.8637	64.2487	n/a
XX-015	63.7542	n/a	n/a	0	64.971	63.5126	n/a
XX-016	63.7064	n/a	n/a	0	64.2452	63.9214	n/a
XX-017	64.128	n/a	n/a	0	64.1227	64.7535	n/a
XX-018	63.8829	n/a	n/a	0	65.4553	63.4824	n/a
XX-019	63.9519	n/a	n/a	0	65.6768	64.184	n/a
XX-020	63.6522	n/a	n/a	0	64.4927	62.8561	n/a
XX-021	64.6768	n/a	n/a	0	64.4899	64.5365	n/a
XX-022	64.2163	n/a	n/a	0	64.3834	64.943	n/a
XX-023	64.6597	n/a	n/a	0	64.4413	63.9168	n/a
XX-024	63.8923	n/a	n/a	0	64.8616	63.9222	n/a
XX-025	63.8951	n/a	n/a	0	64.8251	64.7644	n/a
XX-026	63.9802	n/a	n/a	0	64.396	63.0159	n/a
XX-027	64.1254	n/a	n/a	0	64.6087	63.8986	n/a
XX-028	63.7735	n/a	n/a	0	65.3758	63.5482	n/a
XX-029	64.0049	n/a	n/a	0	65.1667	63.6113	n/a
XX-030	64.2628	n/a	n/a	0	64.6769	63.776	n/a
XX-031	63.6633	n/a	n/a	n/a	n/a	63.8302	n/a
XX-032	64.401	n/a	n/a	n/a	n/a	63.8596	n/a
XX-033	64.2066	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	63.421	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	63.5043	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	64.1263	n/a	n/a	n/a	n/a	n/a	n/a
Mean	64.0976	n/a	n/a	64.568	64.709	63.9821	63.955
Stdev	0.340623	n/a	n/a	0.505645	0.4154	0.490018	0.736585
Min	63.421	n/a	n/a	63.4963	64.1217	62.8561	63.294
Max	64.8693	n/a	n/a	65.5016	65.6768	64.943	64.7598
Range	1.44834	n/a	n/a	2.00532	1.55508	2.08693	1.46573
Median	64.1233	n/a	n/a	64.6328	64.6428	63.9191	63.883
CV	0.00531413	n/a	n/a	0.00783120	0.00641951	0.00765867	0.0115172

Cup Seal Geometry: Inner Diameter (DIM 2)	Artifact A6

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.0
Tests Performed by: Christopher Mattson, and Hans Ottosson
Test Date: 31 July 2018 (photos taken on various days leading to analysis)
Test Location: Gulu, Uganda

Purpose of the Test:
DIM 2 is the inner diameter of the cup seal for the India Mark II and India Mark III hand pumps for boreholes. The purpose if this test is to measure the purchased seals using an optical method in order to characterize the variation in the seal's inner diameter (DIM2).

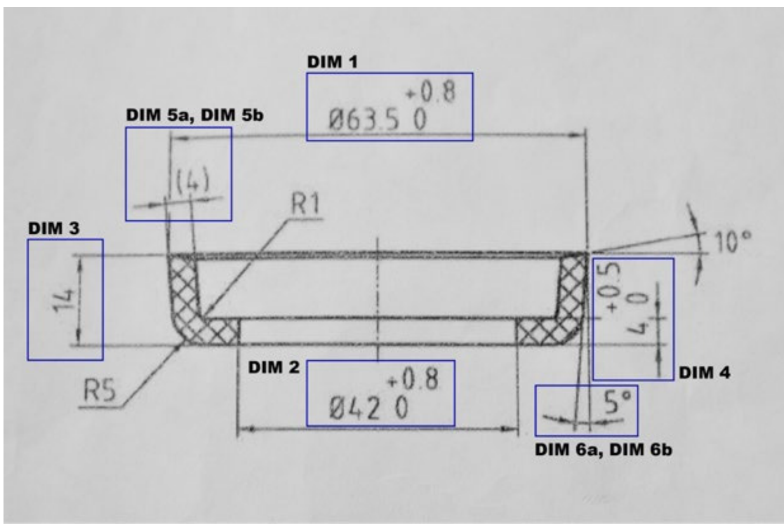

Figure A6.1. Cup seal dimensions.

Summary of Test Results:
Table A6.1 shows the summary statistics for all stores and all parts combined.

Table A6.1. Summary of test results.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
42.0	42.0	42.8	110	41.8651	0.227975	41.4178	42.7086	1.29075	41.8484

Test Equipment and Set up:
A test fixture was used to simultaneously take a top, right and left side photo of each seal. This was done for every seal as it was placed in the "bucket down position" (cup seal with the opening of the cup downward), opposite of that shown in Figure A6.2. The seal was placed in an edge fixture, which helped place the seal in the camera frame.

Camera Settings:

Camera = GoPro Hero 5

Trigger = GoPro Smart Remote (activates the shutter of all cameras simultaneously).

Macro Lens = 2x macro

Wide Angle Setting: Narrow

Resolution: 12 MP

MATLAB Settings:

Function =
```
[center2, radius2] = imfindcircles(RGBs,[Rmin …
    Rmax],'ObjectPolarity','bright','Sensitivity',.993);
```
Sensitivity = 0.993 (1.0 is max sensitivity)

File Resolution Adjustment = 50% reduction via `RGBs = imresize(RGBc, .5);`

Reference:

A black washer was used as a known reference that was a black circle. Its diameter was measured at 18.7825 mm. This was used to scale MATLAB’s pixel measurements to mm.

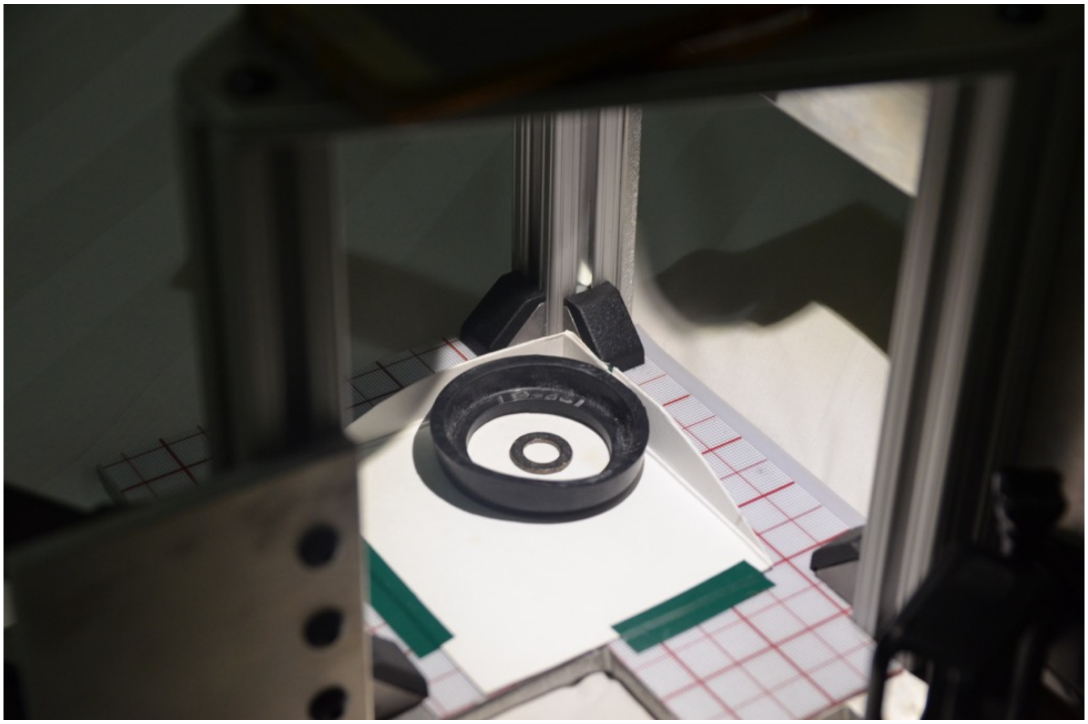

Figure A6.2. Placement of the cup seal in the photo test fixture.

Test Procedure:

1. Set test fixture on stable surface in a well-lit area.
2. Ensure that top camera is turned on and connected to the GoPro Smart remote.
3. Place washer on the white surface so that it will be inside of the seal.
4. Place cup seal in the upward position next to the white walls (as seen in picture).
5. Take picture with the remote.
6. Replace seal with new seal and repeat until done, keeping track of the order of seals.

7. Once done, upload pictures to computer and rename files ('store number'-'seal number'-cb).
8. Run MATLAB script and save the results.

Test Results:
Figure A6.3 is produced by MATLAB as the result of the DIM2 analysis for one seal. Images of this nature were kept for all DIM2 measurements made. Table A6.2 has the complete set of collected data, with summary statistics.

Figure A6.3. Automatic measurement of the inner diameter.

Accounting for Internal Measurement Error:
A study of internal measurement error was carried out for this measurement set up. The results of this study is provided in Artifact A25. In that artifact it is shown that the error associated with this measurement device is approximately ¼ percent. This means that the measurements displayed in this artifact could be larger by 0.31 mm or smaller by 0.31 mm simply because of measurement error.

Observations and Conclusions:
Note that there were no Nitrile cup seals purchased from stores 2 or 3; therefore, there are no measurements recorded or reported for those stores in this document.

An important observation is that 75% of the seals are lower than the lower limit of the specification. It is quite possible that being below the specification limit is better than being above the specification limit in this case.

All stores are showing as similar, as shown in the box plot. It is also worth noting that the standard deviation of this measurement is significantly lower than the standard deviation of DIM1. DIM2 is a feature in a more structurally sound area of the seal as compared to DIM1.

Because it was determined that two of the seals from store 7, were not for the India Mark II or III, even though they were sold as such. They were not measured as part of this test. Therefore, the number of samples for this test is 110 (not 112, as for most other tests performed).

Files Associated with this Artifact:
Within the archive the analysis associated with DIM can be found in the folder called "Bucket_Seal_Dimensional_Analysis/DIM2". The photos analyzed and the MATLAB code are included in the folder.

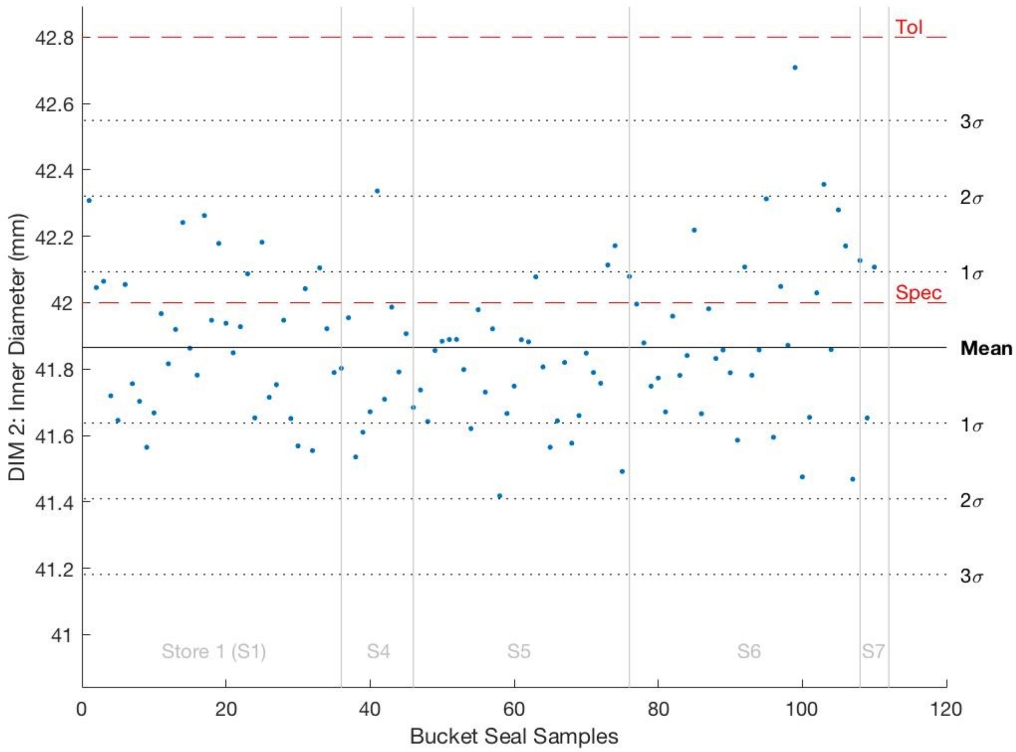

Figure A6.4. DIM 2: Inner diameter. Ordered as tested.

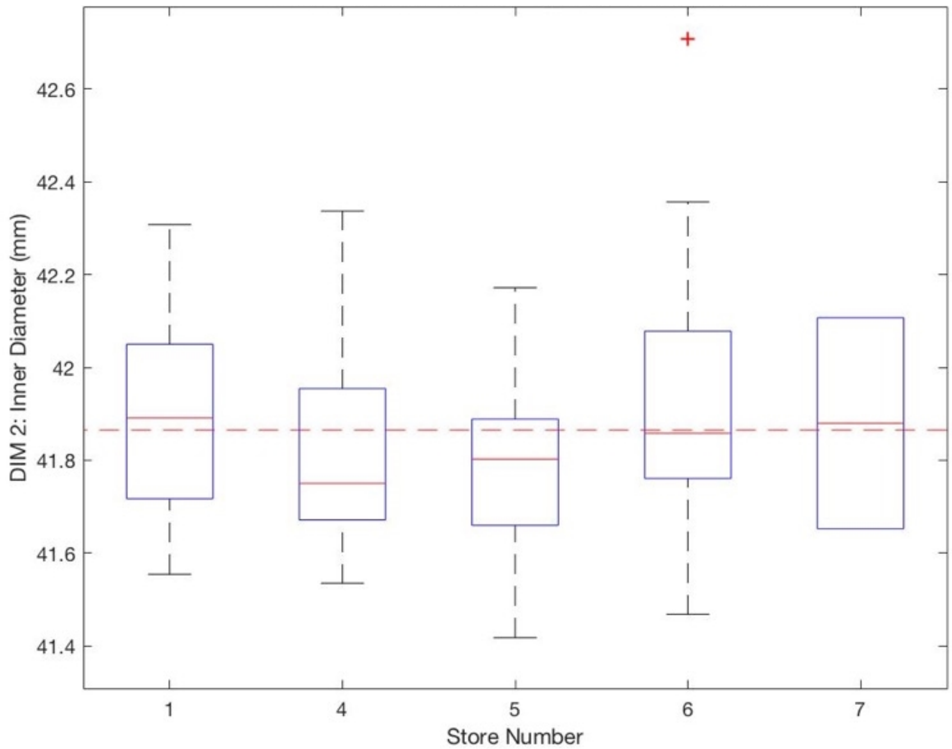

Figure A6.5. DIM 2: Inner diameter. Boxplot for each store.

Table A6.2. Raw data for DIM2 (inner diameter) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	42.308	n/a	n/a	41.9546	41.7368	41.9958	n/a
XX-002	42.0454	n/a	n/a	41.5351	41.6418	41.8789	41.6525
XX-003	42.0645	n/a	n/a	41.6097	41.856	41.7483	n/a
XX-004	41.7193	n/a	n/a	41.6713	41.8838	41.773	42.1071
XX-005	41.6454	n/a	n/a	42.3367	41.8888	41.6709	n/a
XX-006	42.0548	n/a	n/a	41.709	41.8893	41.9594	n/a
XX-007	41.756	n/a	n/a	41.9867	41.7985	41.781	n/a
XX-008	41.7028	n/a	n/a	41.7912	41.6207	41.8408	n/a
XX-009	41.5644	n/a	n/a	41.9065	41.9787	42.2185	n/a
XX-010	41.6678	n/a	n/a	41.6843	41.7305	41.6654	n/a
XX-011	41.9671	n/a	n/a	0	41.9212	41.9818	n/a
XX-012	41.8159	n/a	n/a	0	41.4178	41.8319	n/a
XX-013	41.9194	n/a	n/a	0	41.6663	41.8572	n/a
XX-014	42.2416	n/a	n/a	0	41.7487	41.7888	n/a
XX-015	41.8627	n/a	n/a	0	41.8884	41.5855	n/a
XX-016	41.7817	n/a	n/a	0	41.8818	42.1074	n/a
XX-017	42.2626	n/a	n/a	0	42.0778	41.7813	n/a
XX-018	41.9471	n/a	n/a	0	41.8064	41.8577	n/a
XX-019	42.1784	n/a	n/a	0	41.5643	42.3128	n/a
XX-020	41.938	n/a	n/a	0	41.6438	41.5944	n/a
XX-021	41.849	n/a	n/a	0	41.8199	42.049	n/a
XX-022	41.9276	n/a	n/a	0	41.5768	41.8716	n/a
XX-023	42.0869	n/a	n/a	0	41.6598	42.7086	n/a
XX-024	41.6527	n/a	n/a	0	41.8479	41.4751	n/a
XX-025	42.1822	n/a	n/a	0	41.7897	41.6545	n/a
XX-026	41.7148	n/a	n/a	0	41.7571	42.0295	n/a
XX-027	41.7528	n/a	n/a	0	42.1134	42.3566	n/a
XX-028	41.9472	n/a	n/a	0	42.1716	41.8588	n/a
XX-029	41.6509	n/a	n/a	0	41.4916	42.2796	n/a
XX-030	41.5682	n/a	n/a	0	42.0789	42.1709	n/a
XX-031	42.0421	n/a	n/a	n/a	n/a	41.4682	n/a
XX-032	41.5544	n/a	n/a	n/a	n/a	42.127	n/a
XX-033	42.105	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	41.9215	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	41.7895	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	41.8021	n/a	n/a	n/a	n/a	n/a	n/a
Mean	41.8886	n/a	n/a	41.8185	41.7983	41.915	41.8798
Stdev	0.20892	n/a	n/a	0.235574	0.181953	0.273491	0.321507
Min	41.5544	n/a	n/a	41.5351	41.4178	41.4682	41.6525
Max	42.308	n/a	n/a	42.3367	42.1716	42.7086	42.1071
Range	0.753612	n/a	n/a	0.801659	0.753796	1.24039	0.454679
Median	41.8911	n/a	n/a	41.7501	41.8024	41.8583	41.8798
CV	0.00498751	n/a	n/a	0.00563325	0.00435312	0.00652490	0.00767690

Cup Seal Geometry: Height (DIM 3)	Artifact A7

Artifact Prepared by: Hans Ottosson and Christopher Mattson | Revision 1.0
Tests Performed by: Hans Ottosson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
The purpose of this test is to measure the overall height of the cup seal, and to do this is 4 places along the circumference of the seal.

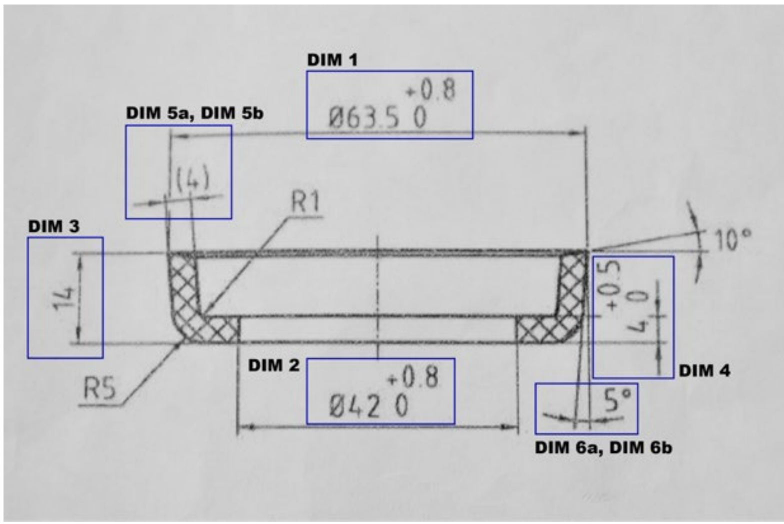

Figure A7.1. Cup seal dimensions.

Summary of Test Results:
The results shown in Table A7.1 represent the statistics for the average heights for each seal.

Table A7.1. Summary of test results.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
14	13.5	14.5	112	12.4019	0.429384	11.355	13.1475	1.7925	12.4625

Test Equipment and Set up:
A Mitotoyo Digimatic Indicator (manufacturers part number 575-123) was used to measure the height of each seal in four places (at 0, PI/2, PI, 3/2PI, and 2PI). The indicator accuracy is 0.02 mm, and a measurement force of 1.8 N. A custom stand was built to hold the indicator and provide a flat surface for the sample to rest on (see Figure A7.2). Each seal was measured with the indicator head near the center of the wall thickness.

Figure A7.2. Measurement of the seal height.

Test Procedure:

1. Make sure that the instrument is at zero before taking measurement.
2. Place the needle of the indicator at the center of the top edge of the seal as seen in image.
3. Read and record measurement.
4. Rotate the seal 90° and record measurement (do this 3 times for a total of 4 measurements).
5. Replace seal with new seal and repeat until done, keeping track of the order of seals.

Test Results:

The following plots and tables provide the data and results.

Observations and Conclusions:

No data was collected from store 2 or 3.

It is worth noticing that all (100%) of the seals are below specification for the height. A lower dimension here, would make the seal stiffer in the bucket region. At this point in the research, it is unclear if this would be desirable or not.

Also note that seals from store 1 measure noticeably more consistent than the others. While the scatter plot with variation in height across samples, suggests the variation in height across individual seals appears to be the smallest with story 5.

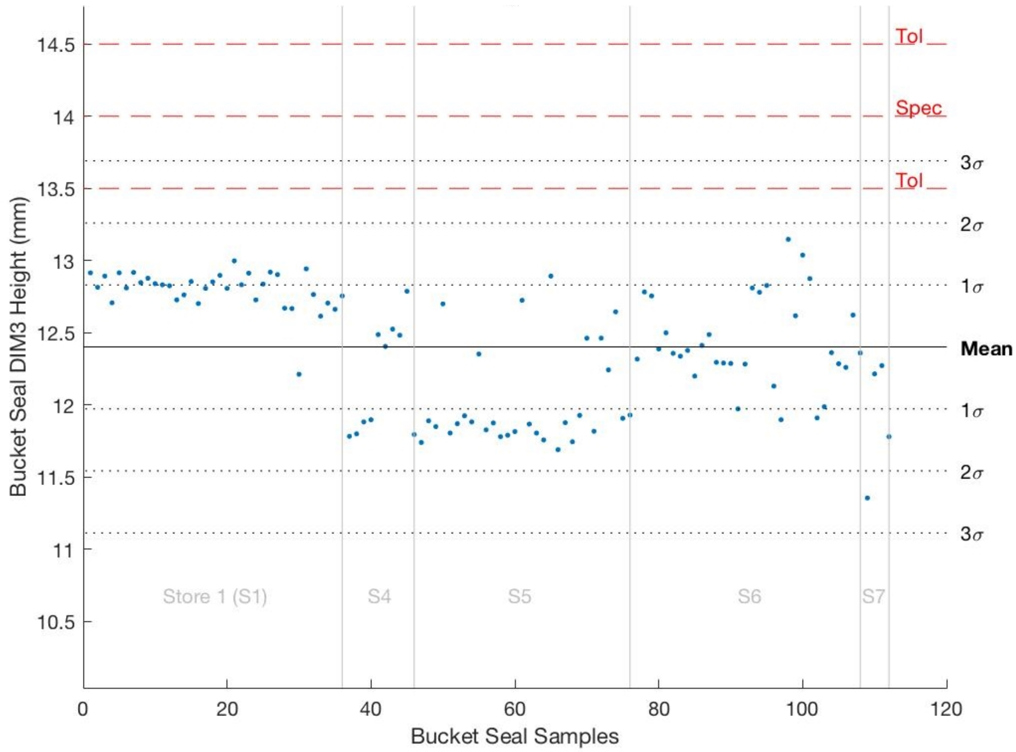

Figure A7.3. DIM 3: Cup seal height. Ordered as tested.

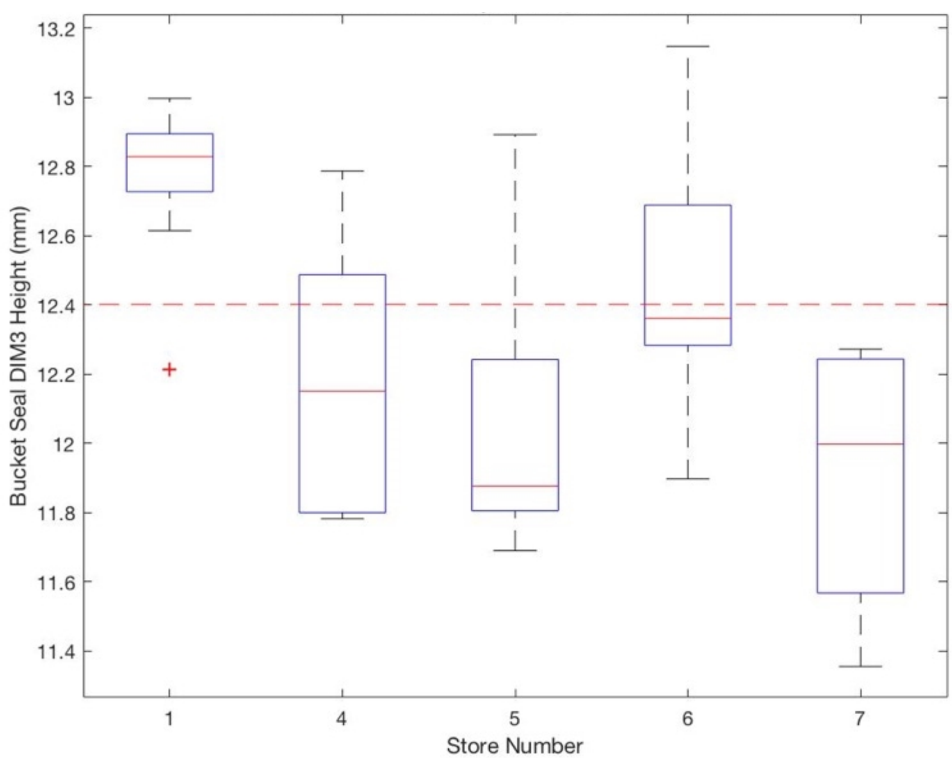

Figure A7.4. DIM 3: Cup seal height. Boxplots for each store.

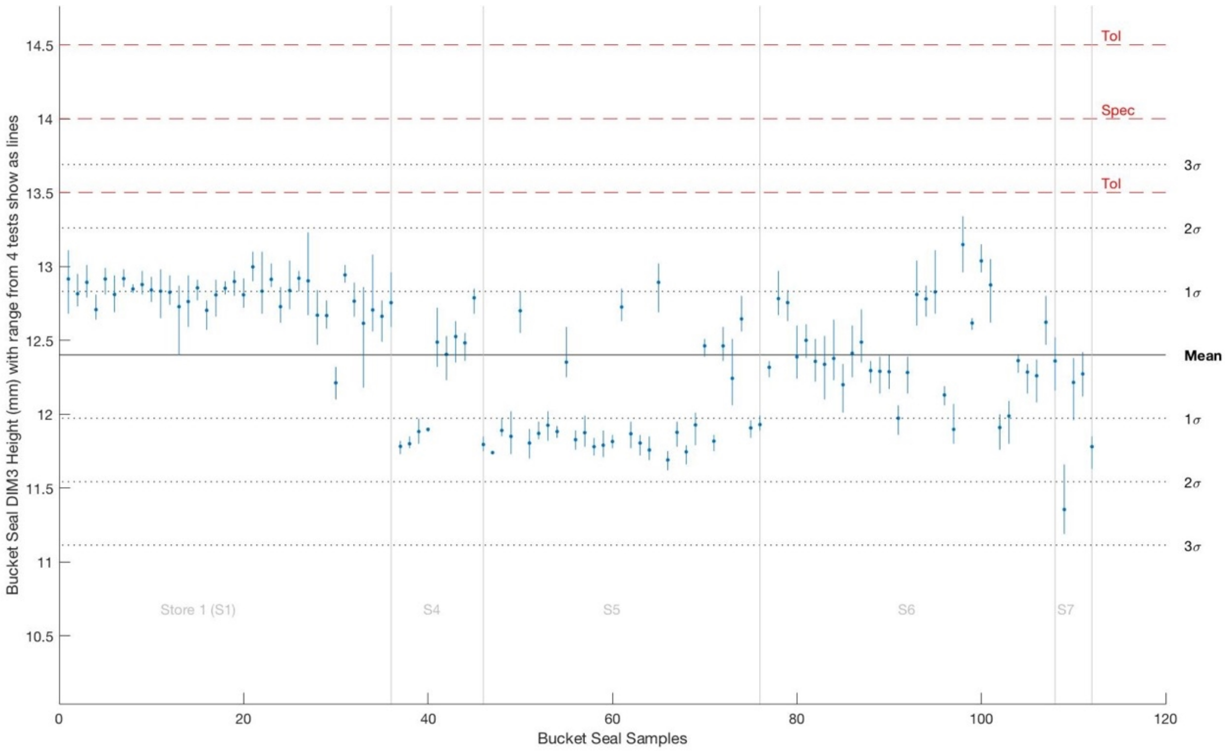

Figure A7.4. DIM 3: Cup seal height variation within sample. Four tests per sample.

Table A7.2. Raw data for DIM3 (height) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	12.915	n/a	n/a	11.7825	11.74	12.3175	11.355
XX-002	12.815	n/a	n/a	11.8	11.89	12.7825	12.215
XX-003	12.8925	n/a	n/a	11.8825	11.85	12.755	12.2725
XX-004	12.7075	n/a	n/a	11.8975	12.7	12.3875	11.78
XX-005	12.915	n/a	n/a	12.4875	11.805	12.5	n/a
XX-006	12.81	n/a	n/a	12.405	11.87	12.3575	n/a
XX-007	12.9175	n/a	n/a	12.525	11.925	12.3375	n/a
XX-008	12.8475	n/a	n/a	12.4825	11.8825	12.3775	n/a
XX-009	12.8775	n/a	n/a	12.7875	12.3525	12.2	n/a
XX-010	12.84	n/a	n/a	11.795	11.8275	12.4125	n/a
XX-011	12.8325	n/a	n/a	n/a	11.875	12.4875	n/a
XX-012	12.825	n/a	n/a	n/a	11.78	12.295	n/a
XX-013	12.7275	n/a	n/a	n/a	11.79	12.29	n/a
XX-014	12.7625	n/a	n/a	n/a	11.815	12.2875	n/a
XX-015	12.855	n/a	n/a	n/a	12.725	11.9725	n/a
XX-016	12.7025	n/a	n/a	n/a	11.8675	12.2825	n/a
XX-017	12.8075	n/a	n/a	n/a	11.805	12.81	n/a
XX-018	12.8525	n/a	n/a	n/a	11.7575	12.78	n/a
XX-019	12.8975	n/a	n/a	n/a	12.8925	12.8275	n/a
XX-020	12.8075	n/a	n/a	n/a	11.69	12.13	n/a
XX-021	12.9975	n/a	n/a	n/a	11.8775	11.8975	n/a
XX-022	12.8325	n/a	n/a	n/a	11.745	13.1475	n/a
XX-023	12.9125	n/a	n/a	n/a	11.9275	12.6175	n/a
XX-024	12.7275	n/a	n/a	n/a	12.4625	13.0375	n/a
XX-025	12.8375	n/a	n/a	n/a	11.8175	12.875	n/a
XX-026	12.92	n/a	n/a	n/a	12.4625	11.91	n/a
XX-027	12.9025	n/a	n/a	n/a	12.2425	11.9875	n/a
XX-028	12.67	n/a	n/a	n/a	12.645	12.3625	n/a
XX-029	12.6675	n/a	n/a	n/a	11.9075	12.285	n/a
XX-030	12.2125	n/a	n/a	n/a	11.93	12.26	n/a
XX-031	12.9425	n/a	n/a	n/a	n/a	12.6225	n/a
XX-032	12.765	n/a	n/a	n/a	n/a	12.36	n/a
XX-033	12.615	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	12.705	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	12.6625	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	12.755	n/a	n/a	n/a	n/a	n/a	n/a
Mean	12.7981	n/a	n/a	12.1845	12.0286	12.436	11.9056
Stdev	0.136308	n/a	n/a	0.386366	0.34769	0.315641	0.427894
Min	12.2125	n/a	n/a	11.7825	11.69	11.8975	11.355
Max	12.9975	n/a	n/a	12.7875	12.8925	13.1475	12.2725
Range	0.785	n/a	n/a	1.005	1.2025	1.25	0.9175
Median	12.8287	n/a	n/a	12.1513	11.8762	12.3613	11.9975
CV	0.0106506	n/a	n/a	0.0317096	0.0289053	0.0253812	0.0359406

Cup Seal Geometry: Base Thickness (DIM 4)	Artifact A8

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.0
Tests Performed by: Hans Ottosson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
This test is to characterize the base thickness, which is DIM 4 in the image below.

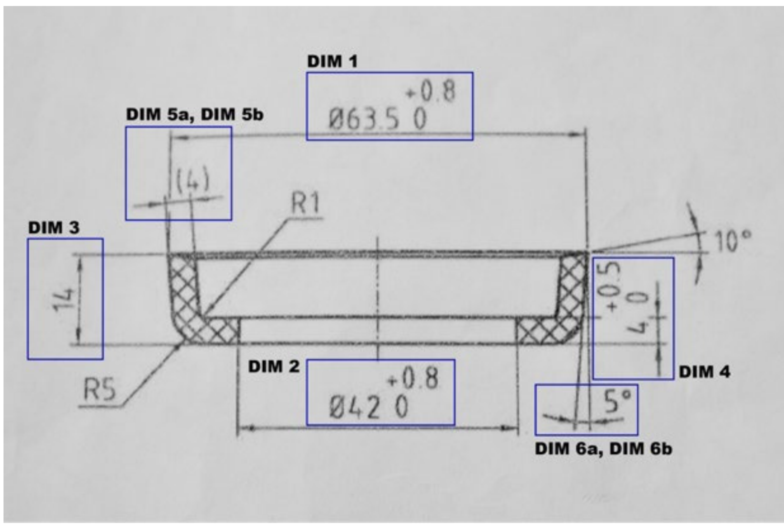

Figure A8.1. Cup seal dimensions.

Summary of Test Results:

Summary of test results can be seen in Table A8.1.

Table A8.1. Summary of test results.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
4.0	4.0	4.5	112	4.22616	0.175371	3.7525	4.77	1.0175	4.2425

Test Equipment and Set up:
A Mitotoyo Digimatic Indicator (manufacturers part number 575-123) was used to measure the height of each seal in four places (at 0, PI/2, PI, 3/2PI, and 2PI). The indicator accuracy is 0.02 mm, and a measurement force of 1.8 N. A custom stand was built to hold the indicator and provide a flat surface for the sample to rest on. Each seal was measured without the indicator tip touching the walls of the seal.

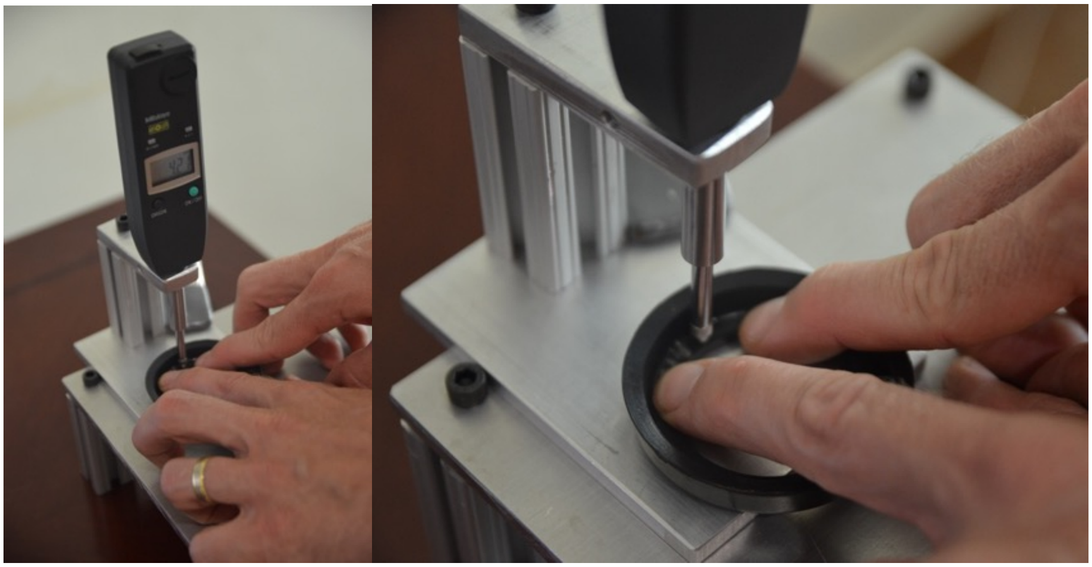

Figure A8.2. Measurement of the cup seal base.

Test Procedure:

1. Make sure that the instrument is at zero before taking measurement.
2. Place the needle of the indicator close to the edge of the seal as seen in image.
3. Read and record measurement.
4. Rotate the seal 90° and record measurement (do this 3 times for a total of 4 measurements).
5. Replace seal with new seal and repeat until done, keeping track of the order of seals.

Test Results:

The following plots and tables provide the data and results.

Observations and Conclusions:

No data was collected from store 2 or 3.

Nearly all of the measurements are within the specification limits. From a molding perspective, this is one of the easiest dimensions to control. The box plots show that stores 4 and 5 pull the mean down, while stores 1 and 6 pull it up. This is possibly meaningful as stores 4 and 5 have the characteristic of being the only seals from Jinja.

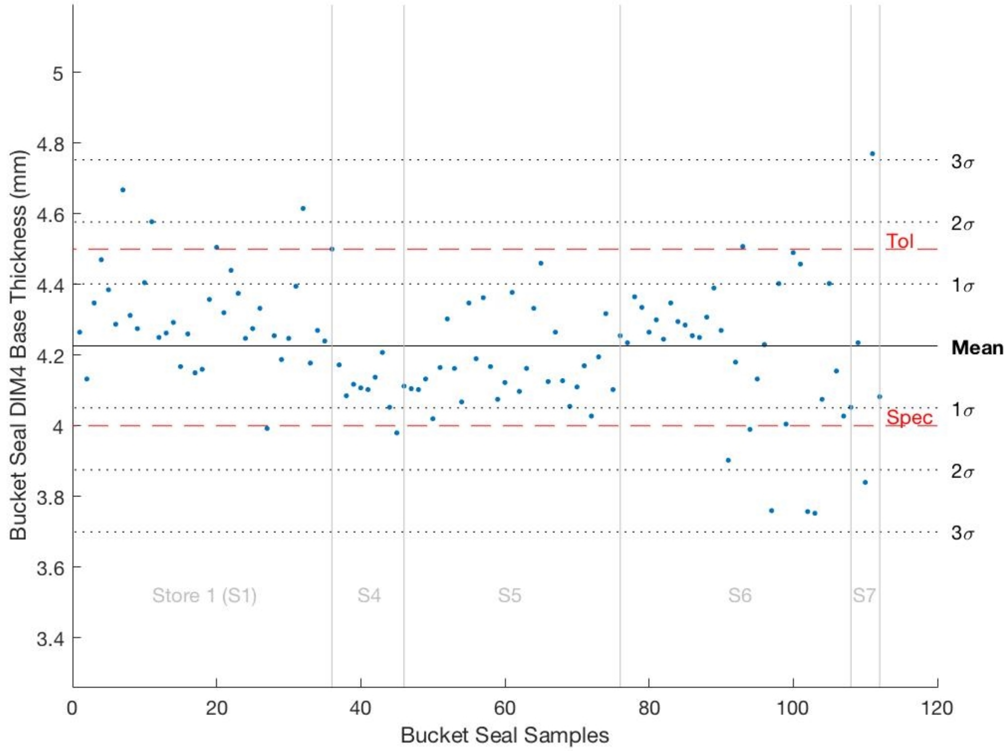

Figure A8.3. DIM 4: Cup seal base thickness. Ordered as tested.

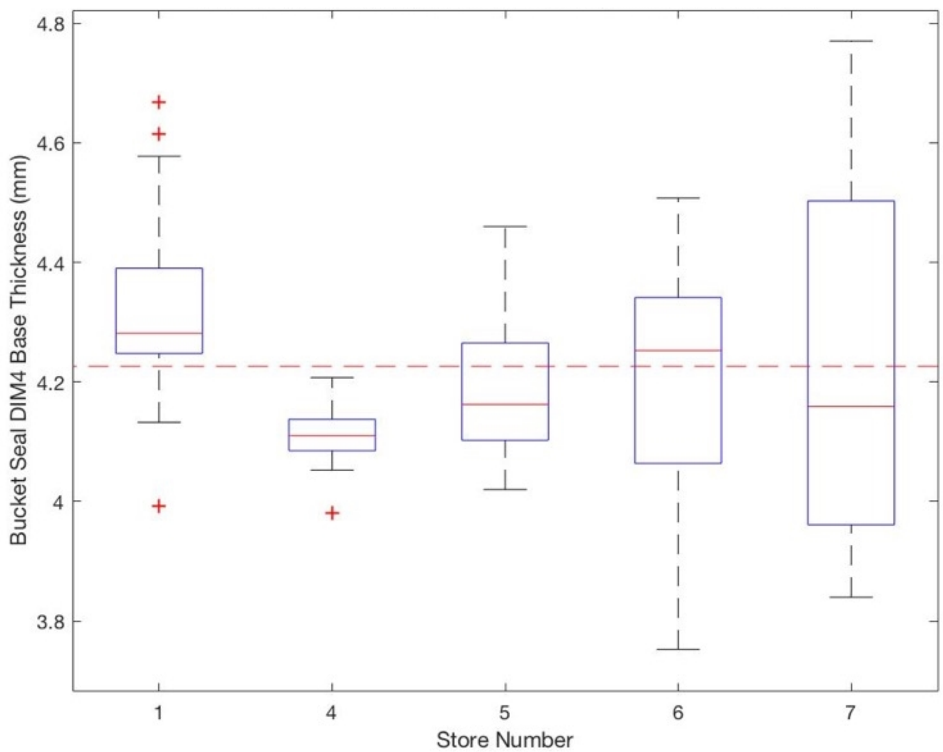

Figure A8.4. DIM 4: Cup seal base thickness. Boxplots for each store.

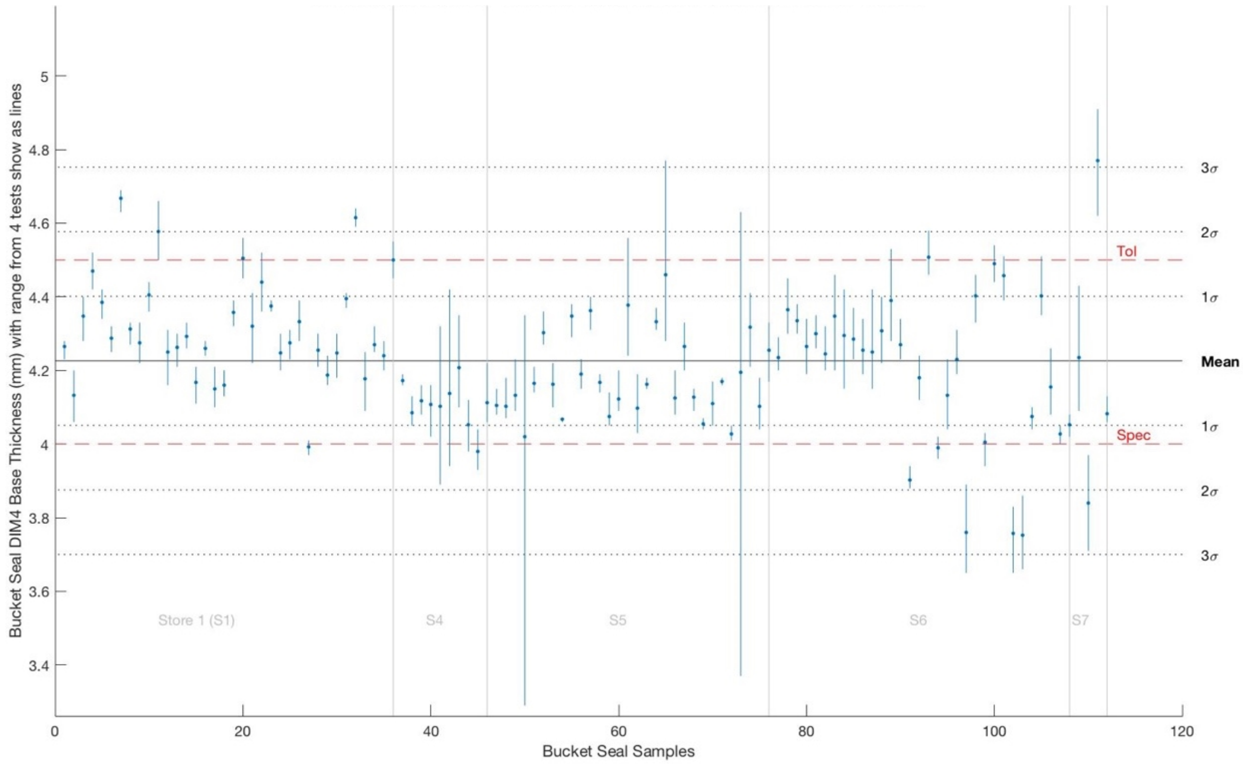

Figure A8.5. DIM 4: Cup seal base thickness variation within sample. Four tests per sample.

Table A8.2. Raw data for DIM4 (base thickness) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	4.265	n/a	n/a	4.1725	4.105	4.235	4.235
XX-002	4.1325	n/a	n/a	4.085	4.1025	4.365	3.84
XX-003	4.3475	n/a	n/a	4.1175	4.1325	4.335	4.77
XX-004	4.47	n/a	n/a	4.1075	4.02	4.265	4.0825
XX-005	4.385	n/a	n/a	4.1025	4.165	4.3	n/a
XX-006	4.2875	n/a	n/a	4.1375	4.3025	4.245	n/a
XX-007	4.6675	n/a	n/a	4.2075	4.1625	4.3475	n/a
XX-008	4.3125	n/a	n/a	4.0525	4.0675	4.295	n/a
XX-009	4.275	n/a	n/a	3.98	4.3475	4.285	n/a
XX-010	4.405	n/a	n/a	4.1125	4.19	4.255	n/a
XX-011	4.5775	n/a	n/a	n/a	4.3625	4.25	n/a
XX-012	4.25	n/a	n/a	n/a	4.1675	4.3075	n/a
XX-013	4.2625	n/a	n/a	n/a	4.075	4.39	n/a
XX-014	4.2925	n/a	n/a	n/a	4.1225	4.27	n/a
XX-015	4.1675	n/a	n/a	n/a	4.3775	3.9025	n/a
XX-016	4.26	n/a	n/a	n/a	4.0975	4.18	n/a
XX-017	4.15	n/a	n/a	n/a	4.1625	4.5075	n/a
XX-018	4.16	n/a	n/a	n/a	4.3325	3.99	n/a
XX-019	4.3575	n/a	n/a	n/a	4.46	4.1325	n/a
XX-020	4.505	n/a	n/a	n/a	4.125	4.23	n/a
XX-021	4.32	n/a	n/a	n/a	4.265	3.76	n/a
XX-022	4.44	n/a	n/a	n/a	4.1275	4.4025	n/a
XX-023	4.375	n/a	n/a	n/a	4.055	4.005	n/a
XX-024	4.2475	n/a	n/a	n/a	4.11	4.49	n/a
XX-025	4.275	n/a	n/a	n/a	4.17	4.4575	n/a
XX-026	4.3325	n/a	n/a	n/a	4.0275	3.7575	n/a
XX-027	3.9925	n/a	n/a	n/a	4.195	3.7525	n/a
XX-028	4.255	n/a	n/a	n/a	4.3175	4.075	n/a
XX-029	4.1875	n/a	n/a	n/a	4.1025	4.4025	n/a
XX-030	4.2475	n/a	n/a	n/a	4.255	4.155	n/a
XX-031	4.395	n/a	n/a	n/a	n/a	4.0275	n/a
XX-032	4.615	n/a	n/a	n/a	n/a	4.0525	n/a
XX-033	4.1775	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	4.27	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	4.24	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	4.5	n/a	n/a	n/a	n/a	n/a	n/a
Mean	4.31667	n/a	n/a	4.1075	4.18342	4.20078	4.23187
Stdev	0.141628	n/a	n/a	0.0624166	0.114275	0.206451	0.393898
Min	3.9925	n/a	n/a	3.98	4.02	3.7525	3.84
Max	4.6675	n/a	n/a	4.2075	4.46	4.5075	4.77
Range	0.675	n/a	n/a	0.2275	0.44	0.755	0.93
Median	4.28125	n/a	n/a	4.11	4.1625	4.2525	4.15875
CV	0.0328096	n/a	n/a	0.0151958	0.0273162	0.0491459	0.0930789

Cup Seal Geometry: Wall Thickness (DIM 5)	Artifact A9

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.0
Tests Performed by: Hans Ottosson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand and describe the wall thickness as it varies seal to seal, and across a given seal. We do this by measuring the wall thickness at both the base (near R1) and at the edge (near the 10 deg dimension).

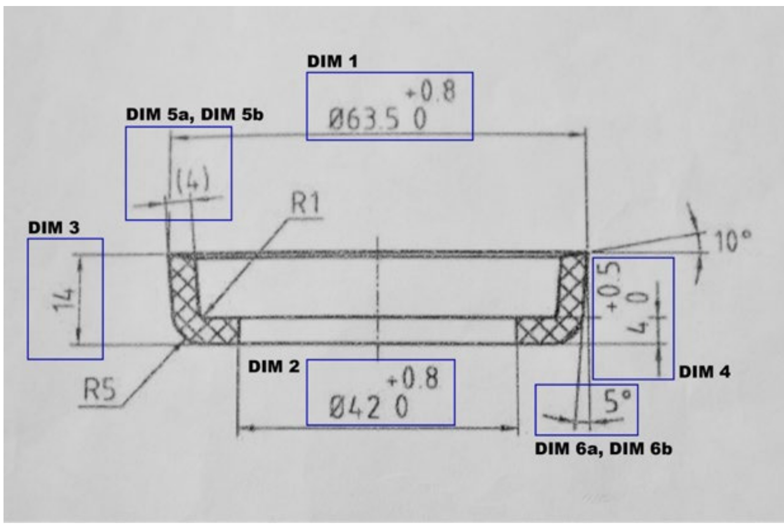

Figure A9.1. Cup seal dimensions.

Summary of Test Results:
Summary of test results can be seen in Tables A9.1 and A9.2.

Table A9.1. Summary of test results at base.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
4.0	3.5	4.5	112	4.182	0.188661	3.8175	4.6375	0.82	4.16125

Table A9.2. Summary of test results at edge.

Spec (mm)	Spec Min (mm)	Spec Max (mm)	Samples (count)	Mean (mm)	Stdev (mm)	Min (mm)	Max (mm)	Range (mm)	Median (mm)
4.0	3.5	4.5	112	4.1533	0.180924	3.7	4.6025	0.9025	4.16

Test Equipment and Set up:
A Mitotoyo Digimatic Indicator (manufacturers part number 575-123) was used to measure the wall thickness of each seal in four places (at 0, PI/2, PI, 3/2PI, and 2PI). The indicator accuracy is 0.02 mm, and a measurement force of 1.8 N. A custom stand was built to hold the indicator and provide a flat surface for the sample to rest on. Each seal was measured with the indicator head near the base of the seal (as seen in the left photo) and near the edge of the seal (as seen in the right photo). The center photo indicated that the finger was used to line up the indicator with the edge for the wall thickness measurement at the edge.

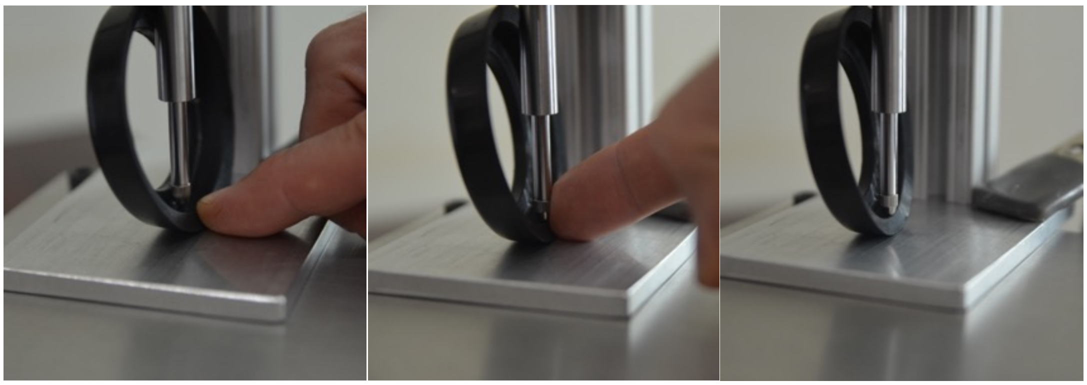

Figure A9.2. Measurement of the seal wall thickness.

Test Procedure:
1. Make sure that the instrument is at zero before taking measurement.
2. Place the needle of the indicator close to the base as seen in above image on the left.
3. Read and record measurement. Place the needle of the indicator close to the edge of the seal as seen in middle and left images, using finger as a guide.
4. Read and record measurement.
5. Rotate the seal 90° and repeat steps 2-4 (do this 3 times for a total of 8 measurements).
6. Replace seal with new seal and repeat until done, keeping track of the order of seals.

Test Results:
The following plots and tables provide the data and results.

Observations and Conclusions:
No data was collected from store 2 or 3.

The first scatter plot shows the average of 4 measurements per seal, plotted as just one point (the mean). The second scatter plot shows the range as well as the mean.

Nearly all measurements (all but 5) are within the specification limit, and none are below the specifications. A thicker seal in this dimension is most likely more desirable than one that is thinner.

It is interesting to note that there does not appear to be a correlation between the base thickness and the wall thickness. A deeper analysis may reveal a correlation not obviously seen now. At both the base and the edge the seals from store 1 appear most consistent.

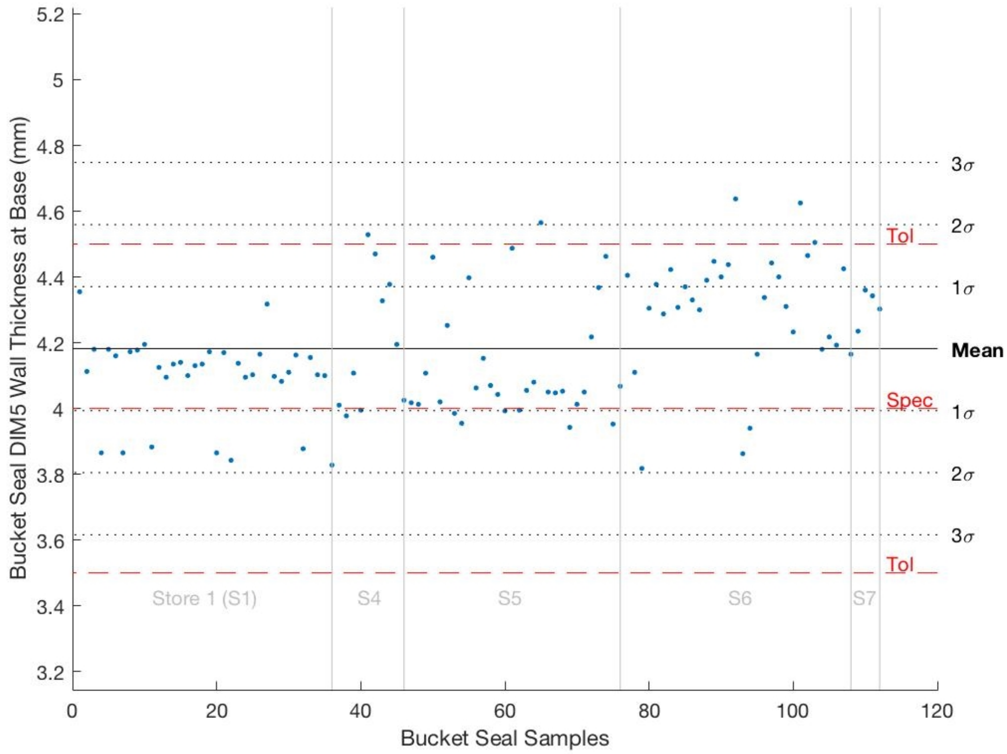

Figure A9.3. DIM 5: Cup seal wall thickness at base. Ordered as tested.

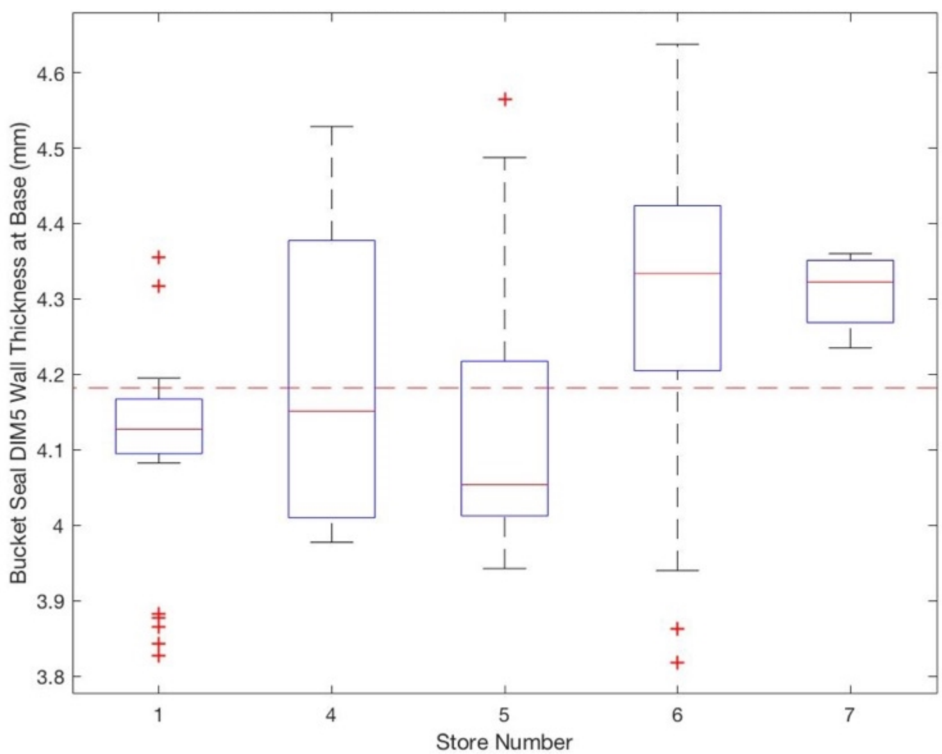

Figure A9.4. DIM 5: Cup seal wall thickness at base. Boxplots for each store.

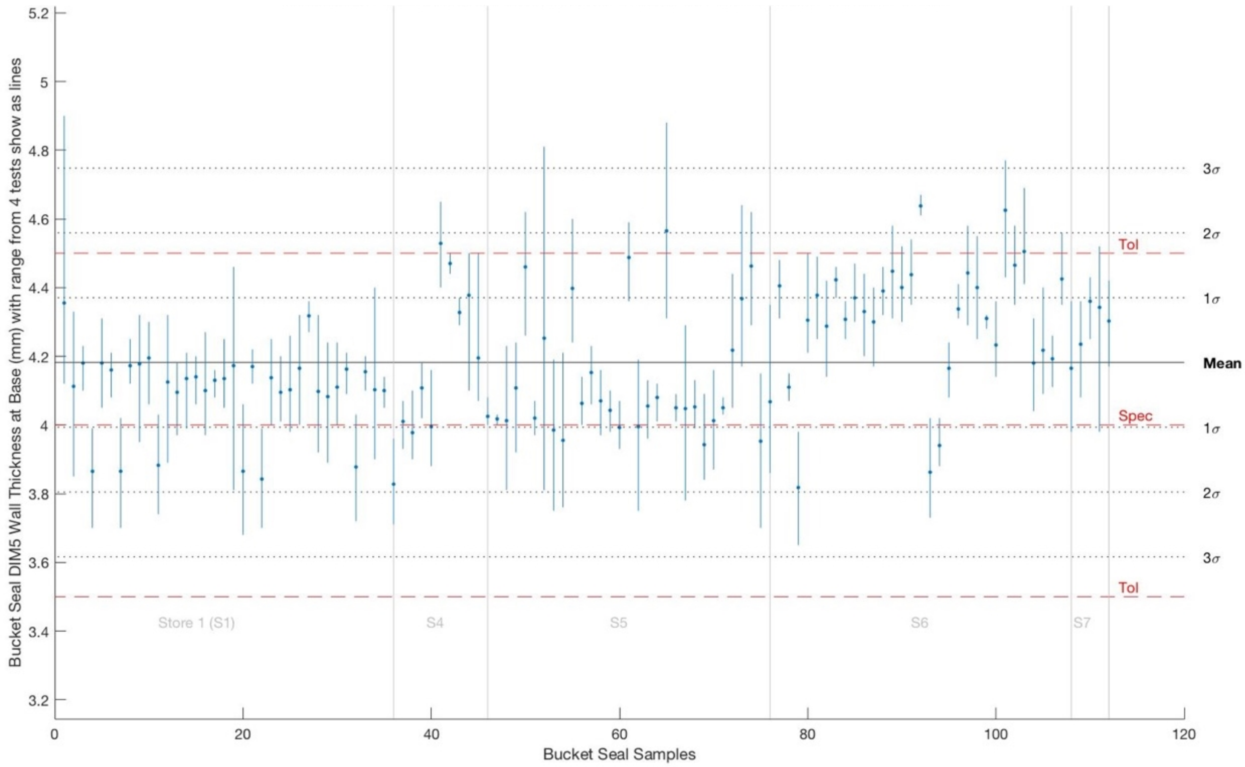

Figure A9.5. DIM 5: Cup seal wall thickness at base variation within sample. Four tests per sample.

Table A9.3. Raw data for DIM5 (wall thickness at base) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	4.355	n/a	n/a	4.01	4.0175	4.405	4.235
XX-002	4.1125	n/a	n/a	3.9775	4.0125	4.11	4.36
XX-003	4.18	n/a	n/a	4.1075	4.1075	3.8175	4.3425
XX-004	3.865	n/a	n/a	3.995	4.46	4.305	4.3025
XX-005	4.18	n/a	n/a	4.5285	4.02	4.3775	n/a
XX-006	4.16	n/a	n/a	4.47	4.2525	4.2875	n/a
XX-007	3.865	n/a	n/a	4.3275	3.985	4.4225	n/a
XX-008	4.1725	n/a	n/a	4.3775	3.955	4.3075	n/a
XX-009	4.1775	n/a	n/a	4.195	4.3975	4.37	n/a
XX-010	4.195	n/a	n/a	4.025	4.0625	4.33	n/a
XX-011	3.8825	n/a	n/a	n/a	4.1525	4.3	n/a
XX-012	4.125	n/a	n/a	n/a	4.07	4.39	n/a
XX-013	4.095	n/a	n/a	n/a	4.0425	4.4475	n/a
XX-014	4.135	n/a	n/a	n/a	3.9925	4.4	n/a
XX-015	4.14	n/a	n/a	n/a	4.4875	4.4375	n/a
XX-016	4.1	n/a	n/a	n/a	3.995	4.6375	n/a
XX-017	4.13	n/a	n/a	n/a	4.055	3.8625	n/a
XX-018	4.135	n/a	n/a	n/a	4.08	3.94	n/a
XX-019	4.1725	n/a	n/a	n/a	4.565	4.165	n/a
XX-020	3.865	n/a	n/a	n/a	4.05	4.3375	n/a
XX-021	4.17	n/a	n/a	n/a	4.0475	4.4425	n/a
XX-022	3.8425	n/a	n/a	n/a	4.0525	4.4	n/a
XX-023	4.1375	n/a	n/a	n/a	3.9425	4.31	n/a
XX-024	4.095	n/a	n/a	n/a	4.0125	4.2325	n/a
XX-025	4.1025	n/a	n/a	n/a	4.05	4.625	n/a
XX-026	4.165	n/a	n/a	n/a	4.2175	4.465	n/a
XX-027	4.3175	n/a	n/a	n/a	4.3675	4.505	n/a
XX-028	4.0975	n/a	n/a	n/a	4.4625	4.18	n/a
XX-029	4.0825	n/a	n/a	n/a	3.9525	4.2175	n/a
XX-030	4.11	n/a	n/a	n/a	4.0675	4.1925	n/a
XX-031	4.1625	n/a	n/a	n/a	n/a	4.425	n/a
XX-032	3.8775	n/a	n/a	n/a	n/a	4.165	n/a
XX-033	4.155	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	4.1025	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	4.1	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	3.8275	n/a	n/a	n/a	n/a	n/a	n/a
Mean	4.0941	n/a	n/a	4.20135	4.13108	4.30656	4.31
Stdev	0.128701	n/a	n/a	0.209601	0.180932	0.187974	0.0554902
Min	3.8275	n/a	n/a	3.9775	3.9425	3.8175	4.235
Max	4.355	n/a	n/a	4.5285	4.565	4.6375	4.36
Range	0.5275	n/a	n/a	0.551	0.6225	0.82	0.125
Median	4.1275	n/a	n/a	4.15125	4.05375	4.33375	4.3225
CV	0.0314357	n/a	n/a	0.0498890	0.0437977	0.0436483	0.0128748

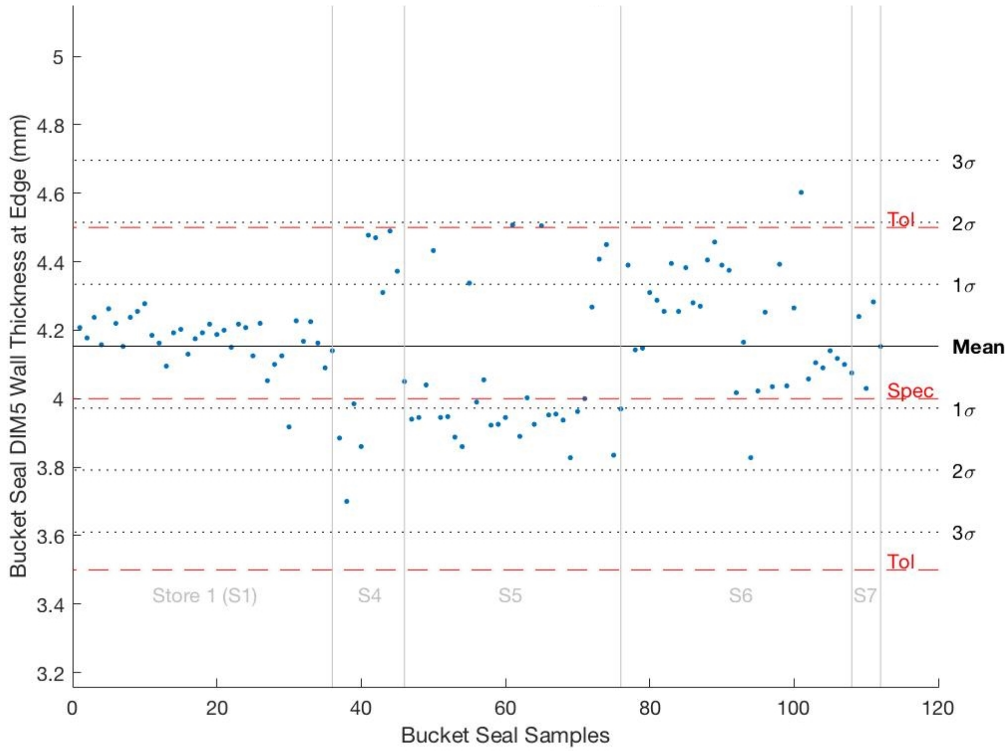

Figure A9.6. DIM 5: Cup seal wall thickness at edge. Ordered as tested.

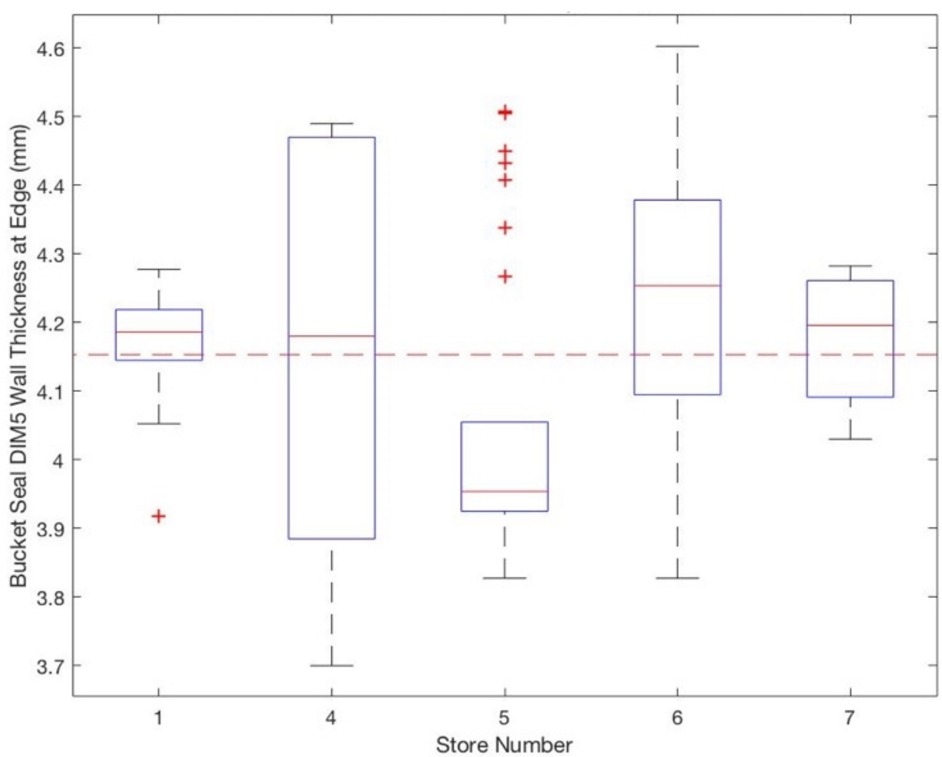

Figure A9.7. DIM 5: Cup seal wall thickness at Edge. Boxplots for each store.

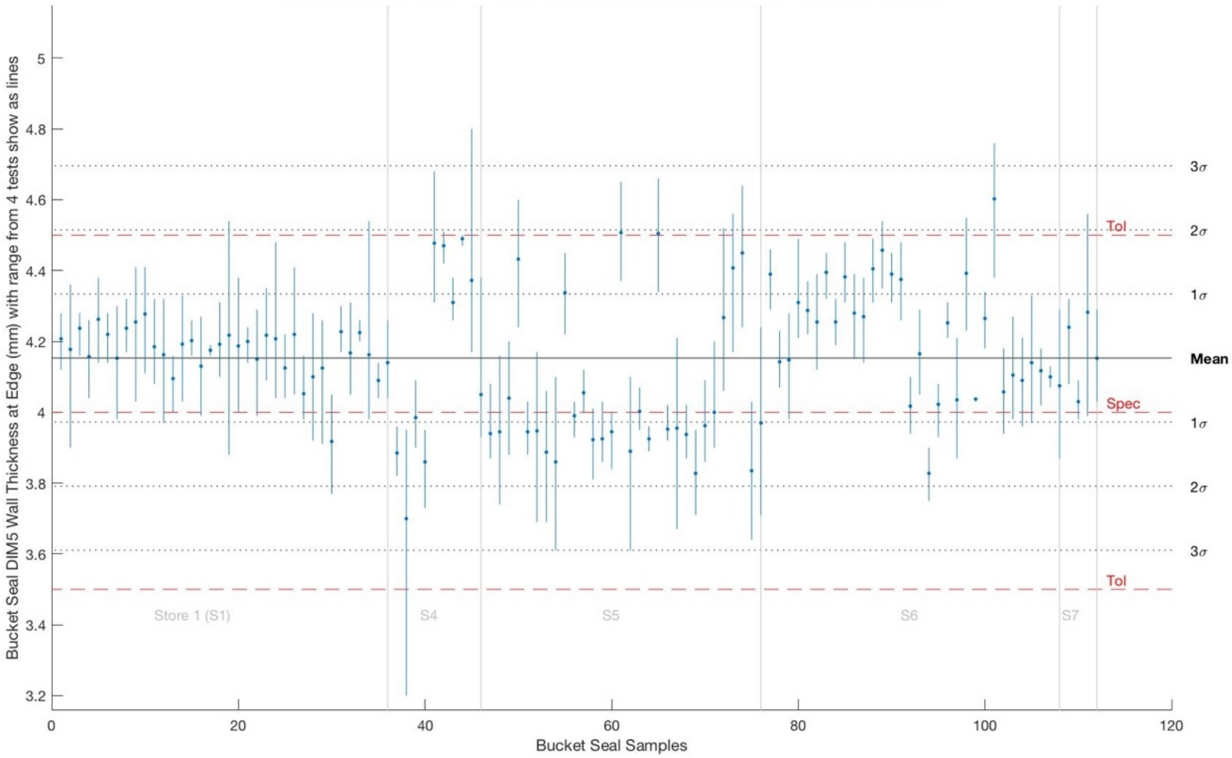

Figure A9.8. DIM 5: Cup seal wall thickness at edge variation within sample. Four tests per sample.

Table A9.4. Raw data for DIM5 (wall thickness at edge) measurements. Units = mm.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	4.2075	n/a	n/a	3.885	3.94	4.39	4.24
XX-002	4.1775	n/a	n/a	3.7	3.945	4.1425	4.03
XX-003	4.2375	n/a	n/a	3.985	4.04	4.1475	4.2825
XX-004	4.1575	n/a	n/a	3.86	4.4325	4.31	4.1525
XX-005	4.2625	n/a	n/a	4.4775	3.945	4.2875	n/a
XX-006	4.22	n/a	n/a	4.47	3.9475	4.255	n/a
XX-007	4.1525	n/a	n/a	4.31	3.8875	4.395	n/a
XX-008	4.2375	n/a	n/a	4.49	3.86	4.255	n/a
XX-009	4.255	n/a	n/a	4.3725	4.3375	4.3825	n/a
XX-010	4.2775	n/a	n/a	4.05	3.99	4.28	n/a
XX-011	4.185	n/a	n/a	n/a	4.055	4.27	n/a
XX-012	4.1625	n/a	n/a	n/a	3.9225	4.405	n/a
XX-013	4.095	n/a	n/a	n/a	3.925	4.4575	n/a
XX-014	4.1925	n/a	n/a	n/a	3.945	4.39	n/a
XX-015	4.2025	n/a	n/a	n/a	4.5075	4.375	n/a
XX-016	4.13	n/a	n/a	n/a	3.89	4.0175	n/a
XX-017	4.175	n/a	n/a	n/a	4.0025	4.165	n/a
XX-018	4.1925	n/a	n/a	n/a	3.925	3.8275	n/a
XX-019	4.2175	n/a	n/a	n/a	4.505	4.0225	n/a
XX-020	4.1875	n/a	n/a	n/a	3.9525	4.2525	n/a
XX-021	4.2	n/a	n/a	n/a	3.955	4.035	n/a
XX-022	4.15	n/a	n/a	n/a	3.9375	4.3925	n/a
XX-023	4.2175	n/a	n/a	n/a	3.8275	4.0375	n/a
XX-024	4.2075	n/a	n/a	n/a	3.9625	4.265	n/a
XX-025	4.125	n/a	n/a	n/a	4	4.6025	n/a
XX-026	4.22	n/a	n/a	n/a	4.2675	4.0575	n/a
XX-027	4.0525	n/a	n/a	n/a	4.4075	4.105	n/a
XX-028	4.1	n/a	n/a	n/a	4.45	4.09	n/a
XX-029	4.125	n/a	n/a	n/a	3.835	4.14	n/a
XX-030	3.9175	n/a	n/a	n/a	3.97	4.1175	n/a
XX-031	4.2275	n/a	n/a	n/a	n/a	4.1	n/a
XX-032	4.1675	n/a	n/a	n/a	n/a	4.075	n/a
XX-033	4.225	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	4.1625	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	4.09	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	4.14	n/a	n/a	n/a	n/a	n/a	n/a
Mean	4.17368	n/a	n/a	4.16	4.05225	4.22016	4.17625
Stdev	0.0676585	n/a	n/a	0.296912	0.213429	0.166034	0.111514
Min	3.9175	n/a	n/a	3.7	3.8275	3.8275	4.03
Max	4.2775	n/a	n/a	4.49	4.5075	4.6025	4.2825
Range	0.36	n/a	n/a	0.79	0.68	0.775	0.2525
Median	4.18625	n/a	n/a	4.18	3.95375	4.25375	4.19625
CV	0.0162108	n/a	n/a	0.0713731	0.0526693	0.0393431	0.0267019

Cup Seal Geometry: Wall Angle (DIM 6)	Artifact A10

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.0
Tests Performed by: Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
This test measures the angle of the side walls, shown as being 5 degrees in the image below. No tolerance is specified, but +/- 2 degrees is assumed.

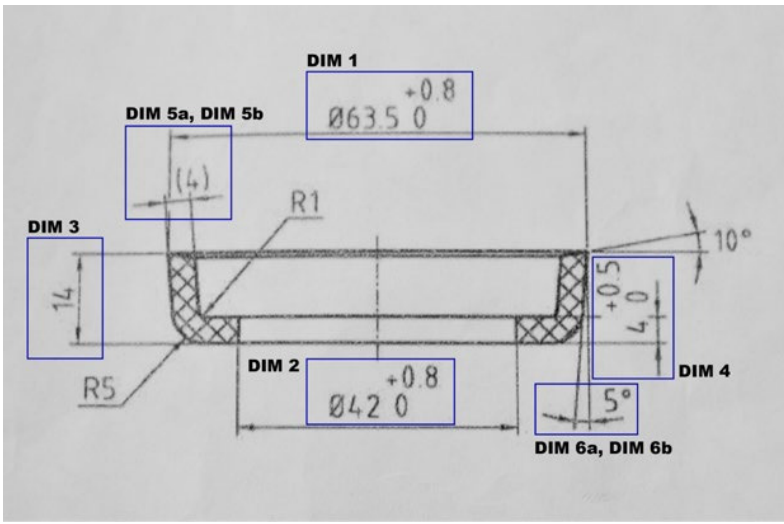

Figure A10.1. Cup seal dimensions.

Summary of Test Results:

Summary of test results can be seen in Table A10.1.

Table A10.1. Summary of test results.

Spec (°)	Spec Min (°)	Spec Max (°)	Samples (count)	Mean (°)	Stdev (°)	Min (°)	Max (°)	Range (°)	Median (°)
5°	4. 5°	5. 5°	112	7.52808°	2.22381°	1.56507°	12.496°	10.9309°	7.48053°

Test Equipment and Set up:
The same test fixture used to take photos for DIM 1 (see Artifact A1) was used to take photos for the DIM 6 analysis. This was done for every seal as it was placed in the "bucket up position".

Test Procedure:
1. Ensure that the pictures are located in the right folder, accessible to MATLAB.
2. Run MATLAB script.

3. For each image, mark a line for the slope.
4. Repeat until done.
5. Check the MATLAB results to ensure that the script completed.

Test Results:

A representative visual result can be seen in Figure A10.2. Notice the blue line in the image that represents the edge of the seal. The angle of this line is assumed to be the wall angle.

Figure A10.2. Images used for finding cup seal angle.

Observations and Conclusions:

No data was collected from store 2 or 3.

The first observation is that the mean is outside of the spec limits. Recall that the spec limits are artificial (i.e., not actually specified), but are generously large for angle measurements.

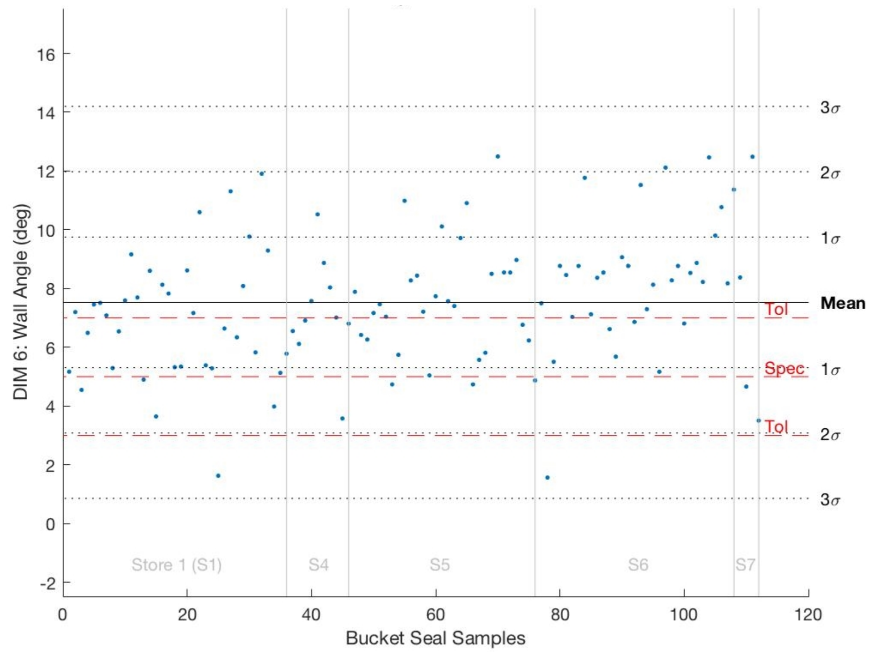

Figure A10.3. DIM 6: Cup seal wall angle. Ordered as tested.

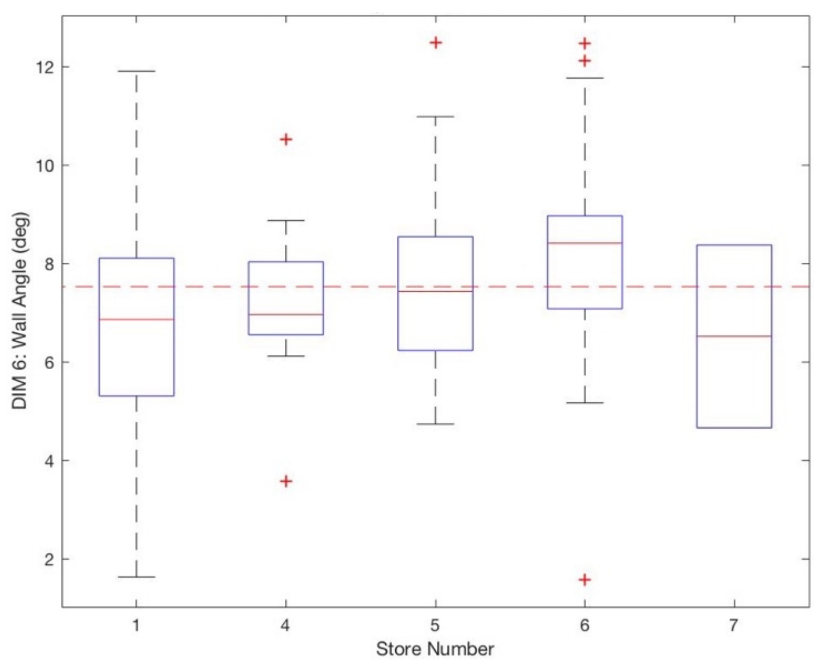

Figure A10.4. DIM 6: Cup seal wall angle. Boxplots for each store.

Table A10.2. Raw data for DIM6 (wall angle) measurements. Units = deg.

Seal	Store 1	Store 2	Store 3	Store 4	Store 5	Store 6	Store 7
XX-001	5.16847	n/a	n/a	6.55255	7.88835	7.49586	8.37601
XX-002	7.19923	n/a	n/a	6.1155	6.41879	1.56507	4.66055
XX-003	4.54804	n/a	n/a	6.91123	6.26349	5.50548	12.4881
XX-004	6.49077	n/a	n/a	7.57295	7.16724	8.76906	3.50353
XX-005	7.45706	n/a	n/a	10.5251	7.46519	8.45891	n/a
XX-006	7.51214	n/a	n/a	8.87056	7.04204	7.03342	n/a
XX-007	7.08517	n/a	n/a	8.03571	4.73558	8.76906	n/a
XX-008	5.29008	n/a	n/a	7.01186	5.74416	11.7683	n/a
XX-009	6.54039	n/a	n/a	3.57633	10.9855	7.12502	n/a
XX-010	7.59464	n/a	n/a	6.80426	8.27589	8.36589	n/a
XX-011	9.16235	n/a	n/a	0	8.43838	8.54528	n/a
XX-012	7.69605	n/a	n/a	0	7.20996	6.61799	n/a
XX-013	4.89909	n/a	n/a	0	5.04245	5.67925	n/a
XX-014	8.60448	n/a	n/a	0	7.73737	9.0665	n/a
XX-015	3.64449	n/a	n/a	0	10.114	8.77076	n/a
XX-016	8.1301	n/a	n/a	0	7.57089	6.86369	n/a
XX-017	7.82908	n/a	n/a	0	7.40373	11.5237	n/a
XX-018	5.32275	n/a	n/a	0	9.71879	7.29864	n/a
XX-019	5.34545	n/a	n/a	0	10.9077	8.1301	n/a
XX-020	8.61565	n/a	n/a	0	4.73558	5.16524	n/a
XX-021	7.16724	n/a	n/a	0	5.5722	12.1169	n/a
XX-022	10.5994	n/a	n/a	0	5.81248	8.28068	n/a
XX-023	5.3837	n/a	n/a	0	8.49856	8.76906	n/a
XX-024	5.284	n/a	n/a	0	12.496	6.80905	n/a
XX-025	1.62728	n/a	n/a	0	8.54696	8.53077	n/a
XX-026	6.63947	n/a	n/a	0	8.54528	8.87056	n/a
XX-027	11.3099	n/a	n/a	0	8.97263	8.22281	n/a
XX-028	6.34019	n/a	n/a	0	6.76617	12.4649	n/a
XX-029	8.08626	n/a	n/a	0	6.23175	9.8025	n/a
XX-030	9.7697	n/a	n/a	0	4.87139	10.77	n/a
XX-031	5.82634	n/a	n/a	n/a	n/a	8.1762	n/a
XX-032	11.9083	n/a	n/a	n/a	n/a	11.3682	n/a
XX-033	9.29331	n/a	n/a	n/a	n/a	n/a	n/a
XX-034	3.98252	n/a	n/a	n/a	n/a	n/a	n/a
XX-035	5.12819	n/a	n/a	n/a	n/a	n/a	n/a
XX-036	5.78239	n/a	n/a	n/a	n/a	n/a	n/a
Mean	6.89621	n/a	n/a	7.19761	7.57262	8.33434	7.25705
Stdev	2.18434	n/a	n/a	1.81617	1.95209	2.24091	4.05983
Min	1.62728	n/a	n/a	3.57633	4.73558	1.56507	3.50353
Max	11.9083	n/a	n/a	10.5251	12.496	12.4649	12.4881
Range	10.281	n/a	n/a	6.94877	7.76042	10.8998	8.98457
Median	6.86232	n/a	n/a	6.96155	7.43446	8.4124	6.51828
CV	0.316745	n/a	n/a	0.252330	0.257783	0.268877	0.559433

Locations of Stores and Boreholes	Artifact A11

Artifact Prepared by: Tom Naylor and Christopher Mattson | Revision 1.1
Information compiled by: Tom Naylor and Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of this Artifact:
The purpose of this artifact is to clearly describe where the tests performed for this study took place.

Information Regarding Stores:

Table A11.1 contains name, contact information, location, and number of seals purchased.

Table A11.1. Store information, Uganda.

Store (city in Uganda)	Name	Phone Number[6]	GPS Location	Samples Purchased (count)
Store 1 (Kampala)	Buyaya Technical Services LTD	0774613444	0.3120200, 32.5804750	36
Store 2 (Kampala)	Bukasa Traders	0784745827	0.3119129, 32.5802447	0
Store 3 (Kampala)	Buyaya Technical Services LTD	0701251130	0.3007919, 32.5764662	0
Store 4 (Jinja)	Jogobalin Mudima Electrical & Plumbing Engineers	0772451170	0.4299121, 33.216026	10
Store 5 (Jinja)	Plumber Sanchois Tecn & Cons	0753595981	0.431205, 33.213630	30
Store 6 (Gulu)	Vintoy Enterprises - SMC LTD	0759426263	2.770391, 32.298859	32
Store 7 (Gulu)	Dam & J Agro Machinery	0772634607, 0752634607, 0701634607	2.770682, 32.298802	4

[6] Uganda Country Code is 256, when dialing Uganda from the USA, omit the 0 (first digit) in the telephone number.

Description of each store:

Store 1 (Kampala)
Store temp = 81.2°F
Store humidity = 54 %
The shop is in the old town market area. The shop is a garage-style store front with inventory going deep into the shop. The cashier sits near the opening of the garage door and patrons can enter and look, though crowded. Many other people affiliated with the store are also in the store, possibly ready to help. Pump cup seals are in a large box directly behind the cashier at shoulder height when sitting. The box is approximately 30 cm by 30 cm by 50 cm. There are hundreds of Nitrile cup seals within. Seals are sold in pairs. Leather seals are kept strung up with approximately 30 on the string (like a necklace). These are kept hanging 3 m into the shop at approximately elbow height.

Figure A11.1. Store 1: Buyaya Technical Services LTD.

This shop is a branch outlet to the company's larger shop (Store 3). We purchased many seals of varying types in this shop. This shop was identified as Godfrey asked people in advance, where we might buy borehole pump parts. There was one pump technician in the store. He was relatively quiet. He led us to Store 3.

Upon arrival, it was apparent that the presence of 4 Americans made them nervous. We quickly split in two and left only 2 Americans in the store.

Store 2 (Kampala)
Store temp = Not recorded
Store humidity = Not recorded
This shop was very near Store 1. It was found as two of the researchers left store 1 to ease the American presence. Store two was a small storefront with many people and much material. The store was approximately as deep as it was wide. When asked about the cup seals, the owners responded that they had leather cup seals only. We purchased 6. No Nitrile seals were purchased from this store.

Store 3 (Kampala)
Store temp = 79.9°F
Store humidity = 59.7 %
This shop was the main store for which store one was a branch outlet. This store was a more developed, customer centric place compared to store 1. Seals were kept on strings. A portion of seals were measured but not purchased at this store. These measurements are not included in this report.

Figure A11.2. Store 3: Buyaya Technical Services LTD (main branch).

Store 4 (Jinja)
Store temp = 84.3°F
Store humidity = 41.3 %
Finding cup seals in Jinja was initially much more difficult than in Kampala. Eventually after visiting multiple shops and displaying the cup seal as an example of what we wanted, we found store 4. Store 4 is a very small shop, roughly half the size of store 2 (which is smaller than store 1). To access the store front, three or four steps are climbed. The shop is not one you can enter, but largely one where the shop owner finds what is wanted and brings it out. The cup seals were available and kept in a plastic bag within a bucket with other parts. This store had only 14 seals. Initially the price was much higher than expected, so we did not buy any. After discovering very few places to purchase cup seals, we returned and purchased 10 seals.

Figure A11.3. Store 4: Jogobalin Mudima Electrical & Plumbing Engineers.

Store 5 (Jinja)
Store temp = 77.3°F
Store humidity = 63.2 %
Store 5 was within Jinja's main market, it was about equal in size to store 4. We were led to store 5 when Godfrey asked another vendor (he knew in the central market) if he knew of a place that sold borehole pump parts.

The person at the store was the son of the store's owner, he was extremely open and interested in what research we were performing.

They had only a few cup seals on hand, but after learning we wanted to buy more they left for 5 minutes and came back with more (presumably from another store in the central market). We are unsure of how the seals brought back were kept (on a string, in a box, etc.). The seals cost more than twice that of the seals purchased in store 1.

Figure A11.4. Store 5: Plumber Sanchois Tecn & Cons.

Store 6 (Gulu)
Store temp = 89.4°F
Store humidity = 35.6 %
Store 6 was considered by many who we talked to be the only location in Gulu to purchase cup seals. It was located directly next to a high-end pump store that sold electric pumps and hand irrigation pumps. That store did not sell cup seals but did direct us to the neighboring store were we initial bought a few sets (4 seals), as the store owner had indicated he did not have more. After returning from Store 7, across the street, the worker at Store 6 indicated that he had found more seals for us in his shop, and we bought an additional 28 seals.

Store six was constructed as a wider less deep shop, not of garage style as the other stores were. Cup seals were kept on a string, necklace style.

Figure A11.5. Store 6: Vintoy Enterprises - SMC LTD.

Store 7 (Gulu)
Store temp = 88°F
Store humidity = 45.1 %
Store 7 was a very small shop across the street from Store 6. This shop sold primarily belt driven equipment and replacement belts. They did sell borehole pump systems and when asked about the cup seal, the shop worker quickly found a small box of pump seals. Each seal was in a bagged seal set containing roughly 10 seals. The shop worker described these seals as certified seals for our application. He opened a seal set, and when asked if we could purchase only the cup seal he quickly agreed. We purchased 4 seals. We later learned that two of the seals were of a noticeably different inner diameter (DIM2).

Figure A11.6. Store 7: Dam & J Agro Machinery.

Information Regarding Boreholes:

Table A11.2 contains information regarding the boreholes that were visited for this study.

Table A11.2. Borehole information, Uganda.

Borehole Pump (city in Uganda)	Caretaker	Phone Number	GPS Location	Observation Date
Borehole 1 (Near Jinja)	Mr. Sandee (Caretaker)	Immy (lives to the west of the borehole by two houses) 0705832096 0784324432	0˚ 29.499' N, 33˚ 10.993' E	24 July 2018
Borehole 2 (Near Jinja)	Mr. Stephen (Caretaker)	Alfred (lives directly to the east of the borehole) 0784355555 0753661555	0˚ 28.638' N, 33˚ 12.223' E	25 July 2018
Borehole 3 (Gulu)	Mr. Kilama (Caretaker) Mrs. Evelynn[7] (Technician)	Evelynn (lives across the street, down a cross street) 0782827904	2.7878157, 32.2997101	30 July 2018
Borehole 4 (Gulu)	Mr. Christopher (Caretaker)	Evelynn (lives further down across the street, down a cross street) 0782827904	2.7876261, 32.2967024	31 July 2018

Description of each borehole:

Borehole 1 (Near Jinja)

Borehole 1 is located 20 minutes outside of Jinja by motorcycle. The borehole is in a rural setting, where the population density is less than the other boreholes studied. Figure A11.7 shows the setting and the sensor setup directly below. The wooden fence surrounding the borehole pump is in line with India Mark II and III installation specs indicating that a fence should be constructed around the borehole to keep animals out of the water supply area.

[7] Evelynn is also a trained pump technician.

Figure A11.7. Borehole 1 near Jinja.

The borehole pump is an India Mark III and was recently repaired for a cracked coupler pipe (failed coupler shown in Figure A11.8). There is noticeable side to side pump handle movement, which has caused the top plate guiding the pump rod into the pipe to become worn. This causes significant lateral movement in the pump rod. It is believed by many that the lateral movement of pump rods eventually causes riser pipe failure as the PVC failure shown in Figure A11.9.

Figure A11.8. Borehole 1 near Jinja.

Figure A11.9. PVC pipe failure due to the pump rod being out of alignment.

From the early morning pump start up test (counting full strokes until water is dispensed), it is believed that the foot value for this pump needs cleaning or replacement.

Figure A11.10. Failed riser pipe coupler.

Borehole 2 (Near Jinja)

Borehole 2 is located 2 km closer to town than borehole 1. It is in an area with slightly greater population density and is near municipal water tap. The borehole was repaired July 7th 0f this year, though it was later discovered that only the head and chain parts where repaired, not the cylinder parts. A technician that came by while we observed the pump described to us that borehole pump 2 needs new cup seals.

Figure A11.11. Borehole 2 near Jinja.

Borehole 3 (Gulu)

Borehole 3 is located in a more populated village within Gulu. It is within a 15 minutes' walk from our hotel (Churchill Courts). The pump on borehole 3 is an India Mark II, with a 1 ¼ inch PVC riser pipe (see Figure A11.9).

Figure A11.12. Borehole 3 in Gulu.

It was originally anticipated that the next closest borehole pump would be closed and under repair on the day we observed borehole 3. We expected a larger than normal showing at the pump. We in the day we verified that the other borehole had not closed at all that day.

Borehole 3's pump had recently been repaired by Evelynn, the pump technician. The failure was in the PVC riser pipe. The pump rod had rubbed against the side of the PVC until it failed. We purchased the failed sample from Evelynn.

Borehole 4 (Gulu)

Borehole 4 is approximately 300 meters from borehole 3 and was scheduled to be under repair for drainage on the day we observed borehole 3. It was not repaired on the day we observed borehole 3 or 4.

Figure A11.13. Borehole 4 in Gulu.

Operating Environment: Water pH Test	Artifact A12

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor, Hans Ottosson, Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand the acidity of the borehole pump water and the variation thereof. This information will used to establish the working environment of the pump parts and seals.

Results:
Table A12.1 shows the collected data. All numbers are on the 0.0-14.0 pH Scale.

Table A12.1. Water pH test results.

Test	Borehole 1	Borehole 2	Borehole 3	Borehole 4	LaPonya (hotel)	Churchill (hotel)
1	4.5	6.8	4.5	4.5	4.5	4.5
2	5	6.8	5	4.5	--	--
3	5	6.8	4.5	4.5	--	--
4	--	6.5	5.5	4.5	--	--
5	--	--	4.5	--	--	--
Mean	4.833	6.725	4.8	4.5	4.5	4.5
Stdev	0.2887	0.15	0.4472	0	n/a	n/a
Min	4.5	6.5	4.5	4.5	4.5	4.5
Max	5	6.8	5.5	4.5	4.5	4.5
Range	0.5	0.3	1	0	0	0
Median	5	6.8	4.5	4.5	4.5	4.5
CV	0.05974	0.02230	0.09317	0	n/a	n/a

Test Equipment and Set up:
Plastic pH indicator strips were used to measure the pH level in the water. One set of strips was used to measure in the range of 0.0 – 14.0 and another set was used to measure in the range 6.5 – 10.0. The first set was the Hydrion strips from Micro Essential Lab and the second set was the MColorpHast strips from EMD Millipore Corporation.

Figure A12.1. Measuring pH values.

Test Procedure:

1. Take water sample from pump.
2. Immerse pH strip (range 0.0 – 14.0) in water and hold still.
3. Remove strip and immediately match strip to correct pH level.
4. If the pH level is in the 6 – 10 range, also test with the strip with range 6.5 – 10.0.
5. Record pH level.

Conclusions:

Typical drinking water has a pH value between 6 and 10 on the pH scale.

Operating Environment: Water Hardness Test	Artifact A13

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor, Hans Ottosson, Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand the hardness of the borehole pump water and the variation thereof. This information will used to establish the working environment of the pump parts and seals.

Results:
The table below shows the collected data. All numbers ppm (mg/l) on the 0 to 1000 scale (0 = soft, 150 = hard, and 1000 = very hard)

Table A13.1. Water hardness test results.

Test	Borehole 1	Borehole 2	Borehole 3	Borehole 4	LaPonya (hotel)	Churchhill (hotel)
1	100	180	80	20	60	100
2	120	180	100	20	--	--
3	100	180	60	20	--	--
4	--	180	40	20	--	--
5	--	--	60	--	--	--
Mean	106.6667	180	68	20	60	100
Stdev	11.5470	0	22.8035	0	n/a	n/a
Min	100	180	40	20	60	100
Max	120	180	100	20	60	100
Range	20	0	60	0	0	0
Median	100	180	80	20	60	100
CV	0.108253	0	0.335346	0	n/a	n/a

Test Equipment and Set up:
WaterWorks Total Hardness test strips were used to test hardness of the water. A color chart on the container shows 8 different hardness levels from soft to very hard.

Test Procedure:
1. Take water sample from pump.
2. Immerse hardness strip in water and hold still for 3 seconds.
3. Remove and immediately match strip to correct hardness level (use black scale – ppm).
4. Complete color matching within 1 minute.
5. Record hardness level.

Conclusions:

There is wide variation in the water hardness tests performed in Uganda by the team. Generally, the data shows harder water is found in the Jinja area compared to Gulu, and the single test performed in Kampala. Hard water is known to create scaling in pipes and appliances.

Operating Environment: Water Salinity Test	Artifact A14

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor, Hans Ottosson, Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand the salinity of the borehole pump water and the variation thereof. This information will used to establish the working environment of the pump parts and seals.

Results:
Table A14.1 shows the collected data. All numbers ppt (parts per trillion).

Table A14.1. Water salinity test results.

Test	Borehole 1	Borehole 2	Borehole 3	Borehole 4	LaPonya (hotel)	Churchill (hotel)
1	0.0933	0.29	0.058	0.09	0.05	0.1
2	0.0643	--	0.0110	0.0082	--	--
3	0.02	0.29	0.05	0.08	--	--
4	0.14	0.29	0.07	0.1	--	--
5	0.12	--	0.02	0.02	--	--
Mean	0.12	0.29	0.05	0.09	0.05	0.1
Stdev	0.0933	0	0.058	0.09	n/a	n/a
Min	0.0643	0.29	0.0110	0.0082	0.05	0.1
Max	0.02	0.29	0.05	0.08	0.05	0.1
Range	0.14	0	0.07	0.1	0	0
Median	0.12	0.29	0.02	0.02	0.05	0.1
CV	0.778	0	1.16	1	n/a	n/a

Test Equipment and Set up:
Salinity tester EC170, manufactured by Extech Instruments was used to measure salinity. The EC170 has a resolution of 0.01ppt and a basic accuracy of ±2% FS.

Test Procedure:
1. Take water sample from pump.
2. Immerse salinity tester in water and hold still.
3. Record the salinity level shown on the display.

Conclusions:
The salinity is noticeably higher in the Jinja area when compared to Gulu and the single test carried out in Kampala.

Operating Environment: Water Temperature Test	Artifact A15

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests Performed by: Tom Naylor, Hans Ottosson, Christopher Mattson
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand the temperature of the borehole pump water and the variation thereof. This information will used to establish the working environment of the pump parts and seals.

Results:
Table A15.1 shows the collected data. All numbers in degrees F.

Table A15.1. Water temperature test results.

Test	Borehole 1	Borehole 2	Borehole 3	Borehole 4	LaPonya (hotel)	Churchill (hotel)
1	Not recorded	71.8	74.3	72.9	Not recorded	Not recorded
2	74.3	74.8	80	79	--	--
3	81.7	77.0	81	79.5	--	--
4	--	74.9	78.8	79	--	--
5	--	--	78.6	--	--	--
Mean	78.0000	74.625	78.54	77.6	n/a	n/a
Stdev	5.2326	2.1391	2.5609	3.1422	n/a	n/a
Min	74.3	71.8	74.3	72.9	n/a	n/a
Max	81.7	77	81	79.5	n/a	n/a
Range	7.4	5.2	6.7	6.6	n/a	n/a
Median	78	74.8	80	79	n/a	n/a
CV	0.0670846	0.0286647	0.0326063	0.0404923	n/a	n/a

Test Equipment and Set up:
Salinity tester EC170, manufactured by Extech Instruments was used to measure the water temperature. The EC170 has a resolution of 0.1°F and a basic accuracy of ±0.9°F.

Test Procedure:
1. Take water sample from pump.
2. Immerse salinity tester in water and hold still.
3. Record the temperature shown on the display.

Conclusions:
The overall temperature conditions are described by this test, showing an overall average of 77.19 degrees F, with a max range of 7.4. Any variation from hole to hole is not obviously meaningful.

Pump Performance: Borehole 1 (Jinja)	Artifact A16

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson and Tom Naylor
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how much water each borehole pump discharges based on varying stroke length and stroke frequency. This information will used to characterize the pump performance as a function of stroke frequency and stroke length.

Results:
The data collected is shown in Table A16.1.

Table A16.1. Pump performance test results for borehole 1.

Test	Stroke length (deg estimated)	Stroke length (deg measured)	Stroke frequency (Hz estimated)	Stroke frequency (Hz measured)	User (for coding)	Water Volume (liters)
1	30	29.9	0.67	0.68	4	1.86
2	20	23.1	1.33	1.29	6	2.18
3	30	30.4	1.33	1.25	9	3.40
4	40	37.9	1.00	1.02	11	5.26
5	30	23.0	1.00	1.04	13	2.95
6	20	21.3	1.00	1.03	15	1.22
7	40	38.2	0.67	0.68	17	3.13
8	20	20.2	0.67	0.70	19	0.13
9	40	36.4	1.33	1.32	21	4.35
10	30	28.7	0.67	0.71	23	1.50
11	20	20.7	1.33	1.345	25	2.04
12	30	27.8	1.33	1.38	27	3.13
13	40	37.5	1.00	1.00	29	3.99
14	30	28.8	1.00	1.01	31	2.72
15	20	20.3	1.00	0.99	33	1.27
16	40	35.4	0.67	1.04	35	3.99
17	20	20.0	0.67	1.01	37	1.27
18	40	36.4	1.33	1.33	39	4.45

Test Equipment and Set up:
A full factorial Design-of-Experience (DOE) was planned where stroke length of 20, 30, and 40 degrees were paired with the frequencies 0.67, 1.00, and 1.33 Hz. A metronome app was used

on an Android phone to set the pace. The experience was randomized using MATLAB, and a scale was used to measure the weight of the water after each experience.

Test Procedure:

1. Set correct frequency on the metronome.
2. Pump until water flows.
3. Forward user on sensor remote.
4. Put bucket under spout.
5. Pump 20 strokes.
6. Weigh water.
7. Record user number and weight.
8. Forward user on sensor remote.
9. Repeat steps 2 – 8 until each experiment is done.

Observations and Conclusions:

A response surface was created to visualize the results from the DOE (see Figure A16.1). It can be said that in general, a longer stroke and a higher frequency will yield a larger volume of water for borehole 1. Each borehole DOE vary due to the efficiency of the pump, making it hard to compare their individual outputs.

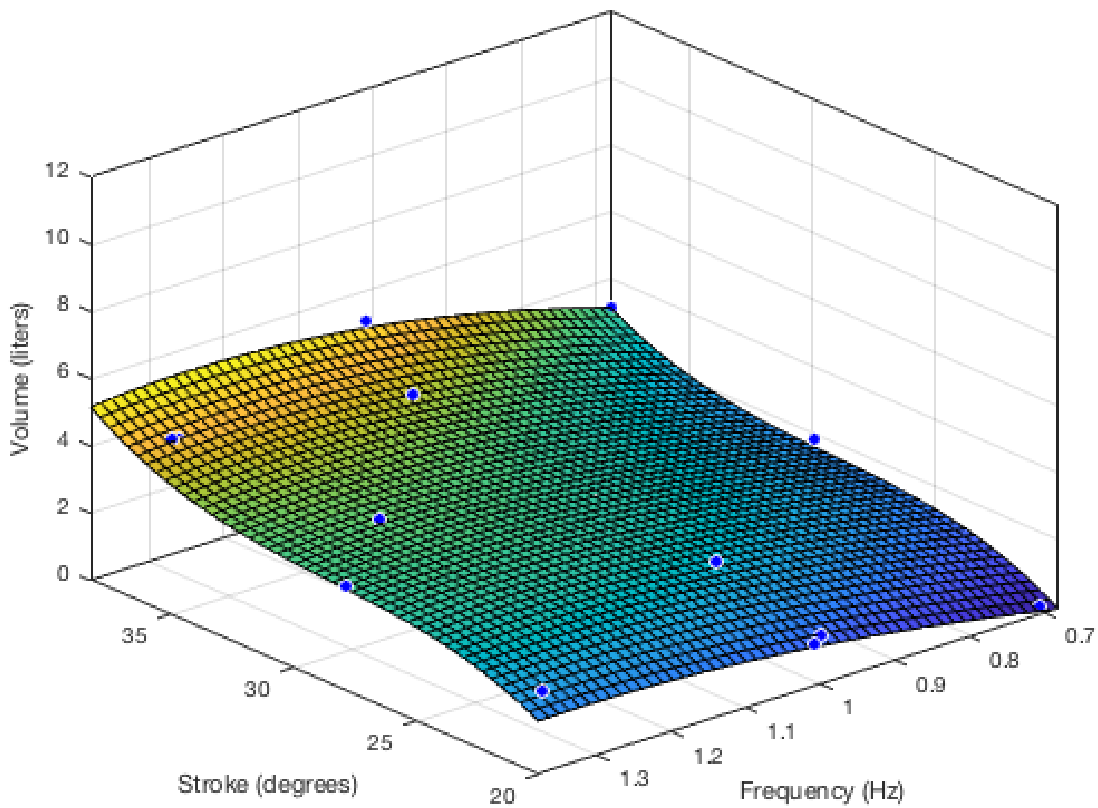

Figure A16.1. DOE borehole 1.

Equation for the response surface:

Linear model Poly33:

```
f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y
              + p12*x*y^2 + p03*y^3
```

Coefficients (with 95% confidence bounds):

```
p00 = -45.16  (-139.2, 48.87)
p10 = 4.441  (-3.144, 12.03)
p01 = 3.288  (-185.9, 192.5)
p20 = -0.1529  (-0.4109, 0.105)
p11 = 0.03618  (-2.472, 2.544)
p02 = 3.135  (-177.6, 183.9)
p30 = 0.0017  (-0.001156, 0.004556)
p21 = 0.005708  (-0.02763, 0.03904)
p12 = -0.164  (-0.8996, 0.5717)
p03 = -1.104  (-58.39, 56.18)
```

Goodness of fit:

SSE: 1.64

R-square: 0.9493

Adjusted R-square: 0.8922

RMSE: 0.4527

Files Associated with this Artifact:

Within the archive the MATLAB code associated with this artifact can be found in the folder called “DOE_Analysis”.

Pump Performance: Borehole 2 (Jinja)	Artifact A17

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson and Tom Naylor
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how much water each borehole pump discharges based on varying stroke length and stroke frequency. This information will used to characterize the pump performance as a function of stroke frequency and stroke length.

Results:
The data collected is shown in Table A17.1.

Table A17.1. Pump performance test results for borehole 2.

Test	Stroke length (deg estimated)	Stroke length (deg measured)	Stroke frequency (Hz estimated)	Stroke frequency (Hz measured)	User (for coding)	Water Volume (liters)
1	20	17.6	0.67	0.68	30	5.99
2	20	17.6	1.00	0.98	21	8.62
3	20	21.3	1.33	1.19	22	5.31
4	30	28.4	1.33	1.22	28	6.08
5	40	40.7	1.33	1.07	24	5.90
6	30	32.1	1.00	0.97	20	8.30
7	20	21.2	1.00	0.97	29	7.35
8	40	32.8	1.00	0.92	19	6.89
9	40	32.9	0.67	0.53	23	7.94
10	30	32.8	0.67	0.65	35	6.30
11	20	20.4	0.67	0.66	40	10.70
12	30	33.7	0.67	0.66	39	6.40
13	40	41.1	0.67	0.67	37	7.30
14	30	35.3	1.00	0.89	35	6.30
15	40	43.7	1.00	0.95	25	9.30
16	40	41.1	1.33	1.05	34	7.80
17	30	31.6	1.33	1.16	31	7.71
18	20	22.7	1.33	1.29	38	9.39

Test Equipment and Set up:
A full factorial DOE was planned where stroke length of 20, 30, and 40 degrees were paired with the frequencies 0.67, 1.00, and 1.33 Hz. A metronome app was used on an Android phone

to set the pace. The experience was randomized using MATLAB, and a scale was used to measure the weight of the water after each experience.

Test Procedure:

1. Set correct frequency on the metronome.
2. Pump until water flows.
3. Forward user on sensor remote.
4. Put bucket under spout.
5. Pump 20 strokes.
6. Weigh water.
7. Record user number and weight.
8. Forward user on sensor remote.
9. Repeat steps 2 – 8 until each experiment is done.

Observations and Conclusions:

A response surface was created to visualize the results from the DOE (see Figure A17.1). The irregularities in the DOE results for borehole 2 could be due to cup seals needing to be replaced (as stated by technician). Each borehole DOE vary due to the efficiency of the pump, making it hard to compare their individual outputs.

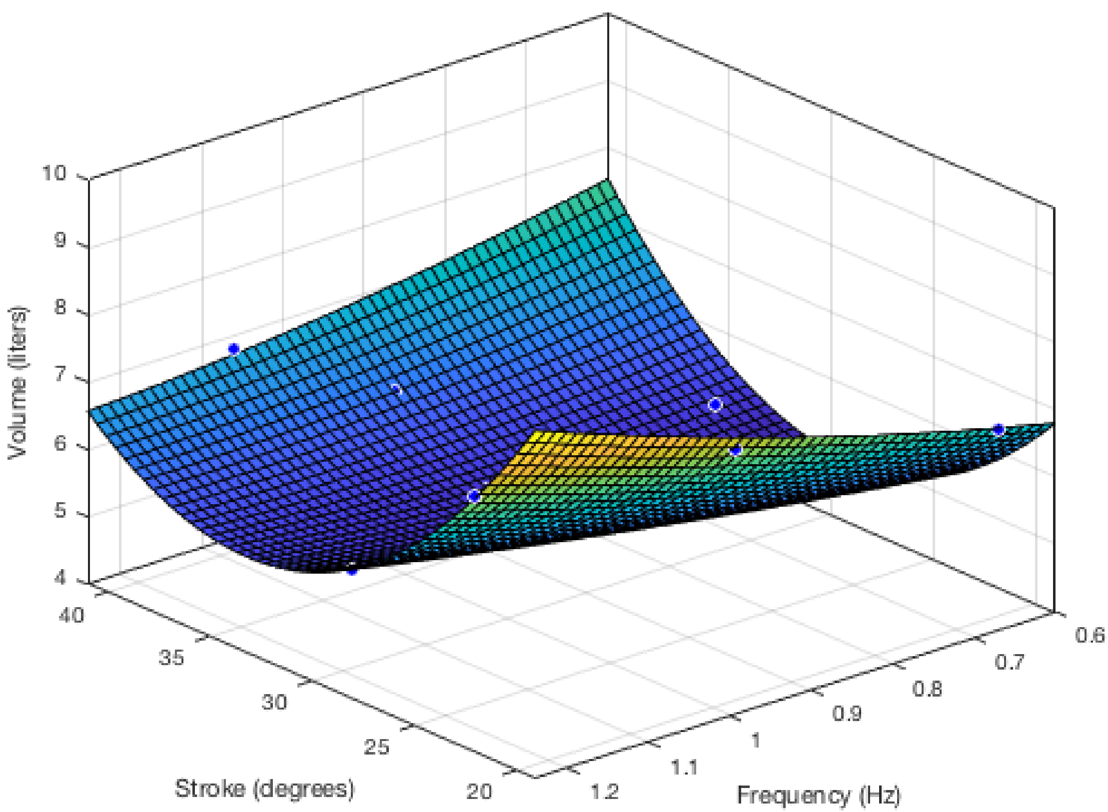

Figure A17.1. DOE borehole 2.

Equation for the response surface:
Linear model Poly22:
f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2
Coefficients (with 95% confidence bounds):
p00 = 17.02 (8.998, 25.05)
p10 = -0.9515 (-1.243, -0.6604)
p01 = 5.384 (-8.056, 18.82)
p20 = 0.01883 (0.01352, 0.02415)
p11 = -0.2388 (-0.3969, -0.08079)
p02 = 1.561 (-4.418, 7.54)

Goodness of fit:
SSE: 0.1053
R-square: 0.9872
Adjusted R-square: 0.966
RMSE: 0.1873

Files Associated with this Artifact:
Within the archive the MATLAB code associated with this artifact can be found in the folder called “DOE_Analysis”.

Pump Performance: Borehole 3 (Gulu)	Artifact A18

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson and Tom Naylor
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how much water each borehole pump discharges based on varying stroke length and stroke frequency. This information will used to characterize the pump performance as a function of stroke frequency and stroke length.

Results:
The data collected is shown in Table A18.1.

Table A18.1. Pump performance test results for borehole 3.

Test	Stroke length (deg estimated)	Stroke length (deg measured)	Stroke frequency (Hz estimated)	Stroke frequency (Hz measured)	User (for coding)	Water Volume (liters)
1	20	24.5	0.67	0.68	7	2.90
2	20	32.6	1.33	1.35	9	5.99
3	30	33.9	1.33	1.29	11	6.03
4	40	42.7	1.00	1.02	13	7.03
5	30	34.0	1.00	1.03	16	5.31
6	20	24.0	1.00	1.02	19	3.67
7	40	42.0	0.67	0.68	22	6.94
8	30	34.2	0.67	0.67	26	5.35
9	40	41.7	1.33	1.35	29	7.67
10	30	34.1	0.67	0.68	32	5.44
11	20	24.8	1.33	1.36	35	4.35
12	30	33.2	1.33	1.35	37	5.76
13	40	42.3	1.00	0.97	39	6.94
14	30	34.2	1.00	1.05	41	5.76
15	20	23.8	1.00	1.03	43	3.86
16	40	43.0	0.67	0.71	45	7.17
17	20	24.5	0.67	0.67	47	3.67
18	40	42.3	1.33	1.3	49	7.44

Test Equipment and Set up:
A full factorial DOE was planned where stroke length of 20, 30, and 40 degrees were paired with the frequencies 0.67, 1.00, and 1.33 Hz. A metronome app was used on an Android phone to set the pace. The experience was randomized using MATLAB, and a scale was used to

measure the weight of the water after each experience.

Test Procedure:

1. Set correct frequency on the metronome.
2. Pump until water flows.
3. Forward user on sensor remote.
4. Put bucket under spout.
5. Pump 20 strokes.
6. Weigh water.
7. Record user number and weight.
8. Forward user on sensor remote.
9. Repeat steps 2 – 8 until each experiment is done.

Observations and Conclusions:

A response surface was created to visualize the results from the DOE (see Figure 18.1). It can be said that in general, a longer stroke will yield a larger volume of water for borehole 3. Each borehole DOE vary due to the efficiency of the pump, making it hard to compare their individual outputs.

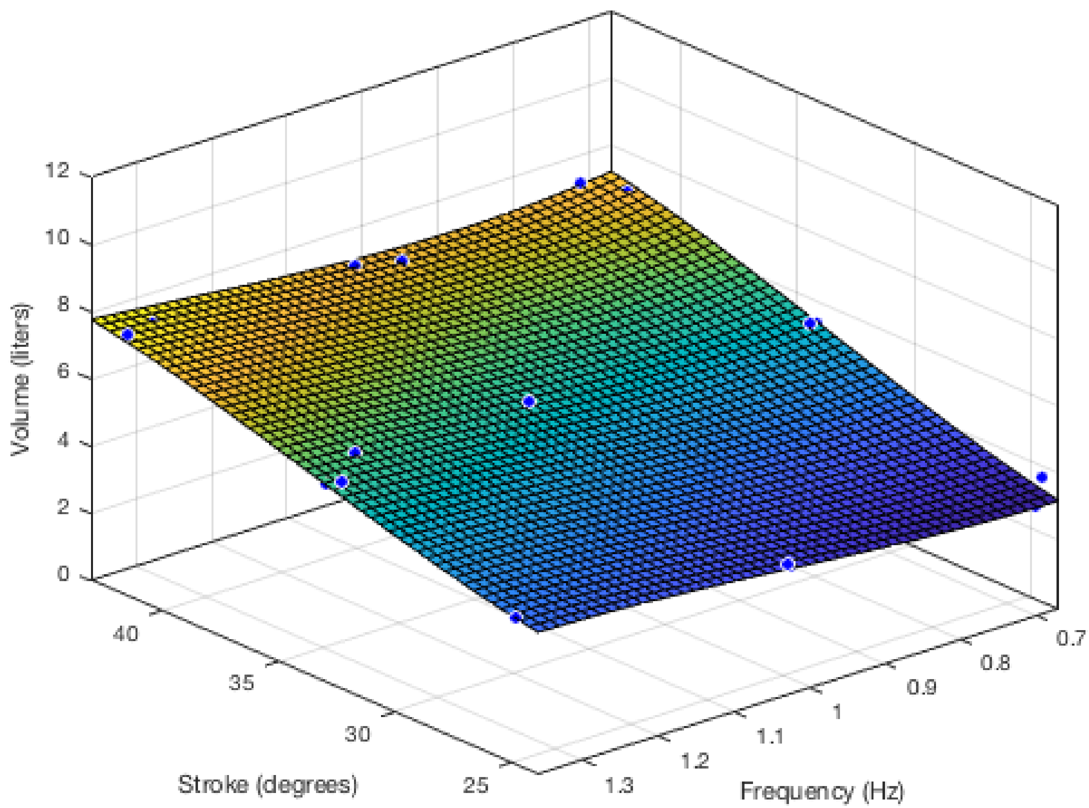

Figure A18.1. DOE borehole 3.

Equation for the response surface:

```
Linear model Poly33:
    f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y
                  + p12*x*y^2 + p03*y^3
Coefficients (with 95% confidence bounds):
      p00 = 8.941  (-159.2, 177.1)
      p10 = -0.6836  (-15.3, 13.93)
      p01 = -4.342  (-154.2, 145.5)
      p20 = 0.03366  (-0.3937, 0.4611)
      p11 = -0.434  (-2.147, 1.279)
      p02 = 11.91  (-135.2, 159)
      p30 = -0.000336  (-0.004497, 0.003825)
      p21 = 9.905e-05  (-0.01604, 0.01624)
      p12 = 0.1921  (-0.3363, 0.7205)
      p03 = -5.393  (-52.76, 41.97)

Goodness of fit:
  SSE: 0.4971
  R-square: 0.9861
  Adjusted R-square: 0.9704
  RMSE: 0.2493
```

Files Associated with this Artifact:

Within the archive the MATLAB code associated with this artifact can be found in the folder called “DOE_Analysis”.

Pump Performance: Borehole 4 (Gulu)	Artifact A19

Artifact Prepared by: Christopher Mattson and Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson and Tom Naylor
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how much water each borehole pump discharges based on varying stroke length and stroke frequency. This information will used to characterize the pump performance as a function of stroke frequency and stroke length.

Results:
The data collected is shown in Table A16.1.

Table A19.1. Pump performance test results for borehole 4.

Test	Stroke length (deg estimated)	Stroke length (deg measured)	Stroke frequency (Hz estimated)	Stroke frequency (Hz measured)	User (for coding)	Water Volume (liters)
1	30	33.0	0.67	0.71	3	5.90
2	20	23.6	1.33	1.37	5	6.17
3	30	35.4	1.33	1.29	7	9.34
4	40	46.0	1.00	1.01	9	9.80
5	30	35.7	1.00	1.00	11	7.67
6	20	23.9	1.00	0.98	13	4.54
7	40	42.0	0.67	0.68	15	7.53
8	20	22.1	0.67	0.66	18	3.31
9	40	43.1	1.33	1.21	20	9.62
10	30	32.6	0.67	0.69	22	5.31
11	20	24.0	1.33	1.32	24	5.17
12	30	32.5	1.33	1.34	26	8.12
13	40	43.9	1.00	0.98	28	9.07
14	30	31.1	1.00	0.94	30	6.67
15	20	21.7	1.00	0.99	34	3.86
16	40	40.4	0.67	0.68	36	7.17
17	20	22.3	0.67	0.68	39	3.99
18	40	42.6	1.33	1.34	42	10.98

Test Equipment and Set up:
A full factorial DOE was planned where stroke length of 20, 30, and 40 degrees were paired with the frequencies 0.67, 1.00, and 1.33 Hz. A metronome app was used on an Android phone

to set the pace. The experience was randomized using MATLAB, and a scale was used to measure the weight of the water after each experience.

Test Procedure:

1. Set correct frequency on the metronome.
2. Pump until water flows.
3. Forward user on sensor remote.
4. Put bucket under spout.
5. Pump 20 strokes.
6. Weigh water.
7. Record user number and weight.
8. Forward user on sensor remote.
9. Repeat steps 2 – 8 until each experiment is done.

Observations and Conclusions:

A response surface was created to visualize the results from the DOE (see Figure 19.1). It can be said that in general, a longer stroke and a higher frequency will yield a larger volume of water for borehole 4. Each borehole DOE vary due to the efficiency of the pump, making it hard to compare their individual outputs.

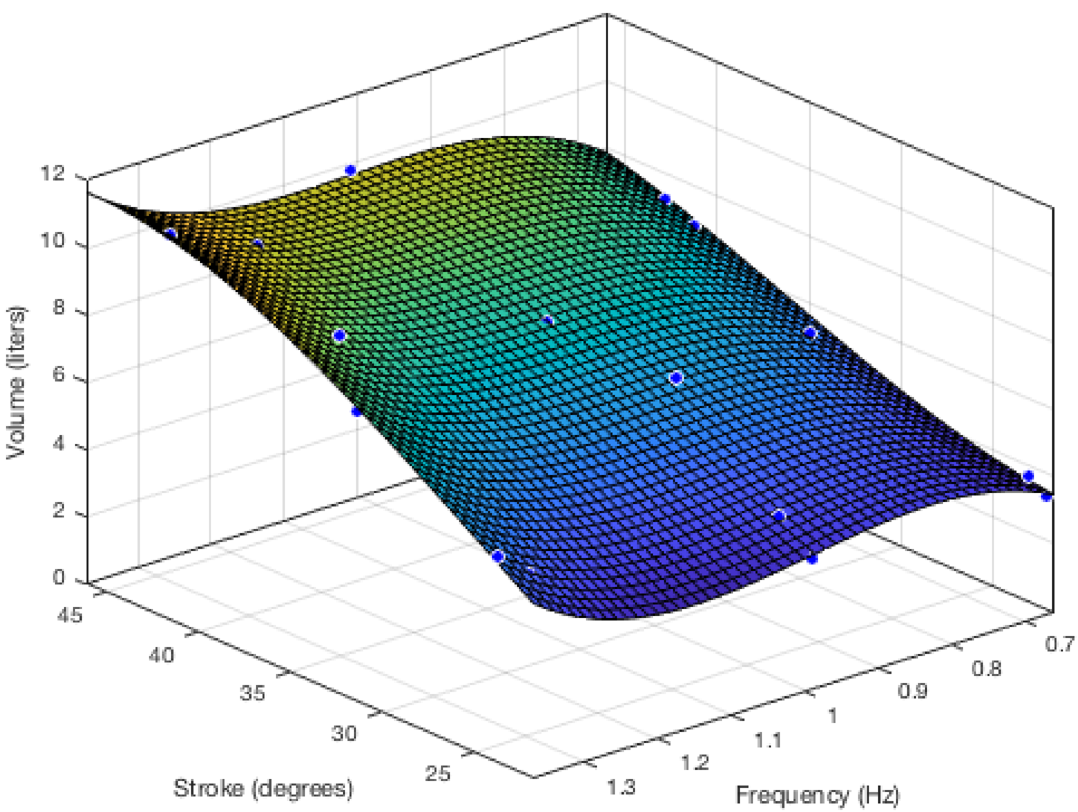

Figure A19.1. DOE borehole 4.

Equation for the response surface:

Linear model Poly33:

f(x,y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3

Coefficients (with 95% confidence bounds):

p00 = -16.98 (-66.22, 32.26)
p10 = -1.622 (-5.343, 2.099)
p01 = 109.8 (-28.69, 248.3)
p20 = 0.0384 (-0.06692, 0.1437)
p11 = 1.255 (-0.2545, 2.764)
p02 = -133.1 (-279.6, 13.35)
p30 = -0.0002693 (-0.001345, 0.000806)
p21 = -0.01382 (-0.0329, 0.005268)
p12 = -0.09833 (-0.6615, 0.4648)
p03 = 45.54 (-3.459, 94.53)

Goodness of fit:

SSE: 1.002
R-square: 0.9887
Adjusted R-square: 0.9761
RMSE: 0.3538

Files Associated with this Artifact:

Within the archive the MATLAB code associated with this artifact can be found in the folder called “DOE_Analysis”.

Pump Usage: Borehole 1 (Jinja)	Artifact A20

Artifact Prepared by: Christopher Mattson and Jake Hunter | Revision 1.1
Gender Balance Tests Performed by: Jake Hunter
Gender Balance Test Date: Test Date: 07 August 2018
Gender Balance Test Location: Video footage from Uganda, Video analysis in Provo, Utah USA

Purpose of the Test:
To understand how borehole pumps are used. The extent to which they are used, the frequency of stroke, the stroke length, the down time, the gender balance and more.

Borehole Statistics
The data gathered from borehole 1 showed that there were 526 users with 5 or more strokes. The average stroke length was 34 degrees, and the average frequency was 0.89 Hz. The effective time the pump was used was 9.51 hours. With the results from the DOE for this borehole, it is estimated that 7200 liters of water was pumped. The wave form for all users can be seen in Figure A20.1.

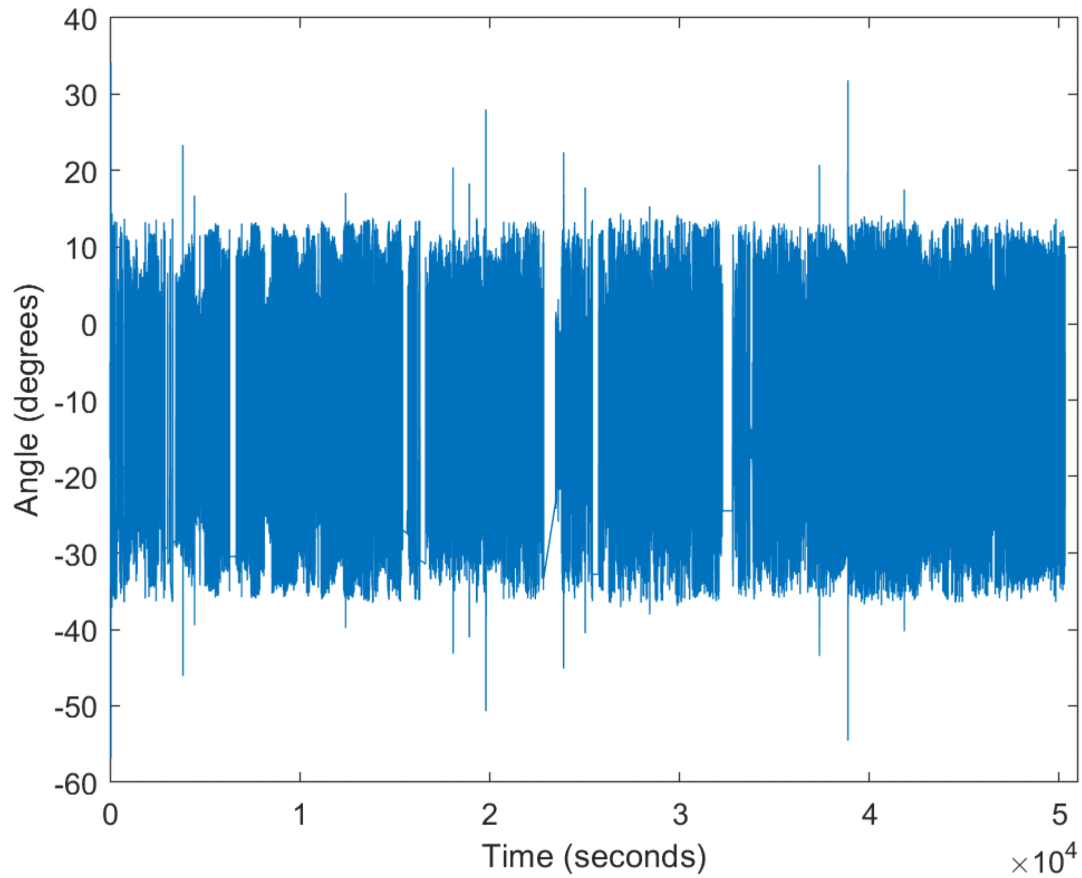

Figure A20.1. Time series for borehole 1.

Test Equipment and Set up for collecting usage data:
A sensor and an accompanying remote were used to gather user stroke and frequency data. The sensor and the remote communicate over Bluetooth. Data is collected and stored on the sensor that is attached to the pump handle. Inside the sensor is an accelerometer to measure handle movement. The remote has a user interface, notifying the operator about pump handle movement and has a button to tell the sensor when a new user starts. Both the sensor and remote were powered by battery packs.

Gender Balance Test Results:
The data collected is shown in Table A20.1.

Table A20.1. Gender balance test results for borehole 1.

Test	People deemed to be of Child Stature	People deemed to be female	People deemed to be male	Combined female and male
Number of users (fraction of total)	497 (0.82)	62 (0.10)	47 (0.08)	109 (0.18)
Minutes of pumping (fraction of total)	316 (0.478)	170 (0.257)	175 (0.265)	345 (0.522)

Gender Balance Test Procedure
Video footage was taken at each borehole site. The footage was analyzed, and each user was deemed to be either of child stature, or to be female or male. Females were identified by their clothing, which are noticeably different than those of the males. The start time and stop time of each user was recorded (see Figure A20.2).

If a user was filling a bucket, then paused to change buckets, then continued pumping, this was considered one user. If while changing the buckets someone else started pumping, however briefly, this was considered another user. People who returned to the pump site multiple times were considered new users each time.

Video footage was only analyzed during the visible light period of the day.

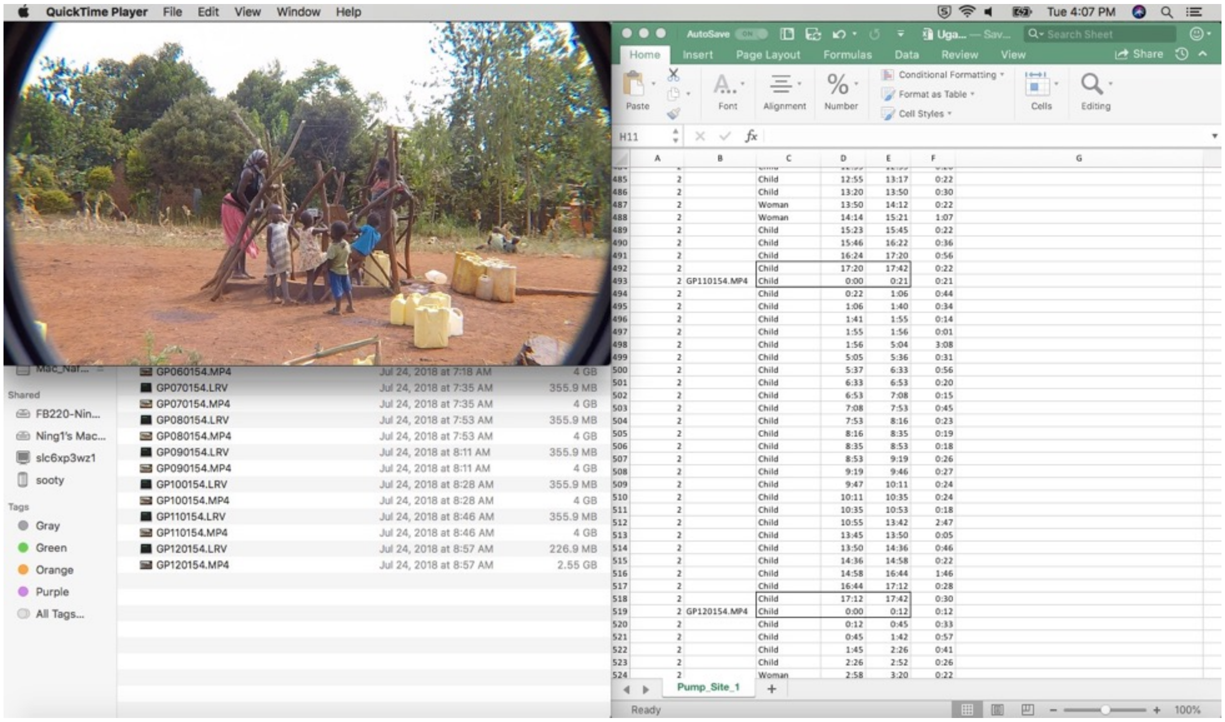

Figure A20.2. Gender analysis for borehole 1.

Pump Usage: Borehole 2 (Jinja)	Artifact A21

Artifact Prepared by: Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how borehole pumps are used. The extent to which they are used, the frequency of stroke, the stroke length, the down time, the gender balance and more.

Borehole Statistics
The data gathered from borehole 2 showed that there were 204 users with 5 or more strokes. The average stroke length was 30 degrees, and the average frequency was 1.14 Hz. The effective time the pump was used was 3.43 hours. With the results from the DOE for this borehole, it is estimated that 4470 liters of water was pumped. The wave form for all users can be seen in Figure A21.1.

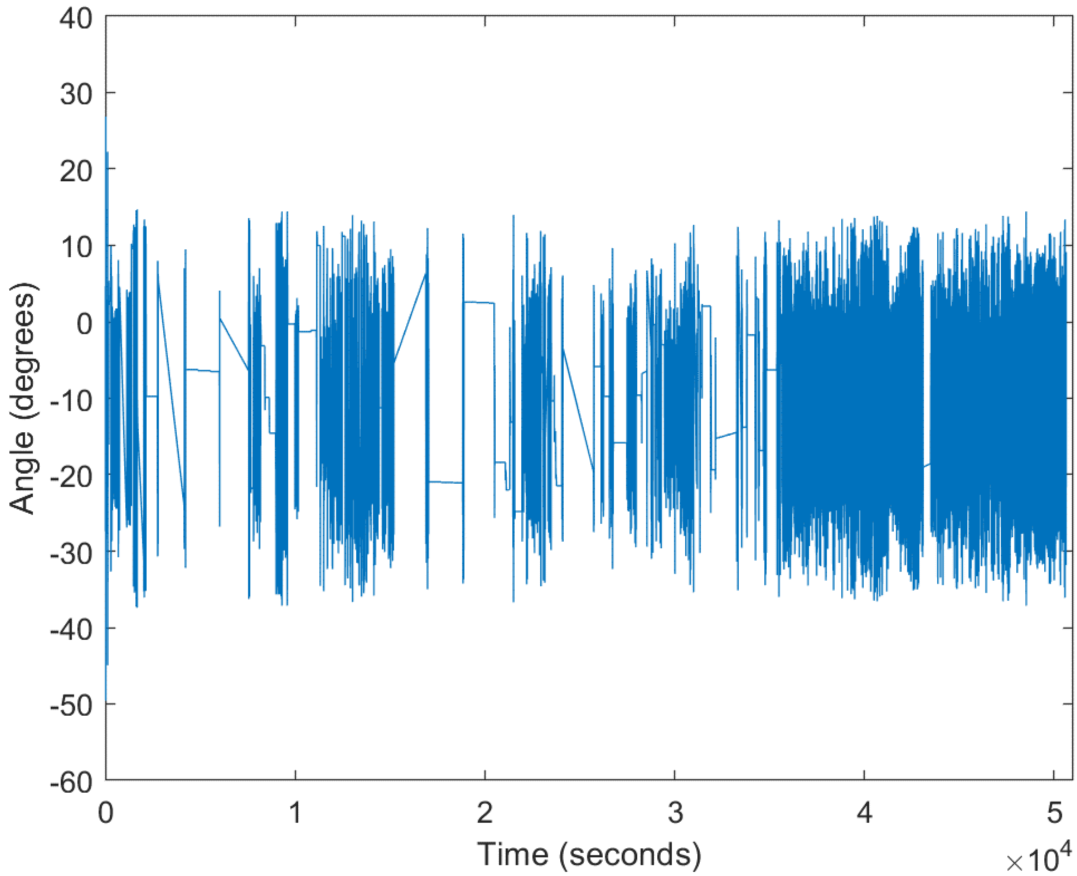

Figure A21.1. Time series for borehole 2.

Test Equipment and Set up for collecting usage data:
A sensor and an accompanying remote were used to gather user stroke and frequency data. The sensor and the remote communicate over Bluetooth. Data is collected and stored on the sensor that is attached to the pump handle. Inside the sensor is an accelerometer to measure handle movement. The remote has a user interface, notifying the operator about pump handle movement and has a button to tell the sensor when a new user starts. Both the sensor and remote were powered by battery packs.

Gender Balance Test Results:
The data collected is shown in Table A21.1.

Table A21.1. Gender balance test results for borehole 2.

Test	People deemed to be of Child Stature	People deemed to be female	People deemed to be male	Combined female and male
Number of users (fraction of total)	177 (0.80)	25 (0.11)	20 (0.09)	45 (0.20)
Minutes of pumping (fraction of total)	201 (0.640)	49 (0.156)	64 (0.204)	113 (0.360)

Gender Balance Test Procedure
Video footage was taken at each borehole site. The footage was analyzed, and each user was deemed to be either of child stature, or to be female or male. Females were identified by their clothing, which are noticeably different than those of the males. The start time and stop time of each user was recorded.

If a user was filling a bucket, then paused to change buckets, then continued pumping, this was considered one user. If while changing the buckets someone else started pumping, however briefly, this was considered another user. People who returned to the pump site multiple times were considered new users each time.

Video footage was only analyzed during the visible light period of the day.

Pump Usage: Borehole 3 (Gulu)	Artifact A22

Artifact Prepared by: Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how borehole pumps are used. The extent to which they are used, the frequency of stroke, the stroke length, the down time, the gender balance and more.

Borehole Statistics
The data gathered from borehole 3 showed that there were 214 users with 5 or more strokes. The average stroke length was 36 degrees, and the average frequency was 0.94 Hz. The effective time the pump was used was 6.24 hours. With the results from the DOE for this borehole, it is estimated that 6220 liters of water was pumped. The wave form for all users can be seen in Figure A22.1.

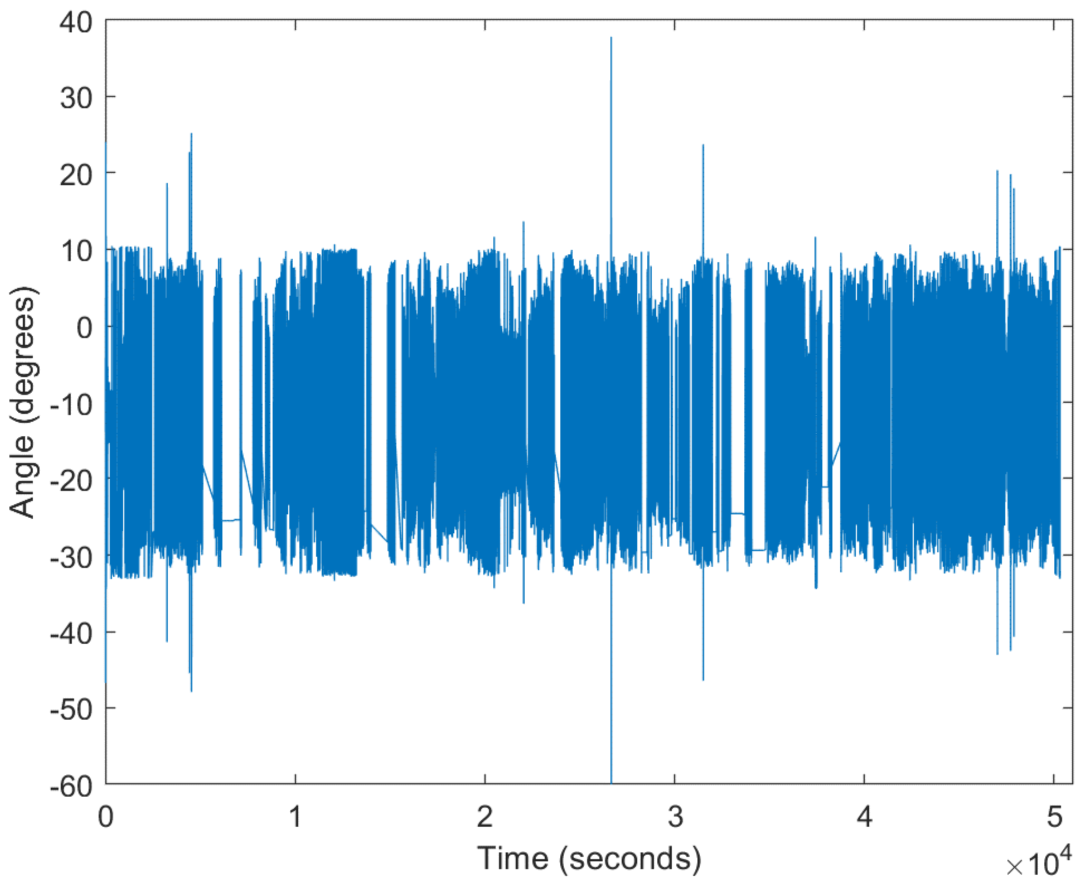

Figure A22.1. Time series for borehole 3.

Test Equipment and Set up for collecting usage data:
A sensor and an accompanying remote were used to gather user stroke and frequency data. The sensor and the remote communicate over Bluetooth. Data is collected and stored on the sensor that is attached to the pump handle. Inside the sensor is an accelerometer to measure handle movement. The remote has a user interface, notifying the operator about pump handle movement and has a button to tell the sensor when a new user starts. Both the sensor and remote were powered by battery packs.

Gender Balance Test Results:
The data collected is shown in Table A22.1.

Table A22.1. Gender balance test results for borehole 3.

Test	People deemed to be of Child Stature	People deemed to be female	People deemed to be male	Combined female and male
Number of users (fraction of total)	73 (0.38)	98 (0.52)	19 (0.1)	117 (0.62)
Minutes of pumping (fraction of total)	172 (0.301)	362 (0.634)	37 (0.065)	399 (0.699)

Gender Balance Test Procedure
Video footage was taken at each borehole site. The footage was analyzed, and each user was deemed to be either of child stature, or to be female or male. Females were identified by their clothing, which are noticeably different than those of the males. The start time and stop time of each user was recorded.

If a user was filling a bucket, then paused to change buckets, then continued pumping, this was considered one user. If while changing the buckets someone else started pumping, however briefly, this was considered another user. People who returned to the pump site multiple times were considered new users each time.

Video footage was only analyzed during the visible light period of the day.

Pump Usage: Borehole 4 (Gulu)	Artifact A23

Artifact Prepared by: Hans Ottosson | Revision 1.1
Tests Performed by: Hans Ottosson
Test Date: Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of the Test:
To understand how borehole pumps are used. The extent to which they are used, the frequency of stroke, the stroke length, the down time, the gender balance and more.

Borehole Statistics
The data gathered from borehole 4 showed that there were 392 users with 5 or more strokes. The average stroke length was 31 degrees, and the average frequency was 0.94 Hz. The effective time the pump was used was 8.62 hours. With the results from the DOE for this borehole, it is estimated that 10350 liters of water was pumped. The wave form for all users can be seen in Figure A22.1.

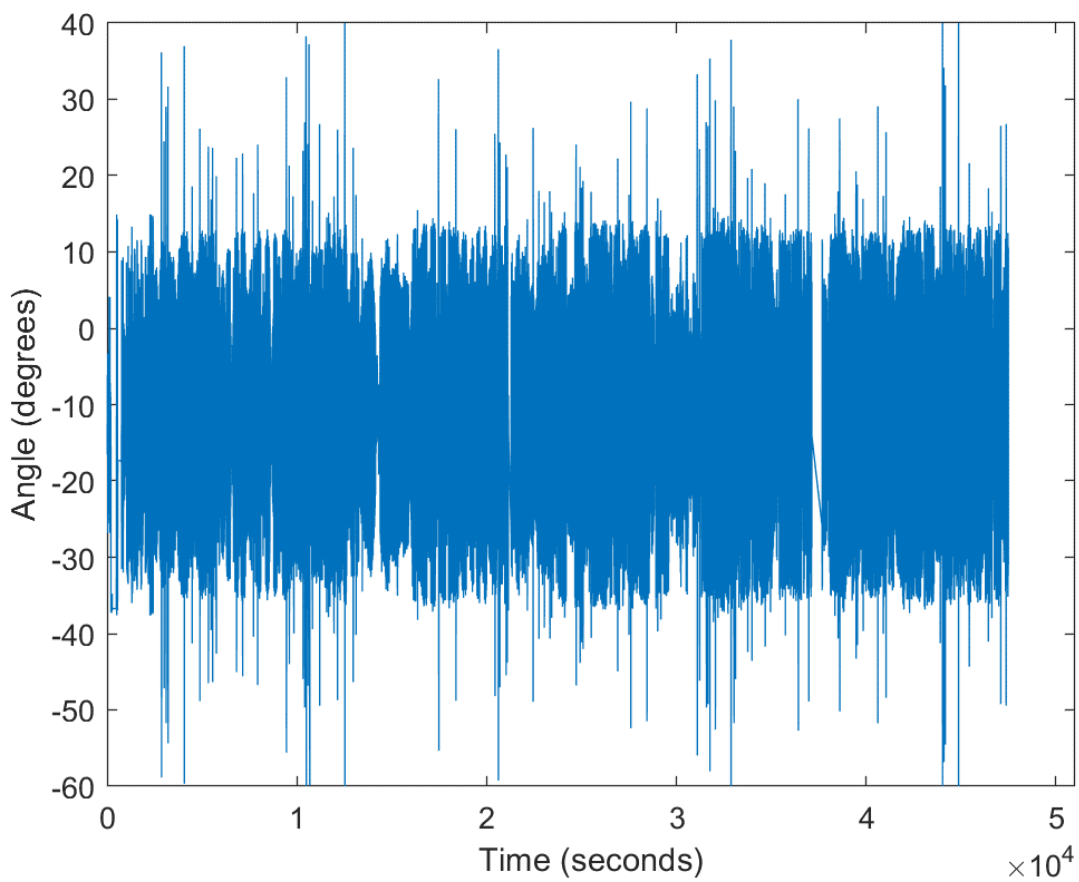

Figure A23.1. Time series for borehole 4.

Test Equipment and Set up for collecting usage data:
A sensor and an accompanying remote were used to gather user stroke and frequency data. The sensor and the remote communicate over Bluetooth. Data is collected and stored on the sensor that is attached to the pump handle. Inside the sensor is an accelerometer to measure handle movement. The remote has a user interface, notifying the operator about pump handle movement and has a button to tell the sensor when a new user starts. Both the sensor and remote were powered by battery packs.

Gender Balance Test Results:
The data collected is shown in Table A23.1.

Table A23.1. Gender balance test results for borehole 4.

Test	People deemed to be of Child Stature	People deemed to be female	People deemed to be male	Combined female and male
Number of users (fraction of total)	88 (0.34)	144 (0.56)	26 (0.10)	170 (0.66)
Minutes of pumping (fraction of total)	80 (0.161)	354 (0.714)	62 (0.125)	416 (0.839)

Gender Balance Test Procedure
Video footage was taken at each borehole site. The footage was analyzed, and each user was deemed to be either of child stature, or to be female or male. Females were identified by their clothing, which are noticeably different than those of the males. The start time and stop time of each user was recorded.

If a user was filling a bucket, then paused to change buckets, then continued pumping, this was considered one user. If while changing the buckets someone else started pumping, however briefly, this was considered another user. People who returned to the pump site multiple times were considered new users each time.

Video footage was only analyzed during the visible light period of the day.

Anecdotal Findings	Artifact A24

Artifact Prepared by: James Mattson and Hans Ottosson | Revision 1.1
Observations by: James Mattson, Christopher Mattson, Hans Ottosson, Tom Naylor
Test Date: 20 July 2018 – 03 August 2018
Test Location: Uganda

Purpose of this Artifact:
To capture some of the anecdotal findings that we believe to be true. To the extent possible, these findings were validated through non-leading discussion with Ugandans.

Findings:
Additional research can and needs to be completed around improving the performance and longevity of borehole pumps in Uganda. This includes but is not limited to collecting data to determine failure conditions that have been reported during the field study. These include:

Handle Assemble
Handle assembly including bearing, bearing house (seat), axle alignment and movement causing possible effect on chain and pump rod function and movement resulting in possible wear on the riser pipe. See photos of failed PVC, Pump rod bushing and handle.

Chain Malfunction
Chain breakage due to lack of preventative maintenance (monthly greasing) and improper pump handle use.

Pump Head Assembly failures
This includes the handle stabilizers, chain and flange-pump rod bushing and its effect on pump rod function.

Riser Pipe failure

PVC pipe fails at a high rate with vertical cracks, wear from side-to-side pump rod movement and wear from warn or missing pump rod gaskets.

Galvanized pipe fails at a moderate rate with failure due to horizontal breaking where threads meet the socket, general rust and pitting and wear do to side to side movement in the pump rod and warn or missing pump rod gaskets.

Stainless steel pipe failures were reported at a very low rate. Only one failure was noted, and it was at the thread socket joint.

Pump Rod failures
A moderate rate of failure was reported for galvanized pump rod and at a very low rate with stainless steel pump rods.

Cylinder Assembly failures

Cup seal with excessive wear due to the method of pump handle use, particulates in the water, and other factors to be determined.

Foot valve failure due to warn seals and debris at valve seat.

Upper check valve failure due to warn seals and debris that valve seat.

Figure A24.1. Failed pump cylinder copper lining.

Nitrile Cup Seal

Pump caretakers and mechanics reported that the nitrile cup seal wears out and needs to be changed frequently. Some mechanics keep old cup seals with them as backups. Some reported that they still install leather cup seals.

Pump rod Grommets

Including wear and absence. These grommets are designed to stabilize the pump rod and prevent side-to-side movement of the pump rod.

Dynamic Water Table

The depth of the cylinder in the borehole needs to be adjusted according to the specifications in the Operator’s manual.

Observations and anecdotal reports from Users, Pump Caretakers, Pump Mechanics, and Government Officials indicate following:

Boreholes and pumps are developed by both government and no-government efforts. In this studies area there were 1300 government sponsored pumps and 700 non-government sponsored pumps.

Government sponsored pumps may be developed based on the following: 1. That a water source is found. 2. That the new site is not close to an existing functioning pump. 3. That monies for the cost of the new borehole and pump be paid to the government in advance of the work beginning. 4. That each site/community form a pump committee comprising of nine members who oversee the pump use, maintenance, and repair. 5. It was reported that cost for a new borehole and pump were.

A sizable portion of many Village/Communities depend on pumps to deliver clean water.

When pumps fail it affects the user by requiring them to spend more time getting a day's supply water.

Users spend between 45 minutes to 90 minutes a day in the water collecting process.

Users may be required to pay a monthly fee to use the pump. Often this fee is not collected. This fee is approximately 1,000 shillings per household per month. These fees are often the only source of funds to repair borehole pumps.

Collected money may be used to pay the Caretaker and is saved for use when repairs are needed.

The price to service the cup seals in an India Mark II hand pump in Jinja, Uganda as of May 8th, 2021 is 40,000 Ugandan Shillings for the seals and 160,000 Ugandan Shillings for labor.

Government sponsored pumps are maintained and repaired by Government Pump Mechanics for a fee. If the Pump Committee cannot afford to repair the pump it is not fixed and government options are not offered. The community must find water at another source.

The caretaker may receive a stipend fee for managing the use of the pump. A caretaker in Gulu received 30,000 shillings per month to care for the borehole.

Governance model of Water District is organized as follows
1. User. 2. Local pump committee. 2. Sub-country Water Official. 3. County Water Official
4. State Water Minister 5. Ugandan Minister of Water. This hierarchy of governance also shows the flow of a repair request.

Maintenance and availability of pump mechanics:

Government sponsored pumps are repaired by qualified Government Pump Mechanics for a fee.

Private pumps are not repaired or maintain by government pump mechanics. Private pumps are maintained and repaired by the owner or community. The availability of private pump mechanics is unknown but is reported that they do exist.

Repairs to both private and government pumps require payment in full prior to service. It is commonly reported by users that pumps will stand unrepaired for weeks or months until funds for the repair can be gathered by the local committees or community.

It was reported that many pump mechanics feel overwhelmed due to the workload.

The cost to service an India Mark II hand pump to replace the two cup seals costs USD 58-85.

Availability of repair parts:

Repair parts for the Mark II were available in this research area through local retail shops and large suppliers of the new and used parts.

Locating and access to pump sites:

Locating and gaining access to pumps was not a barrier for this research team.

Permission to do this research was sought and granted by local water officials and support was given by local committees. It was noted that the research process did not seem to affect the users.

Summary

There is a large, yet unmeasured number, of people who depend on Borehole Pumps for clean potable water and when existing pumps fail it places these communities at risk of the health complications from using poor quality water and places an extra burden time and energy on users to secure water from another borehole.

Gaining access to the location of and permission to study borehole pumps was not a barrier in this study. There was general understanding and support for this and future study efforts.

Additional research can and needs to be completed around improving the performance and longevity of borehole pumps in Uganda. This should include collecting data to determine failure conditions that have been observed and reported during this research project. Specifically, the subassemblies of; the handle, pump head, flange-pump rod bushing, pump rod grommets, cylinder design, plunger assembly and pipe/socket.

There is general support from Government Officials and Local Committees for this work.

Internal Measurement Error Analysis	Artifact A25

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests by: Christopher Mattson
Data for tests collected by: Christopher Mattson, Hans Ottosson, Tom Naylor
Test Date: 07 August 2018
Test Data collected: 20 July 2018 – 03 August 2018
Test Location: Data collected in Uganda, Analysis done in Provo, Utah, USA

Purpose of this Test:
The purpose of this test is to characterize the uncertainty associated with the measurements methods themselves. We are interested in this uncertainty because it cannot be attributed to part variation, and therefore must be discovered to more fully characterize a part's actual variation. There is potential error in the measurements of Weight, Volume, Durometer, DIM1-DIM6. For each, a single seal was measured repeatedly 33 times or more, each time the researchers tried to reduce bias by ignoring previously measured values.

Summary of Results:
Table A25.2 shows the coefficient of variation (CV), the % error, and 3*Standard Deviation.

Table A25.1. Summary of results.

Test	Weight	Volume	Durometer	DIM1 Outer Diam	DIM2 Inner Diam	DIM3 Height	DIM4 Thickness	DIM6 Angle
CV	0.0002	0.0011	0.0337	0.0049	0.0025	0.0025	0.0030	0.0165
% Error	0.02%	0.11%	3.37%	0.49%	0.25%	0.25%	0.30%	1.65%
Stdev	0.0028	0.0130	2.9058	0.3146	0.1029	0.0296	0.0124	0.1770
3*Stdev	0.0084	0.039	8.7174	0.9438	0.3087	0.0888	0.0372	0.531

In all cases except the durometer tests and the wall angle test (DIM6), the percent error is less than half a percent. For the wall angle test, it is reasonable to expect a larger number as the test for the angle was not automated, but instead required a human to subjectively draw a line representing the wall angle on top of an image. The durometer percent error is comparatively high, but the reason for this is not known.

The number representing 3*Stdev is important as it represents the idea that we are 99.73% confident that the actual error is less than the amount shown. Note that the units for the amount shown for 3*Stdev is the native units for the item being evaluated. I.e., for weight it is grams, for volume it is g/cm^3, etc.

Test Procedure:
A single sample (IME-1) was tested many times (33 times or more). The procedure called for the complete measuring method to be carried out 33 times or more. This meant that the same part was put into and removed from the test fixture each time. Measurements were collected and the statistics were calculated on the whole set of measurements for that sample.

Table A25.2. Data for the internal measurement error analysis (weight and volume)

Test	Seal	Weight (g)	Volume (cm^3)
1	IME-1	16.76	12.014
2	IME-1	16.758	12.004
3	IME-1	16.759	12.035
4	IME-1	16.762	12.026
5	IME-1	16.754	12.036
6	IME-1	16.759	12.036
7	IME-1	16.757	12.024
8	IME-1	16.756	12.025
9	IME-1	16.762	12.018
10	IME-1	16.756	12.055
11	IME-1	16.76	12.041
12	IME-1	16.758	12.023
13	IME-1	16.759	12.05
14	IME-1	16.76	12.044
15	IME-1	16.756	12.016
16	IME-1	16.761	12.022
17	IME-1	16.764	12.02
18	IME-1	16.758	12.049
19	IME-1	16.755	12.023
20	IME-1	16.757	12.027
21	IME-1	16.757	12.024
22	IME-1	16.75	12.014
23	IME-1	16.76	12.028
24	IME-1	16.756	12.024
25	IME-1	16.759	12.02
26	IME-1	16.758	12.033
27	IME-1	16.759	12.036
28	IME-1	16.76	12.006
29	IME-1	16.754	12.035
30	IME-1	16.756	12.024
31	IME-1	16.758	12.031
32	IME-1	16.753	12.045
33	IME-1	16.76	12.056
mean		16.7579	12.0292
standard deviation		0.0028	0.0130
min		16.7500	12.0040
max		16.7640	12.0560
range		0.0140	0.0520
median		16.7580	12.0260
coefficient of variation		**0.0002**	**0.0011**

Table A25.3. Data for the internal measurement error analysis (hardness)

Test	Seal	Durometer L1 (HSA)	Durometer L2 (HSA)	Durometer L3 (HSA)	Durometer L4 (HSA)
1	IME-1	85	87.5	78	85.5
2	IME-1	82.5	81.5	80	79.5
3	IME-1	82.5	84.5	83.5	84.5
4	IME-1	81.5	82.5	83	86
5	IME-1	81.5	85	85.5	84.5
6	IME-1	82	84	85	84.5
7	IME-1	82.5	83.5	81.5	84.5
8	IME-1	84.5	82	87.5	86.5
9	IME-1	83	82.5	85	85.5
10	IME-1	85.5	85	86	83
11	IME-1	82	88.5	84.5	87
12	IME-1	84	83.5	89	86.5
13	IME-1	85.5	85.5	87	87.5
14	IME-1	86	86.5	87	87
15	IME-1	81	84	86.5	89.5
16	IME-1	79.5	86.5	89.5	88.5
17	IME-1	80.5	86.5	86	85
18	IME-1	80	89.5	89.5	89.5
19	IME-1	88	89.5	91.5	89.5
20	IME-1	87	90	91	89
21	IME-1	86	86	88	91
22	IME-1	87	89	90.5	90.5
23	IME-1	89.5	86	86	85.5
24	IME-1	82	90.5	91	89.5
25	IME-1	89	85	90	91
26	IME-1	81.5	89	85.5	87.5
27	IME-1	87.5	89	87	85.5
28	IME-1	83	87.5	88	90.5
29	IME-1	88.5	87	90.5	89
30	IME-1	86	88.5	85.5	87.5
31	IME-1	80	91	89.5	84.5
32	IME-1	89	87.5	89.5	89
33	IME-1	90.5	87.5	91	87.5
mean		84.3485	86.4091	86.9242	87.0152
standard deviation		3.1412	2.6054	3.2861	2.5905
min		79.5000	81.5000	78.0000	79.5000
max		90.5000	91.0000	91.5000	91.0000
range		11.0000	9.5000	13.5000	11.5000
median		84.0000	86.5000	87.0000	87.0000
coefficient of variation		**0.0372**	**0.0302**	**0.0378**	**0.0298**

Table A25.4. Data for the internal measurement error analysis (height)

Test	Seal	Height L1 (mm)	Height L2 (mm)	Height L3 (mm)	Height L4 (mm)
1	IME-1	11.87	11.9	11.87	11.79
2	IME-1	11.87	11.76	11.91	11.79
3	IME-1	11.99	11.76	11.92	11.8
4	IME-1	11.96	11.85	11.84	11.79
5	IME-1	11.93	11.83	11.87	11.81
6	IME-1	11.94	11.75	11.88	11.78
7	IME-1	11.88	11.82	11.91	11.82
8	IME-1	11.94	11.83	11.91	11.81
9	IME-1	11.92	11.87	11.9	11.79
10	IME-1	11.87	11.85	11.85	11.8
11	IME-1	11.94	11.84	11.89	11.81
12	IME-1	11.95	11.82	11.89	11.82
13	IME-1	11.88	11.83	11.89	11.82
14	IME-1	11.95	11.84	11.9	11.84
15	IME-1	11.95	11.83	11.86	11.82
16	IME-1	11.94	11.87	11.84	11.83
17	IME-1	11.95	11.81	11.85	11.77
18	IME-1	11.97	11.75	11.88	11.85
19	IME-1	11.97	11.89	11.89	11.81
20	IME-1	11.92	11.81	11.88	11.81
21	IME-1	11.97	11.84	11.87	11.78
22	IME-1	11.93	11.86	11.83	11.78
23	IME-1	11.92	11.79	11.86	11.84
24	IME-1	11.94	11.83	11.86	11.81
25	IME-1	11.95	11.87	11.9	11.83
26	IME-1	11.91	11.85	11.87	11.79
27	IME-1	11.91	11.84	11.86	11.81
28	IME-1	11.97	11.81	11.86	11.82
29	IME-1	11.81	11.81	11.89	11.78
30	IME-1	11.99	11.81	11.88	11.82
31	IME-1	11.91	11.87	11.86	11.8
32	IME-1	11.91	11.83	11.87	11.81
33	IME-1	11.96	11.84	11.88	11.82
mean		11.9294	11.8291	11.8764	11.8076
standard deviation		0.0395	0.0370	0.0223	0.0195
min		11.8100	11.7500	11.8300	11.7700
max		11.9900	11.9000	11.9200	11.8500
range		0.1800	0.1500	0.0900	0.0800
median		11.9400	11.8300	11.8800	11.8100
coefficient of variation		**0.0033**	**0.0031**	**0.0019**	**0.0017**

Table A25.5. Data for the internal measurement error analysis (thickness)

Test	Seal	Thickness L1 (mm)	Thickness L2 (mm)	Thickness L3 (mm)	Thickness L4 (mm)
1	IME-1	4.25	4.13	4.16	4.17
2	IME-1	4.23	4.13	4.16	4.19
3	IME-1	4.24	4.14	4.16	4.17
4	IME-1	4.23	4.15	4.17	4.18
5	IME-1	4.24	4.13	4.17	4.17
6	IME-1	4.21	4.15	4.16	4.21
7	IME-1	4.23	4.14	4.16	4.19
8	IME-1	4.22	4.12	4.16	4.17
9	IME-1	4.25	4.13	4.17	4.17
10	IME-1	4.22	4.13	4.17	4.21
11	IME-1	4.26	4.14	4.17	4.18
12	IME-1	4.25	4.13	4.17	4.17
13	IME-1	4.2	4.14	4.17	4.19
14	IME-1	4.24	4.13	4.16	4.18
15	IME-1	4.27	4.13	4.17	4.2
16	IME-1	4.26	4.14	4.17	4.21
17	IME-1	4.27	4.13	4.17	4.17
18	IME-1	4.26	4.15	4.17	4.19
19	IME-1	4.2	4.14	4.17	4.18
20	IME-1	4.27	4.14	4.17	4.22
21	IME-1	4.26	4.12	4.16	4.18
22	IME-1	4.24	4.13	4.17	4.2
23	IME-1	4.2	4.13	4.17	4.17
24	IME-1	4.25	4.12	4.17	4.2
25	IME-1	4.22	4.15	4.17	4.17
26	IME-1	4.24	4.13	4.17	4.18
27	IME-1	4.24	4.13	4.17	4.17
28	IME-1	4.26	4.13	4.16	4.19
29	IME-1	4.23	4.14	4.16	4.18
30	IME-1	4.25	4.13	4.18	4.17
31	IME-1	4.2	4.12	4.17	4.18
32	IME-1	4.24	4.13	4.17	4.19
33	IME-1	4.23	4.15	4.17	4.17
mean		4.2382	4.1342	4.1673	4.1839
standard deviation		0.0210	0.0090	0.0052	0.0146
min		4.2000	4.1200	4.1600	4.1700
max		4.2700	4.1500	4.1800	4.2200
range		0.0700	0.0300	0.0200	0.0500
median		4.2400	4.1300	4.1700	4.1800
coefficient of variation		**0.0050**	**0.0022**	**0.0012**	**0.0035**

Table A25.6. Data for the internal measurement error analysis (outside diameter, inside diameter, and wall angle)

Test	Seal	Outside Diam. (mm)	Inside Diam. (mm)	Wall Angle (deg)
1	IME-1	64.2799	41.8398	10.751
2	IME-1	64.0315	41.8965	10.7131
3	IME-1	64.25	41.6876	10.722
4	IME-1	63.8495	41.8731	10.8987
5	IME-1	63.489	41.7982	10.7681
6	IME-1	64.1377	41.4879	10.751
7	IME-1	64.0707	41.7241	10.8855
8	IME-1	64.2004	41.6485	10.3048
9	IME-1	64.3824	41.806	10.5948
10	IME-1	64.4536	41.9639	10.5948
11	IME-1	63.8006	41.7627	10.416
12	IME-1	63.8949	41.8429	10.9391
13	IME-1	64.2696	41.8275	10.6197
14	IME-1	63.7639	41.7342	10.8685
15	IME-1	64.4486	41.7452	10.9422
16	IME-1	63.7146	41.7476	10.5948
17	IME-1	64.6399	41.95	10.9013
18	IME-1	64.5341	41.7902	10.416
19	IME-1	63.8608	41.6497	10.3048
20	IME-1	63.7267	41.7239	10.6922
21	IME-1	64.4775	41.8836	10.823
22	IME-1	63.7861	41.7142	10.4915
23	IME-1	64.3154	41.7083	10.823
24	IME-1	64.0061	41.7168	10.8403
25	IME-1	64.3203	41.6725	10.6457
26	IME-1	64.1205	41.9869	11.0035
27	IME-1	64.4979	41.8385	10.7014
28	IME-1	63.9603	41.8102	10.8685
29	IME-1	63.9515	41.6168	10.6457
30	IME-1	64.7374	41.843	10.7014
31	IME-1	64.6342	41.6115	10.5915
32	IME-1	63.9456	41.7667	10.6698
33	IME-1	63.9474	41.6193	10.5948
34	IME-1	63.8391	41.7552	10.7244
35	IME-1	63.8988	41.8083	10.5915
36	IME-1	64.1076	41.7729	10.9422
37	IME-1	63.6103	41.8232	--
38	IME-1	--	41.8474	--
39	IME-1	--	41.8464	--
40	IME-1	--	41.7833	--
mean		64.1069	41.7731	10.7038
standard deviation		0.3146	0.1029	0.1770
min		63.4890	41.4879	10.3048
max		64.7374	41.9869	11.0035
range		1.2484	0.4990	0.6987
median		64.0707	41.7781	10.7073
coefficient of variation		**0.0049**	**0.0025**	**0.0165**

Water Coverage Report (Gulu and Jinja)	Artifact A26

Artifact Prepared by: Christopher Mattson | Revision 1.0
Tests Performed by: Bosco Kilama (Gulu Water District Manager)
Test Date: Test Date: 2014—2018
Test Location: Gulu, Uganda

Purpose of this Test and Artifact:
In Gulu and Jinja we met with the district water supervisor. The goal in meeting the supervisors was to disclose our research objectives, ask for their support, and ask for access to any records regarding the number of boreholes, pumps, defects, etc.

Our visit to the supervisor in Jinja resulted in general numbers, described below. Our visit in Gulu results in multiple blank forms for water/borehole assessment, and yearly data on boreholes numbers and water coverage. The reports were given to us as is, without modification.

The purpose of this artifact is to convey the data shared with us by the district water manager.

Results from Gulu:
Water District Manager: Mr. Bosco Kilama, Civil Engineer
Telephone Number: 0775594463
Email: kilamabiky@gmail.com

The following tables come directly from Mr. Kilama. They are reformatted to match the table style of this document, but the numbers are identical, the words are identical, the bolded items and highlighted items are exactly as he had them.

Note that there is no data from 2017. Note as well that it does not appear that the population information is regularly updated. The assumptions about how many people are served by a borehole vs a tap vs a protected spring is valuable. It is also interesting in the sense that we did not observe the numbers to be as stated here. With limited observations we saw the same number of people or less using a tap vs a borehole, and the same number of people using protected springs as boreholes.

Table A26.1. Water coverage report 2014.

THE DISTRIBUTION OF SAFE WATER SOURCES BY TYPE PER SUBCOUNTY AS OF JUNE 2014										
RURAL AND URBAN WATER COVERAGE										
County	Sub-County	Population	BH[8]	SP	SW	Piped Water	HDW	Total water point	Population Served	% Coverage
ASWA	1. Awach	15,229	30	10	7	1	7	55	12,100	79.5
	2. Patiko	11,319	28	7	5	0	0	40	8,800	77.7
	3. Bungatira	31,385	37	29	14	0	6	86	16,600	52.9
	4. Unyama	16,216	30	22	6	0	1	59	11,850	73.1
	5. Paicho	17,741	25	20	2	0	4	51	10,150	57.2
	6. Palaro	9,056	28	2	1	0	5	36	8,200	90.5
	Sub Total	100,946	178	90	35	1	23	327	67,700	67.1
	Total for RWS	**100,946**	**178**	**90**	**35**	**1**	**23**	**327**	**67,700**	67.1
URBAN WATER COVERAGE										
Gulu Municipal	1. Laroo	29,018	26	13	13	1	6	59	21,300	73.4
	2. Layibi	34,677	18	14	9	1	8	50	19,150	55.2
	3. Pece	49,495	16	18	7	1	7	49	18,800	38.0
	4. Bar-dege	50,112	21	11	18	1	4	55	20,200	40.3
	Sub Total	163,302	81	56	47	4	25	213	79,450	48.7
	Grand Total	264,248	259	146	82	5	48	540	147,150	55.7
Note:										
Deep borehole serves 250 people										
Shallow well serves 150 people										
Piped water network serves 1000 people										
Protected spring serves 150 people										

[8] BH = borehole, SP = protected spring, SW = shallow well, HDW = hand dug well, and all BH are assumed to be deep water wells.

Table A26.2. Water coverage report 2015.

THE DISTRIBUTION OF SAFE WATER SOURCES BY TYPE PER SUBCOUNTY AS OF JUNE 2015										
RURAL AND URBAN WATER COVERAGE										
County	Sub-County	Population	BH	SP	SW	Piped Water	HDW	Total water point	Population Served	% Coverage
ASWA	1. Awach	19,502	36	10	7	1	7	61	13,600	69.7
	2. Patiko	18,540	31	7	5	0	0	43	9,550	51.5
	3. Bungatira	32,948	39	29	14	0	6	88	17,100	51.9
	4. Unyama	17,009	32	22	6	0	1	61	12,350	72.6
	5. Paicho	24,306	29	20	3	0	4	56	11,300	46.5
	6. Palaro	13,510	31	2	1	1	5	40	9,950	73.6
	Sub Total	**125,815**	**198**	**90**	**36**	**2**	**23**	**349**	73,850	58.7
	Total for RWS	**125,815**	**198**	**90**	**36**	**2**	**23**	**349**	**73,850**	58.7
URBAN WATER COVERAGE										
Gulu Municipal	1. Laroo	32,410	26	13	13	1	6	59	21,300	65.7
	2. Layibi	36,445	18	14	9	1	8	50	19,150	52.5
	3. Pece	48,405	16	18	7	1	7	49	18,800	38.8
	4. Bar-dege	35,016	21	11	18	1	4	55	28,501	81.4
	Sub Total	**152,276**	**81**	**56**	**47**	**4**	**25**	**213**	**87,751**	57.6
	Grand Total	**278,091**	**279**	**146**	**83**	**6**	**48**	**562**	**161,601**	58.1
Note:										
Deep borehole serves 250 people										
Shallow well serves 150 people										
Piped water network serves 1000 people										
Protected spring serves 150 people										

Table A26.3. Water coverage report 2016.

THE DISTRIBUTION OF SAFE WATER SOURCES BY TYPE PER SUBCOUNTY AS OF JUNE 2016										
RURAL AND URBAN WATER COVERAGE										
County	Sub-County	Population	BH	SP	SW	Piped Water	HDW	Total water point	Population Served	% Coverage
ASWA	1. Awach	19,502	38	10	7	1	7	63	14,100	72.3
	2. Patiko	18,540	33	7	5	0	0	45	11,700	63.1
	3. Bungatira	32,948	42	30	14	0	6	92	20,100	61.0
	4. Unyama	17,009	33	22	7	1	1	64	15,400	90.5
	5. Paicho	24,306	33	20	3	0	4	60	13,950	57.4
	6. Palaro	13,510	31	2	1	0	5	39	10,500	77.7
	Sub Total	**125,815**	**210**	**91**	**37**	**2**	**23**	**363**	85,750	68.2
	Total for RWS	**125,815**	**210**	**91**	**37**	**2**	**23**	**363**	**85,750**	68.2
URBAN WATER COVERAGE										
Gulu Municipal	1. Laroo	29,018	26	13	13	1	6	59	21,300	73.4
	2. Layibi	34,677	18	14	9	1	8	50	19,150	55.2
	3. Pece	49,495	16	18	7	1	7	49	18,800	38.0
	4. Bar-dege	50,112	21	11	18	1	4	55	20,200	40.3
	Sub Total	163,302	81	56	47	4	25	213	79,450	48.7
	Grand Total	264,248	259	146	82	5	48	540	147,150	55.7
Note:										
Deep borehole serves 250 people										
Shallow well serves 150 people										
Piped water network serves 1000 people										
Protected spring serves 150 people										

Table A26.4. Water coverage report 2018.

THE DISTRIBUTION OF SAFE WATER SOURCES BY TYPE PER SUBCOUNTY AS OF JUNE 2018										
RURAL AND URBAN WATER COVERAGE										
County	Sub-County	Population	BH	SP	SW	Piped Water	HDW	Total water point	Population Served	% Coverage
ASWA	1. Awach	19,502	40	10	7	1	7	65	14,600	74.9
	2. Patiko	18,540	34	7	5	0	0	46	12,000	64.7
	3. Bungatira	32,948	45	30	14	0	6	95	21,000	63.7
	4. Unyama	17,009	34	22	7	1	1	65	15,700	92.3
	5. Paicho	24,306	36	20	3	0	4	63	14,850	61.1
	6. Palaro	13,510	31	2	1	0	5	39	10,500	77.7
	Sub Total	**125,815**	**220**	**91**	**37**	**2**	**23**	**373**	88,650	70.5
	Total for RWS	**125,815**	**220**	**91**	**37**	**2**	**23**	**373**	**88,650**	70.5
URBAN WATER COVERAGE										
Gulu Municipal	1. Laroo	32,410	26	13	13	1	6	59	21,300	65.7
	2. Layibi	36,445	26	14	9	1	8	58	21,150	58.0
	3. Pece	48,405	20	18	7	1	7	53	19,800	40.9
	4. Bar-dege	35,015	25	11	18	1	4	59	21,200	60.5
	Sub Total	**152,275**	**97**	**56**	**47**	**4**	**25**	**229**	**83,450**	54.8
	Grand Total	**278,090**	**317**	**147**	**84**	**6**	**48**	**602**	**172,100**	61.9
Note:										
Deep borehole serves 250 people										
Shallow well serves 150 people										
Piped water network serves 1000 people										
Protected spring serves 150 people										

Additional information from Gulu:
The district supervisor indicated without reference to documents that 377 boreholes are scheduled for decommission or have been decommissioned since 2014. And that currently there are 70+ boreholes awaiting repair.

Information from Jinja:
Water District Manager: Mr. David Ereemye
Telephone Number: 0772699778, 0759968334
Email: dereemye@yahoo.co.uk

We asked for a map of borehole locations. Mr. Ereemye's assistant (Alex) indicated that we could have such a document, but it did not materialize, even after reminders.

The district supervisor indicated, however, without reference to documents that the district had 1400 borehole pumps and that roughly 5% or 70 were dysfunctional. He also indicated that 40 boreholes were scheduled for decommission, but that none had yet been decommissioned because of the difficulty with paperwork and approval higher up, as decommissioning a borehole requires a place for an alternative water source.

Uganda Contact List	Artifact A27

Artifact Prepared by: Christopher Mattson | Revision 1.1

Purpose of this Artifact:
The purpose of this list is to facilitate future work within Uganda.

Table A27.1. Uganda contact list.

Name	City	Phone[9]	Email
Godfrey Lufafa (facilitator)	Kampala	0782 358 673	busogabird@gmail.com
Steven (Driver, 4-5 people + gear)	Kampala	0781 295 925 0793 617 861 0703 509 416	steveteb@gmail.com
Helen (shop worker, Shop 3)	Kampala	0777 158 999	
Paul M'Panga (US educated owner of Shop 3, and manufacturer of PVC extrusions in Mukono)	Kampala	0771 874 334 US 651 500 6573	paulmpanga@buyaya.co.ug
Edwin (Housing Jaaj's Home of Angles)	Jinja	0779 488 922	
Immy Irot (Okware) (Finance graduate living near borehole 1)	Jinja	0705 832 096 0784 324 432	emmieimma@gmail.com
Fred (steel vendor)	Kampala	0700 322 175	
Simon-Peter (Secretary of Butik Mataala, where there was during our visit a broken-down borehole pump)	Jinja	0775 567 947	
Henry Mugimba (Chairman near borehole 1)	Jinja	0752 548 801 0782 548 880	
Muhammad Mgobi (hand pump mechanic)	Jinja	0775 828 201	
David Mawerere (head of the association of hand pump mechanics)	Jinja	0772 631 368	

[9] Uganda country code is 256. Omit the 0 (first digit of the phone number when using the country code).

David Ereemye (District Water Officer, Jinja)	Jinja	0772 699 778 0759 968 334	dereemye@yahoo.co.uk
Abubaker Sekimuli Runs a drill team	Jinja	0752 082 970	
Alred (man living next to borehole 2)	Jinja	0784 355 555 0753 661 555	
Wahab (Driver, large safari van)	Entebee	0774 672 202 0704 910 776	
John (Worker Safari Guide, Son at YEBO lodge)	Murchison Falls Park		Muhumuzabonny2@gmail.com
Polycarp (Village Drill operator in Gulu)	Gulu	0777 762 311	
Bosco Kilama (Assistant District Water Officer, Gulu)	Gulu	0775 594 463	kilamabiky@gmail.com
Martin Luquere (Hand Pump Mechanic)	Gulu	0777 327 374	
Evelynn Aber (Hand Pump Mechanic, lives near borehole 3)	Gulu	0782 827 904	aberevelyne@gmail.com
Ravi (Indian salesman of pumps, high tech and low)	Kampala	0757 290 403	accounts@sevenhills.co.ug
Roy Labeja (RM, guide/helper in Gulu, lives near borehole 3)	Gulu	0772 795 251	
Dennis Okello (Assistant of in charge Water at the Sub-county level)	Gulu	0773 228 215	
Robinson Akena **(**Chairman of Sub-county)	Gulu	0788 381 925	
Charles Boton (Sub-county office worker)	Gulu	0775 848 930	
Orombi Patrick (Has a borehole needs a pump but not sure there is water)	Jinja	0782 758 639	Pat_orombi@yahoo.com

Alex Kyombo Fredrick (Assistant at Jijna Water Department)	Jinja	0772 304 796	
Magunda (Pump Mechanic)		0772 348 464	
Ojok (Pump mechanic who repaired borehole pump # 1)	Jinja		
Jacol (Street contact. Says he knows pump/parts supply retailers)	Gulu	0772 863 131	
Brian Gitta (Innovator – Bloodless Malaria test)	Kampala	0704 319 257	gittabrian@gmail.com, matibabu@thinkitlimited.com
Namansa Brayan (Plumber...Son of the owner of store #5)	Jinja	0753 595 981	Namansabrayan8@yahoo.com
Christopher (Keeper of Borehole #4)	Gulu	0770 549 777	
Innocent Kilama (Keeper of Borehole #3)	Gulu	0706 191 122	
Phillip Odiambo (Capable, articulate college student at church)	Gulu		fideliophill19899@gmail.com

Discharge Test: Borehole 1, (Jinja) Done by Immy Irot	Artifact A28

Artifact Prepared by: Hans Ottosson | Revision 1.0
Tests Performed by: Immy Irot
Test Date: Test Date: 2:30 pm, 15 August 2018
Test Location: Jinja, Uganda

Purpose of the Test:
To see variations over time and difference of pump performance after service. A discharge test is performed to measure the functionality of the borehole pump.

Test Equipment and Set up:
The same sensor that was used for testing pump performance and usage was left with Immy Irot at Borehole 1 to be used for testing borehole performance over time. The sensor data is to be sent to BYU after performed tests.

Test Procedure:

1. Charge sensor battery.
2. Attach sensor to pump handle.
3. Pump until water flows.
4. Put water container under spout.
5. Pump 40 strokes in about one minute.
6. Weigh water.
7. Record weight.
8. Send data file to BYU.
9. Charge sensor battery.
10. Delete sensor data from sensor.

Results:
It took 7 strokes to prime the pump (pumped at 1.1517Hz at an average stroke length of 45.4712°). After that, Immy pumped 40 continuous full strokes at a frequency of 1.0706Hz with an average stroke length of 49.0163° and got a volume of 11.2 liters.

Figure A28.1 displays the time series for the discharge test and Figure A28.2 shows the jerry can used for collecting water and the sensor placement.

Observations and Conclusions:
For an India Mark II and III hand pump to function well, at least 16 liters of water should be pumped during the 40 strokes. Something is not working well with the pump at borehole 1 to only produce 11.2 liters. When we were there, the pump needed 214 strokes to get primed in the morning, so we suspect the foot valve to be malfunctioning, but we also think that the cup seals need to be replaced. We hope to get discharge data after they have serviced the hand pump again to see if we get better results.

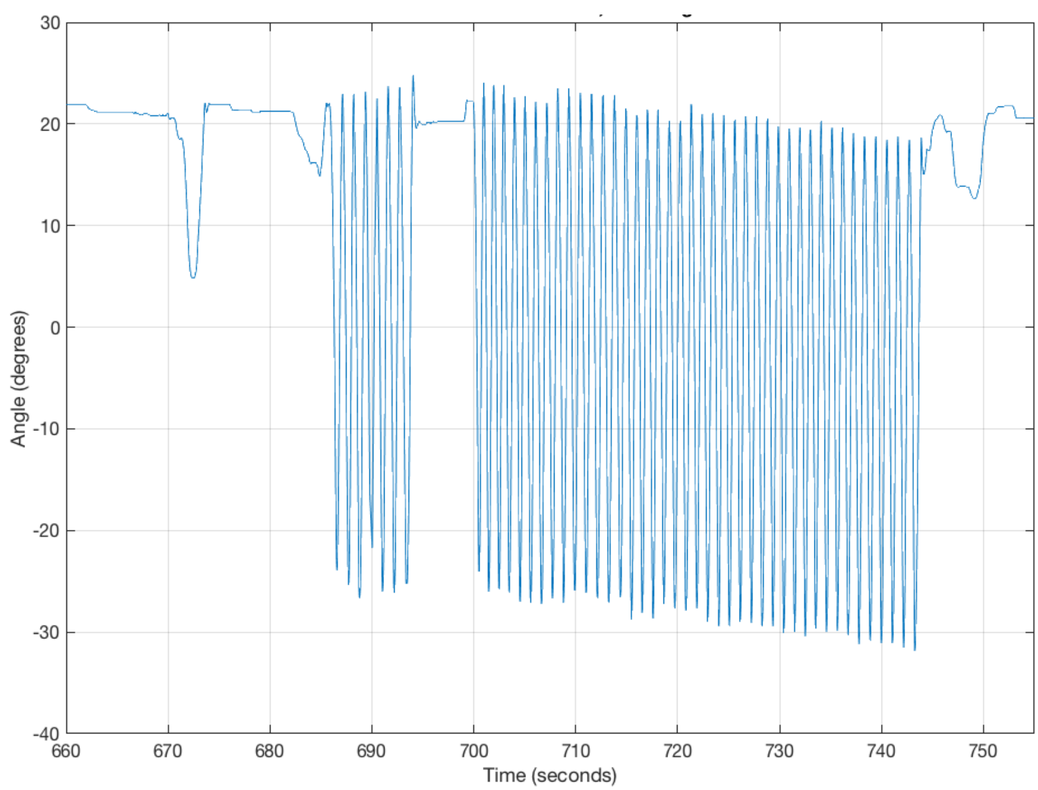

Figure A28.1. Time series for discharge test.

Figure A28.2. Jerry can used for test and placement of pump sensor.